Multifunctional integration of breakwaters: taking ecological protection and restoration as an example

Yuyang Xia[*]

Shanghai Ocean University, College of Marine Science and Ecology, China

Abstract. This paper focuses on breakwater design and development in coastal and ecosystem protection contexts. It investigates traditional breakwaters' negative impacts on the marine ecosystem, like disrupting sediment transport and reducing water exchange, causing sediment accumulation and pollution. Current research deficiencies are identified, including a lack of long-term ecological impact studies, insufficient research on sustainable materials, and incomplete impact assessments on local communities and the economy. The review investigates breakwater-ecosystem integration in three aspects. For water exchange, it discusses culverts and permeable breakwaters, considering their effectiveness and factors like location and size. Eco-friendly materials like ecological concrete and its benefits for organisms and the environment are presented, along with other recycled materials' economic advantages. The importance of providing biological habitats to increase biodiversity is also investigated. Case studies illustrate these concepts. However, current breakwater design and research have limitations. Future research should focus on ecological functions, compensation and restoration strategies, sustainable materials, and impact assessments. International cooperation should be enhanced for more effective breakwater design and sustainable coastal development.

1 Introduction

In the past decade, economic development and population migration have led to a significant increase in coastal population density, for example, in China's southeastern coastal cities from 2000 to 2010[1]. Moreover, China's floating population continues to migrate to the eastern coast. At the same time, disasters such as rising sea levels threaten coastal and island developing countries, disrupting the ecological balance and economy. Coastal protection projects are crucial for local development [2]. Breakwaters, as traditional protection structures, are built offshore to reduce the power of waves and protect coastal areas. Ancient coastal residents used stones to resist waves. In Roman times, concrete promoted the construction of breakwaters. Since the 20th century, their development has diversified, and the number of structural combinations has increased. Nowadays, in addition to wave dissipation, breakwater designs also incorporate sustainable development elements. When

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[*] Corresponding author: 2229517@st.shou.edu.cn

designing breakwaters, five aspects should be considered: determining wave conditions, selecting the appropriate type, ensuring the source of materials, and verifying and improving the results of model tests.

Under the concept of sustainable development, there are currently deficiencies in breakwater design research, which limits innovation and also poses challenges to marine ecological protection, resource utilization, and regional development. For example, environmentally unfriendly situations are common. In terms of ecological protection, research on the long-term impact of breakwater construction and operation on the ecosystem is not comprehensive, and there is little research on ecological compensation and restoration measures for its negative impacts. In terms of material selection, there has been insufficient research on sustainable and environmentally friendly materials. Most breakwaters still rely on traditional materials, which increases resource consumption and environmental pressure. The impact of breakwater construction on local communities and economies has not been fully assessed. With the continuous progress of engineering technology, the materials of breakwaters have become more diverse, ranging from the initial natural stone to concrete and more. There have also been innovations in the shape and structure of breakwaters to adapt to different marine environments and protection needs. Research has found that in recent years there has been a trend that more and more breakwaters are designed to incorporate wave attenuation and other functions. The materials, shapes, and structures of traditional breakwaters have been modified to minimize these adverse effects by increasing their ecological functions. For example, breakwaters are integrated with wave dissipation dikes and ecosystem protection and restoration, which can help enhance ecosystem stability and biodiversity.

This study explores the coordinated development of coastal protection and ecosystem protection and restoration in the form of a literature review based on a large amount of literature on the multi-functional integration of breakwaters.

2 Types of integration of breakwaters with ecosystem protection and restoration

2.1 Breakwaters to Promote Water Exchange

Traditional breakwaters can impede the transport of sediment by the exchange of water along the coast, thereby affecting the natural sediment transport process and leading to the accumulation of sediment in the water area [3]. In addition, the reduction in water exchange can also cause polluted water nearby to accumulate in the harbour basin and surrounding sea areas under the push of waves. For example, on the coast of the East China Sea with a relatively high sediment content, the encircling port breakwaters are commonly seen in muddy coastal areas. These encircling port breakwaters are composed of traditional gravity breakwaters. Although they provide good stability for moored ships, there are problems such as water pollution in the harbour basin and a decline in water environment capacity [4]. To mitigate the impact of sediment deposition and declining water quality on the marine ecosystem, there are currently two improved designs for traditional breakwaters: breakwaters with culverts and open-cell breakwaters.

Excavating a culvert on the surface of a traditional breakwater is an economical and effective way. It can connect the basin to the open sea to a certain extent and enhance water exchange by utilizing the hydrodynamic force of rising and falling tides. However, due to the differences in hydrodynamic conditions of each water area, the location and size of the culvert will affect the stability of ship mooring and water exchange in the port [5]. For example, Chaofan Lv and Xizeng Zhao found through experimental calculations that an increase in relative length leads to a reduction in the maximum oscillatory flow and thus weakens the water exchange capacity [6]. In coastal areas with small tidal ranges, setting the culvert location at sea level has a better water exchange effect than being located below sea level [7].

Weigel proposed in 1961 that a permeable breakwater composed of multiple rows of rigid piles spaced closely can effectively improve the water exchange capacity [8]. The lower support structure of the permeable breakwater is different from the traditional breakwater surface. There is a certain gap between the structures below the water surface, and water can pass freely below. A wave-blocking structure can be set at the water surface to effectively reduce wave energy. The gap can cause the incoming waves to form vortices inside, thereby further dissipating wave energy. There are four structures of permeable breakwaters, namely perforated baffle type, pile foundation type, curtain wall type, and caisson pier type [9]. In recent years, three new types of permeable breakwaters, namely comb type, buttress type, and perforated caisson type, have been proposed [10]. The semi-permeable breakwater is made of block materials with pores (such as porous concrete blocks or irregular gravel). Another type of semi-permeable breakwater is a combination of a rigid breakwater surface and an internal partially permeable structure.

2.2 Breakwaters made of eco-friendly materials

Rock and concrete from quarries are the two common construction materials used in traditional breakwaters. However, quarrying causes serious damage to local vegetation, water bodies and soil, leading to soil erosion and a decrease in biomass [11].

Ecological concrete is a concrete material specially designed for environmental protection and ecological restoration. Unlike commonly used concrete, the aggregate of ecological concrete can be recycled from construction waste, industrial waste and domestic waste that meets certain standards. Some natural aggregates can also be used. This is in line with the concept of sustainable development and resource recycling [12]. In addition, ecological concrete has a uniformly and continuously distributed pore structure and a certain degree of water permeability. It can also provide a habitat for marine animals and plants, forming a biological community. This makes ecological concrete breakwaters part of the ecosystem, compensating for the traditional breakwaters' inability to serve the ecosystem. As a result, ecological concrete breakwaters combine the dual functions of being environmentally friendly and providing a habitat for organisms.

Some recycled waste materials can exhibit great potential if properly processed. They can be reused in the construction of eco-friendly breakwaters, thereby achieving resource recycling and reducing negative environmental impacts. From the perspective of resource consumption, the production of traditional breakwater construction materials usually requires a large amount of mining of natural resources such as ore and gravel. The use of recycled waste materials for breakwater construction can effectively reduce the demand for new resources and the environmental pressure caused by resource mining. Furthermore, the use of recycled waste materials as construction materials has significant advantages in terms of economic costs. Recycled materials are generally low-cost, as the acquisition costs of waste such as used tyres and waste plastics are relatively low, often lower than the cost of purchasing new building materials. In some areas, these wastes can even be obtained for free, and builders or construction companies only need to pay the transportation and processing costs to turn these wastes into usable building materials.

2.3 Breakwaters with Biological Habitat Functions

The smooth and repetitive surface of traditional breakwaters is not conducive to the habitat and reproduction of organisms. Instead, it attracts invasive species that are highly tolerant of various environments, changing the competition pattern. This results in the diversity of marine animal and plant communities on the surface of infrastructure being generally lower than that in natural communities [11]. Moisés A. Aguilera et al. compared the biodiversity of a granite breakwater with that of a natural rocky shore. They found that the species diversity and abundance of the natural habitat were higher. The lack of microhabitats on the breakwater results in a decrease in biodiversity. In addition, Moisés A. Aguilera et al. studied the thermal patterns of artificial breakwaters and their impact on biodiversity. They found that the rock temperatures of artificial breakwaters were higher and less variable spatially, resulting in lower biodiversity and reduced species richness and species density [13].

3 Case studies on the integration of breakwaters and ecosystem protection and restoration

3.1 Research and case studies on breakwaters that promote water exchange

V.K. Tsoukala and C.I. Moutzouris proposed that in coastal areas with low tidal ranges such as those along the Mediterranean coast, for example, in Greece. To be more in line with the main mechanism of tidal hydrodynamics, the flushing culvert formed by aligning the longitudinal axis of the culvert on the breakwater with sea level is a common layout. The water exchange through the culvert creates a flushing effect in the port and helps reduce the pollution levels of chemicals, organisms and floating solids. The flushing culvert can reduce the pollutant concentration in the port basin by between 70% and 90% within 24 hours. The effect of wave penetration, that is, the effect of water exchange, can be quantified by the wave transmission coefficient. The higher the wave transmission coefficient, the better the effect of water exchange. From the perspective of culvert geometric characteristics, studies have found that increasing the width, height and submergence depth of the flushing culvert and reducing the length of the culvert can increase the transmission coefficient, thereby enhancing water circulation and exchange, helping to reduce pollutant concentration and improve water quality. From the perspective of wave characteristics, studies have found that the wave transmission coefficient increases with the increase of wave period and decreases with the increase of incident wave height. For vertically incident waves, the wave transmission coefficient is relatively higher [14,15].

Chaofan Lv, Xizeng Zhao and Mingchang Li proposed a new type of ecologically protective breakwater, the inclined culvert vertical breakwater, based on the original horizontal culvert vertical breakwater to further promote water exchange and reduce sediment deposition. The characteristic of this breakwater is that inclined culverts are set on the vertical breakwater. When the inlet of the culvert located in the open sea is higher than the outlet of the culvert located in the port, the high-turbidity water at the bottom of the port will flow into the sea through oscillatory flow, and the low-turbidity water on the sea surface will flush the port area. The lower foundation is a permeable gravel pile, which can effectively dissipate wave energy, reduce the reflection coefficient and wave force on the inclined culvert vertical breakwater, and maintain the stability of the structure. The inclined culvert vertical breakwater is more conducive to engineering applications than the horizontal culvert vertical breakwater. It can effectively improve the stability of ship berthing and structure, further promote water exchange, and improve the port environment.

Charles K Sollitt and Ralph H Cross pointed out the relationship between the wave transmission coefficient and the geometric characteristics of the permeable breakwater. The wave transmission coefficient decreases with the decrease of the porosity and permeability of the permeable breakwater, decreases with the increase of the width of the breakwater, and decreases with the increase of the steepness of the breakwater [16, 17].

The Huangqi fishing port is in the Huangqi Bay on the south side of the Huangqi Peninsula in Lianjiang County, Fujian Province. Huaidong Xie pointed out that the lower permeable structure of the new permeable breakwater of the Huangqi fishing port is a pile foundation. Several inclined piles in different directions form a group. Different pile foundation structure units are staggered in two rows back and forth and connected by longitudinal and transverse beam systems. The superstructure is a spatial frame structure, which is composed of upper and lower pile caps and trapezoidal rigid columns connecting them and is integrated with the pile foundation. The vertical piles are staggered back and forth. Multiple rows of permeable baffle plates are set between the piles. Multiple rows of cantilever wave-blocking structures are set under the lower pile cap, and the bottom end extends below the checked low water level. A proper amount of riprap is laid under the breakwater and together with multiple rows of inclined pile groups in different directions, it forms a wave dissipation system at medium and low water levels [18].

The new port area of Yeosu in South Korea plans to expand the northern port area on the original basis. A new type of water exchange breakwater structure, namely the perforated caisson permeable breakwater, is adopted in a local section of about 33m at the root of the breakwater on the outside of the northern port area. Yusheng Shen and others pointed out that the outside of this breakwater is a sloping breakwater, and the inside is a caisson structure. The caisson includes four compartments, and each compartment is perforated. The innermost perforation position is relatively low. This new type of water exchange breakwater has a certain water exchange capacity [19].

3.2 Research and cases of breakwaters using eco-friendly materials

Ecological concrete has a pore structure that is evenly and continuously distributed and has a certain degree of water permeability. It can also provide a habitat for marine animals and plants, forming a biological community, so that the breakwaters built with ecological concrete become an integral part of the ecosystem. Bas W. Borsje and others proposed that the introduction of ecological concrete in the construction of ecologically enhanced breakwaters can effectively alleviate the problem of declining biodiversity. The holes and gaps in the breakwater provide shelter and hiding places for small benthic organisms. These organisms usually live in caves and crevices. The holes and gaps in the breakwater also provide a habitat for the larval stages of non-benthic organisms. In the study, it was found that the proportion of invasive species to native species on the ecologically enhanced breakwater was significantly lower than that on the standard breakwater. Although 12 invasive invertebrates were also found on the ecologically enhanced breakwaters, there were also 21 native species. In contrast, there were only 10 invasive species and 5 native species on the standard breakwater. This suggests that the design of the ecologically enhanced breakwater helps to attract and support communities of native species, which are better able to compete with invasive species for space [20].

Steven B. Scyphers et al. conducted experiments at two sites along the rapidly eroding coastline of Alabama. At each site, two subtidal breakwaters made of loose oyster shells were constructed, and an unaltered plot was set up as a control, using a randomized paired design. The fish and mobile invertebrate communities near the breakwaters were more diverse than those in the control areas. The total abundance of species captured in 10-cm gill nets was higher near the breakwaters. For benthic fish, the 10 cm gill net catch was richer near the breakwater. From the data captured by the purse seine, there was no difference in the total abundance of benthic fish, but the total abundance of decapod crustaceans such as crabs was higher near the breakwater. The abundance of some economically important species such as blue crabs, red drums, spotted trout and flatfish increased significantly near the breakwater [21].

Lea T. Mamo et al. found that the rock elements that make up the breakwater have a significant impact on benthic organisms. In an ecological engineering modification of an upgraded breakwater in Coffs Harbour, Australia, the impact of different rock elements on benthic organisms was assessed through research. The assemblage of primary grey rocks was more diverse than the assemblage of granites at one site, and the diversity of endangered algae on the rock bottom was higher than on the top at this site. The results suggest that incorporating different sizes of primary rocks into the blocks and layers that make up the breakwater can improve the biodiversity of coastal protection infrastructure [22].

4 Conclusion

Breakwaters play a vital role in coastal protection and the protection of port facilities, and their effectiveness should not be overlooked. However, the materials traditionally used for breakwaters have several negative impacts on the marine ecosystem. With the advancement of engineering technology, environmentally friendly materials such as ecological concrete have begun to be used in the construction of breakwaters. The shape and structure of breakwaters are also constantly being innovated and evolved. For example, new structures such as breakwaters with culverts and permeable breakwaters with open cells can effectively promote water exchange, reduce sedimentation, and improve water quality. In addition, breakwater designs with biological habitats are beneficial for increasing biodiversity and maintaining ecosystem balance.

However, there are still some limitations in the current design and research of breakwaters. For example, the long-term impact of breakwater construction and operation on the ecosystem has not been fully studied, and there is a lack of quantitative research on the effect of permeable breakwaters on water quality improvement. There has been relatively little research on ecological compensation and restoration measures for their negative impacts. In terms of material selection, research and application of sustainable and environmentally friendly materials still need to be strengthened. At the same time, the impact of breakwater construction on local communities and the economy has not been fully assessed. Future research should focus on the following areas:

Moreover, further research on the ecological functions of breakwaters should be conducted, a comprehensive exploration of the impact mechanisms on the marine ecosystem should be made, and more scientific and reasonable ecological compensation and restoration strategies should be developed. For example, research and development efforts on sustainable and environmentally friendly materials should be intensified, newer environmentally friendly materials should be actively explored, and their wide application in breakwater construction should be promoted, to effectively reduce resource consumption and environmental pressure. Furthermore, a comprehensive assessment of the impact of breakwater construction on local communities and the economy should be carried out, and more comprehensive and holistic planning and decision-making should be formulated to achieve coordinated and sustainable development of the economy, society and environment.

Finally, international cooperation and exchanges should be vigorously strengthened to widely share the experience and technology of breakwater construction and jointly respond to global challenges such as sea level rise. In summary, through continuous research and innovation, breakwaters are expected to achieve more significant ecological benefits while improving their protective effectiveness, contributing to the sustainable development of coastal areas.

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