

Performance Evaluation of Pile-Restrained Floating Breakwater using the Multi-domain Boundary Element Method

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Abstract

This study investigates wave interactions with different configurations of pile-restrained floating breakwater (T-shaped, $\perp$ -shaped, Π -shaped, H-shaped, I-shaped, and rectangular) with the multi-domain boundary element method. The analysis incorporates horizontal and vertical stratification in floating structures. Key scattering factors, including reflection, transmission, and dissipation coefficients, are evaluated to determine the influences of the structural and geometric parameters on floating breakwater performance. Additionally, this study examines the horizontal wave forces exerted on the seaward and leeward sides of the structures. Model convergence is validated, and the accuracy of the computational results is confirmed by comparing the wave reflection and transmission coefficient for rectangular floating pontoon and stratified submerged porous box. Further validation is provided by comparing the numerical results for an H-shaped model with experimental data obtained from wave flume testing. Findings indicate that the H-type breakwater demonstrates superior performance in deep-water environments, whereas the $\perp$ -type structure exhibits greater wave energy transmission and reflection in shallow-water environments. Moreover, the H-type configuration experiences the highest wave forces, whereas the $\perp$ -type structure experiences the least. The findings of this study offer valuable insights into the design and analysis of floating breakwaters in offshore environments.

Keywords Pile-restrained breakwater; Multi-Domain boundary element method (MDBEM); Reflection coefficient; Wave force coefficient

1 Introduction

Floating breakwaters as alternatives to permanent constructions efficiently prevent erosion along susceptible shorelines. They are less expensive to construct than conventional fixed breakwaters and are especially suitable for deployment in deep-water environments where fixed structures are technically unfeasible (McCartney, 1985). In addition, these structures reduce environmental disturbances by permitting fish

migration, sediment movement, and natural water circulation. Their functional value can be further enhanced by integrating wave energy conversion technologies (Mustapa et al., 2017). Owing to their low-profile design, these structures are well suited for areas with notable tidal variations and offer reduced visual impact, often being perceived as more aesthetically pleasing than permanent breakwaters. Recent studies have focused on addressing issues, such as growing offshore construction costs, environmental constraints in deep-water settings, and mooring space shortage due to increased recreational boating activities (Hales, 1981). Depending on their application and design, floating breakwaters have been shown to protect coastlines in deep waters and reduce wave reflection (Dai et al., 2018). By stabilizing ship operations, floating breakwaters improve harbor safety in addition to providing coastline protection.

In recent years, numerical simulations have been increasingly integrated into theoretical and physical model analyses to enhance the practical application of floating breakwaters. This integration has allowed for a more effective study of their performance and adaptability. Among the various structural forms, the rectangular box-shaped floating structure has been extensively studied because of its simplicity (Carr, 1951; Hay, 1966; Bottin and Turner, 1980). Mei and Black (1969) established the groundwork for fur-

Article Highlights

- The hydrodynamic performance of different configurations of pile-restrained floating breakwaters is analyzed on the basis of small-amplitude wave theory.
- Hydrodynamic parameters, such as wave reflection, transmission, and energy dissipation coefficients, are evaluated using the multi-domain boundary element method.
- The H-type breakwater configuration exhibits superior performance in deep-water environments, whereas the $\perp$ -type structure transmits and reflects the majority of wave energy in shallower water environments.

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ther studies by comparing the wave scattering properties of surface and submerged structures. The substantial impact of the width-to-wavelength ratio on wave transmission was emphasized by Mani (1991). Thereafter, Williams and Abul-Azm (1997) analyzed wave interactions in dual pontoon breakwaters through theoretical and numerical investigations. A diverse range of structural configurations, including T-shaped, $\perp$ -shaped, U-shaped, Π -shaped, F-shaped, and H-shaped structures, have been investigated (Neelamani and Rajendran, 2002; Geshraha, 2006; Günaydın and Kabdaşlı, 2004; Günaydın and Kabdaşlı, 2007; Zhan et al., 2017; Deng et al., 2019). Innovative and composite designs, such as cylindrical breakwaters equipped with flexible mesh cages and suspending balls, have also been studied, as demonstrated by Ji et al. (2015). The performance of floating breakwaters is influenced by various parameters, such as geometry, mooring methods, and wave interactions. As demonstrated by Peng et al. (2013) and Ji et al. (2019), numerical modeling approaches have emerged as essential tools for comprehending and improving the designs of floating breakwater systems.

To effectively address issues associated with wave-function interactions, the boundary element method (BEM), which was first introduced by Brebbia and Dominguez (1992), has emerged as a useful numerical approach. The BEM provides computational advantages over domain-based approaches by concentrating on border computations and lowering the dimensionality of a problem. As demonstrated by Choi et al. (2000), the BEM is well suited for examining wave diffraction and radiation surrounding floating bodies, and its application in the study of floating structures has gained widespread acceptance in recent years. Zheng et al. (2007) successfully used the BEM to examine the relationship between oblique waves and long prismatic formations. Additionally, Yanna et al. (2011) employed a time-domain BEM to investigate wave interactions in a box-type floating structure equipped with a mooring system. To evaluate the performance of an F-type floating breakwater and optimize its dimensions for minimal material consumption, Duan et al. (2016) compared experimental and numerical analyses using the BEM. Esmaeelpour et al. (2016) employed the BEM to examine wave-induced pressure and forces to evaluate the hydrodynamic performance of floating breakwaters supporting wind turbines. Wang et al. (2019) investigated the performance of an upper arc-shaped plate breakwater using the BEM, incorporating diffraction and radiation theories. Behera and Ghosh (2019) demonstrated that wave reflection can be reduced to near-zero levels through the careful selection of wave and structural characteristics, which are useful for creating a tranquil environment next to a rigid wall when a step bottom is present. Expanding the use of the BEM, Vijay et al. (2021) examined wave-structure interactions in several inverted trapezoidal porous structures and incorporated nonlinear pressure drop

conditions; their study analyzed the porosity, shape, and wave properties that affected the functionality of the structures. Using the BEM approach, Trivedi and Koley (2021) examined the radiation problem associated with water waves interacting with a floating porous box, focusing on different seabed conditions that affect the oscillatory patterns of damping coefficients and additional mass. To examine the impacts of porosity and structural geometry on wave force reduction, Nishad et al. (2021) used a dual BEM to investigate wave scattering in an H-shaped porous barrier. They incorporated nonlinear pressure drop boundary conditions into the investigation by using BEM. Paul and Behera (2024) observed a periodic pattern in wave energy dissipation and an increase in normalized space between the structures they studied; these effects facilitated wave reflection and transmission. The rationale for using multiple barriers is to reduce wave forces on floating docks. Venkateswarlu et al. (2024) stated that Bragg reflection induced by multiple bottom-standing breakwaters reduces the efficiency of oscillating water columns (OWCs) for specific wavelengths.

Sustainable breakwater solutions are increasingly necessary to address the growing demand for coastal protection. In response, researchers have explored the use of multilayer porous structures composed of different materials with varying friction factors and porosities. These multilayer arrangements have been shown to effectively shield the lee-side of a structure from wave action (Koley, 2019). Yu and Chwang (1994) examined wave interaction with double-layer porous structures, considering different degrees of dissipation inside a medium; using the eigenfunction expansion method, they examined the wave reflection, transmission, and dissipation properties of rectangular porous boxes with varying thicknesses and dissipative qualities. Additionally, Twu et al. (2001) conducted a numerical study on the impact of oblique wave incidence on vertically stratified breakwaters with different porosities in deep seas; their findings demonstrated that multilayer topologies are superior to single-layer constructions and at an appropriate width-to-depth ratio, high porosity can dramatically reduce wave transmission. Tanneau et al. (2006) analyzed multilayer porous structures with a coupled numerical approach incorporating the FEM and BEM, showcasing the computational resource efficiency of the BEM. Liu et al. (2007) examined a modified perforated structure consisting of a double-layer porous box and examined the impact of porosity on wave forces. The performance of trapezoidal porous structures with different material properties was further investigated by Koley (2019), who showed that a strong wave reflection can result from increased friction inside layers. Expanding upon these studies, Venkateswarlu et al. (2020) examined the performance of double- and triple-layered stratified breakwaters, accounting for the effects of structural characteristics, such as porosity, friction factor, and oblique wave incidence. Furthermore, Sahoo et al. (2023)

showed that waves reflected by the wall and structure diminish with increasing structural porosity.

The increasing demand for adaptable and eco-friendly coastal infrastructure has positioned floating breakwaters as viable options for harbor expansion and coastal protection. However, the study remains limited regarding the identification of optimal floating structure configurations with maximized performance in harbor areas. In the present study, different floating breakwater configurations, such as rectangular, T-shaped, $\perp$ -shaped, Π -shaped, H-shaped, and I-shaped structures, are hydrodynamically compared to determine the most efficient configuration in terms of reflection and stability. Unlike massive rectangular breakwaters, the T-shaped, H-shaped, and Π -shaped structures, which primarily consist of barriers and plates of a finite thickness, are efficient in minimizing wave transmission (Liu et al., 2025) and lowering horizontal wave force (Zhang et al., 2024). In deep-water areas, H-shaped floating breakwaters exhibit better wave attenuation than rectangular floating breakwaters (Vishwakarma and Karmakar, 2024). Hassanpour et al. (2025) analyzed variations in transmission and reflection patterns to identify the most efficient breakwater configuration under varying wave conditions; they employed the multi-domain boundary element method (MDBEM) to assess the hydrodynamic performance in terms of wave reflection, transmission, and energy dissipation coefficients. Then, a comparative study of each configuration was performed by analyzing incident wave forces. Section 2 presents an overview of the theoretical formulation of the governing equations and corresponding boundary conditions applied to the presented models. Section 3 outlines the numerical methodology, detailing the discretization of the boundary elements and final boundary integral equations used to solve the problem within the MDBEM framework. Section 4 provides the numerical and experimental validations along with the numerical results. Finally, Section 5 summarizes the core findings and conclusions.

2 Theoretical formulation

Using the MDBEM approach, the numerical analysis is conducted to investigate wave interactions in various floating porous structure configurations (with or without stratification). The ideal geometries of the structures are illustrated in Figures 1(a)–(f), which details various structural parameters, fluid and structural borders, and geometrical coordinate systems. In the MDBEM framework, fluid and structural boundaries are considered for the hydrodynamic assessment of wave-structure interactions (Patil and Karmakar, 2021). Problems are solved with the two-dimensional Cartesian coordinate system. The horizontal x axis and vertical y axis are referenced to the still water level. The monochromatic wave is an incident wave along the

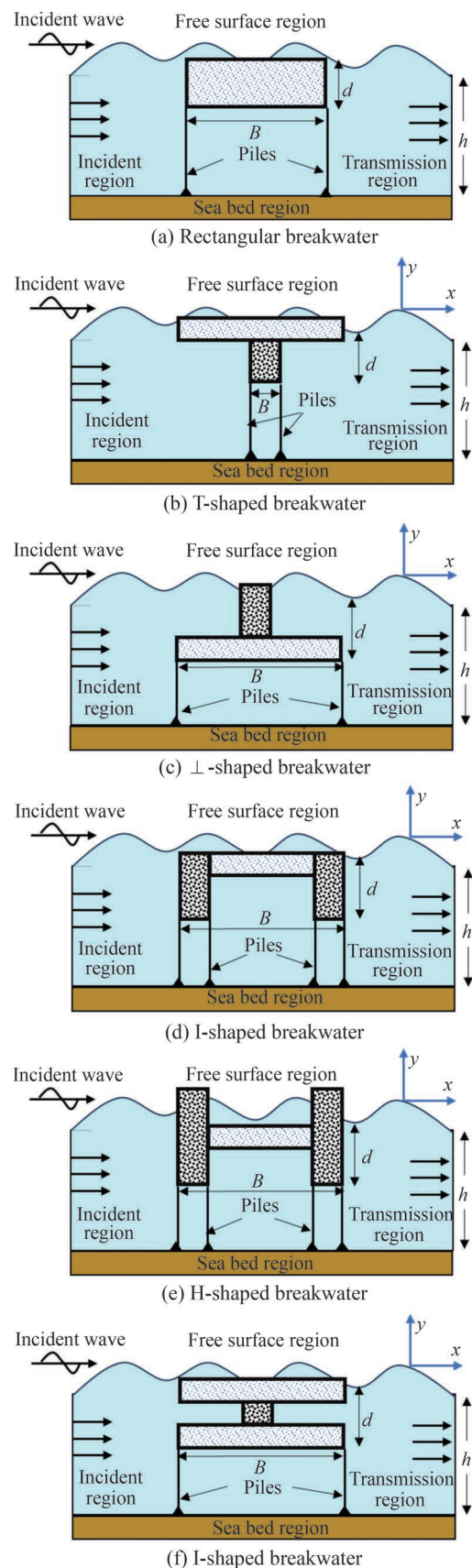


Figure 1 Schematic representation of a pile-restrained floating breakwater

positive x direction. The incident wave on the structural boundary is considered regular, with small-wave amplitude α and wavelength λ propagating from left to right toward the breakwater at water depth h .

The fluid is assumed to be inviscid, incompressible, and irrotational fluid flow. Thus, the total velocity potential $\Phi(x, y, t)$ for the fluid and structural region can be expressed as $\Phi(x, y, t) = \text{Re}\{\phi(x, y)e^{-i\omega t}\}$, where Re is the real part of $\phi(x, y)$, which satisfies Laplace's equation represented as

$$\nabla^2 \phi(x, y) = 0 \text{ for the fluid domain } \Omega \quad (1)$$

In the formulation of fluid domain Ω , Γ_{SB} represents the seabed region, Γ_{STR} represents the structure-fluid interface, and Γ_{FS} represents the free surface region. The fluid is assumed to flow from the negative x axis to the positive x axis. Hence, the input and output open boundary regions are expressed respectively as Γ_{INPUT} , which indicates the incident region, and Γ_{OUTPUT} , which indicates the transmitted region. The boundary condition on the free surface Γ_{FS} is derived from Bernoulli's equation under the assumption of small-wave amplitudes.

$$\frac{\partial \phi}{\partial y} - \frac{\omega^2}{g} \phi = 0 \quad (2)$$

The sea bed is assumed to be flat and impermeable. Accordingly, the impervious horizontal seabed Γ_{SB} boundary condition is expressed as

$$\frac{\partial \phi}{\partial y} = 0 \text{ at } y = -h \quad (3)$$

The interaction between a porous structure and a surrounding fluid at each interface leads to the continuity of mass flow and pressure (Sollitt and Cross, 1972; Chwang and Chan, 1998). Thus, the edge conditions for the porous structure region on the Γ_{STR} boundary can be expressed as

$$\frac{\partial \phi_{\text{STR}}^f}{\partial n} = \varepsilon \frac{\partial \phi_{\text{STR}}^s}{\partial n}, \quad \phi_{\text{STR}}^f = (S + if) \phi_{\text{STR}}^f \quad (4)$$

where ε is the structural porosity, S is the inertia effect parameter of a porous medium, and f is the friction factor of the porous medium. The structure modeled is assumed to be situated between the two auxiliary boundaries Γ_{INPUT} and Γ_{OUTPUT} . Therefore, the far-field radiation condition for the input and output open boundary conditions is expressed as

$$\lim_{r \rightarrow \infty} \sqrt{r} \left(\frac{\partial \phi}{\partial r} - ik\phi \right) = 0 \quad (5)$$

where $r = \sqrt{x^2 + y^2}$. The velocity potential function at the input and output boundaries can be expressed as

$$\phi_{\text{Input}} = \phi_I + \phi_R, \quad \phi_{\text{Output}} = \phi_T \quad (6)$$

where ϕ_I , ϕ_R , and ϕ_T are the velocity potential for the inci-

dent, reflected, and transmitted waves, respectively. Under the assumption of small-amplitude wave theory, the velocity potential functions can be expressed as

$$\begin{aligned} \phi_{\text{Input}} &= \frac{ig}{\omega} [I_0 e^{ikx} f(y) + R_0 e^{-ikx} f(y)], \text{ as } x \rightarrow \infty \\ \phi_{\text{Output}} &= \frac{ig}{\omega} [T_0 e^{ikx}] f(y), \text{ as } x \rightarrow -\infty \end{aligned} \quad (7)$$

where I_0 , R_0 and T_0 represent the wave amplitude for the incident, reflected, and transmitted waves, respectively. The eigenfunction $f(y)$ is given by

$$f(y) = \frac{\cosh k(h+y)}{\cosh kh} \quad (8)$$

The wave number k and the angular wave frequency ω satisfy the dispersion relation

$$\omega^2 = gk \tanh kh \quad (9)$$

The boundary conditions for different structural configurations examined in the present study for the analysis of wave interaction with floating breakwaters are discussed in detail in the next subsection.

3 Solution methodology using the multi-domain boundary element method (MDBEM)

The hydrodynamic analysis of wave interactions in the various configurations of pile-restrained breakwaters is conducted using the MDBEM technique. The current computational domain consists of a source point and a general field point. Figures 2(a)–(f) provides a detailed account of the boundaries associated with fluid regions, structural regions, and associated fluid-structure interfaces for all the configurations.

The fundamental solution to the governing equation, as presented in Equation (1), is expressed as

$$\frac{\partial^2 G}{\partial x^2} + \frac{\partial^2 G}{\partial y^2} + \delta(\xi - x, \eta - y) = 0 \quad (10)$$

where δ is the Dirac-delta function in 2-D and can be expressed as

$$\delta(t) = \begin{cases} 0, & t \neq 0 \\ \infty, & t = 0 \end{cases} \quad (11)$$

Taking (ξ, η) as the point source and r as the radius, Laplace's equation is transformed to radial coordinates as

$$\nabla^2 G = \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial G}{\partial r} \right) + \frac{1}{r^2} \left(\frac{\partial^2 G}{\partial \theta^2} \right) \quad (12)$$

where $r = \sqrt{(x - \xi)^2 + (y - \eta)^2}$ is the distance between the field point $P(x, y)$ and the source point $Q(\xi, \eta)$. Thus,

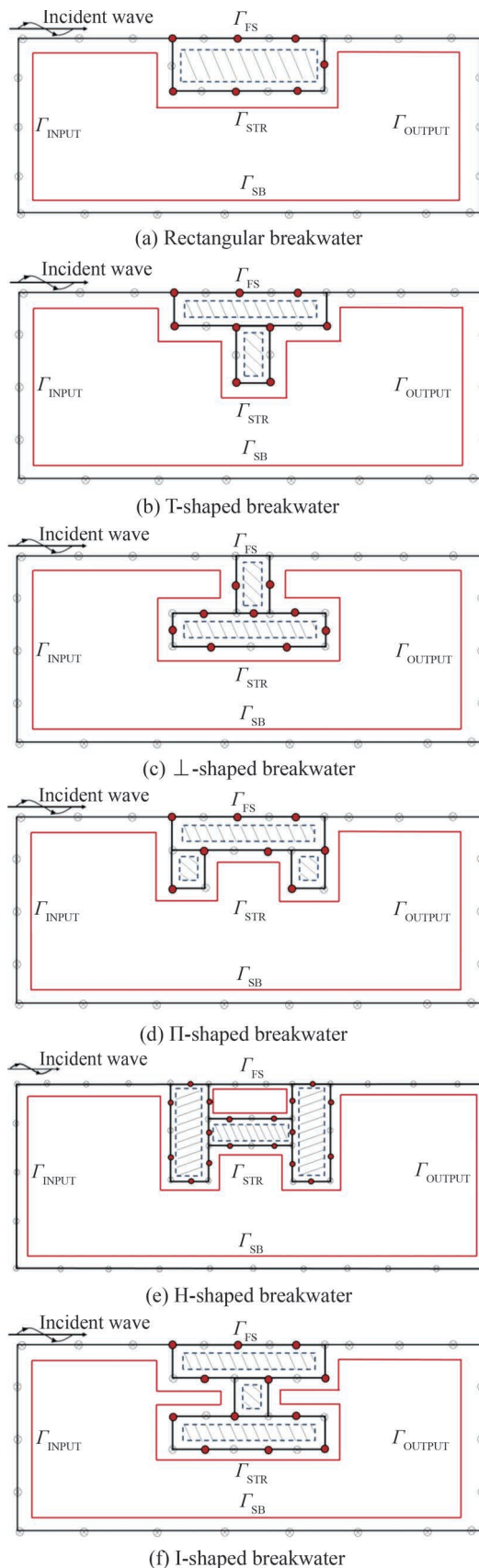


Figure 2 Schematic representation of boundary elements for pile-restrained floating breakwaters

the transformed equation can be expressed as

$$G(x, y) = \begin{cases} \frac{1}{2\pi} \ln\left(\frac{1}{r}\right), & \text{in 2D} \\ \frac{1}{4\pi r}, & \text{in 3D} \end{cases} \quad (13)$$

By employing free-space Green's function and Green's second identity, the generalized form of the boundary integral equation is obtained as

$$c(P)\phi(P) + \int_{\Gamma} \phi \frac{\partial G}{\partial n} d\Gamma = \int_{\Gamma} G \frac{\partial \phi}{\partial n} d\Gamma \quad (14)$$

with $c(P)$ is denoted by

$$c(P) = \begin{cases} 1, & \text{if } P \in \Omega \\ \frac{1}{2}, & \text{if } P \in \Gamma \text{ is smooth} \\ 0, & \text{if } P \in \Omega, \Gamma \end{cases} \quad (15)$$

where Γ denotes the boundary of the computational domain under consideration. Therefore, the final boundary integral equation can be expressed as

$$\frac{\phi(P)}{2} + \int_{\Gamma} \frac{\partial G}{\partial n} \phi d\Gamma = \int_{\Gamma} G \frac{\partial \phi}{\partial n} d\Gamma \quad (16)$$

The boundary domain is split up into N constant elements, and at the mid-element node, the ϕ value is considered constant throughout all the elements. Therefore, Equation (17) is discretized into N constant boundary elements (Figure 2), and the discretized boundary integral equation is represented as

$$\frac{\phi(P)}{2} + \sum_{j=1}^N \left(\int_{\Gamma_j} \frac{\partial G}{\partial n} \phi_j d\Gamma \right) = \sum_{j=1}^N \left(\int_{\Gamma_j} G \frac{\partial \phi}{\partial n} d\Gamma \right) \quad (17)$$

where Γ_j is the boundary of the j th element.

Given that $\int_{\Gamma_j} \frac{\partial G}{\partial n} d\Gamma = H_{ij}$ and $\int_{\Gamma_j} G d\Gamma = Q_{ij}$, the boundary integral equation in Equation (16) can be expressed as

$$-\frac{\phi(P)}{2} + \sum_{j=1}^N (H_{ij} \phi_j) = \sum_{j=1}^N (Q_{ij} \frac{\partial \phi}{\partial n}) \quad (18)$$

The terms H_{ij} and G_{ij} are the influence factors between the elements i and j where the fundamental solution is applied (Patil and Karmakar, 2021). When fluid interacts with a floating structure, the free surface and seabed, along with the corresponding dimensions and physical qualities, are substituted in the boundary conditions for the breakwater zones. Therefore, the expanded discretized equation can be expressed as

$$\begin{aligned}
& -\frac{1}{2}\phi_r^f + \sum_{j=1}^N (H_{ij}\phi_{SB}^f) + \sum_{j=1}^N (H_{ij} - ikQ_{ij})\phi_{OUTPUT}^f + \\
& \sum_{j=1}^N \left(H_{ij} - \frac{\omega^2}{g} Q_{ij} \right) \phi_{FS1}^f + \sum_{j=1}^N (H_{ij}\phi_{STR}^f) - \\
& \sum_{j=1}^N \left(Q_{ij} \frac{\partial \phi_{STR}^f}{\partial n} \right) + \sum_{j=1}^N \left(H_{ij} - \frac{\omega^2}{g} Q_{ij} \right) \phi_{FS2}^f + \\
& \sum_{j=1}^N (H_{ij} - ikQ_{ij})\phi_{INPUT}^f = 0 \quad (19)
\end{aligned}$$

The discretized equations for the leeside and seaside breakwaters, considering structural region boundary conditions, are expressed as follows:

$$-\frac{1}{2}\phi_s^s + \sum_{j=1}^N (H_{ij}\phi_{STR}^s) - \sum_{j=1}^N \left(Q_{ij} \frac{\partial \phi_{STR}^s}{\partial n} \right) = 0 \quad (20)$$

For the fluid region, the revised discretized equation, incorporating the input and output velocity potentials as defined in Equation (7), can be stated as

$$\begin{aligned}
& -\frac{1}{2}\phi_r^f + \sum_{j=1}^N (H_{ij}\phi_{SB}^f) + \sum_{j=1}^N (H_{ij} - ikQ_{ij})\phi_T^f + \\
& \sum_{j=1}^N \left(H_{ij} - \frac{\omega^2}{g} Q_{ij} \right) \phi_{FS1}^f + \sum_{j=1}^N (H_{ij}\phi_{STR}^f) - \\
& \sum_{j=1}^N \left(Q_{ij} \frac{\partial \phi_{STR}^f}{\partial n} \right) + \sum_{j=1}^N \left(H_{ij} - \frac{\omega^2}{g} Q_{ij} \right) \phi_{FS2}^f + \\
& \sum_{j=1}^N (H_{ij} - ikQ_{ij})\phi_R^f = -\sum_{j=1}^N (H_{ij} - ikQ_{ij})\phi_i^f \quad (21)
\end{aligned}$$

For each velocity potential, the superscripts f and s in Equations (19)–(21) denote the fluid region and porous structure domain, respectively. In Equation (13), the velocity potentials for seabed, transmission region, free surface between structure and transmission boundary, structure region, free surface between structure and incident region, and far-field boundary are represented as ϕ_{SB} , ϕ_T , ϕ_{FS1} , ϕ_{STR} , ϕ_{FS2} and ϕ_R , respectively. The interfaces between the structure and the sea bed and between the structure and structure-free surface are assumed rigid. Hence, the boundaries at the interface of fluid and structure regions have the same potential ϕ_{STR}^m and flux $\frac{\partial \phi_{STR}^m}{\partial n}$, which can be expressed as

$$\frac{\partial \phi_{STR}^m}{\partial n} = 0 \quad (22)$$

To solve the system of linear equations, the matching boundary conditions are applied and arranged in matrix form to determine the values of unknown potentials. The unknown potentials ϕ_R and ϕ_T from the system of equations are solved by the Gauss-elimination technique implemented

in MATLAB. The reflection coefficient K_r , transmission coefficient K_t , and dissipation coefficient K_d are calculated by the relations

$$K_r = \left| \frac{R_0}{I_0} \right|, K_t = \left| \frac{T_0}{I_0} \right|, K_d = \sqrt{1 - K_r^2 - K_t^2} \quad (23)$$

The relationship that establishes the horizontal wave force acting on the breakwater defined by Abul-Azm and Gesraha (2000) is given by

$$F_{xB} = \text{Re} \left[i\rho\omega \int_{\Gamma_{STRj}} (\mathbf{n}_x) \phi_{STR} d\Gamma \right] \quad (24)$$

where $\mathbf{n}_x$ is the unit normal vector in x direction on Γ_{STR} . The horizontal wave force coefficient can be expressed as

$$K_{Fx} = \frac{F_{xB}}{\rho gh^2} \quad (25)$$

4 Numerical results and discussion

The present study, in association with the numerical model using MDBEM for wave interaction with different floating structure configurations, is outlined in Section 2. This section discusses hydrodynamic parameters, including the reflection coefficient K_r , transmission coefficient K_t and dissipation coefficient K_d for various physical and structural parameters, such as porosity ε , friction factor f , relative water depth d/h , and relative width B/h . These parameters are assessed to determine their impact on efficiency and cost-effectiveness and to identify the most suitable structure for practical application. Wave parameters, such as acceleration due to gravity ($g = 9.81 \text{ m/s}^2$), wave amplitude ($a_0 = 1$), and water depth h , are assumed to be constant throughout the analysis. Unless stated otherwise, all structures are considered porous and are modeled using the assumed parameters provided in Table 1.

4.1 Convergence of the boundary elements for a rectangular breakwater

The convergence of the proposed MDBEM technique, evaluated in terms of the transmission and reflection coefficients for a pile-retained rectangular structure under normal wave incidence, is displayed in Table 2. As illustrated in Figure 2, the boundaries are discretized into N constant elements. The element length ($\Delta x = 0.01$) is used to analyze the structural characteristics, and the convergence of K_r and K_t is noted for the constant element length $\Delta x = 0.01$ and $\Delta x = 0.005$ up to four decimal places. The BEM mesh is constructed using the discretized elements of size 1/100th at each boundary length of 1 m.

Table 1 Structural dimensions of the floating breakwater models

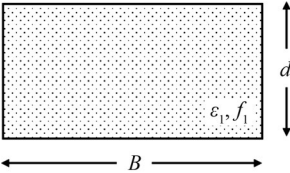
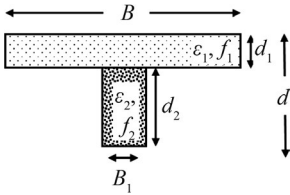
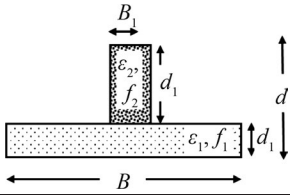
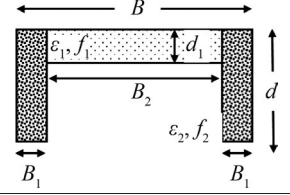
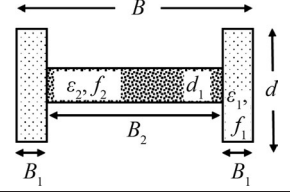
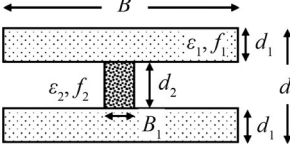
Configuration	Pictorial representation	Dimensions	Properties
Rectangular breakwater		$d = 0.2h$ $B = 2h$	$\varepsilon = 0.2$ $f = 1.2$ $S = 1$
T-shaped breakwater		$d = 0.2h, d_1 = 0.35d$ $d_2 = 0.65d$ $B = 2h, B_1 = 0.28B$	$\varepsilon_1 = 0.2, \varepsilon_2 = 0.5$ $f_1 = 1.2, f_2 = 1.0$ $S_1 = 1, S_2 = 1$
└-shaped breakwater		$d = 0.2h, d_1 = 0.65d$ $d_2 = 0.35d$ $B = 2h, B_1 = 0.28B$	$\varepsilon_1 = 0.2, \varepsilon_2 = 0.5$ $f_1 = 1.2, f_2 = 1.0$ $S_1 = 1, S_2 = 1$
Π-shaped breakwater		$d = 0.2h, d_1 = 0.65d$ $B = 2h, B_1 = 0.16B$ $B_2 = 0.68B$	$\varepsilon_1 = 0.2, \varepsilon_2 = 0.5$ $f_1 = 1.2, f_2 = 1.0$ $S_1 = 1, S_2 = 1$
H-shaped breakwater		$d = 0.2h, d_1 = 0.4d$ $B = 2h, B_1 = 0.16B$ $B_2 = 0.68B$	$\varepsilon_1 = 0.2, \varepsilon_2 = 0.5$ $f_1 = 1.2, f_2 = 1.0$ $S_1 = 1, S_2 = 1$
I-shaped breakwater		$d = 0.2h, d_1 = 0.3d$ $d_2 = 0.4d$ $B = 2h, B_1 = 0.28B$	$\varepsilon_1 = 0.2, \varepsilon_2 = 0.5$ $f_1 = 1.2, f_2 = 1.0$ $S_1 = 1, S_2 = 1$

Table 2 Convergence of K_r and K_t with increasing boundary elements

Γ_{SB}	Γ_{SW}	Γ_{FS_1}	$\Gamma_{STR_{1-3}}$	Γ_{FS_2}	Γ_{Input}	Δx	N	K_r	K_t
40	10	10	25	10	10	0.100	110	0.090637	0.996318
80	20	20	50	20	20	0.050	220	0.089868	0.996247
400	100	100	250	100	100	0.010	1100	0.089231	0.996010
800	200	200	500	200	200	0.005	2200	0.089154	0.995799

4.2 Validation of the present numerical model

A numerical method of discretizing the boundary in multi-domain is developed to analyze wave-floating structure interactions. The proposed model is validated using the model developed by McDougal and Sulisz (1989), and for stratification, a double-layer structure is modeled according to the approach of Yu and Chwang (1994). Further-

more, the MDBEM model is validated using the experimental results obtained with a physical model test conducted in the wave flume.

4.2.1 Comparative study with numerical method

The numerical model for the fixed floating rectangular structure as in McDougal and Sulisz (1989) is validated with the present BEM approach, as shown in Figure 3(a).

The numerical results obtained for K_r and K_t indicate that the transmission is maximized and reflection is minimized for shallow water depths at high kh values. The cross-section of the structure is assumed to be rectangular, with draft d and width $2b$. The depth is assumed to be 10 m, and the wave amplitude is 1 m. The ratio of the cross-sectional area of the structure to the square of the water depth serves as an approximation indicating the structure's size. Structural mass is assumed to be equally distributed and has a density of half that of seawater. Given the reflective nature of the fixed structure, a standing wave will likely form. Except at large wave numbers and near the natural pitch frequency, the free-floating structures generally exhibit greater wave transmission. The results obtained for the current model are consistent with the result of McDougal and Sulisz (1989), underscoring the validity of the model and suggesting avenues for further research.

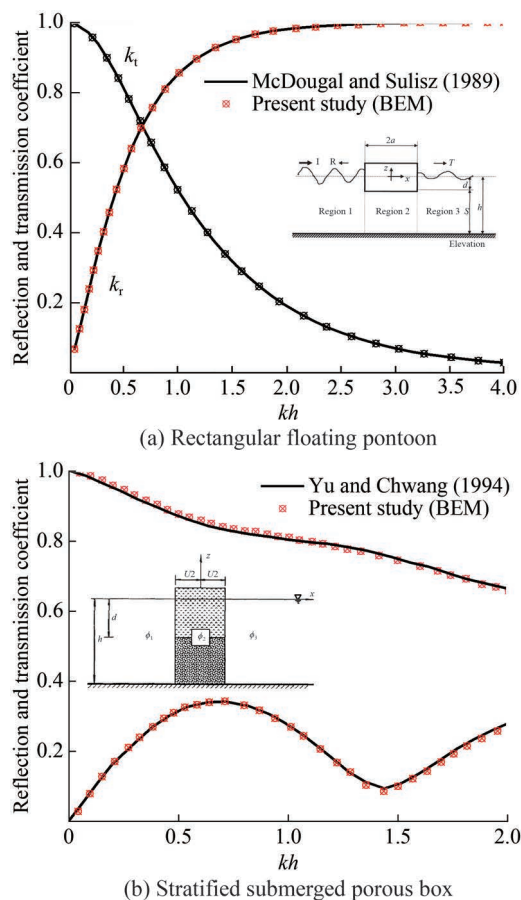


Figure 3 Comparative study of K_r and K_t for a rectangular fixed floating structure with McDougal and Sulisz (1989) and stratified submerged porous box of different porosities with Yu and Chwang (1994)

Additionally, the current MDBEM technique is applied to analyze wave interaction with the horizontal stratified structure as shown in Figure 3(b) and validated with Yu and Chwang

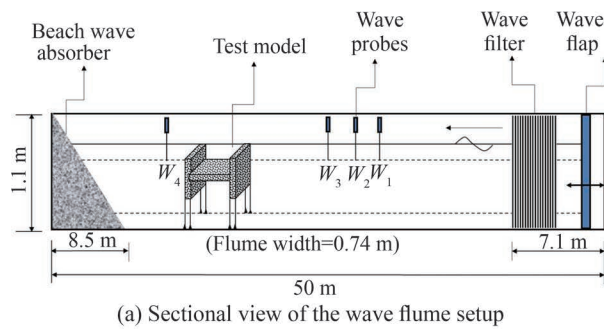
(1994), where $\varepsilon_1 = \varepsilon_2 = 0.8$, $S_1 = S_2 = 0.2$, and $f_1 = f_2 = 2$; their findings indicate that a structure with low porosity exhibits increased wave reflection and reduced transmission, demonstrating enhanced energy dissipation; when waves travel through a medium with high porosity, they dissipate energy, and when porosity falls, they dissipate less energy. The MDBEM approach is extended for the investigation, and the numerical results obtained utilizing the current MDBEM approach and the EFEM stratified structure predicted by Yu and Chwang (1994) are noted to have good agreement.

4.2.2 Comparative study with the experimental method

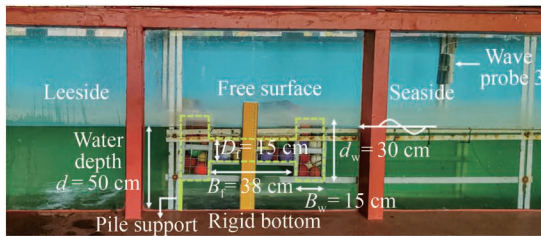
The experimental investigation is performed in the wave flume at the Department of Water Resources and Ocean Engineering, National Institute of Technology Karnataka, Surathkal, India. Figure 4(a) depicts the experimental configuration. The flumes are 50 m long, 0.74 m wide, and 1.1 m deep. At one end, a 1.4 m deep chamber houses a bottom-hinged flap that generates regular waves. To reduce wave reflection, a rubble mound wave absorber is placed at the opposite end of the wave flume. A flap-type wave-maker that runs electrically on an 11 kW induction motor at 1450 r/min controls the wave flume. This laboratory facility can generate regular waves with a maximum water depth of 0.70 m, with wave periods of 1.0–3.0 s and wave height of 0.06–0.20 m.

Before the experimental trials, the wave flume is calibrated to determine the appropriate wave height for a certain generator stroke and wave period combination at varying water depths. Wave surface elevation on the water surface is measured using capacitance-type wave probes. The methodology proposed by Goda and Suzuki (1976) is employed. Three-wave probes are placed at L , $L/3$, and $2L/3$ distances from the test model to the direction of wave propagation to measure incident and reflected wave heights. The sectional view of the wave flume setup is presented in Figure 4(a).

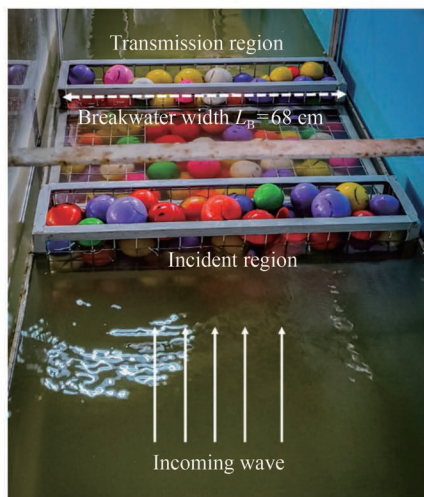
The experimental investigation is performed on an H-shaped pile-restrained breakwater. The H-shaped structure consists of three rectangular structures, as shown in Figure 4(b): two vertical members (webs) and one horizontal member (flange). The porosity of the structures is varied by using concrete balls of various diameters (0.02, 0.04, 0.06, and 0.08 m). The H-shaped breakwater model utilized in the study is tightly packed with concrete balls of varying sizes, which are arranged in different combinations to achieve the desired levels of porosity. The concrete balls are placed within the breakwater's meshed walls, along with an additional removable top mesh to secure the uppermost layer. Observations during the experiments indicate negligible drift owing to the close packing of the balls. The schematic of the H-shaped porous structures restrained by the piles and notations used in the experiment is shown in Figures 4(b) and 4(c). The notations with the range for the experiment are presented in Table 3.



(a) Sectional view of the wave flume setup



(b) Front view of experimental setup



(c) Top view of experimental setup

Figure 4 Sectional, front, and top views of the experimental setup for pile-restrained H-shaped porous breakwater**Table 3** Physical parameters for the different configurations of the composite breakwater

Symbol	Description	Range (m)
d	Water depth	0.50
d_w	Depth of web	0.30
d_f	Depth of flange	0.15
B_w	Width of web	0.15
B_f	Width of flange	0.38
L_B	Breakwater width	0.68

The current investigation involves an experimental analysis to study the hydrodynamic behavior of a pile-restrained H-shaped porous breakwater. The analysis was performed under regular wave conditions, and the results are compared with those obtained using the numerical model developed with the MDBEM. Wave interaction is studied under

various levels of porosity of the breakwaters to evaluate reflection and transmission coefficients on the basis of the nondimensional wave number kh . The breakwater is pile restrained under a surface-piercing condition, tested on the wave flume with 0.5 m water depth, as shown in Figure 4(a). The regular waves with a fixed wave height of 12 m are used, with $1.4 \leq T \leq 2.6$ s. The webs and flange sections of the H-shaped model have varying uniform porosity within $0.2 \leq \varepsilon_{1,2} \leq 0.4$. The model dimensions are illustrated in Figures 4(b) and 4(c). The parameters are kept constant: $\rho = 1000 \text{ kg/m}^3$, $g = 9.81 \text{ m/s}^2$, $S_1 = S_2 = 1$, and $f_1 = f_2 = 0.5$ throughout the computation.

This study examines measurement uncertainties, quantifying uncertainty components (Sener et al., 2023) and using the standard error of the mean for repeated testing. Uncertainty analysis provides a quantitative range with a specified confidence level, within which the true value most likely falls. To obtain accurate measurement results, uncertainty estimations and corresponding confidence levels are included. Table 4 shows the uncertainty parameters in terms of standard deviation and standard error of the mean. The mean value of repeated test results from n samples is computed as

$$Y_m = \sum_{i=1}^n Y_i \quad (26)$$

The dispersion of findings from several measurements can be quantified using the standard deviation, which is expressed as

$$SD = \sqrt{\frac{\sum_{i=1}^n (Y_i - Y_m)^2}{n - 1}} \quad (27)$$

The standard error of the mean is calculated as

$$SEM = \frac{SD}{\sqrt{n}} \quad (28)$$

Table 4 Uncertainty parameters for the incident wave with different wave heights

Wave height (cm)	SD	SEM
6	0.009	0.001
8	0.008	0.001
10	0.007	0.000
12	0.010	0.001

Figures 5(a)–(c) presents a comparison of variations in K_r and K_t with the nondimensional wave number kh for the pile-restrained H-shaped model. The comparison is based on experimental and numerical results for different levels of porosity in shallow water conditions. In the experimental studies, the time period is considered in the range of 1.4–2.6. Hence, the nondimensional wave number varies from 0.5 to 1.2. Increasing the porosity of the breakwater in inter-

mediate- and deep-water regions ($kh \geq 0.3$) lowers the reflected energy, and increased wave energy dissipation and absorption mechanisms within the structure are the prime causes of this effect. A slight decrease in transmission coefficient is observed as porosity increases. This behavior is primarily attributed to increased energy dissipation, long-wave interaction length, wave refraction, and diffraction effects. The pile-restrained H-shaped breakwater

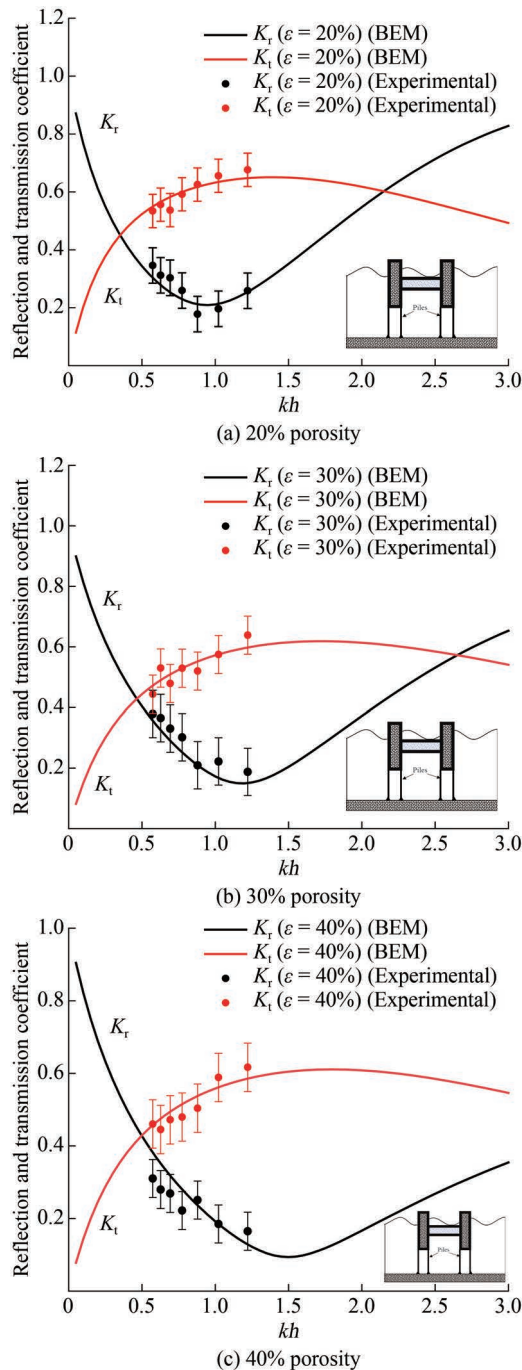


Figure 5 Comparison of reflection and transmission coefficient for different levels of porosity of breakwater versus nondimensional wave number kh , validated using experimental study and the MDBEM

is observed as efficient in shallow-water regions by maximizing the reflection and minimizing the transmission. A close agreement with the numerical and experimental results of K_r and K_t with the change in the porosity is observed for wave numbers of 0.5–1.2.

4.2.3 Rectangular porous box

Figures 6(a) and 6(b) show variations in reflection coefficient K_r , transmission coefficient K_t , and dissipation coefficient K_d as a function of nondimensional wave number kh at different levels of porosity and friction factors of 0.6–1.5 for a porous rectangular box. At low porosity ($\varepsilon_1 = 0.1$) and high friction factor ($f_1 = 1.5$), a high wave reflection (Figure 6(a)) of 80% and nearly zero wave transmission are observed because of restricted flow through the structure. Given the minimal friction-induced movement of the fluid through the structure, the wave dissipation is moderate.

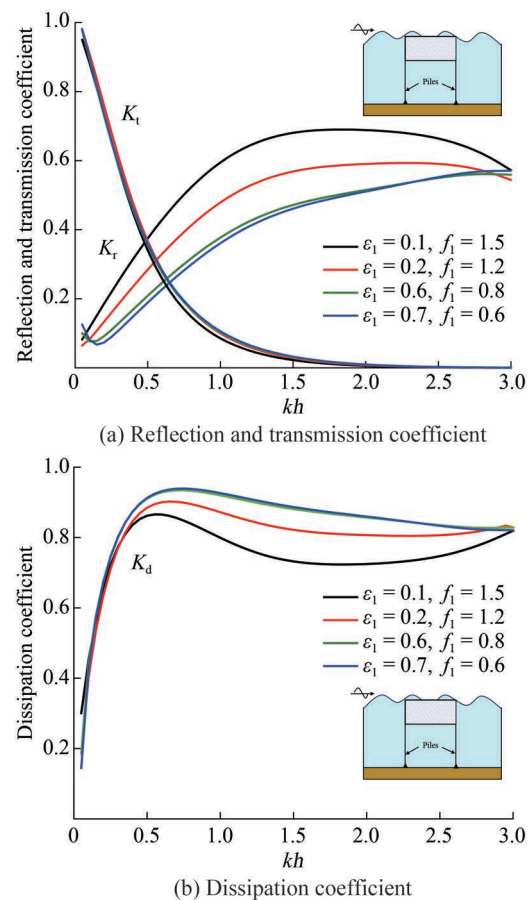


Figure 6 Variations in reflection, transmission, and dissipation coefficient K_d versus nondimensional wave number kh for different levels of porosity and friction factor at $d/h = 0.2$ and $B/h = 2$ for a rectangular porous box breakwater.

At high porosity ($\varepsilon_1 = 0.7$) and low friction factor ($f_1 = 0.6$), wave reflection is minimal, and a high wave transmission of 70% is achieved, given that waves can easily flow through the permeable structure. Hence, for less fric-

tion fraction, minimal dissipation is observed. Given the moderate porosity ($\varepsilon_1 = 0.6$) and low friction factor ($f_1 = 0.6$), maximum energy dissipation (Figure 6(b)) of up to 60% is noted by maintaining a balance between significant friction and sufficient flow through the structure. At low porosity ($\varepsilon_1 = 0.1$) and high friction factor ($f_1 = 1.5$), a small portion of fluid enters the structure despite considerable friction, and the dissipation is restricted. At a low kh value (long waves/shallow water), a high wave reflection and wave dissipation result from waves interacting with the structure, but for high kh (deep water/short waves), waves transmit more readily, lowering wave dissipation and wave reflection. Particularly for long waves, wave dissipation and wave reflection increase because of improved wave–structure interactions in a structure with dimensions $d/h = 0.2$ and $B/h = 2$. The hydrodynamic coefficients are determined by the interaction of wave characteristics, friction (dissipating energy), and porosity (enabling flow). High friction promotes wave dissipation, but low porosity improves wave reflection. At reasonable porosity and friction coefficient, optimal energy dissipation occurs. At a low friction coefficient, wave transmission is dominant.

Figures 7(a) and 7(b) depict the variation of reflection coefficient K_r , transmission coefficient K_t and dissipation coefficient K_d as a function of nondimensional wave number kh for changing relative water depth values of 0.1–0.5. Regardless of water depth, a low draft for a rectangular structure in Figure 7(a) transmits high wave energy in the breakwater with $d/h = 0.1$, resulting in over 80% wave transmission in shallow-water regions. The effectiveness of the breakwater in diffracting or scattering incoming wave energy may be limited during low drafts. High wave transmission is a result of this decreased diffraction capability. The K_r value (Figure 7(a)) exhibits a high value for the low draft in shallow- and intermediate-water regions ($kh \leq 2.0$) but shows an inverse trend in deep-water regions where the reflection is high. Given that wave energy is concentrated close to the surface in shallow water, the low draft has a high reflection; in deep-water regions, the maximum draft is effective because wave energy is distributed vertically throughout the water column. In Figure 7(b), the rectangular pile-restrained breakwater at the free surface with a high draft in shallow water ($kh \leq 2.0$) dissipates more energy than that with a high draft in deep-water regions ($kh \geq 2.0$). High draft leads to low energy dissipation in deep water depth because of reduced obstruction effects and increased dispersed wave energy. By contrast, the waves in shallow water depths generate high wave energy dissipation because of strong flow constriction.

Figures 8(a) and 8(b) show variations in K_r , K_t , and K_d as a function of dimensionless wave number kh for different relative widths ($0.25 \leq B/h \leq 2$) for the pile-restrained rectangular porous box breakwater. Variation in K_t versus kh in Figure 8(a) indicates that the wave transmission

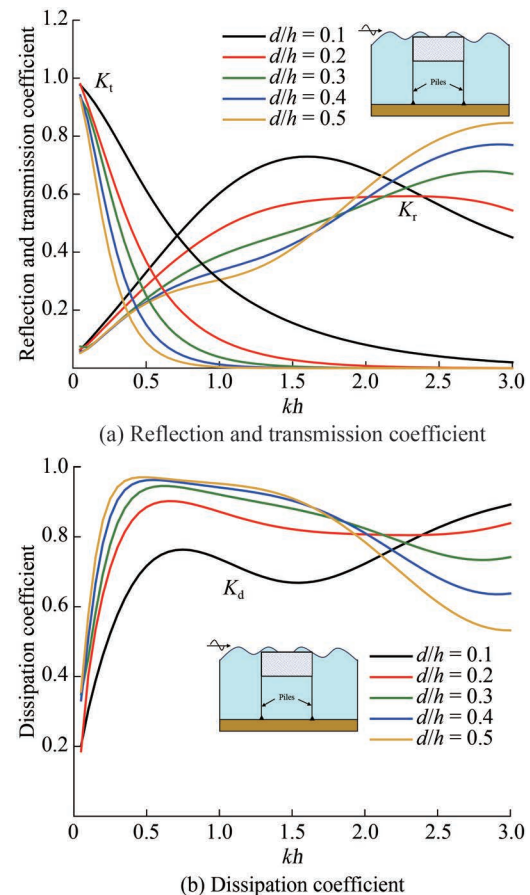


Figure 7 Variations in reflection, transmission, and dissipation coefficient versus nondimensional wave number kh changing d/h in the rectangular porous box breakwater

through the structure is unaffected by changes in relative width. The K_t values are nearly converging with each other for all the cases when $B/h \leq 2$.

However, owing to the trapping for low-frequency waves, the broadest structure transmits less wave energy for the long-wave regime, resulting in a decline in K_t . The rectangular breakwater experiences zero wave transmission regardless of width at increasing wave frequency in the short-wave region. Variation in K_r is directly proportional to the relative width B/h . As the surface area of the breakwater increases, the widest structure produces a high reflected wave. As shown in Figure 8(b), variation in the wave energy dissipation for low-frequency waves is minimal when $kh \leq 0.5$. As the wave transitions occur from the long-wave region to the intermediate and short-wave regions, the wave energy damping coefficient is observed to increase with decreasing structural breadth. An increasing tendency for wave dissipation is observed when $kh \geq 2.6$. The K_d value increases when waves shift from long to short wavelengths or high frequencies, whereas structural breadth reduces. Variations may be attributed to the difference between short and long-wave interactions. The effectiveness of energy dissipation mechanisms increases with decreasing structure width.

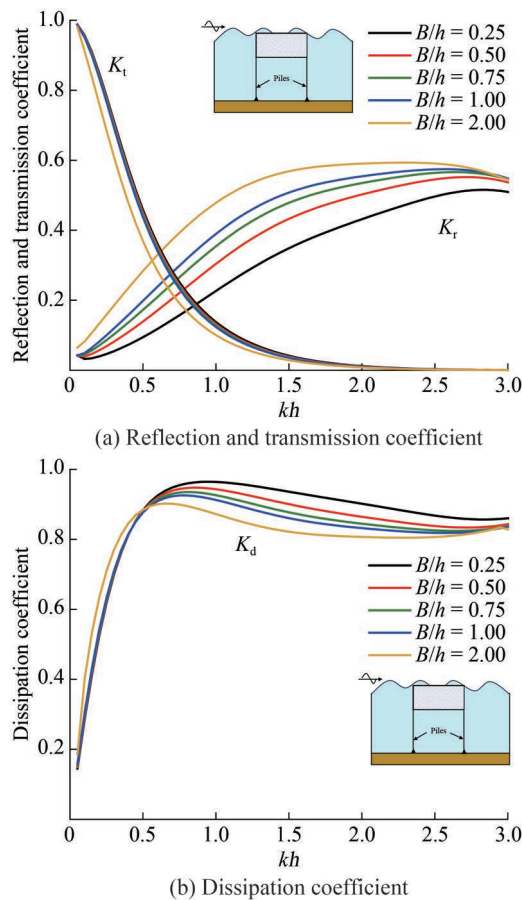


Figure 8 Variations in reflection, transmission, and dissipation coefficient versus nondimensional wave number kh changing B/h in the rectangular porous box breakwater

4.2.4 T-shaped breakwater

Figures 9(a) and 9(b) presents variations in K_r , K_t , and K_d values as functions of dimensionless wave parameter kh for different levels of porosity when $0.1 \leq \varepsilon_1 \leq 0.7$ and $0.6 \leq f_1 \leq 1.5$ for a T-type breakwater. The K_r value (Figure 9(a)) is high for high porosity and low friction coefficient in shallow and intermediate water depths ($kh \leq 3.0$). The high porosity and low friction coefficient result in increased reflection because large empty spaces improve wave resonance, and reduced friction diminishes wave energy dissipation. Furthermore, an opposite trend is observed for K_t value at intermediate water depth ($kh \leq 1.0$), and the combined effects of increased pore space, which facilitates fluid flow, and decreased resistance to movement, optimize fluid dynamics in porous media, primarily accounting for the increase in relative permeability with high porosity and low friction coefficients in shallow and intermediate water depths. At deep-water regions, the K_t value is negligible for the T-shaped floating breakwater; increasing the relative water depth considerably reduces wave transmission. In deep-water regions, floating breakwaters are more cost-effective than permanent breakwaters. Figure 9(b) shows

that the K_d value is high in shallow and intermediate water depths when the porosity is low and the friction coefficient is high. Increased flow velocities in small pore spaces and increased friction-induced turbulence exert synergistic effects to increase dissipation, intensifying energy dissipation in porous structures.

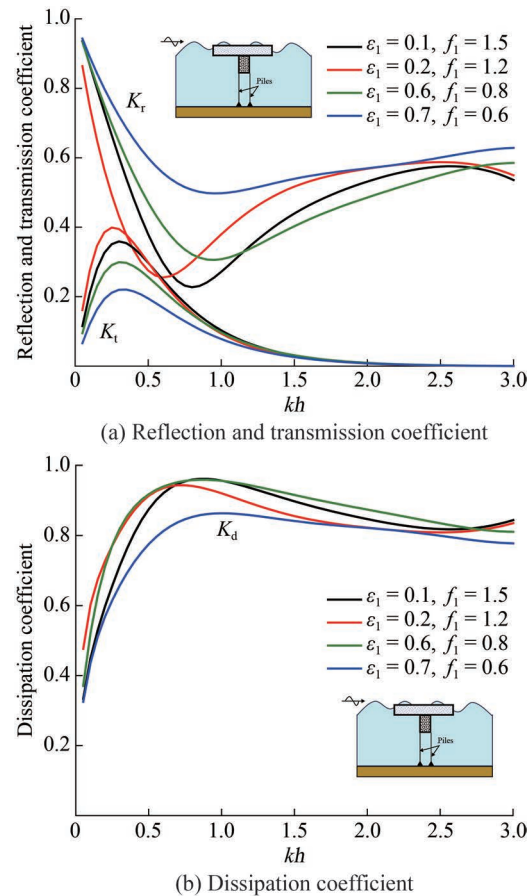


Figure 9 Variations in reflection, transmission, and dissipation coefficient versus nondimensional wave number kh for changing porosity and friction coefficient when $d/h = 0.2$ and $B/h = 2$ in the T-type floating breakwater

Variations in K_r , K_t , and K_d are presented in Figures 10(a) and 10(b) as a function of dimensionless wavenumber kh at changing relative water depth ($0.1 \leq d/h \leq 0.5$) in the T-type breakwater. The oscillating crest and trough in K_r (Figure 10(a)) are visible when $d/h = 0.4$. Variations in oscillations between the long-wave and intermediate depth are considerably lower. Owing to the effective presence of the web section, which induces more wave reflection than simple rectangular structures, notable alterations in K_r are observed (Figure 10(a)). High-frequency waves are reflected because of wave entrapment. By contrast, waves in the long-wave regime can easily pass through the structure with extremely little wave reflections because of the low wave frequency. The presence of a T-type breakwater lowers wave transmission when $kh \geq 1.0$ regardless of changes in

relative depth. For each type of wave frequency at $d/h = 0.4$, notable crests and troughs are observed, and the wave dissipation coefficient (Figure 10(b)) is noted to have an oscillating nature. The nonidentical porous structures interacting with a wave can cause a specific type of orientation in the numerical findings. As a result, increased energy dissipation occurs at low wave frequencies when surface layer porosity is low.

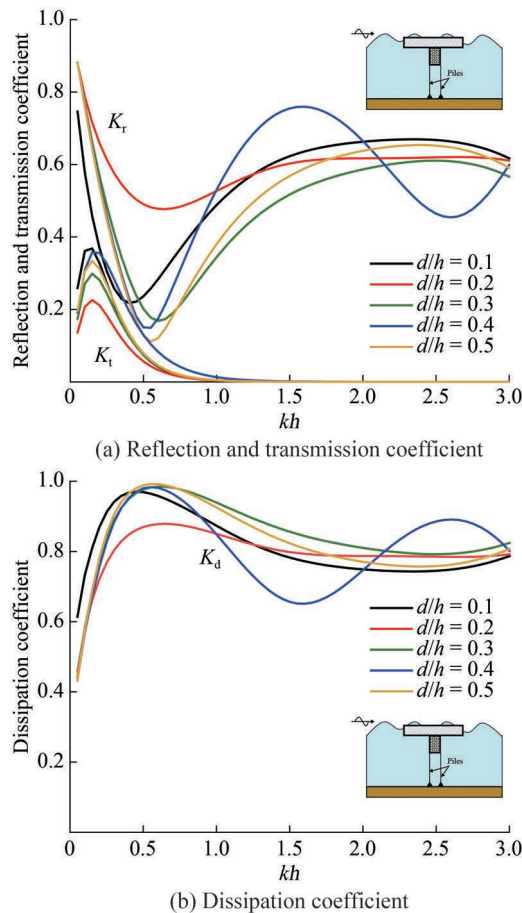


Figure 10 Variation of reflection, transmission and dissipation coefficient versus nondimensional wave number kh changing d/h in the case of T-type floating breakwater

Figures 11(a) and 11(b) show variations in K_r , K_t , and K_d as functions of dimensionless wavenumber kh for different relative widths ($0.25 \leq B/h \leq 2$) for a T-type floating porous breakwater. In intermediate water depth ($kh \geq 0.5$), the T-type breakwater with a high B/h reflects wave energy, as indicated by the high K_r (Figure 11(a)) values at a shallow water depth. In addition, the effect is minimal. The minimal effect in shallow water depth is due to the dominant bottom friction and horizontally concentrated wave energy, whereas K_r values increase with relative width at an intermediate water depth because of improved wave-structure interaction and uniform energy distribution. Wave energy is transmitted through the breakwater for a high

width at a shallow water depth but is insignificant in intermediate water depth. Given that bottom friction predominates and wave energy is concentrated horizontally in shallow water, B/h increases with wave energy transfer K_r , rendering the T-type breakwater width negligible. High width has little influence on wave energy transmission at intermediate water depths. In shallow water depth, the effect is minimal, but in intermediate water depth, the wave dissipation K_d (Figure 11(b)) increases with decreasing width. Given that wave dissipation is mostly regulated by bottom friction in shallow water, rendering width effects insignificant, dissipation increases in narrow channels in intermediate water depth because of enhanced wall effects and wave focusing. Thus, to develop and optimize T-type floating porous breakwater for efficient wave energy management in offshore and coastal environments, engineers and researchers need to understand design factors that affect structural performance in wave attenuation.

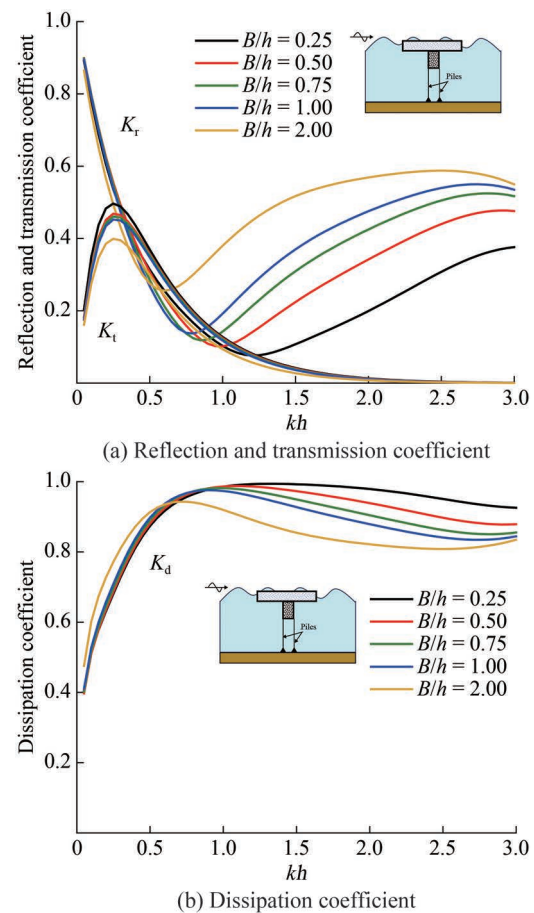


Figure 11 Variations in reflection, transmission, and dissipation coefficient versus nondimensional wave number kh changing B/h in the case of T-type breakwater

4.2.5 $\perp$ -shaped breakwater

Figures 12(a) and 12(b) depict variations in K_r , K_t , and K_d as functions of dimensionless wave parameter kh for differ-

ent levels of porosity ($0.1 \leq \varepsilon_1 \leq 0.7$) and friction factors ($0.6 \leq f_1 \leq 1.5$) for a $\perp$ -type breakwater. Figure 12(a) illustrates that K_t is affected because of changes in porosity and friction factor in shallow-water regions ($kh \leq 0.5$) but unaffected at intermediate and deep water depths ($kh \geq 0.5$). Moreover, K_r increases with increasing friction factor and decreasing porosity. Porosity and friction affect the transmission coefficient in shallow water because of bottom interaction and increased energy dissipation. However, they exert minimal effects in deep water because of insignificant bottom effects. Hence, more wave energy is reflected, and less is transmitted through the $\perp$ -type breakwater, and the reflection coefficient increases with increasing friction and decreasing porosity at all depths. K_d (Figure 12(b)) is noted to be high for low friction factors and high porosity regardless of water depth. A small amount of energy is lost through friction within the porous material, and more wave energy can be transported and dissipated through other means, resulting in a greater dissipation coefficient. Conversely, large porosity results in a high dissipation coefficient because more water may pass through the structure, increasing the dissipation of wave energy.

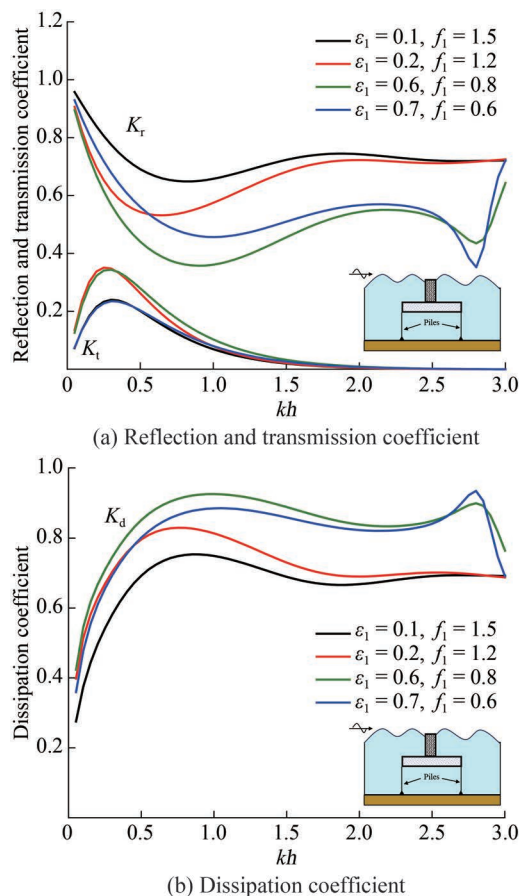
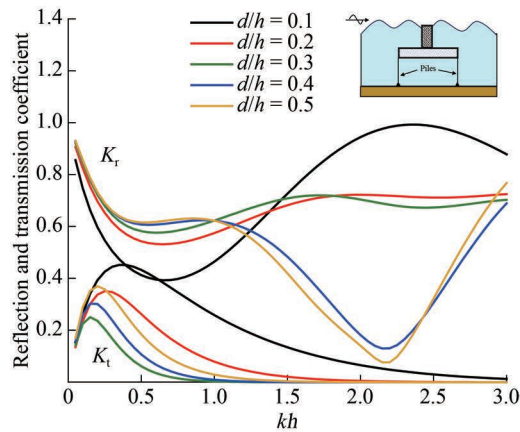


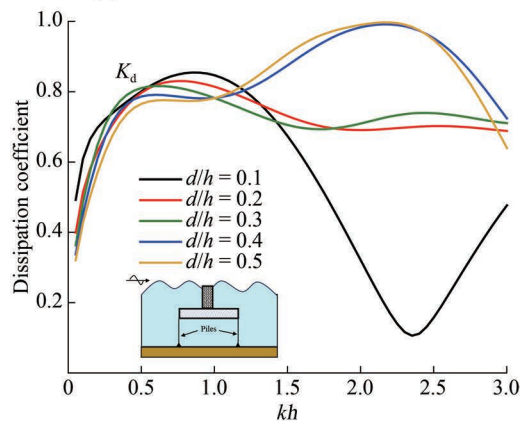
Figure 12 Variations in reflection, transmission, and dissipation coefficient versus nondimensional wave number kh changing porosity and friction coefficient considering $d/h = 0.2$ and $B/h = 2$ in the $\perp$ -type breakwater

Figures 13(a) and 13(b) show variations in K_r , K_t , and K_d values as functions of dimensionless wave number kh for various relative structural depths ($0.1 \leq d/h \leq 0.5$) for an $\perp$ -type breakwater. At low wave frequencies, variations in K_r (Figure 13(a)) are observed as d/h changes. When $d/h \leq 0.3$, the notable undulating troughs are observed. The $\perp$ -type breakwater with the highest relative draft ($d/h \geq 0.4$) exhibits a sharp decline to reach the minima as the wave transitions from the long-wave to the short-wave domain, and the structure with the lowest draft ($d/h = 0.1$) exhibits an oscillating crest and reaches the peak value. Given that water mass is allowed within the flange area, a highly frequent wave is slightly reflected as the structural draft increases, including the web of the $\perp$ -type breakwater. Furthermore, for high-frequency waves, the undulating peak in K_t (Figure 13(a)) is observed in the long-wave regime, but the number of oscillations in the transmission coefficient decreases in the short-wave regime. Additionally, the K_t value increases with decreasing d/h , and a deviation in the trend is observed when $d/h \geq 0.4$. As the web of the $\perp$ -type breakwater is submerged deeper, wave transmission at high-frequency waves decreases. Large crests and troughs are observed for each type of wave frequency, and K_d (Figure 13(b)) exhibits an oscillating nature when $d/h = 0.1$. During the transition from the long-wave regime to the short-wave regime, the $\perp$ -type breakwater dissipates a relatively small amount of wave energy. High energy dissipation is significantly greater in the short-wave range. Therefore, when structural depth increases, high-frequency wave energy dissipation is enhanced, leading to wave entrapment instead of transmission. Given that the increased surface area of a porous breakwater interacts with incident waves, the high dissipation of high-frequency wave energy occurs as the structural depth increases. As a result, wave energy dissipation increases, and wave energy reflection decreases.

Figures 14(a) and 14(b) show variations in K_r , K_t , and K_d as functions of dimensionless wave number kh for different relative widths ($0.25 \leq B/h \leq 2$) for a $\perp$ -type floating breakwater. K_r (Figure 14(a)) is higher for wider structures in intermediate- and deep-water regions ($kh \geq 0.3$). However, the effect of variation in the width of the structure is negligible in shallow water depths. The fundamental natural frequency of the system may decrease with increasing relative structural width. A wide structure is more effective as a breakwater because it distributes more wave energy. As B/h increases, the wave transmission decreases, as depicted in Figure 14(a) and is mostly significant in shallow-water regions. The low wave frequencies and a rising oscillation trend result in less wave dissipation (Figure 14(b)). In the long-wave regime ($0.0 \leq kh \leq 0.45$), K_d increases with B/h . In the intermediate and deep-water region ($kh \geq 0.45$), oscillation in K_d trends displays an opposite trend and exhibits large oscillation magnitudes for low values. High-frequency waves dissipate energy because of wave trapping



(a) Reflection and transmission coefficient



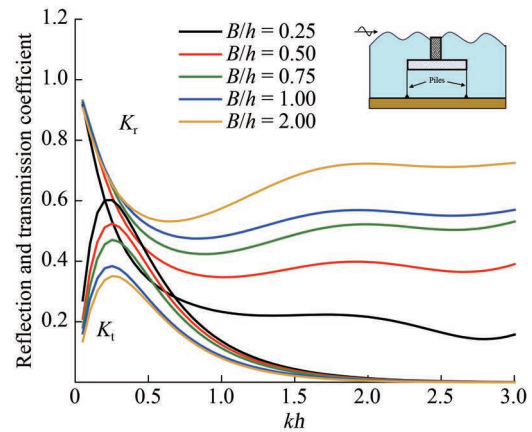
(b) Dissipation coefficient

Figure 13 Variation of reflection, transmission and dissipation coefficient versus nondimensional wave number kh changing d/h in the case of $\perp$ -type breakwater

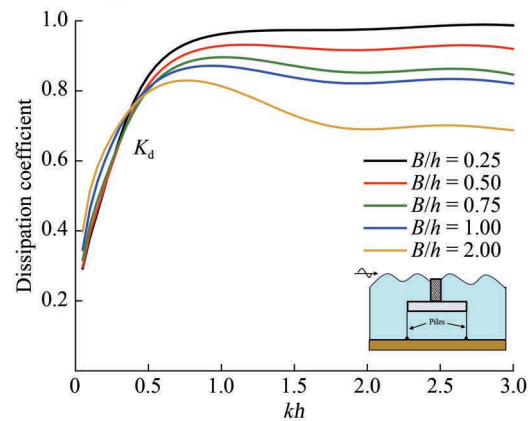
when they interact with a broad structure, which causes oscillations to invert. Wide structures dissipate less turbulent energy because of improved flow, reduced vortex shedding, and stable pressure distribution across the $\perp$ -type breakwater.

4.2.6 Π -shaped breakwater

Figures 15(a) and 15(b) depict variations in K_r , K_t , and K_d as functions of dimensionless wave parameter kh for different levels of porosity when $0.1 \leq \varepsilon_1 \leq 0.7$ and $0.6 \leq f_1 \leq 1.5$ for the Π -type breakwater. Increases in porosity and water depth result in a reduction in K_r (Figure 15(a)). This result indicates that the Π -type breakwater reflects less wave energy when kh increases. Short wavelengths in relation to water depth are associated with high kh values, which may cause wave energy to be dissipated or transmitted rather than reflected. Additionally, by permitting more wave energy to pass through or get absorbed, high porosity and friction factors can lessen the reflection. Enhanced transmission in Figure 15(a) is caused by high porosity, which facilitates the movement of the waves in the Π -type breakwater. The Π -type breakwater and wave interaction are modified for energy dissipation through turbulence and



(a) Reflection and transmission coefficient



(b) Dissipation coefficient

Figure 14 Variation of reflection, transmission and dissipation coefficient versus nondimensional wave number kh changing B/h in the case of $\perp$ -type breakwater

friction at intermediate depth. The waves may be short to interact with the breakwater efficiently at extremely high kh values, which would reduce wave dissipation (Figure 15(b)). More wave energy may pass through the Π -type breakwater because of increased porosity, which increases K_t and lowers K_r . Owing to the increased turbulence and friction inside the porous structure, the energy dissipation of Π -type breakwater is improved. Given that wave energy is lost to friction, a high friction factor results in energy dissipation. As the breakwater absorbs more energy, K_r and K_t decrease. The way waves interact with the Π -type breakwater is determined by the dimensionless wave parameter kh . High kh values (shorter waves) tend to transmit more energy and can be dissipated more efficiently at specific ranges, while lower kh values (longer waves) tend to reflect more energy.

Figures 16(a) and 16(b) present variations in the K_r , K_t , and K_d value of waves interacting with an Π -type breakwater as a function of dimensionless wave number kh for different values of relative water depth d/h when $0.1 \leq d/h \leq 0.5$. Figure 16(a) shows that the oscillatory trend for K_r is large for small values in the intermediate water region ($kh \geq 0.5$) and shows an opposite trend in the deep-water region.

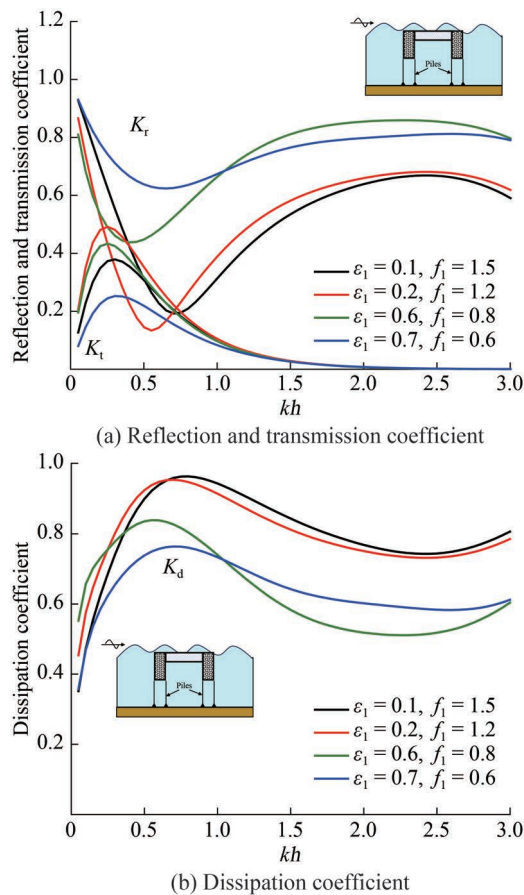


Figure 15 Variations in reflection, transmission, and dissipation coefficient versus nondimensional wave number kh changing porosity and friction coefficient when $d/h = 0.2$ and $B/h = 2$ in Π -type breakwater

Waves prefer to travel through structures at low wave frequencies, and as the frequency increases, the front web of the Π -type breakwater creates a barrier that reflects the wave in the short-wave regime. Variations in K_t (Figure 16(a)) demonstrate that the change in transmission coefficient is inversely proportional to d/h . As a result, as the structural draft increases, the wave transmission decreases, and as wave frequency increases in deep-water regions, it becomes invalid. At shallow and intermediate water depths ($kh \leq 2.5$), the wave transmission diminishes as the structural draft increases (d/h). However, in deep-water regions, it becomes invalid. In shallow or intermediate water, the wave transmission reduces as structural draft increases because a large percentage of the wave energy is intercepted by the structure. Similarly, energy damping increases at high d/h at shallow and intermediate water depths, as indicated by the variation in K_d (Figure 16(b)). However, frequent waves create wave entrapment inside the structural periphery, and increased structural depth results in reduced dissipation. Wave energy dissipation often increases with structural depth at shallow and intermediate water depths because of wave breaking and seabed friction. This relationship can be changed by

wave entrapment in Π -shaped breakwaters. Standing waves and resonance are produced by wave entrapment, which tends to limit energy dissipation, particularly as structural depth increases.

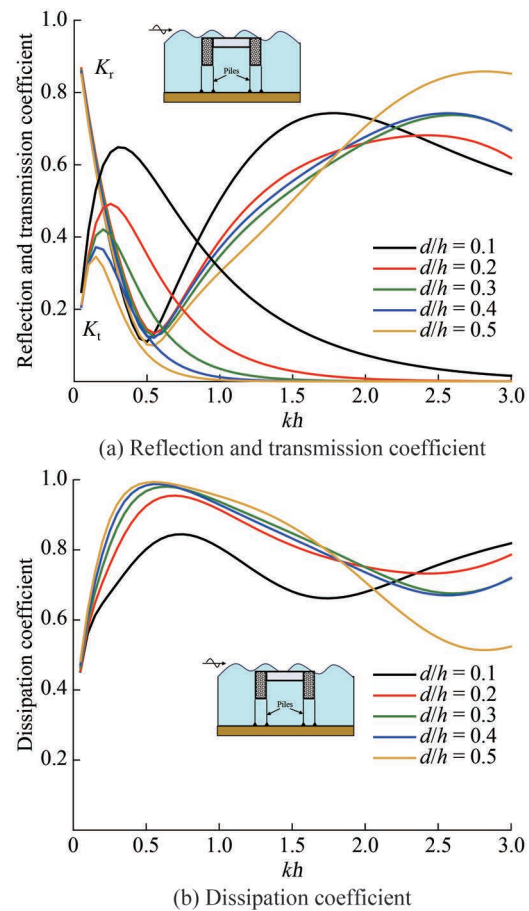


Figure 16 Variation of reflection, transmission and dissipation coefficient versus nondimensional wave number kh changing d/h in the case of a Π -type breakwater

Figures 17(a) and 17(b) show the variation in K_r , K_t , and K_d as a function of dimensionless wave number kh for different relative widths ($0.25 \leq B/h \leq 2$) for the Π -type breakwater. High K_r (Figure 17(a)) values imply that the Π -type breakwater with a high B/h reflects more wave energy in intermediate water depth ($kh \geq 0.5$), and the effect is negligible at shallow water depths ($kh \leq 0.5$).

In shallow water depth, the relative width impact is minimal because of bottom friction and primarily horizontal motion. By contrast, at an intermediate water depth, the increased reflection at a large relative width is caused by enhanced chamber resonance and vertical particle motion. Wave energy is transmitted through the breakwater for a small width in shallow water, but it is insignificant in intermediate water depth. More wave energy is transmitted through narrow breakwaters in shallow water because of concentrated bottom effects and enhanced wave–structure

interaction. In intermediate water, the effect is minimal because of uniform energy distribution throughout the water column. The effect is negligible in shallow water, but as shown in Figure 17(b), K_d increases with decreasing breadth at intermediate water depth. The width of the breakwater has less effect in shallow water depth because bottom friction is the main factor influencing wave energy dissipation. Seabed friction dissipates wave energy, which attenuates waves. As the breakwater width in intermediate water decreases, energy dissipation increases, and as a result, the effects of B/h on energy dissipation vary with water depth.

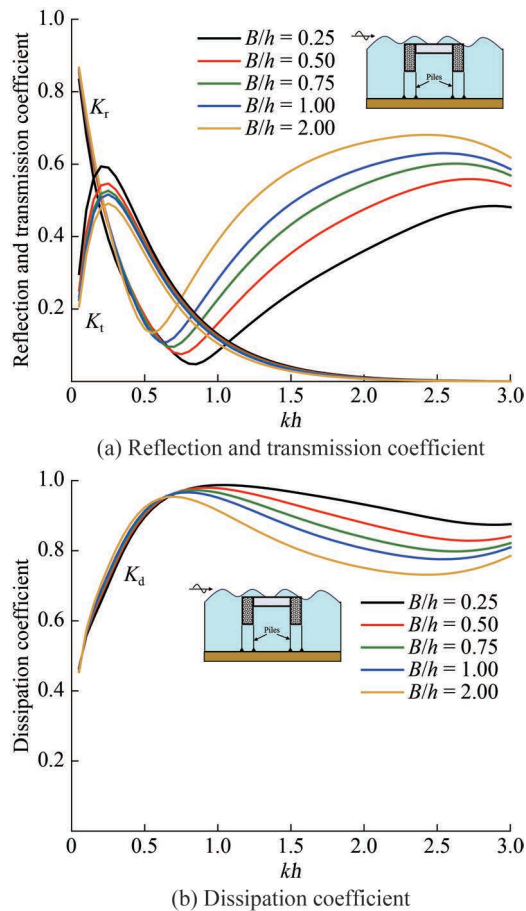


Figure 17 Variation of reflection, transmission and dissipation coefficient versus nondimensional wave number kh for changing B/h in the case of Π -type breakwater

4.2.7 H-shaped breakwater

Figures 18(a) and 18(b) illustrate variations in K_r , K_t , and K_d values as functions of dimensionless wave parameter kh for different levels of porosity ($0.1 \leq \varepsilon_1 \leq 0.7$) and friction factors ($0.6 \leq f_1 \leq 1.5$) for the H-type breakwater. Given that the flange part is less exposed to wave interaction than webs, its properties remain constant. At low porosity, K_r (Figure 18(a)) changes suddenly. Conversely, it undergoes a transition similar to that observed in other configurations at high porosity.

As observed in Figure 18(a), a sharp decline and increase in K_r are observed for the intermediate-water region ($kh \geq 0.5$). A small quantity of water accumulates above the flange and between the webs, reflects waves, and improves wave transmission at a low wave frequency range ($0.0 \leq kh \leq 1.0$). However, Figure 18(a) shows that the trends in K_r and K_t in high water depth do not significantly vary and diminish to zero. The K_d value (Figure 18(b)) exhibits a trend similar to that observed in K_r . At a shallow water depth, energy dissipation increases with decreasing porosity. The tendency is reversed in the intermediate wave region, where porosity is inversely proportional to the high-frequency and short-wave regime. High porosity allows efficient internal turbulence and wave-breaking processes for energy dissipation at intermediate depths. By contrast, low porosity in shallow water promotes flow restriction and friction-based dissipation.

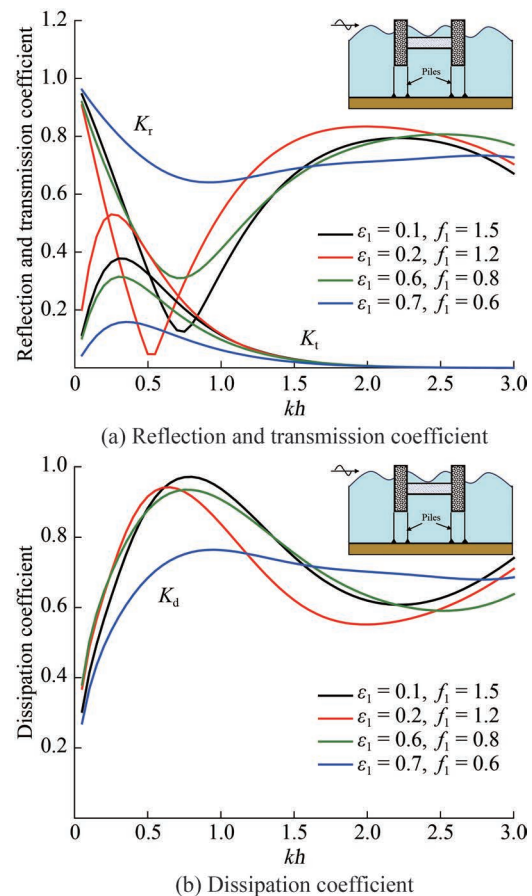
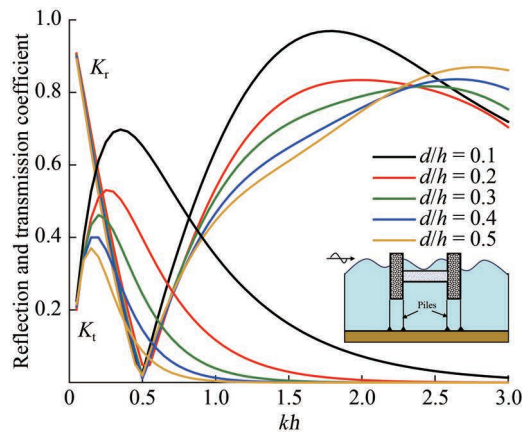


Figure 18 Variations in reflection, transmission, and dissipation coefficient versus nondimensional wave number kh for changing porosity and friction coefficient when $d/h = 0.2$ and $B/h = 2$ in the H-type breakwater

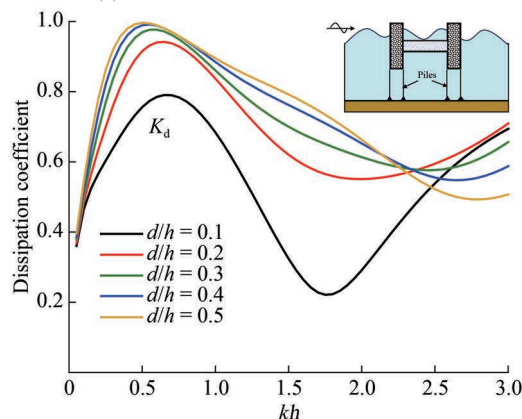
Figures 19(a) and 19(b) present the K_r , K_t , and K_d values as functions of dimensionless number kh at different relative water depths ($0.1 \leq d/h \leq 0.5$) in the H-type floating breakwater. As observed in Figure 19(a), the oscillatory

tendency of K_t is large for small values in the intermediate water depth ($kh \geq 0.5$) and then decreases sharply, particularly in the deep-water region ($kh \geq 2.5$). In the short-wave regime, waves tend to pass through the H-type breakwater with low wave frequencies, and as frequency rises, the sea-side web of the H-shaped breakwater serves as a barrier that reflects wave energy. Variations in K_t (Figure 19(a)) demonstrate that the change in transmission coefficient is inversely proportional to d/h . Given that short waves travel over the H-type breakwater readily at high kh , the wave transmission usually increases with the kh value. As the deep H-type breakwater blocks wave energy and directs it toward reflection or dissipation, the transmission falls for high d/h . Wave-structure interaction is optimal at moderate kh values, where dissipation peaks, as shown in Figure 19(b). Energy loss is probably caused by the H-type design by processes, such as viscous damping, wave breaking, or turbulence. Increased d/h improves K_d (Figure 19(b)) at intermediate depth kh because the submerged structure more efficiently breaks up wave motion. However, interactions between short waves and the structure decrease at an extremely high kh , and thus wave dissipation diminishes.

Figures 20(a) and 20(b) show variations in the K_r , K_p ,



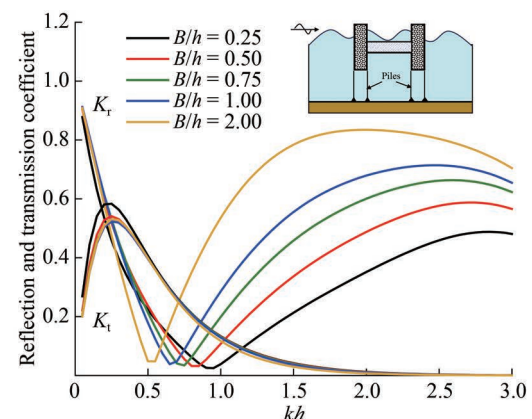
(a) Reflection and transmission coefficient



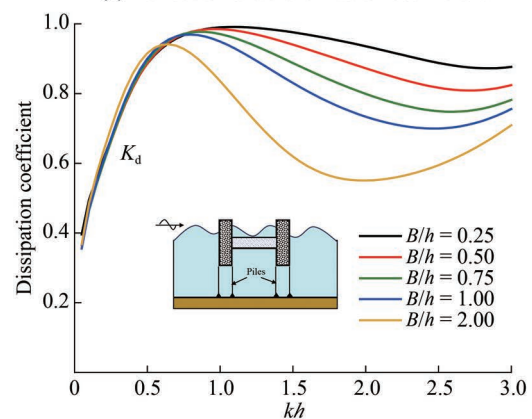
(b) Dissipation coefficient

Figure 19 Variations in reflection, transmission, and dissipation coefficient versus nondimensional wave number kh for changing d/h in the H-type breakwater

and K_d values as functions of dimensionless wave number kh for different relative widths ($0.25 \leq B/h \leq 2$) for an H-type floating porous breakwater. The H-type breakwater with high B/h values is observed to reflect wave energy in intermediate water depth ($kh \geq 0.5$), whereas the effect is lower in shallow water depth. Owing to bottom friction and mostly horizontal motion, the effect of the change in the relative width of the flange in the H-shaped structure is negligible in a shallow water depth. Chamber resonance and vertical particle motion at an intermediate water depth result in increased reflection for a large relative width. Large K_t (Figure 20(a)) values indicate that wave energy is transmitted over the breakwater for a small width in shallow water but is negligible at an intermediate water depth. In shallow water depth ($kh \leq 0.5$), concentrated bottom effects and improved wave-structure interaction facilitate the flow of wave energy through narrow breakwaters. The effect is less pronounced at an intermediate water depth. However, energy is distributed more evenly across the water column. At a shallow water depth, the effect is minimal, but at intermediate water depth ($kh \geq 0.5$), K_d increases with decreasing B/h and can dissipate up to 100% of wave energy. The relative width of the breakwater has less effect



(a) Reflection and transmission coefficient



(b) Dissipation coefficient

Figure 20 Variation of reflection, transmission and dissipation coefficient versus non-dimensional wave number kh for changing B/h in the case of H-type breakwater

in shallow water because bottom friction is the key factor determining wave energy dissipation. Waves are attenuated by the dissipation of wave energy caused by seabed friction. Energy dissipation increases in intermediate water as breakwater width decreases. Consequently, the impact on energy dissipation varies with water depth.

4.2.8 I-type breakwater

Figures 21(a) and 21(b) depict variations in K_r , K_p , and K_d as functions of dimensionless wave parameter kh for different levels of porosity ($0.1 \leq \varepsilon_1 \leq 0.7$) and friction factors ($0.6 \leq f_1 \leq 1.5$) for an I-shaped breakwater. The web portion has less wave interaction than the flange and has a constant porosity and friction factor. When structural gaps that occupy water mass are considered, the I-type structure increases wave transmission when $kh \leq 1.5$ while decreasing wave reflection. When combined with a less porous structure, the water mass produces greater wave transmission and less wave reflection, which considerably lowers reflection and enhances transmission, as observed in Figure 21(a). The configurational effect, which traps the water inside the body and amplifies the wave, may cause the phenomenon at a low porosity range. This effect reduces wave reflection,

transmission, and dissipation in the long-wave regime. As the surface waves become magnified and unable to transfer within vacant spaces, K_t achieves minimal values for structures with high porosity and low friction factor. More energy is lost during wave interaction for the structure with a greater porous structure in Figure 21(b), and less energy is observed at a low wave frequency ($kh \leq 1.0$). Porosity and friction must be balanced for the breakwater to be effective. High friction promotes dissipation, whereas low porosity reduces transmission but increases wave reflection. The need to adjust breakwater specifications to certain wave climates is highlighted by the fact that the ideal design changes with wave conditions.

Figures 22(a) and 22(b) present variations in K_r , K_p , and K_d as functions of nondimensional wave number kh for different values of relative water depth when $0.1 \leq d/h \leq 0.5$ in the I-type breakwater. The oscillatory tendency in K_r (Figure 22(a)) is high at low d/h values in the intermediate water depth ($kh \geq 0.5$) and follows a reverse trend toward deep-water regions ($kh \geq 2.0$). In deep-water regions, the exponential decay of wave motion makes high relative drafts effective at wave reflection, lowering oscillations. At an intermediate water depth, the oscillatory tendency is high for

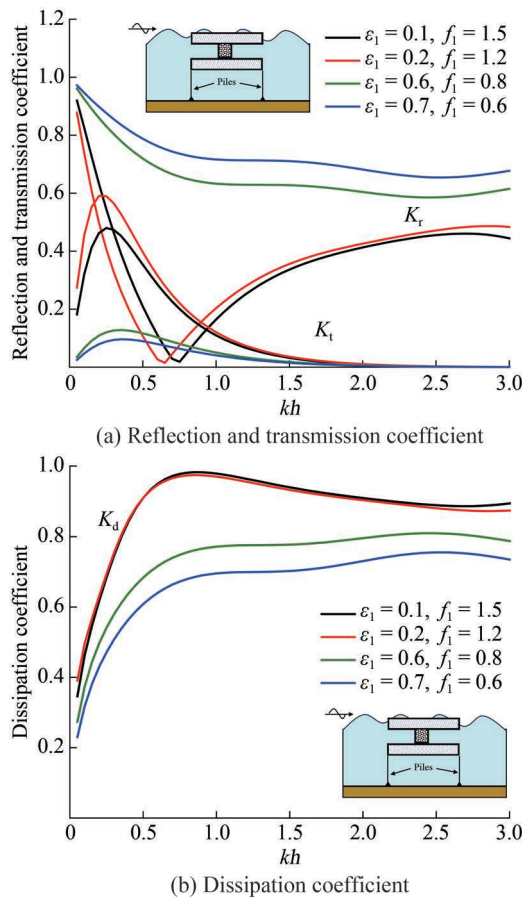


Figure 21 Variations in reflection, transmission, and dissipation coefficient versus nondimensional wave number kh for changing porosity and friction coefficient when $d/h = 0.2$ and $B/h = 2$ in the I-type breakwater

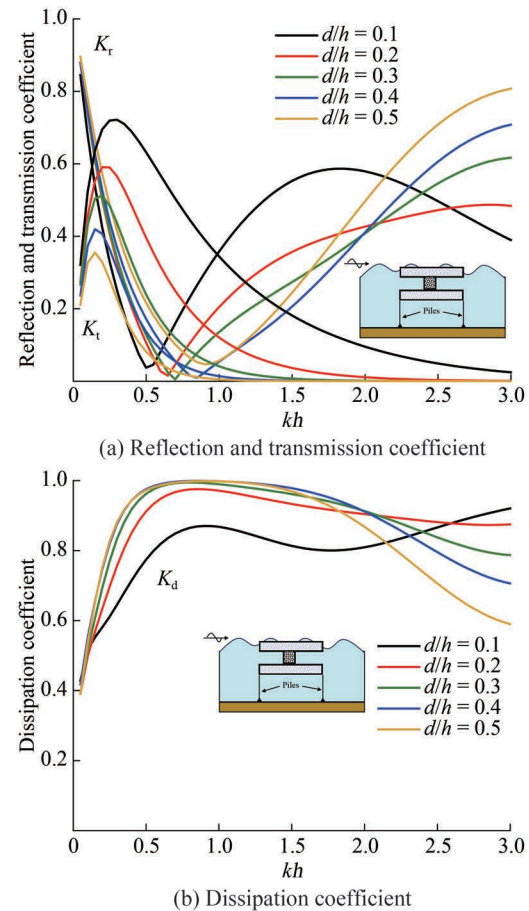


Figure 22 Variations in reflection, transmission, and dissipation coefficient versus nondimensional wave number kh for changing d/h in the I-type breakwater

low relative drafts because of strong vortex shedding and wave reflections. In the short-wave regime, waves tend to pass through structures with low wave frequencies. As frequency increases, the seaside web of the I-shaped structure becomes a barrier that reflects the wave. Variations in K_t is inversely proportional to d/h . When the I-shaped structure is increased by five times the draft in shallow water ($kh \leq 0.5$), wave transmission can be reduced by up to 50%. As the shorter waves travel over the structure more readily at a high kh , the wave transmission usually increases with water depth. At intermediate water depths, K_d (Figure 22(b)) peaks are optimal for wave-structure interaction. Owing to the elliptical orbital motion and increased particle-structure interaction, dissipation is enhanced in intermediate seas. Owing to the increased wetted surface area in the I-shaped configuration and increased violent vortex production, high draft results in increased dissipation.

Figures 23(a) and 23(b) show variations in K_r , K_t , and K_d as functions of dimensionless wave number kh for different relative widths ($0.25 \leq B/h \leq 2$) for the I-type floating breakwater. Figure 23(a) displays large reflection K_r , particularly at low kh in shallow water, and reduced transmission K_t because wave energy is blocked by the structure. Increased transmission and decreased reflection are observed, especially at high kh in deep water. Long waves with low kh are represented by high K_r and low K_t , and waves are reflected by large structures. At a high kh , K_t (Figure 23(a)) increases, whereas K_r declines, indicating that short waves can more readily pass through narrow structures. A large K_d (Figure 23(b)) over a large kh range is due to the extended interaction of waves with porous materials. The maximum wave dissipation is observed at a moderate kh because of the balance between friction and wave penetration. Dissipation peaks are sharp but have a short interaction duration with the structure. The K_d value (Figure 23(b)) peaks in the middle kh as the energy loss is optimal wave-structure interaction. At an extremely high kh , the wave dissipation falls at extremely low or high kh values. An efficient I-type breakwater is formed by wide structures ($B/h = 2.0$), which efficiently reflect long waves in shallow water ($kh \leq 1.0$). For instance, large B/h values are frequently used in coastal breakwaters that are intended to reflect waves. More wave energy can pass through narrow structures, that is, $B/h = 2.0$, particularly for short waves ($kh \geq 2.0$). This phenomenon is applicable to permeable breakwaters in ports where it is permissible for waves to partially pass through. The maximum energy loss K_d occurs when waves interact with the porous structure for a sufficient amount of time to create friction and turbulence.

4.2.9 Comparative study of hydrodynamic and wave force coefficients

In Figures 24(a)–24(c), the comparative study for the wave reflection, transmission, and dissipation coefficient is analyzed for different configurations of the floating break-

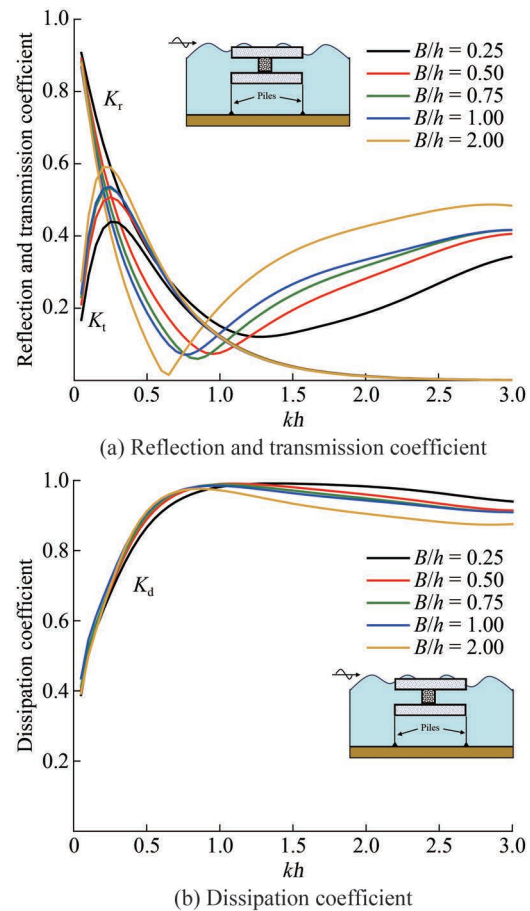


Figure 23 Variations in reflection, transmission, and dissipation coefficient versus nondimensional wave number kh changing B/h in the I-type breakwater

water. The rectangular porous breakwater has a substantially lower reflection coefficient in the long-wave regime than other layouts, as shown in Figure 24(a). The rectangular structure reflects less than 5% of the incident wave energy, but other structures have large wave reflection coefficients (86%–93%). Notably, at low frequencies, the $\perp$ -type structure shows the highest reflection (48.6%) and then maintains a comparatively consistent reflection level. The H-type structure shows the least amount of reflection (3.8%) at low frequencies but progressively increases to 66.3% at high frequencies. The I-type structure has the lowest reflected wave energy (39.5%) in the short-wave region. In deep-water regions, the H-type structure is the most effective configuration, given the reflective nature of waves. Other breakwater configurations lie in the range of 50%–60%, where the highest reflected wave attained by the H-type breakwater is 66%, and the lowest is 41% for the I-type structure. The comparison for transmission coefficients (Figure 24(b)) shows that the rectangular structure has the highest wave transmission of 98.6% in the long-wave regime, whereas the $\perp$ -type structure has the lowest transmission coefficient. Except for the rectangular structures, all structures exhibit an oscillatory transmission trend that peaks at

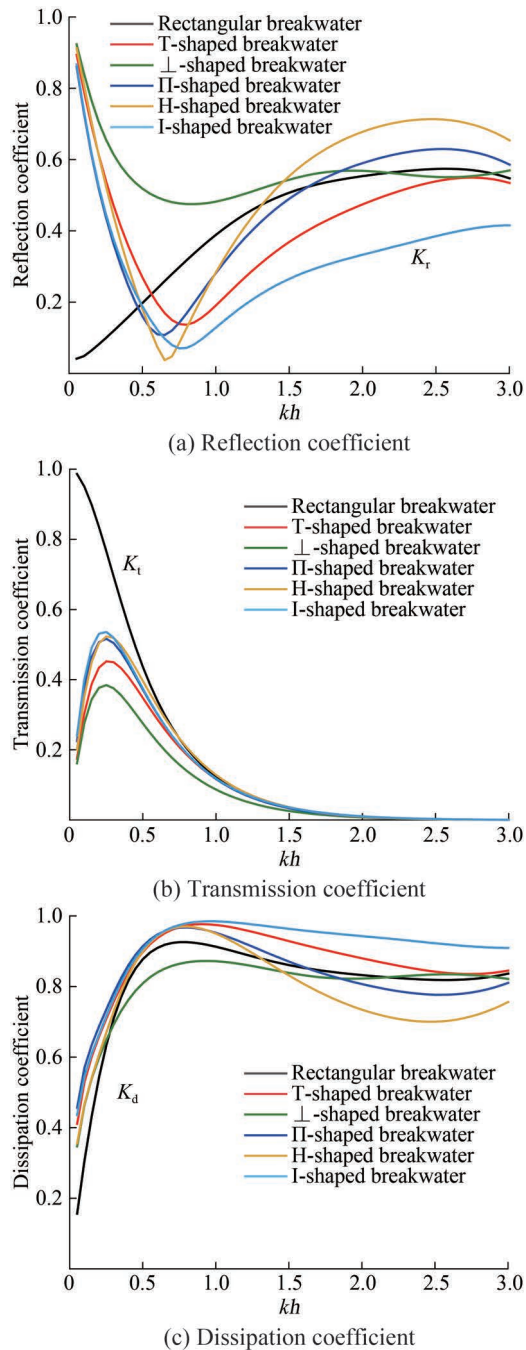


Figure 24 Variations in reflection, transmission, and dissipation coefficient versus nondimensional wave number kh for $\varepsilon_1 = 0.2$, $f_1 = 1.2$, $d/h = 0.2$ and $B/h = 1$

a certain frequency before the minima. All structures show minimal wave transmission at high frequencies. The energy dissipation coefficient (Figure 24(c)) for the rectangular floating breakwater dissipates the least energy of 15.6% in the long-wave regime, whereas the Π -type breakwater dissipates the largest energy of approximately 45.6%. The opposite pattern is observed in the short-wave regime when the I-type structure dissipates the most energy around 99%. Similar performance characteristics are indicated by the

convergence of the reflection, transmission, and dissipation coefficient trends for rectangular floating breakwater as the frequency rises. In conclusion, the $\perp$ -type structure performs better in shallow water depths because of its low transmission and reflection coefficients. In deep-water regions, the H-type structure shows the lowest wave dissipation and high wave reflection. The comparative study of K_r , K_t , and K_d for different configurations of floating breakwater is presented in Table 5.

Table 5 K_r , K_t , and K_d for $kh = 0.5$, $\varepsilon_1 = 0.2$, $f_1 = 1.2$, $d/h = 0.2$ and $B/h = 1$

S. No	Type of breakwater	K_r	K_t	K_d
1.	Rectangular	0.259629	0.299236	0.918178
2.	T-shaped	0.169979	0.258277	0.950999
3.	$\perp$ -shaped	0.486897	0.198888	0.850514
4.	Π -shaped	0.108551	0.268950	0.957017
5.	H-shaped	0.038241	0.291280	0.955873
6.	I-shaped	0.098511	0.269754	0.957877

The horizontal wave force coefficient variation on the seaside K_{FS} and leeside K_{FL} of different configurations of the floating breakwater as a function of the dimensionless wave number kh is shown in Figures 25(a) and 25(b). The

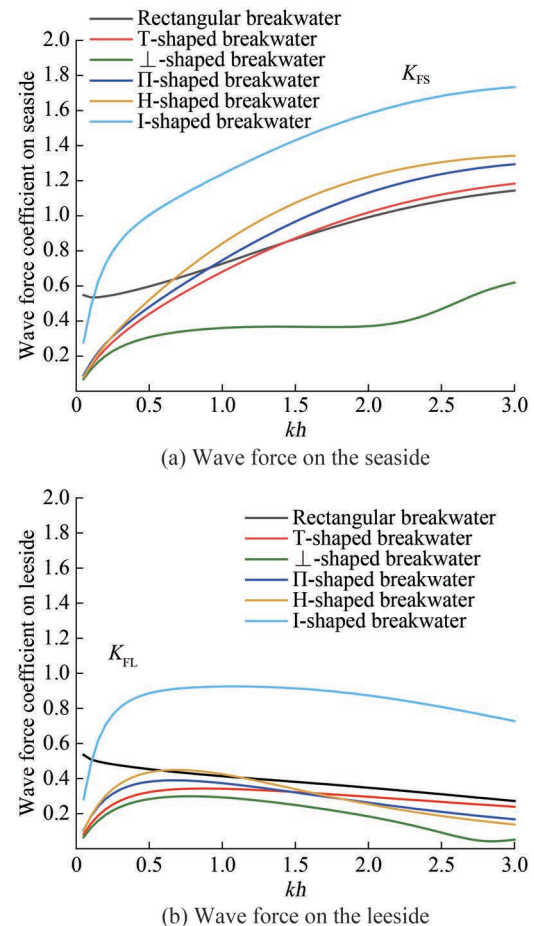


Figure 25 Variation in wave force on the seaside and leeside of breakwater versus nondimensional wave number kh for $\varepsilon_1 = 0.2$, $f_1 = 1.2$, $d/h = 0.2$ and $B/h = 2$

seaside experiences forces that are noticeably higher than those experienced by the back face of the breakwater. Owing to the vast frontal area of the breakwater, the H-type structure faces the highest seaside force among the other breakwater designs. Owing to its small frontal area, the $\perp$ -type structure receives the lowest front face wave force. Particularly in shallow water depths, the $\perp$ -type structure shows little change in wave-induced force on both faces. The rectangular structure exhibits negligible differences in forces on the seaside and leeside, likely because of the uniform cross-sections facilitating relatively undisturbed wave flow.

5 Conclusions

The current study presents the wave hydrodynamic performance and energy dissipation characteristics of pile-restrained structures composed of various porosities of different structural and physical configurations. These models are numerically analyzed by the MDBEM approach based on small amplitude wave theory. The different configurations modeled for analysis of floating breakwater are rectangular structure, T-, $\perp$ -, Π -, H-, and I-type pile-restrained structure. The MDBEM is employed for each case, and boundary conditions are applied for the rigid horizontal seabed, free water surface, incident, and transmission region. The edge conditions for fluid–structure and structure–structure interfaces are applied to achieve wave interaction inside and outside the boundaries of the proposed structure. Furthermore, the convergence study of the numerical model is performed for rectangular structures, and the results are validated with those in the literature. The hydrodynamic performance of an experimental model run in the wave flume is compared with the numerical results obtained using the H-shaped model. The hydrodynamic and dissipation coefficients are analyzed for each structure and compared with other structures to scrutinize their efficiency. The wave force coefficients encountered by the structures are also compared in different sections. The salient conclusions of the present study are as follows:

1) The transmission coefficient is higher, and the reflection coefficient is lower in the rectangular porous breakwater than in the other configurations. The increment in relative depth d/h causes a considerable decrement in K_t values irrespective of the structure type.

2) In the rectangular, Π -, H-, and I-type structures, the impact of varying relative depth d/h on K_d is directly proportional, whereas for T- and $\perp$ -type structures, the effect is the opposite.

3) The transmission coefficient decreases as relative width values increase for T-, $\perp$ -, and H-type structures. For I-type structures, the reverse is observed for the transmission coefficient. The shallow water conditions do not considerably vary among configuration variants.

4) The H-type structure is the most efficient configuration in the deep water in terms of reflecting maximum wave. The highest reflected wave achieved by an H-type breakwater is 66%, and the lowest by the I-type structure is 41%, whereas other configurations of breakwater fall in the range of 50%–60%.

5) The highest reflection (52%) is obtained by the $\perp$ -type structure, whereas reflection is less than 27% for other structures. The $\perp$ -type structure yields the lowest value of 27.5% for the transmission coefficient, whereas other configurations yield values within 34%–44%.

6) The energy dissipated by $\perp$ -type structure is at least 81%, and for other types of structures, the value is higher than 87%. The H-type structure is efficient, with the highest wave reflection of 71.4% and the lowest dissipation of 70% in deep-water regions.

7) H- and Π -type structures show similar kinds of oscillatory trends for changing the relative depth and relative width of the structure. The transmission coefficient is almost zero when the deep-water region is considered.

8) The highest horizontal force coefficient on the front face and back face of the structure is observed in the H-type, and lowest for $\perp$ -type structures during the transition from shallow-water regions to deep-water regions.

The present analysis emphasizes the importance of the $\perp$ - and H-type breakwaters in maintaining tranquil regions on the leeward side. The H-type breakwater effectively attenuates waves in the deeper offshore environment, and the $\perp$ -type offers improved stability and reduced wave forces in shallow water. Notably, floating breakwaters are suitable for shallow water, but cost-effectiveness may be more pronounced in deep regions, suggesting a need for future cost estimations in such environments. In addition, the numerical simulations performed using BEM in the present study can be expanded to analyze the performance of breakwaters in the presence of irregular waves and oblique wave incidence to explore the practical applications of the breakwater model.

Competing interest D. Karmakar is an editorial board member for the Journal of Marine Science and Application and was not involved in the editorial review, or the decision to publish this article. All authors declare that there are no other competing interests.

References

- Abul-Azm AG, Gesraha MR (2000) Approximation to the hydrodynamics of floating pontoons under oblique waves. *Ocean Engineering* 27(4): 365–384. [https://doi.org/10.1016/S0029-8018\(98\)00057-2](https://doi.org/10.1016/S0029-8018(98)00057-2)
- Behera H, Ghosh S (2019) Oblique wave trapping by a surface-piercing flexible porous barrier in the presence of step-type bottoms. *Journal of Marine Science and Application* 18: 433–443. <https://doi.org/10.1007/s11804-018-0036-2>
- Bottin Robert R Jr, Turner Kent A (1980) Seabrook lock complex,

- lake pontchartrain, LA: Design for wave protection at lock entrance: Hydraulic model investigation. Vicksburg, Mississippi: U.S. Army Engineer Research and Development Center (ERDC) Technical Report HL-80-87. <https://hdl.handle.net/20.500.11970/111967>
- Brebbia CA, Dominguez J (1992) Boundary elements: an introductory course. Surrey: WIT Press
- Carr JH (1951) Mobile breakwater. *Coastal Engineering Proceedings* 1(2): 25. <https://doi.org/10.9753/icce.v2.25>
- Choi YR, Hong SY, Choi HS (2000) An analysis of second-order wave forces on floating bodies by using a higher-order boundary element method. *Coastal Engineering* 28(1): 117-138. [https://doi.org/10.1016/S0029-8018\(99\)00064-5](https://doi.org/10.1016/S0029-8018(99)00064-5)
- Chwang AT, Chan AT (1998) Interaction between porous media and wave motion. *Annual Review of Fluid Mechanics* 30(1): 53-84. <https://doi.org/10.1146/annurev.fluid.30.1.53>
- Dai J, Wang CM, Utsunomiya T, Duan W (2018) Review of recent research and developments on floating breakwaters. *Ocean Engineering* 158: 132-151. <https://doi.org/10.1016/j.oceaneng.2018.03.083>
- Deng Z, Wang L, Zhao X, Huang Z (2019) Hydrodynamic performances of a T-shaped floating breakwater. *Applied Ocean Research* 82: 325-336. <https://doi.org/10.1016/j.apor.2018.11.002>
- Duan W, Xu S, Xu Q, Ertekin RC, Ma S (2016) Performance of an F-type floating breakwater: A numerical and experimental study. *Journal of Engineering for the Maritime Environment* 231(2): 583-599. <https://doi.org/10.1177/1475090216673461>
- Esmaelpour K, Shafaghath R, Alamian R, Bayani R (2016) Numerical study of various geometries of breakwaters for the installation of floating wind turbines. *Journal of Naval Architecture and Marine Engineering* 13: 27-37. <https://doi.org/10.3329/jname.v13i1.22866>
- Gesraha MR (2006) Analysis of II shaped floating breakwater in oblique waves: I. Impervious rigid wave boards. *Applied Ocean Research* 28: 327-338. <https://doi.org/10.1016/j.apor.2007.01.002>
- Goda Y, Suzuki Y (1976) Estimation of incident and reflected waves in random wave experiments. *Coastal Engineering* 828-845. <https://doi.org/10.1061/9780872620834.048>
- Günaydın K, Kabdaşlı MS (2004) Performance of solid and perforated U-type breakwaters under regular and irregular waves. *Ocean Engineering* 31: 1377-1405. <https://doi.org/10.1016/j.oceaneng.2004.02.002>
- Günaydın K, Kabdaşlı MS (2007) Investigation of II-type breakwaters performance under regular and irregular waves. *Ocean Engineering* 34: 1028-1043. <https://doi.org/10.1016/j.oceaneng.2006.03.015>
- Hales LZ (1981) Floating Breakwaters: State-of-the-Art Literature Review. U. S. Army, Corps of Engineers, Coastal Engineering Research Center. Technical Report No. 81-1. <https://hdl.handle.net/11681/12605>
- Hassanpour N, Lara JL, Vicinanza D, Contestabile P (2025) Laboratory experiments on transforming emerged into submerged breakwaters. *Ocean Engineering* 324: 120610. <https://doi.org/10.1016/j.oceaneng.2025.120610>
- Hay D (1966) Considerations for the design of a floating breakwater. Vancouver Department of Public Works of Canada
- Ji CY, Chen X, Cui J, Yuan ZM, Incecik A (2015) Experimental study of a new type of floating breakwater. *Ocean Engineering* 105: 295-303. <https://doi.org/10.1016/j.oceaneng.2015.06.046>
- Ji C, Deng X, Cheng Y (2019) An experimental study of double-row floating breakwaters. *Journal of Marine Science and Technology* 24: 359-371. <https://doi.org/10.1007/s00773-018-0554-2>
- Koley S (2019) Wave transmission through multilayered porous breakwater under regular and irregular incident waves. *Engineering Analysis with Boundary Elements* 108: 393-401. <https://doi.org/10.1016/j.enganabound.2019.08.011>
- Liu Y, Li Y, Teng B (2007) Wave interaction with a new type perforated breakwater. *Acta Mechanica Sinica* 23: 351-358. <https://doi.org/10.1007/s10409-007-0086-1>
- Liu R, Chen Y, Wang X, Lian J (2025) Study on wave dissipation performance of permeable plate breakwater. *Ocean Engineering* 321: 120153. <https://doi.org/10.1016/j.oceaneng.2024.120153>
- Mani JS (1991) Design of Y-frame floating breakwater. *Journal of Waterway, Port, Coastal and Ocean Engineering* 117: 105-119. [https://doi.org/10.1061/\(ASCE\)0733-950X\(1991\)117:2\(105\)](https://doi.org/10.1061/(ASCE)0733-950X(1991)117:2(105))
- McCartney BL (1985) Floating Breakwater Design. *Journal of Waterway, Port, Coastal and Ocean Engineering* 111(2): 304-318. [https://doi.org/10.1061/\(ASCE\)0733-950X\(1985\)111:2\(304\)](https://doi.org/10.1061/(ASCE)0733-950X(1985)111:2(304))
- McDougal WG, Sulisz W (1989) Seabed stability near floating structures. *Journal of Waterway, Port, Coastal and Ocean Engineering* 115(6): 727-739. [https://doi.org/10.1061/\(ASCE\)0733-950X\(1989\)115:6\(727\)](https://doi.org/10.1061/(ASCE)0733-950X(1989)115:6(727))
- Mei CC, Black JL (1969) Scattering of surface waves by rectangular obstacles in waters of finite depth. *Journal of Fluid Mechanics* 38(3): 499-511. <https://doi.org/10.1017/S00222112069000309>
- Mustapa MA, Yaakob OB, Ahmed YM, Rheem CK, Koh KK, Adnan FA (2017) Wave energy device and breakwater integration: A review. *Renewable and Sustainable Energy Reviews* 77: 43-58. <https://doi.org/10.1016/j.rser.2017.03.110>
- Neelamani S, Rajendran R (2002) Wave interaction with T-type breakwaters. *Ocean Engineering* 29: 151-175. [https://doi.org/10.1016/S0029-8018\(00\)00060-3](https://doi.org/10.1016/S0029-8018(00)00060-3)
- Nishad CS, Vijay KG, Neelamani S, Chen JT (2021) Dual BEM for wave scattering by an H-type porous barrier with nonlinear pressure drop. *Engineering Analysis with Boundary Elements* 131: 280-294. <https://doi.org/10.1016/j.enganabound.2021.06.011>
- Patil SB, Karmakar D (2021) Performance evaluation of submerged breakwater using Multi-Domain Boundary Element Method. *Applied Ocean Research* 114: 102-760. <https://doi.org/10.1016/j.apor.2021.102760>
- Paul D, Behera H (2024) Wave attenuation on a floating rigid dock by multiple surface-piercing vertical thin perforated barriers. *Engineering Analysis with Boundary Elements* 169: 105985. <https://doi.org/10.1016/j.enganabound.2024.105985>
- Peng W, Lee KH, Shin SH, Mizutani N (2013) Numerical simulation of interactions between water waves and inclined-moored submerged floating breakwaters. *Coastal Engineering* 82: 76-87. <https://doi.org/10.1016/j.coastaleng.2013.07.002>
- Sahoo H, Gayathri R, Khan MB, Behera H (2023) Hybrid boundary element and eigenfunction expansion method for wave trapping by a floating porous box near a rigid wall. *Ships and Offshore Structures* 18(8): 1148-1158. <https://doi.org/10.1080/17445302.2022.2108227>
- Sener MZ, Yoon HK, Nguyen TTD, Park J, Kose E (2023) An experimental study on capacitive and ultrasonic measurement principles and uncertainty assessment in laboratory wave measurements. *Ocean Engineering* 285: 115320. <https://doi.org/10.1016/j.oceaneng.2023.115320>
- Sollitt CK, Cross RH (1972) Wave transmission through permeable breakwaters. *Coastal Engineering Proceedings* 1827-1846. <https://doi.org/10.1061/9780872620490.106>
- Tanneau O, Lamary P, Chevalier Y (2006) A boundary element method for porous media. *The Journal of the Acoustical Society of America* 120(3): 1239-1251. <https://doi.org/10.1121/1.2221407>
- Trivedi K, Koley S (2021) Effect of varying bottom topography on the radiation of water waves by a floating rectangular buoy.

- Fluids 6(2): 59. <https://doi.org/10.3390/fluids 6020059>
- Twu SW, Liu CC, Hsu WH (2001) Wave damping characteristics of deeply submerged breakwaters. *Journal of Waterway, Port, Coastal, Ocean Engineering* 127: 97-105. [https://doi.org/10.1061/\(ASCE\)0733-950X\(2001\)127:2\(97\)](https://doi.org/10.1061/(ASCE)0733-950X(2001)127:2(97))
- Venkateswarlu V, Praveen KM, Karmakar D (2020) Surface gravity wave scattering by multiple energy absorbing structures of variable horizontal porosity. *Coastal Engineering Journal* 62(4): 504-526. <https://doi.org/10.1080/21664250.2020.1794274>
- Venkateswarlu V, Panduranga K, Vijay KG, Behera H (2024) Evaluation of oscillating water column efficiency in the presence of multiple bottom-standing breakwaters under oblique waves. *Physics of Fluids* 36(11): 117175. <https://doi.org/10.1063/5.0237370>
- Vijay KG, Venkateswarlu V, Nishad CS (2021) Wave scattering by inverted trapezoidal porous boxes using dual boundary element method. *Ocean Engineering* 219: 108149. <https://doi.org/10.1016/j.oceaneng.2020.108149>
- Vishwakarma RD, Karmakar D (2024) Hydrodynamic analysis of different shapes of moored hybrid floating breakwater. *Journal of Marine Science and Application* 23(4): 743-761. <https://doi.org/10.1007/s11804-024-00519-x>
- Wang K, Shi P, Chen Y, Cheng X (2019) Study on submerged upper arc-shaped plate type breakwater. *China Ocean Engineering* 33(2): 219-225. <https://doi.org/10.1007/s13344-019-0021-9>
- Williams AN, Abul-Azm AG (1997) Dual pontoon floating breakwater. *Ocean Engineering* 24(5): 456-478. [https://doi.org/10.1016/S0029-8018\(96\)00024-8](https://doi.org/10.1016/S0029-8018(96)00024-8)
- Yanna Z, Guohai D, Benchao G, Changping C (2011) Numerical simulation of single box floating breakwater in time domain. *Advanced Materials Research* 250-253: 3634-3637. <https://doi.org/10.4028/www.scientific.net/AMR.250-253.3634>
- Yu X, Chwang AT (1994) Wave Motion through Porous Structures. *Journal of Engineering Mechanics* 120: 989-1008. [https://doi.org/10.1061/\(ASCE\)0733-9399\(1994\)120:5\(989\)](https://doi.org/10.1061/(ASCE)0733-9399(1994)120:5(989))
- Zhan J, Chen X, Gong Y, Hu W (2017) Numerical investigation of the interaction between an inverse T-type fixed/floating breakwater and regular/irregular waves. *Ocean Engineering* 137: 110-119. <https://doi.org/10.1016/j.oceaneng.2017.03.058>
- Zhang M, Wang G, Qi X, Wan S (2024) Hydrodynamic performance of a dual cylindrical caisson breakwater with dual porous ring plates fixed inside. *Ocean Engineering* 307: 118181. <https://doi.org/10.1016/j.oceaneng.2024.118181>
- Zheng YH, Shen YM, Ng CO (2007) Effective boundary element method for the interaction of oblique waves with long prismatic structures in water of finite depth. *Ocean Engineering* 35: 494-502. <https://doi.org/10.1016/j.oceaneng.2007.12.003>