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Investigation of Wave-Structure Interaction in Floating Breakwaters

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ABSTRACT

Pontoon breakwaters are one of the most common types of floating breakwaters. Floating breakwaters are mainly used for wave reflection and energy dissipation. Wave energy loss by turbulence in the current is caused by the transmission of waves through the structure. Also, since waves break on the upper side of the structure, wave energy decay occurs. The efficiency of floating breakwaters is generally presented by a factor that is called transmission coefficient. The transmission coefficient is a ratio of the transmission wave height to the incident wave. This study tries to investigate the performance of floating breakwaters. For a realistic assessment, the Caspian sea's hydrodynamic conditions are used. Also, two types of floating pontoon breakwaters have been modeled. This research aims to evaluate the performance sensitivity of breakwaters in relation to their geometry and wave characteristics like wave height and period. Hydrodynamic conditions are simulated by ANSYS AQWA finite element software. At first, a rectangular model (No.1) was simulated by hydrostatic analysis and time history analysis by applying average 20-year wave conditions and then using time history analysis by applying the critical wave characteristics. Then, the same procedure was performed on a trapezoidal model (No.2). According to the results, the transmission coefficient increases with increasing the wave period, but the increase in wave height has no effect on the breakwater efficiency.

1. Introduction

Today, the development of maritime industries, such as maritime transport, fishing, tourism, and special ports for the oil and gas industry, and the maritime economy in general requires the construction and development of ports and the protection of the ports and coasts. Hence, marine structures for the protection of beaches and ports have become one of the main and most important concerns of marine and coastal engineers. Most of these structures, such as coastal walls and breakwaters, are used to make safe areas on beaches and ports. Breakwaters are the structures that could generally be connected to the shoreline or be far from the shoreline. Offshore breakwaters are divided into specific groups according to the type of construction, bracing, and shapes. Floating Pontoon breakwaters with a cable bracing system are one of the most common types of these structures. Due to their performance field, breakwaters reduce the energy and height of the colliding waves, creating a calm situation in their back towards the beach, which plays an important role in preserving the beach or existing structures. Floating breakwaters act by reflecting waves and dissipating wave energy by breaking it on the structure and have a significant effect on reducing wave height and energy. Coastal breakwaters are often constructed to protect coastal areas from the effects of waves and currents or tsunami attacks. These structures can play a decisive role in reducing coastal erosion and the destructive effects of waves on coastal walls. Due to its appearance and type of construction, this type of breakwater is used in most recreational harbors. These breakwaters have several duct Pantoone members that are connected to one another. These members are often made of reinforced concrete. Easy assembly and prime cost of this structure are some of the design principles of this structure. Figure (1) shows an example of a Pantoone floating breakwater adjacent to a seawall.

The Pontoon breakwaters have some advantages over other floating breakwaters. For example, they are easy to transport. They are made up of several separate floating elements that are connected. If needed, they can be separated, and then by moving the elements to where they are needed, and even by connecting some other elements, a new composition can be created. Pantoone breakwaters are relatively safe structures so that if one or more limited pantons are damaged by perforation and water penetration into them, the adjacent Pantoones will provide adequate buoyancy for the entire structure. Some of the disadvantages of Pantoone floating breakwaters include

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failure due to fatigue in the connections between elements, failure by the fatigue of the separate pontoons that appear at the stress concentration points, and structural failure due to cracks in the Pantoone concrete.

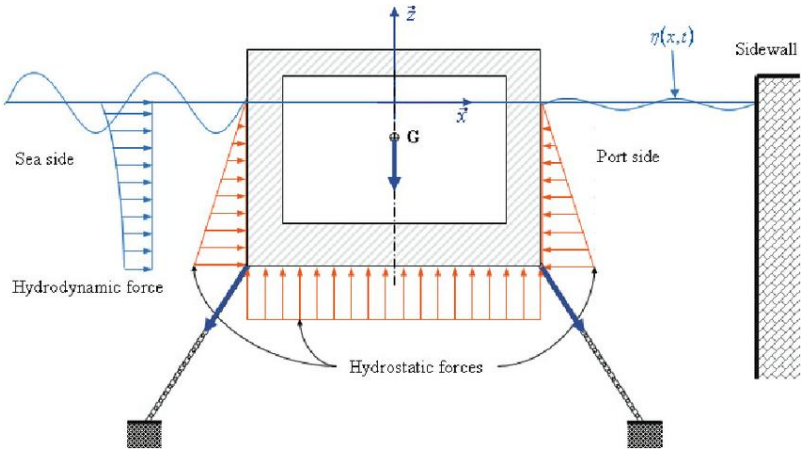


Fig.1. A floating breakwater under dominant loads

1.1. Reviewing the literature and explaining the importance of research

Sutko and Haden (1974) concluded that a rectangular floating breakwater was more effective in reducing the wave height than circular or triangular breakwaters. Carver (1979) found that the ratio of the breakwater width to the wavelength of the collision waves was an effective parameter in the performance of floating breakwaters. Yamamoto et al. (1980) showed that proper alignment of braces significantly affected breakwater performance. Yamamoto (1981) modeled a floating breakwater with an elastic mooring system under regular and random waves. Observations and experimental results showed that the response of the system under the application of regular waves was almost the same as that of random waves. Miller and Christensen (1984) used frequency analysis to study the dynamic response of a floating breakwater structure. They compared the results with field measurements of the built-in floating breakwater structure. The comparisons indicated that the variance in the range of structural responses under frequency domain analysis and field measurements varied from 0.3 to 1.5. McCartney (1985) investigated four types of floating breakwaters (box, pontoon, mat, and the tethered) and analyzed their advantages and disadvantages. Koutandos et al. (2005) conducted an experimental study of the performance of floating breakwater boxes under regular and irregular waves. They examined the effect of collision wave properties and structural geometric properties such as structural width and structure draft on the performance of floating breakwaters. Behzad and Akbari (2007) presented the experimental results of an investigation on the efficiency ofthe floating pontoon type breakwater under random waves. Dong et al. (2008) studied three types ofstructures: single box, double box, and board net. They conducted two-dimensional physical modeltests in a wave-current flume to measure the wave transmission coefficients under regular waves withor without currents. Martinelli et al. (2008) studied the forces on braces and the wave transit coefficient in different floating breakwater locations and concluded that by increasing the angle between the floating breakwater extension and the collision wave, the mooring forces and the wave transmission coefficient increased and the breakwater performance against the wave decreases. In a laboratory study on the coefficient of transmission, reflection, and wave refraction in floating tube breakwaters with different mooring systems, Ozeren and Wren (2009) found that if a pile mooring system was used, wave transmission would be less and if there was a wave overtopping, the transmission of steeper waves would be more.

Mahmoudin and Kashiwagi (2014) presented the results of a study on the design and analysis of high-performance, optimal floating breakwaters and specific geometry in a wide range of frequencies in two-dimensional and three-dimensional conditions. For this purpose, a combination of genetic algorithm methods (GA) and boundary element method (BEM) was used as the main method of numerical calculations. Experimental results confirmed the accuracy of the numerical studies. It is important to note that the combination of these two methods is effective in obtaining the optimal model. In a study at Tehran Polytechnique University, Kolahdoozan et al. (2014) evaluated the hydrodynamic performance of step floating breakwaters by using a physical modeling method and compared their performance with a π-shape floating breakwater with the same width and draft. The results show that using step floating breakwater instead of a floating π-shape one has a

significant impact on its hydrodynamic performance in addition to reducing the amount of material required to make the breakwater. It also improves the performance of step floating breakwaters by increasing the step size. A comparison of the hydrodynamic performance of two and three-step floating breakwaters shows that the performance of these two types of breakwaters depends on the relative draft of the breakwaters, but as the step size increases, the difference in their performance decreases. In a laboratory study, Forouzandeh et al. (2011) examined the performance of a Pantoone floating breakwater and a bladed Pantoone. The parameters are studied by the depth of the draft and the width of the floating breakwater Pantoone and the height of the skirt of the Pantoone-type floating breakwater. To investigate the effect of hydraulic parameters, waves with a height range of 2-12 cm and an average wave range of 0.63 to 1.26 seconds were used. The laboratory models were at a 1:10 scale and the Pantoones were made of waterproof wood. According to the results of the laboratory model, it can be said that with increasing the draft depth of the structure, the transmission coefficient of the floating breakwater decreased, which was the main reason for the increase in the mass of the floating breakwater.

1.2. The importance of the research

Expensive and time-consuming implementation of common rubble mound breakwaters along with disadvantages such as environmental impacts during construction and operation, changing the pattern of erosion and sedimentation in the region, creating a barrier to the free movement of aquatic animals, and similar cases have drawn the attention of researchers to use floating breakwaters in areas with a less severe wave climate. These breakwaters usually cost less to build, and the process of building and installing them is faster than common rubble mound breakwaters, so in certain situations, such as military situations or less important ports, they are a good choice for port protection. However, due to the short history of such breakwaters, there is a need for further research on their optimization and increasing the safety and efficiency of these structures. One of the most important factors influencing the efficiency of colliding wave energy dissipation is the overall shape of the breakwater, which is highly regarded in the world today. Choosing an optimal design, in addition to reducing project costs, will lead to a further reduction in the transmission coefficient and will provide suitable conditions for the mooring of vessels in the port. Due to the advancement of computer modeling technologies and most of the research that has been done in the laboratory, it is also necessary to conduct computer studies on the time and economy of the designs.

2. Materials and Methods

2.1. Hydrodynamic parameters and effective structures for floating breakwater operation

Based on a review of the literature on numerical and laboratory studies performed on floating breakwaters, various indicators have been considered by researchers as target parameters in analyzing the behavior and efficiency of a floating breakwater. These parameters include the wave passing through the breakwater (the ratio of the height of the transferred wave to the input wave), the wave reflection coefficient, the six movements of this floating object, and the efficiency of its mooring system.

2.1.1. Floating breakwater movements

The floating breakwater structure reacts with complex movements, including six degrees of freedom of movement, when dealing with a wave. Six degrees of motion are defined as transmission, including sway, surge, heave, and rotation, including roll, yaw, and pitch. These movements are shown in Figure (2).

The breakwater reaction depends on the natural periods of the moored structure for each movement and the radiant wave period, and the natural periods of the breakwaters are determined by the physical characteristics of the breakwaters and their control system. These specifications include:

- Breakwater geometry
- Breakwater mass
- Distribution of mass and breakwater torques of the breakwater
- Control system specifications, such as the length of the control cables and the unit weight of the cables

The phase relationship between the radiant waves and the secondary waves produced by the motion of the breakwaters depends on the period of the radiated waves and the natural period of the breakwaters. Each degree of freedom of movement of a breakwater has its natural period. These movements depend on the hydrodynamic characteristics of the floating breakwater and its control system around the corresponding axis. The simplest wave breakwater is when the direction of the wave is perpendicular to the longitudinal axis of the breakwater. In these conditions, the movement ideally includes only heaving, rolling, and swaying (two-dimensional mode). The breakwater's movements depend on the height and period of the waves, the physical characteristics of the breakwaters, the mooring system, and the side components of the breakwaters. The breakwater movement is complex if the oblique waves collide with the vertical waves because the resulting motions involve all six motions.

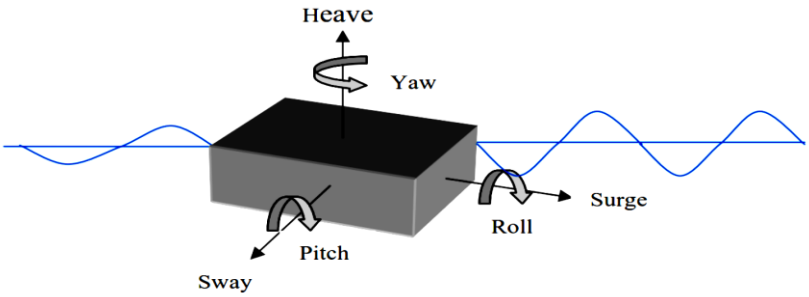


Fig. 2. Defining floating breakwater motions

2.1.2. Floating breakwater hydrodynamics

Floating breakwaters are built on the basis that they absorb most of the wave energy concentrated in the peak part of the wave, thereby reducing the turbulence of the water behind the breakwater. The efficiency of this type of breakwater in reducing the height of the wave depends on the interaction of the structure and the waves. The measurement of length of the wave that has passed the breakwater is a direct measure of this efficiency. In general, floating breakwaters can reduce wave height and, therefore, energy in three ways: a) wave energy reflection, b) wave energy dissipation, and c) wave energy conversion to other wave strands. The method is mostly used for floating breakwaters with the vertical section against the waves. The amount of wave energy reflected from the structure depends on the height of the wave, the breakwater draft, the depth of the water at the site of the breakwater, and the free height of the structure. The distribution of wave energy in the depths of the water changes greatly as the wave approaches the shallow water. A breakwater with a specific draft dissipates less of the energy of the incoming wave in deep water than in shallow water. The amount of energy dissipated by a B-type floating breakwater caused by breaking waves on its sloping surfaces depends on the physical characteristics of the breakwater and its mooring system. In type c breakage, the motion created in the wave breakwater by the waves will convert the input wave to other secondary waves. This mechanism will be most effective when the secondary wave strings are out of phase or have a different wave period than input waves. The efficiency or effectiveness of a floating breakwater is generally expressed by a factor called the transmission coefficient. The transmission coefficient is the ratio of the height of the wave passing from the breakwater to the incident wave. If the height of the incident wave to the breakwater is shown with H_i and the wave passing through the breakwater with H_t, the wave transmission coefficient is

$$C_t = \frac{H_t}{H_i} \quad (1)$$

2.1.3. Wave force

Depending on the size of the marine structure, different methods have been proposed for calculating wave force, the most important of which are the Morrison relationship and the diffraction-diffusion theory.

2.1.3.1. Morrison relationship

This relationship is presented to calculate the force caused by the wave on small members with a diameter-to-wavelength ratio of less than 0.2. This equation is based on the rationale that since the diameter of the structure is small relative to the wavelength, the wave shape and characteristics do not change as a result of the collision with the structure. This equation introduces the total force applied to the structure as the sum of the two forces caused by the acceleration of the fluid particles and the drag force. How to calculate the wave force through Morrison's relationship is shown in Equation (1):

$$df = 0.5\rho D C_D(u_f - u_s)|u_f - u_s| + \rho A C_m \dot{u}_f - \rho A(C_m - 1)\dot{u}_s \quad (2)$$

in which C_D is the drag coefficient, C_m is the inertial coefficient, D is the diameter of the member, u_f is the fluid velocity perpendicular to the direction of the member, $\dot{u}_f$ is the fluid acceleration perpendicular to the direction of the member, u_s is the structure velocity perpendicular to the direction of the member, $\dot{u}_s$ is the structure acceleration

perpendicular to the direction of the member, A is the cross-sectional area of the member in the direction perpendicular to the flow, and ρ is the fluid density. When the dimensions of the structure and its components are considered in comparison with the wavelength (D/L> 0.2), the presence of the structure in the surrounding wave field is expected to cause additional changes and turbulence. Therefore, the wave will diffract after hitting the structure, and this phenomenon must be considered in wave force calculation, which is why Morrison's equation loses its validity.

2.1.3.2. Diffraction-Publishing Theory

The diffraction-publishing theory is a good way to analyze floating objects. The force exerted on a floating object by the waves can be attributed to the following three main factors:

• The force caused by the stationary fluid, assuming the oscillation of the floating object[1]

• The force from the waves into the floating object, assuming that the floating object is constant[2]

• The force caused by the scattering of the waves when the waves hit the stationary floating object[3]

Since incompressible fluid and non-rotational fluid flow are assumed, the fluid field can be defined by the potential function. This function is divided into three main potential functions based on the three main factors mentioned above, from which the total potential function is obtained. This potential function is shown in Equation (2).

$$\emptyset = \emptyset_{\mathrm{w}} + \emptyset_{\mathrm{r}} + \emptyset_{\mathrm{d}}$$

in which $\emptyset_I$ represents the potential to collide with a stationary object, $\emptyset_j$ represents the potential for the oscillating motion of an object in stationary water, and $\emptyset_d$ represents the potential to disintegrate under the assumption that the object is stationary in a fluid. This potential function must apply to the following Laplace differential equation.

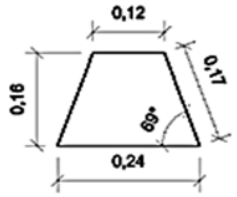
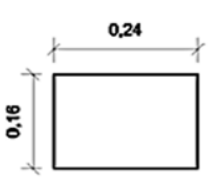
$$\nabla^2 \emptyset_w = \frac{\partial^2 \emptyset_w}{\partial x^2} + \frac{\partial^2 \emptyset_w}{\partial y^2} + \frac{\partial^2 \emptyset_w}{\partial z^2} \quad (3)$$

2.2. Sample modeling

Breakwater modeling was performed by ANSYS AQWA software and then the effect of different structural parameters (such as the overall geometry of the floating breakwater) and hydrodynamic parameters on the breakwater efficiency was investigated. The geometric characteristics of the modeled breakwaters are modeled according to Table 1. The present study suggested that in addition to the ability to simulate the software, it was possible to make and produce them in reality. The third dimension of all options is selected according to a laboratory 85-cm sample, and in simulating them, the draft of the samples is considered constant and equal to eight centimeters. To provide the desired draft in different geometries, the mass proportional to the volume according to the density related to each of the models has been calculated and applied in the software. The scale of the laboratory models presented in Table 1 is 1:50, so the actual sample size of the laboratory models for geometric modeling is 50 times.

The study area is on the coast near Bandar Anzali in the Caspian Sea. The breakwater structure is located at latitudes 49,4568 and 37.49876. The water depth is 10 meters. The area wave specifications are presented in Table 2. Ansys Aqwa software is used in this research. This finite element software can model hydrodynamic conditions and structures and analyze wave and structure interactions. Here, first, the breakwater structure is drawn by the Solid Work software and entered into the Ansys Aqwa environment. Then, it is loaded and analyzed by hydrostatic and limit waves. The structure is configured in the 0.8 m software, which has been one of the most optimal situations. Examples of model breakwaters with connection points for the mooring system in the Ansys Aqwa software environment can be seen in Figures 4 and 5.

Table 1. Geometric characteristics of floating breakwater structure with 1:50 scale (dimensions per meter)

2	1	Model number
		Model geometry
ρ=583.5 Kg/m^3	ρ=500 Kg/m^3	Model specifications

[1] Incident wave potential

[2] Incident wave potential

[3] Diffraction wave potential

Table 2. Wave specifications for the study area

Dir	H_s	T_p	----------
46	3.6	8.56	**Limit mode**

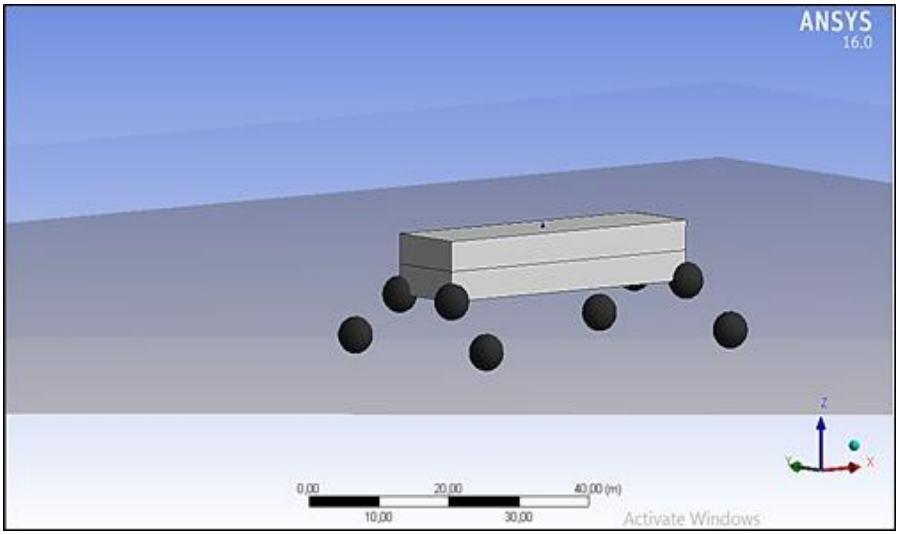


Fig. 3. The floating breakwater with the mooring system

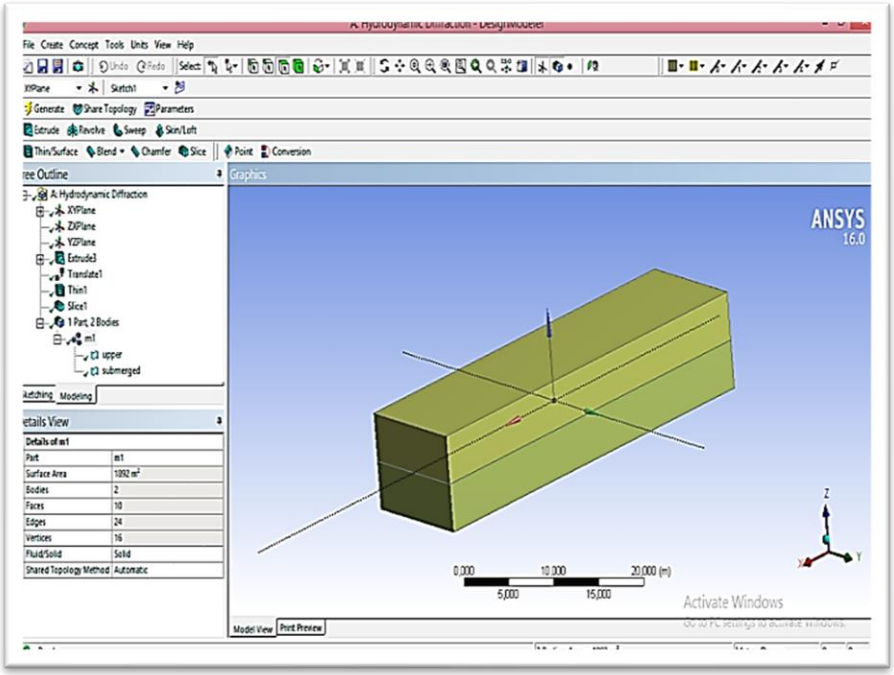


Fig. 4. Modeling in Ansys software

3. Results

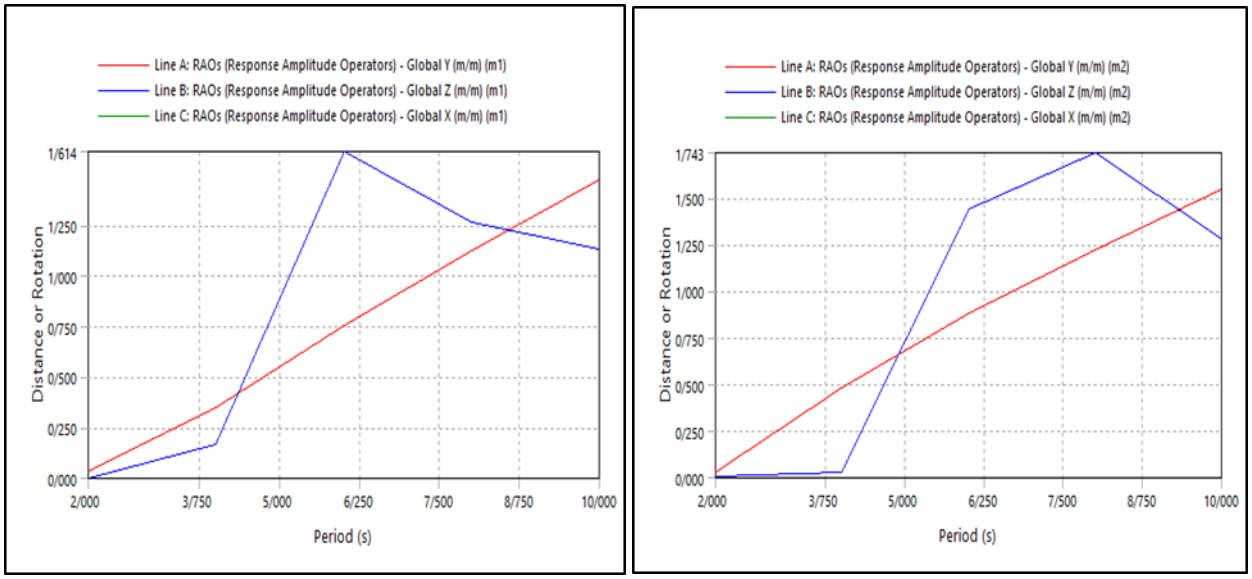
3.1. Hydrostatic analysis of breakwaters

In hydrostatic analysis, the breakwater structure is analyzed for stability against gravitational and buoyancy loads. Important outputs in this section include hydrostatic stiffness, hydrostatic displacement parameters, water zone characteristics, and stability parameters. The structure has been subjected to wave loading in various directions. For this purpose, a wave direction is applied to the structure every 45 degrees. The amount of rotation and displacement and changes in force in all directions in structures No. 1 and 2 under hydrostatic analysis can be seen in Figures 6-12. The Response Amplitude Operator parameter (RAO) is used to obtain the rate of rotation and displacement.

In the (BW.2), the displacement is negligible in the X-direction.

The maximum displacement occurs in the Z direction at 8 s, which is equal to 1.743 m. This displacement, compared to the (BW.1), indicates that in lower periods (lower than 6) we will see better efficiency in (BW.2). In the period of 6 s, (BW.2) has 1.44 m displacement in heaving. In the Y-direction, the maximum displacement is 1.45 m that occurs in 10 seconds, which is approximately equal to the amount of displacement in (BW.1); i.e., 1.47m.

The rotation around the coordinate axes is caused by a wave that is applied to the structure at an angle of 90. Therefore, the rotation rate around the Z and Y axis is very small compared to the X-axis. Also, the maximum values of rotation around the Y and Z axes are less than the minimum rotation around the X-axis with the value of 6.7504e-05 (°/m) which occurs in the period of 2 s. The amount of rotation around the X-axis increases with an increase in the period, and it is visible that the maximum amount of rotation in the period of 10 s is 2.6082e-03 (°/m).



Breakwater No. 1(BW.1) **Breakwater No. 2 (BW.2)**

Fig. 5. The amount of displacement along X, Y, and Z based on the period

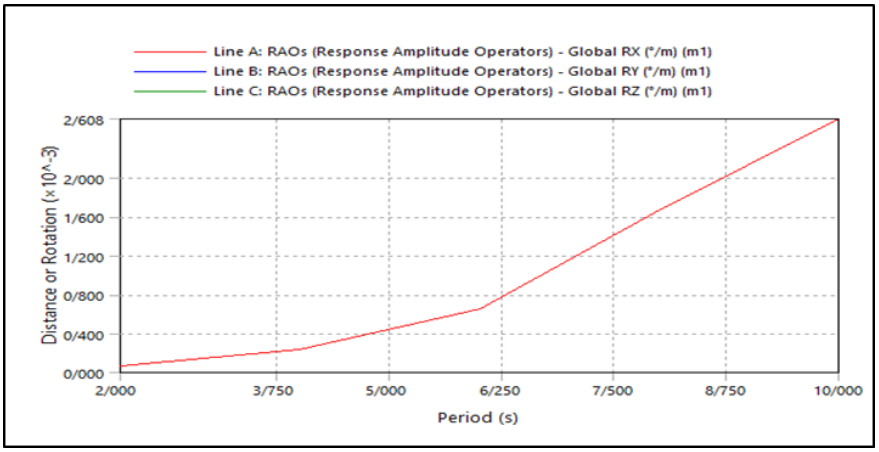


Fig. 6. The rotation rate around X, Y, and Z based on the period (BW.1)

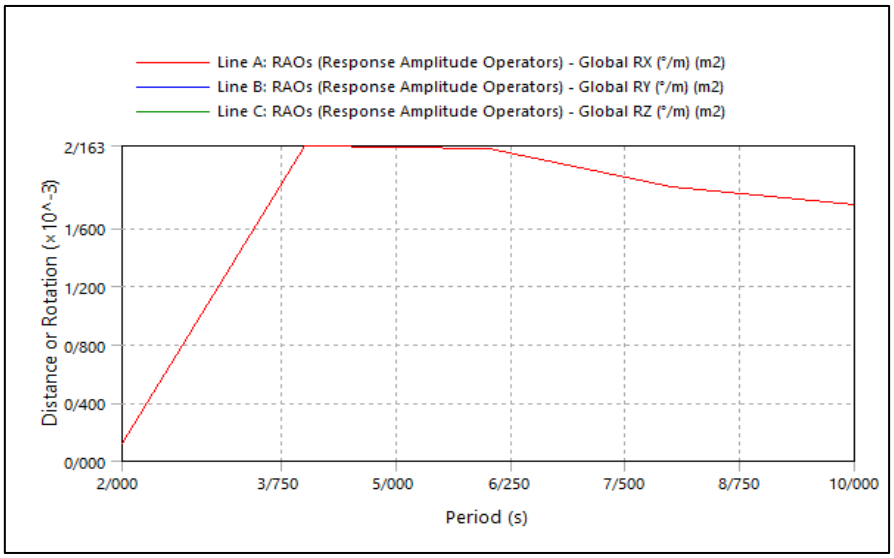
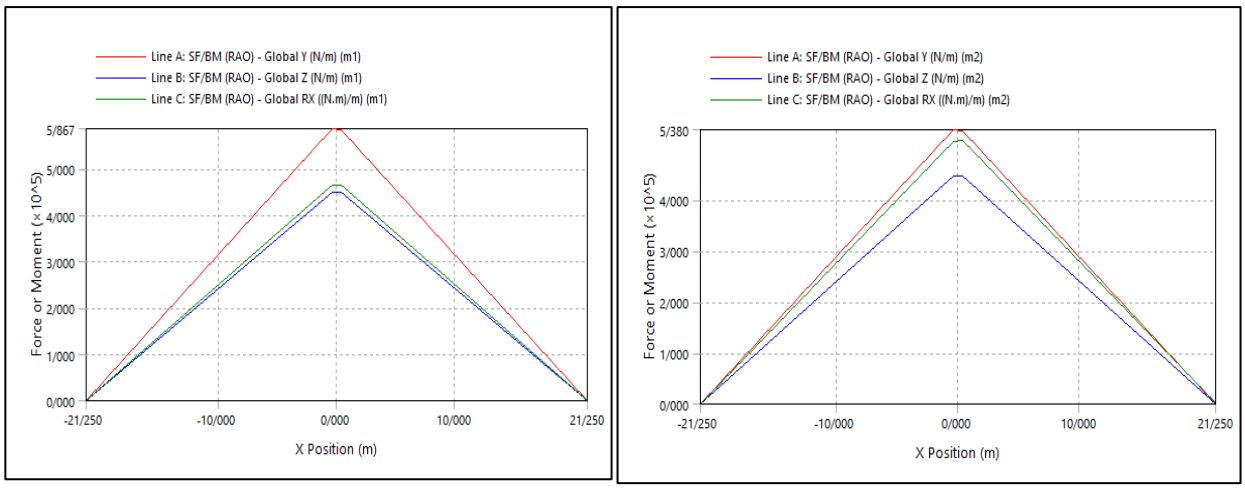


Fig.7. Roll, pitch, and yaw rotation measured based on periods (breakwater 2)

Similar to (BW.1), the rotation around the coordinate axes is caused by a wave that is applied to the structure at an angle of 90. Like (BW.1), there is a small amount of rotation around the Y and Z axes. In the period of 4s, the rotation around the X-axis is 2.163e-03 m, which is lower than that of (BW.1), which has the highest rotation around the X-axis, i.e., 2.6082e-03 m. Therefore, it can be concluded that (BW.1) is more stable in low periods**.**

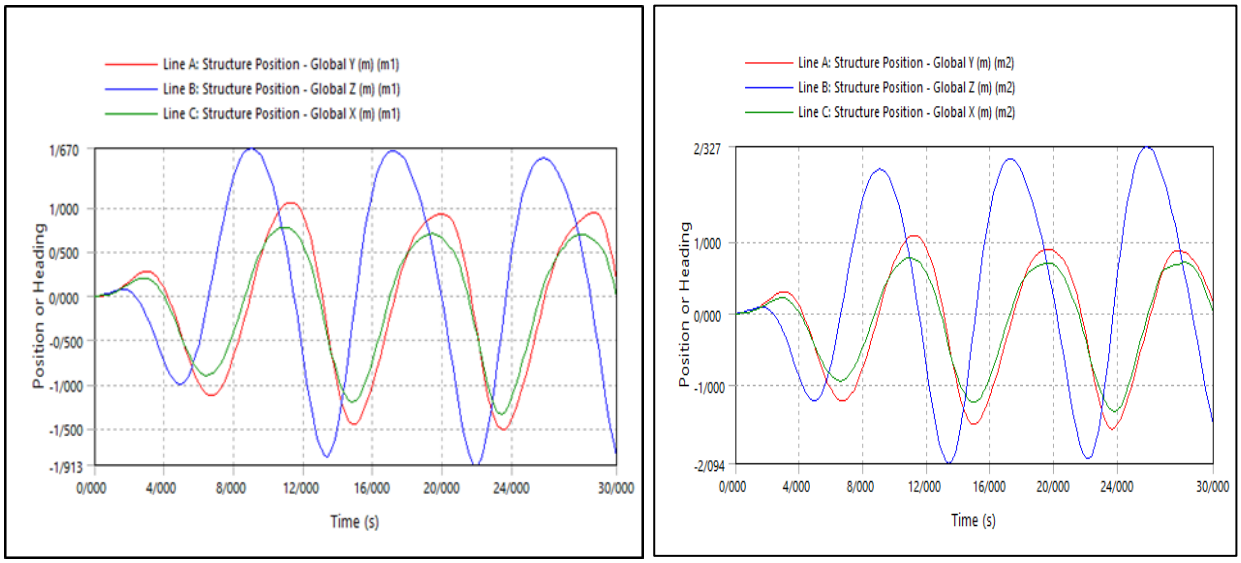
According to Figure 8, it is clear that the maximum values will occur at the center and zero at the corners of the structure. The highest value of shear force occurs along the Y-axis, which is 10^5×5.380 NM. The maximum value of the shear force in the Z direction is 10^5×4.46. The maximum bending moment value around X is also 10^5×5.16.

The pattern of displacement changes in (BW.2) is the same as that of (BW.1). The displacement along the X and Y axes with a small difference is the same as the displacement in (BW.1). However, in the Z direction, the displacement rate in (BW.2) is higher than that in (BW.1).



Breakwater1 **Breakwater2**

Fig. 8. Changes in the shear force and bending torque along with the structure.



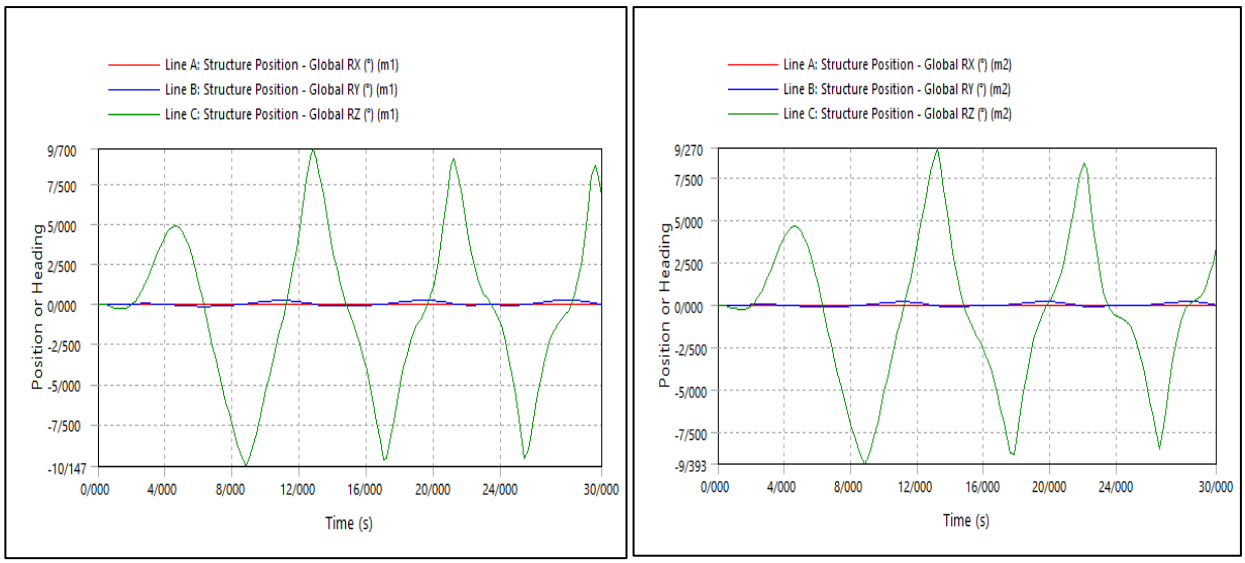
Breakwater1 **Breakwater2**

Fig.9. Surge, sway, and heave displacement rates based on (RAO) over time.

3.1. Loading under extreme wave

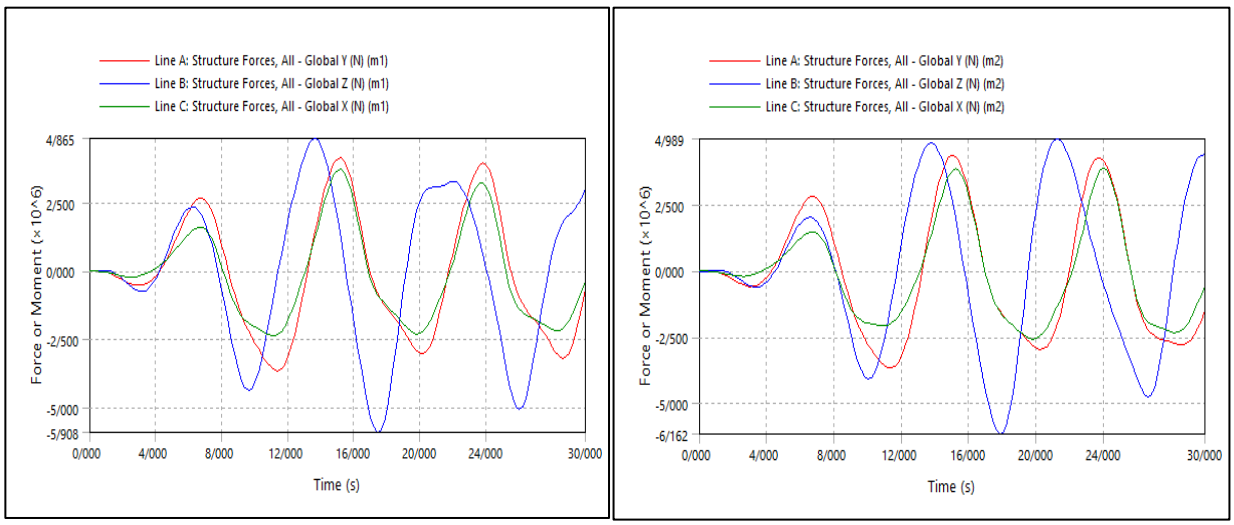
The pattern of displacement changes in (BW.2) is the same as that of (BW.1). The displacement along the X and Y axes with a small difference is the same as the displacement in (BW.1). However, in the Z direction, the displacement rate in (BW.2) is higher than that in (BW.1). According to the diagram, the maximum rotation in (BW.1) is around the Z-axis, which varies between 9.7 and -10.14 degrees. The pattern of rotation changes in (BW.2) is the same as that of (BW.1). The amount of rotation around the X and Y is also very small and negligible as for breakwater (1). The maximum rotation is around Z-axis and its amount is higher for (BW.1) than for (BW.2).

The pattern of force changes over time is almost the same for both breakwaters. While for the 20-year average wave, the maximum amount of force occurs along the Z-axis, which varies between 106×1.720 and 106×-1.85, in (BW.1), the maximum force is in the Z direction and its values are less than that of (BW.2).



Breakwater1 **Breakwater2**

Fig.10. Roll, pitch, and yaw rotation based on (RAO) over time.



Breakwater1 **Breakwater2**

Fig. 11. Total force along Y, Z, and X based on time.

3.3. Investigating the effect of wave height on the efficiency of floating breakwaters

For this purpose, we subjected (BW.1) and (BW.2) to an incident wave with a period of 4 seconds and an angle of 90 degrees. According to the wave height contours presented in Figures 12-16, it can be said that changing the wave height does not affect the wave transmission coefficient.

3.4. Model calibration

For model calibration, the results of reference laboratory models (McCartney, 1985) were used to validate the numerical model built into the software. Figure (16) shows the results of experiments performed on the Pantoone breakwater in McCartney (1985). Using the presented diagram, the transmission coefficient of the laboratory model at a constant wave height for periods 2, 2.5, 3, and 3.5 is calculated. The validation results are presented in Figure (17). The average difference between the results of the numerical and laboratory model is 12.5%.

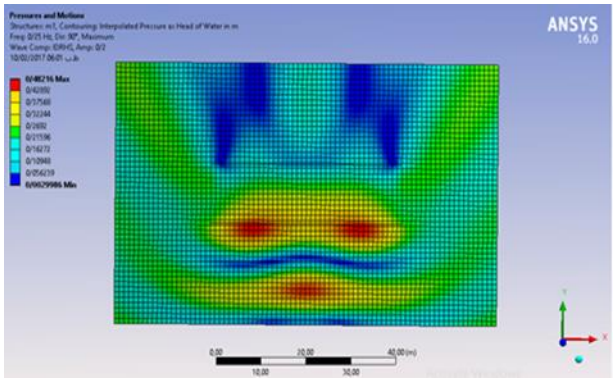


Fig.12. Wave height contour for the wave height of 1 m

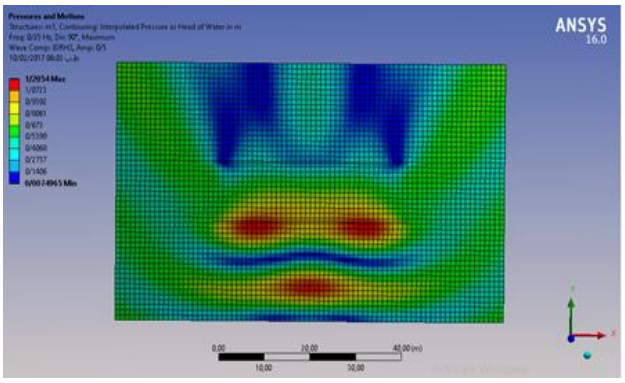


Fig.13. Wave height contour for the wave height of 0.4 m

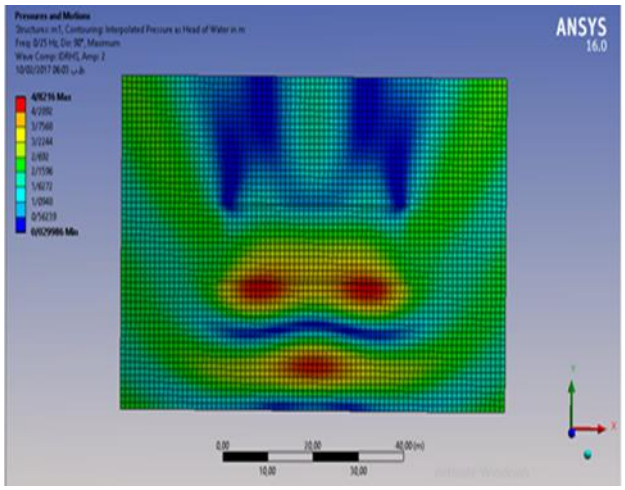


Fig.14. Wave height contour for the wave height of 4 m

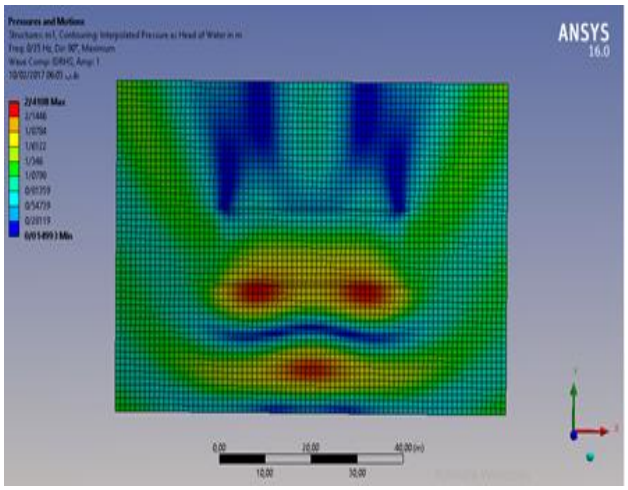


Fig.15. Wave height contour for the wave height of 2 m

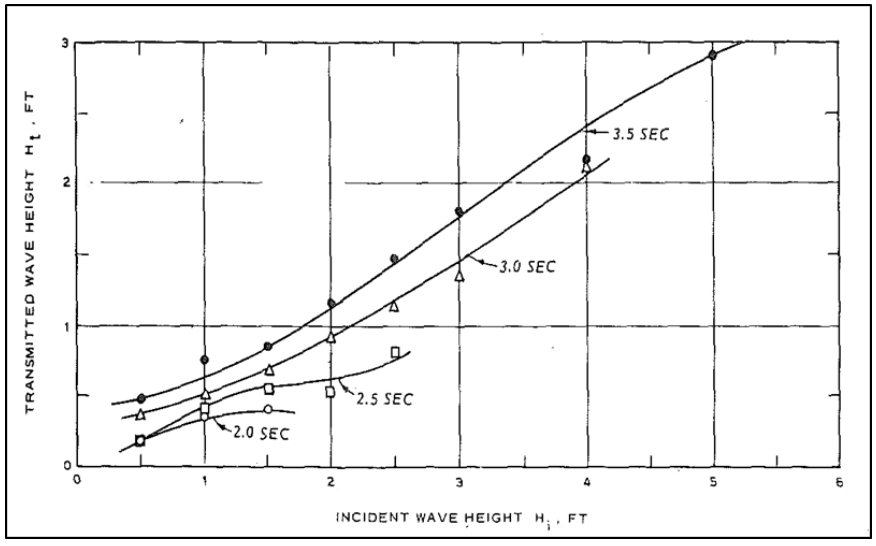


Figure.16. Experimental results of transmitted wave height to an incident wave height (McCartney, 1985)

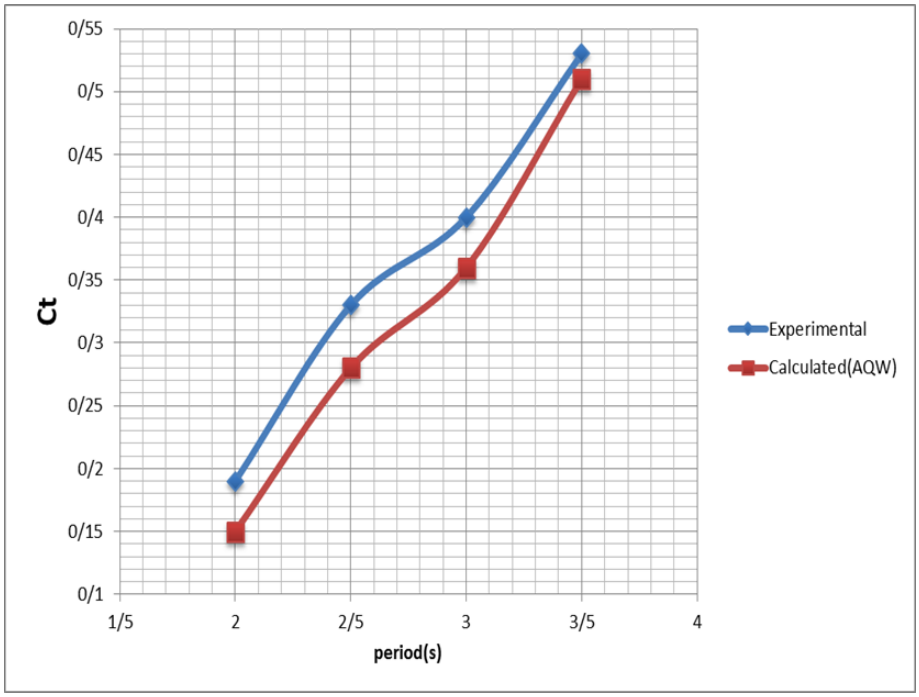


Figure.17. Comparison of laboratory results and numerical model

4. Conclusion

Two breakwaters with different geometries, rectangular (1) and trapezoidal (2), were modeled in this study in that they were subjected to hydrostatic stability analysis and a certain wave load by the Caspian Sea environmental conditions. According to the diagrams presented in the study, it can be seen that the breakwater with a trapezoidal cross-section has more floating stability than the rectangular breakwater. Also, according to the mooring system included, it is more important to check the condition of the structures in the Z-direction. Also, in this study, the effect of wave height on the efficiency and effectiveness of floating breakwaters was investigated under the conditions of a constant wave period. The amount of displacement in the trapezoidal breakwater is more and its rotation is less than rectangular type. The force and diffraction torque are generally lower in the trapezoidal type but the amount of total force in both structures is almost equal with a little difference. According to the modeling and analysis of the contours obtained from the analysis, it can be concluded that the wave height changes have a slight effect on the efficiency of the floating breakwater. Finally, according to this study and under equal conditions, the use of trapezoidal type breakwaters will be a better option than the rectangular breakwater.

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