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RESEARCH ON THE WAVE REDUCTION EFFECTIVENESS OF HOLLOW BREAKWATER, APPLICATION TO THE MEKONG DELTA

Specialization: Technical constructions of hydraulic works
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The Dissertation can be found at:

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FOREWORD

1. The necessity of the dissertation

The coastal strip is an area with a diverse ecosystem and plays an important role in socio-economic development and national security. The coastal area is one of the most dynamically developing areas in the world and currently has about 3.0 billion people, more than 65% of the world's major cities are concentrated in coastal areas. Coastal erosion and sedimentation in the world is taking place, the total area of eroded land is about 28,000 km2, double the area of sedimentation. The coastal area of the Mekong Delta (MD) with an eroded coastline of nearly 300/744 km. Affecting the mangrove ecosystem, coastal infrastructure and people's livelihoods.

To protect the coast, many non-structural and structural solutions have been deployed such as: revetments, bamboo fences, Geotube, rubble dikes, precast hollow structural breakwater... have been built, new structures to protect the coast such as hollow structural wave-reducing breakwaters are being widely applied because of their effective wave-reducing effect, the ability to create sedimentation and restore mangrove forests. Based on the above practical requirements, it is necessary to study technical solutions to protect the coast from erosion and mangrove forest degradation. The solution must be suitable in the conditions of climate change(CC), sea level rise (SLR), coastal protection works need to be highly adaptable to meet the requirements of protecting the coast in changing conditions, as well as protecting the coastal ecosystem and environment. One of those solutions is hollow structural breakwater located far from shore. Therefore, studying the scientific basis of wave transmission, wave interaction and breakwater construction is necessary to understand the this type of breakwater and serve as a basis for practical application in protecting the Mekong Delta coast.

2. Research objectives

- Analyze the wave propagation process through the KCR TC1 to clarify the wave-KCR TC1 interaction, the geometric characteristics of the TC1, the wave transmission coefficient, and the process of flow velocity change through the dike.
- Develop an empirical formula to calculate the wave transmision coefficient (Kt) of the TC1 breakwater.

3. Subjects and scope of research

Research object: A hollow structure breakwater with A-shaped cross-section named TC1 and its characteristics including wave transmission coefficient and flow velocity variation through this breakwater.
Research scope: Coastal area of the Mekong Delta.

4. Approach and research method

The approach: The dissertation selects an integrated approach including: (1) Approach from practical application of breakwaters; (2) The selectively inherited approach from the international and domestic research achievements related to the wave transmission coefficients of the breakwater. (3) The inherited and develope new structure approach.
Research methodology: (1) The inherited method; (2) Experimental research method on physical modelling; (3) Method of applied research; (4) Regression analysis method, (5) Method of experts.

5. Scientific and practical signification

Scientific significance:
This study clarifies the wave-breakwater interaction mechanism, analyzing wave propagation and wave reduction mechanisms of the TC1 hollow structure under different hydrodynamic conditions. It contributes to the refinement of the theoretical basis and design calculations for the TC1. The research results have established a formula for wave transmission through TC1 structure in the coastal Mekong Delta.
Practical significance: The research results have been applied to the construction of wave-reducing breakwater in Go Cong, Tan Phu Dong - Tien Giang, high efficiency in wave reduction, sedimentation and mangrove forest restoration. This open up wide application opportunities to areas with similar conditions in the coastal area of the Mekong Delta.

6. Novelty of the Dissertation

(1) Evaluate the influence of factors on the wave transmission coefficient Kt through the hollow structure breakwater TC1 including: Relative height crest (R_c/H_{m0}); (ii) Relative width (B_{eff}/d); (iii) Wave slope (S_{0m}), (iv) surface porosity of the structure (n) or effective permeability in the hollow medium (Pf), the change in flow velocity when waves pass through the hollow structure breakwater TC1;
(2) The create an experimental formula to calculate wave transmission through the hollow structure TC1 from the results of physical model experiments on a 2D wave flume and validation on a 3D wave basin, using a real scale model 1:1:

$$K_t = -0.112\frac{R_c}{H_{m0}} + 0.765\left(P_f\frac{B_{eff}}{d}\right)^{-0.11}\left[1 - exp\left(\frac{-0.485}{\sqrt{S_{0m}}}\right)\right]$$

CHAPTER 1. OVERVIEW

1.1. Overview of coastal protection solutions

1.1.1. Coastal protection solutions

The Mekong Delta coastline is a region characterized by intense interactions with natural forces such as waves, wind, and storm surges. These processes occur continuously and exhibit complex variations over both time and space. Increasing exploitation of the coastal zone, coupled with changes in natural conditions and socio-economic factors, has led to severe coastal erosion. This phenomenon poses serious threats to local communities, degrades the coastal environment, damages infrastructure, and significantly undermines coastal socio-economic development planning. In response to these challenges, numerous studies-both internationally and dometics-have proposed technological solutions and approaches for coastal protection. A variety of strategies have been developed to safeguard coastal areas and enhance their landscapes, including hard engineering solutions, soft approaches, hybrid solutions and integrated methods.

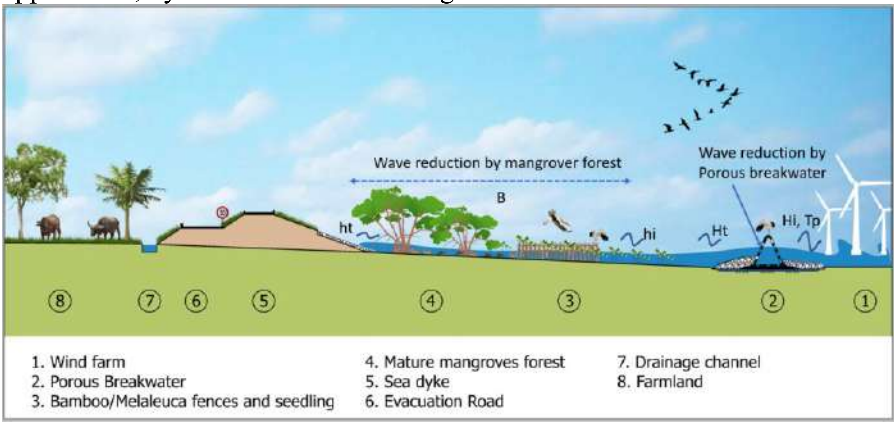

Figure 1-1. Multiple Line of Defense for coast

Currently, in many parts of the world, coastal protection strategies for low-lying areas with conditions similar to those of the Mekong Delta increasingly rely on integrated approaches that combine hard and soft engineering solutions. These methods aim to be environmentally friendly and contribute to ecosystem restoration. A key emerging paradigm in this context is the "Building with Nature" approach, which emphasizes working in harmony with natural systems. Another innovative concept is the "Multiple Line of Defense" strategy, which has been widely adopted in developed countries.

As illustrated in Figure 1-1, the multiple defense lines approach incorporates various elements such as wave-reducing structures, mangrove forests, revetments, and flood protection dikes. The overarching goals are to mitigate erosion and flooding, enhance natural ecosystems, and promote adaptation to climate change and sea level rise.

Among the components of this system, wave-reducing hallow breakwater play a critical role. In terms of cross-sectional geometry, the trapezoidal shape is the most commonly used configuration. Other geometries include rectangular forms such as caisson-type structures or semicircular-shaped dikes. Structurally, hallow breakwater come in a variety of types, selected based on site-specific conditions such as wave climate, topography, and geological characteristics. Common types include: rubble mound dikes; core-filled rubble mound dikes with the outer layer made of precast concrete armor units (e.g., Tetrapod, Tribar, Dolos, Accropode, Racuna IV); and porous or hollow-structure breakwaters such as perforated semicircular hollow columns, or artificial reef structures like Reef Ball, Beach Prism, Wave Attenuation Devices (WAD), and SandSaver.

1.1.2. Overview of breakwaters structure

Breakwater have been widely applied in the Mekong Delta in the past 15 years. Popular structures include: centrifugal concrete piles with rubble core in Ca Mau; Sermi-cicular breakwater in Ca Mau; Non-metallic reinforced wave-reducing breakwater by Busadco; Hollow structure wave-reducing dikes TC1, TC2, Complex the piles system on top of the submerged dike in Ca Mau; Hollow structures made from OCT (Oyster CASTLE-type) hollow blocks; and some other solutions such as bamboo fences by GIZ.

1.2. Overview of wave transmission research through hollow structure breakwater (HSB)

1.2.1. The concepts of wave transmission through breakwater (HSB)

The wave transmission coefficient (K_t), which is the ratio of the wave height transmitted behind the breakwater ($H_{s,t}$) to the wave height in front of the breakwater ($H_{s,i}$) with the following form:

$K_t = H_{s,t} / H_{s,i}$

The wave reduction efficiency of the breakwater structure ε_s % is evaluated:

$$\varepsilon_s = (1 - K_t) * 100\% = (1 - \frac{H_{s,t}}{H_{s,i}}) * 100\%$$

Với: Kt - wave transmission coefficient ($0 \le Kt \le 1,0$); ε_s - is wave reduction efficiency of hollow structure ($0 \le \varepsilon_s \le 100\%$).

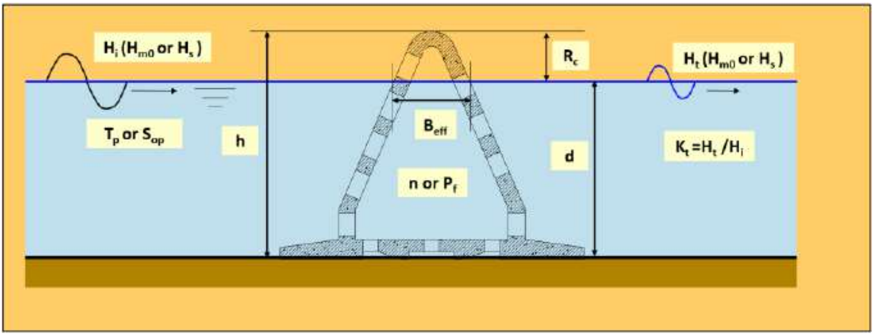

Figure 1-2. Basic parameters affecting transmission coefficient K_t

1.2.2. Empirical formula for wave transmission through hollow structures

In this study, the author focus reviews the wave transmission formulas for hollow structures with functions and working principles similar to the TC1 HSB. Research on the development of empirical formulas for the wave transmission coefficient Kt through the HSB TC1 is still limited and does not fully reflect the influencing factors such as the dike body porosity, effective dike width, wave parameters, etc. Therefore, the study on wave transmission through the TC1 hollow structure will be carried out based on some similar formulas for wave transmission through hollow media, from which to analyze and evaluate to supplement the factors affecting the wave transmission coefficient, increase the accuracy and scope of application of the formula for the TC1 structure.

CHAPTER 2. SCIENTIFIC BASIS OF STUDY ON HOLLOW BREAKWATER

2.1. Reasons for proposing TC1 hollow structure wave attenuator

2.1.1. Description of TC1 hollow structure breakwater

The structure is designed in an A-shaped configuration, with its two inclined faces-one facing the sea and the other facing the shoreline-serving as wave-reducing panels. These panels are perforated with circular openings arranged symmetrically on both the seaward and landward sides to dissipate wave energy.

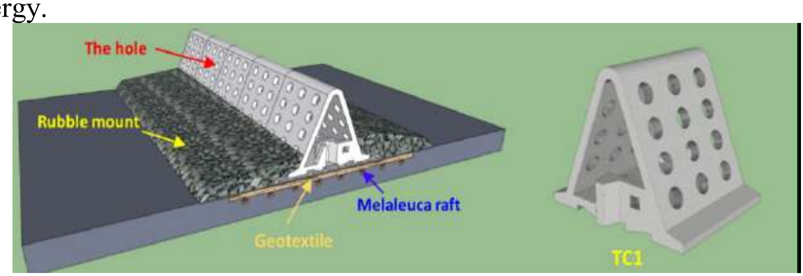

Figure 2-1. Schematic diagram of the TC1

The structure is installed on a foundation composed of Melaleuca log rafts combined with a layer of crushed stone to enhance load distribution and bearing capacity on soft soil. The seaward and landward toes of the dike are reinforced with rubble to prevent scouring and to improve the overall structural stability under wave action.

2.1.2. Reasons for proposing TC1 hollow structure breakwater

Functional requirements for the design of the HSB TC1 wave-reducing dike:

- Environmentally friendly, allowing for water exchange through a porous structure;
- Stable and adaptable on soft soil foundations;
- Durable structure, resistant to sea waves and the corrosive effects of saltwater;
- Rapid construction in marine environments, with the ability to be reused for wave-reducing dikes at other locations.

2.2. Working principle of hollow dike structure

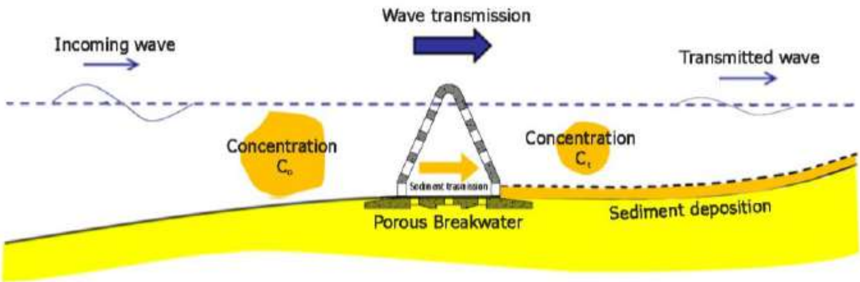

Figure 2-2. Cross-sectional schematic of the working principle of the TC1

The TC1 HSB is designed with surface porosity that effectively reduce wave reflection and dissipate wave energy. These openings also facilitate the passage of sediment, thereby maintaining the continuity of natural sediment transport processes and preventing abrupt interruptions. The underlying working principle is illustrated in Figure 2-2

2.3. Scientific basis of wave transmission through structure TC1

2.3.1. Energy balance of wave transmission through TC1

The energy balance equation governing wave transmission through a wave-dissipating dike structure:

$$E_i = E_r + E_t + E_D \qquad (2\text{-}1)$$

Where: incident wave energy (E_i), reflected wave energy (E_r), dissipated wave energy (E_D), and transmitted wave energy (E_t). The result of this wave energy transformation equation can be expressed in terms of the reflection coefficient (K_r), dissipation coefficient (K_D), and transmission coefficient (K_t).

$$1 = \left(\frac{H_t}{H_i}\right)^2 + \left(\frac{H_r}{H_i}\right)^2 + \frac{E_D}{E_i} \quad (2\text{-}2)$$

$$1 = K_r^2 + K_t^2 + K_D^2$$

$$K_D = \sqrt{1 - (K_r^2 + K_t^2)} \quad (2\text{-}3)$$

In which: $K_t = H_t / H_i$ - Wave transmission coefficient is determined by the ratio of wave height transmitted behind the structure (H_t) and wave height in front of the structure (Hi); $K_r = H_r / H_i$ - Wave reflection coefficient is determined by the ratio of wave height reflected in front of the structure (H_r) and wave height in front of the structure (H_i); K_d - Wave dissipation coefficient is determined based on the formula (2-3).

2.3.2. Structural porosity, permeability through porous media

The formula for calculating permeability through a porous medium, denoted as P_f, is applied to large-scale porous structures. In this context, P_f represents the effective permeability, which is dependent on the bulk porosity *(n)* of the porous structure. The permeability P_f is expressed as a function of parameters *n* as follows:

$$P_f = \frac{(1-n)^2}{n^3} \quad (2\text{-}4)$$

2.3.3. Establishment of the General Equation for the Wave Transmission Coefficient for the Porous Structure breakwater TC1

The wave transmission coefficient through the porous dyke is governed by several key parameter groups: (i) Relative freeboard (Rc/Hm_0,i); (ii) Effective width ($B_{eff}/L_{m-1,0}$ or B_{eff}/d), and (iii) Wave steepness (S_0m).
The surface porosity parameter (n) or the effective permeability (P_f) within the porous medium characterizes the geometrical shape and porosity of the TC1 structure. These parameters serve as the basis for the development of an empirical formula.
Geometrical Characteristics of the Cross-section of the Porous Structure Height of breakwater (h): Relative freeboard (Rc).
Slope of the dyke's seaward face: defines the inclination of the dyke surface with respect to the horizontal. The surface porosity (n) or the effective permeability (P_f) of the porous medium are structural parameters incorporated into the formulation of the empirical equation. The effective width of the breakwater (B_{eff}) characterizes the gap of the porous structure

under varying water levels. As B_{eff} varies with the water level, it is considered a key parameter in the formulation.

- Submerged dyke: $B_{eff} = B_{đỉnh}$
- Emerged dyke: $B_{eff} = B_{đỉnh} + 2.\ Rc\ .cotg\ \alpha$ (2-5)

In which $B_{đỉnh}$: is the crest width; Rc is calculated from the dike crest to the water level

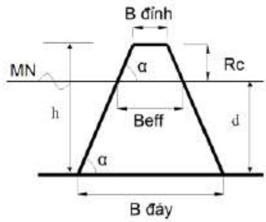

Figure 2-3. Shows the effective breakwater crest width Beff in case of Emerged dyke

Based on the Pi-Buckingham theory to establish a general equation showing the basic parameters governing the wave transmission coefficient K_t

$$\Pi = H_{mo,i}^{\ x1}.\ H_{mo,t}^{\ x2}.\ R_c^{\ x3}\ .\ B_{eff}^{\ x4}.\ L_{m-1,0}^{\ x5} \qquad (2\text{-}6)$$

or $$\Pi = H_{mo,i}^{\ x1}.\ H_{mo,t}^{\ x2}.\ R_c^{\ x3}\ .\ B_{eff}^{\ x4}.\ d^{\ x5} \qquad (2\text{-}7)$$

From this analysis, the general form of the wave transmission coefficient equation can be derived, with the following typical forms:

$$K_t = \frac{H_{m0,i}}{H_{m0,t}} = f\left(\frac{R_c}{H_{m0,i}}, P_f \frac{B_{eff}}{L_{m-1,0}}, S_{0m}\right) \qquad (2\text{-}8)$$

$$K_t = \frac{H_{m0,i}}{H_{m0,t}} = f\left(\frac{R_c}{H_{m0,i}}, P_f \frac{B_{eff}}{d}, S_{0m}\right) \qquad (2\text{-}9)$$

The relationship and influence of various parameters on the wave transmission coefficient through the porous structure dyke will be analyzed based on the results of physical model experiments.

2.4. Physical Model Experiment Setup in the Wave Flume

2.4.1. Selection of experimental input parameters

The experimental boundaries for the physical model are selected based on wave heights ranging from 0.7 to 1.5 meters and wave periods from 3 to 7 seconds. The JONSWAP spectrum is adopted as the representative wave spectrum. The water depth in the experiments varies from 1.4 to 3.5 meters.

2.4.2. Wave Flume Capacity

The experiment was carried out in the wave flume of the River and Marine hydrodynamic laboratory - SIWRR. The wave flume length is 35m, width is 1.2m and height is 1.5m.

2.4.3. Selection of Model Scale

The physical model is constructed at a geometric scale of 1:7, based on calculations that take into account the wave flume capacity and the experimental boundary conditions.

2.4.4. Experimental Setup Diagram

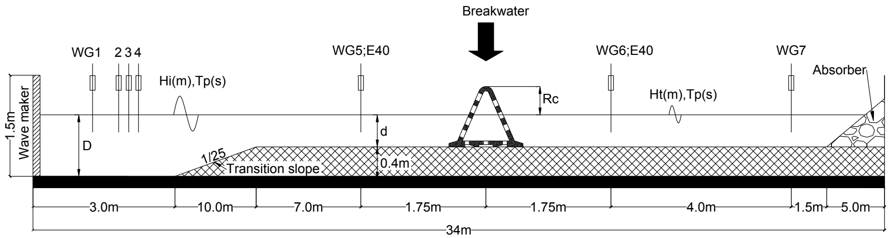

Figure 2-4 Arrangement of Wave Gauges (WG) and E40 Velocity Probes in the Wave Flume

Wave gauges are arranged both in front of and behind the structure, including five gauges (WG1, WG2, WG3, WG4, WG5) placed in front of the structure to determine the incident wave conditions, and two gauges (WG6, WG7) placed behind the structure to measure the wave height after transmission. Among them, four gauges (WG1–WG4) are specifically positioned to separate incident and reflected waves in front of the structure. An E40 velocity probe is used to measure the flow velocity both upstream and downstream of the structure. The duration of each test scenario is approximately 500 times the wave period (500·Tp).

2.4.5. Experimental Scenarios

- In Phase 1, a total of 36 experimental scenarios were conducted to evaluate the effect of structural porosity on wave transmission. Scenario KH0 corresponds to the baseline case without a breakwater. Scenarios KH1 to KH6 involve variations in the porosity ratios of the front (P1) and rear (P2) surfaces of the structure (see Table 2-1 for details).

Table 2-1. The experimental scenarios varying porosity configurations on the landward (rear) and seaward (front) sides of the structure.

Scenarios	Seaward (front)		Landward (rear)	
	P_1 (%)	d_1(m)	P_2 (%)	d_2(m)
KH1	11.8	0.041	11.8	0.041
KH2	22.5	0.057	11.8	0.041
KH3	36.6	0.073	11.8	0.041
KH4	36.6	0.073	22.5	0.057
KH5	22.5	0.057	22.5	0.057
KH6	20.7	0.050	15.2	0.041

All experimental scenarios were conducted under two water depth conditions: h = 0.33 m and h = 0.47 m, corresponding to relative freeboards of Rc = 0.14 m and Rc = 0 m, respectively. For h = 0.33 m, wave conditions were generated with: Hm_0 = 0.10 m, and Tp = 1.5 s and 2.5 s. For h = 0.47 m, wave conditions were: Hm_0 = 0.14 m, and Tp = 1.5 s and 2.5 s.

- Phase 2 consists of experimental scenarios for wave transmission through the TC1 structure, which is placed on a sloping foreshore to simulate shallow-water wave spectra representative of conditions in the Mekong Delta (ĐBSCL). A total of 70 scenarios were conducted. Among these: 70 scenarios involve variations in water level, and 10 wave conditions were tested by varying wave parameters.

Table 2-2 Experimental Scenarios for the TC1 Structure in the Wave Flume

Scenarios		Water depth (d, cm) at the structure toe or Freeboard height (Rc, cm)		Wave parameters
Breakwater TC1	x	d=20cm (R_c=+20cm) d=25cm (R_c=+15cm) d=30cm (R_c=+10cm) d=35cm (R_c=+5cm) d=40cm (R_c=+0cm) d=45cm (R_c=-5cm) d=50cm (R_c=-10cm)	x	H_s=12cm; T_p=1.51s H_s =12cm; T_p =1.89s H_s =12cm; T_p =2.27s H_s =12cm; T_p =2.65s H_s =17cm; T_p =1.89s H_s =17cm; T_p =2.27s H_s =17cm; T_p =2.65s H_s =22cm; T_p =2.27s H_s =22cm; T_p =2.65s H_s =27cm; T_p =2.65s

CHAPTER 3. RESULTS AND DISCUSSION

3.1. Analysis of Factors Influencing the Wave Transmission Coefficient of the Porous Dyke Structure TC1

3.1.1. Effect of porosity on wave transmission, reflection and dissipation coefficients

Figure 3-1 illustrates the relationship between the wave transmission coefficient (Kt) and the wave steepness (Hs/Lp) for two cases: Figure 3-1(a): Rc = 0 cm, and Figure 3-1(b): Rc = +14 cm. By comparing Figures (a) and (b), it can be observed that when the wave steepness varies from 0.02 to 0.05, the case with the emerged breakwater (Rc = +14 cm) shows greater dispersion in the transmission coefficient (Kt = 0.25–0.60) among different porosity configurations compared to the fully submerged case (Rc = 0 cm), where Kt ranges from 0.55 to 0.72. This trend indicates that Scenario KH4

(P1 = 36.6%; P2 = 22.5%) exhibits the highest wave transmission coefficient, due to its largest surface porosity. Conversely, Scenario KH1 (P1 = 11.8%; P2 = 11.8%) has the lowest transmission coefficient, corresponding to the lowest surface porosity. This distinction is consistently observed in both long-wave and short-wave conditions.

When comparing the three scenarios KH1, KH2, and KH3 where the landward porosity remains constant while the seaward porosity increases, it is observed that the Kt tends to increase with higher seaward porosity.

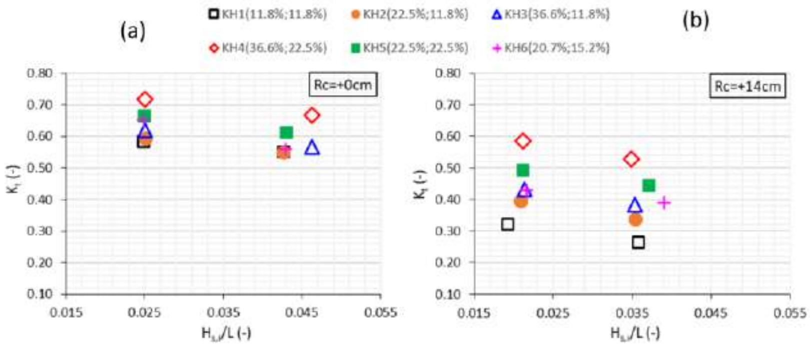

Figure 3-1. Transmission coefficient Kt at two different water levels

Figure 3-2 illustrates the relationship between the wave reflection coefficient Kr and the incident wave steepness Hs/L. When the landward surface porosity is constant and the seaward surface porosity increases—as in the scenarios KH1 (P1 = 11.8%, P2 = 11.8%), KH2 (P1 = 22.5%, P2 = 11.8%), and KH3 (P1 = 36.6%, P2 = 11.8%), or in the comparison between KH4 (P1 = 36.6%, P2 = 22.5%) and KH5 (P1 = 22.5%, P2 = 22.5%)—the Kr coefficient decreases. This indicates that greater seaward porosity results in a lower wave Kr coefficient.

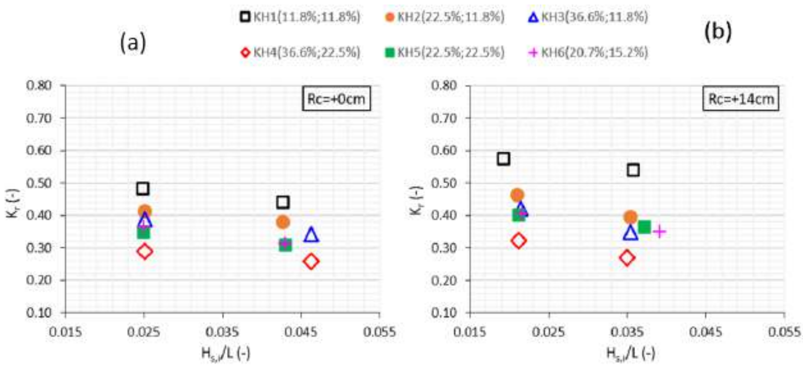

Figure 3-2. Wave reflection coefficient at two different water levels

Figure 3-3 presents the relationship between the wave energy dissipation coefficient (Kd) and the incident wave steepness (Hs/L). When the breakwater crest is elevated above the still water level (i.e., Rc=+14cm), more wave energy is dissipated compared to the case where the water level is equal to the crest elevation (Rc=0cm). The lowest energy dissipation coefficients are observed in the scenario with the smallest surface porosity, KH1 (P1 = 11.8%; P2 = 11.8%), and the scenario with the highest porosity KH4 (P1 = 36.6%; P2 = 22.5%). Conversely, in scenarios where the seaward surface porosity is greater than the landward porosity—namely KH2 (P1 = 22.5%; P2 = 11.8%), KH3 (P1 = 36.6%; P2 = 11.8%), and KH6 (P1 = 20.7%; P2 = 15.2%)—the wave energy dissipation coefficient reaches its highest values.

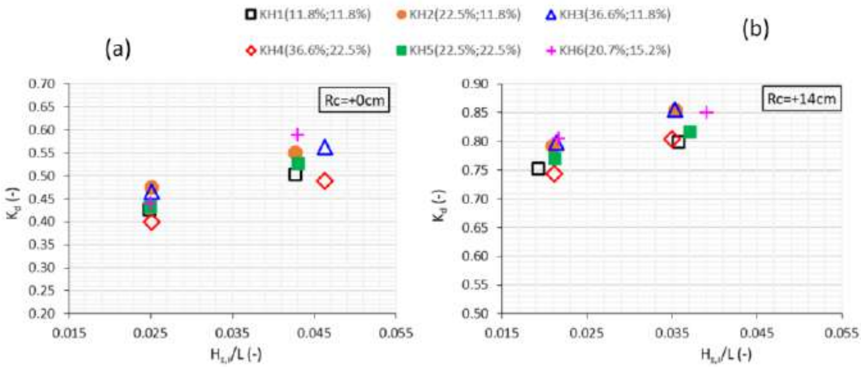

Figure 3-3. Wave dissipation coefficient at two different water levels

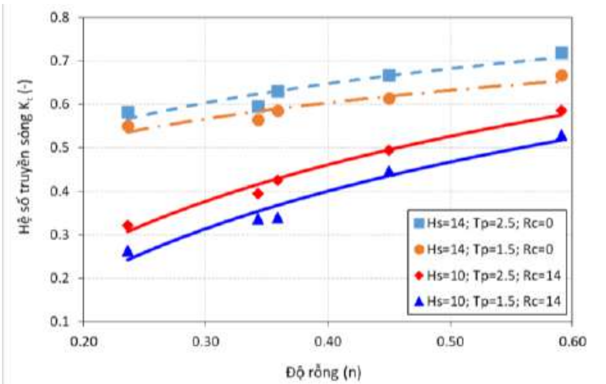

Figure 3-4. Relationship between coefficient Kt and porosity (n)

Figure 3-4 illustrates the relationship between the wave transmission coefficient (Kt) and porosity (n) under different wave and water level conditions. When the breakwater operates under submerged conditions (Rc=0), the effect of surface porosity on Kt is minimal. Specifically, as the porosity increases from n=0.236 to n=0.591 (an increase of approximately 2.5 times), the Kt only increases from 0.55 to 0.67 (approximately 1.2 times). In contrast, when the breakwater operates in an emerged condition (Rc=14cm), the Kt increases proportionally with porosity. In this case, as porosity increases from n=0.236 to n=0.591, the Kt increases from 0.26 to 0.53, representing a twofold increase.

In addition, based on fabrication conditions, structural stability, and the spatial arrangement of precast concrete elements, this study selects configuration KH6 with porosity values of P1=20.7% and P2=15.4%, which ensures a high wave energy dissipation coefficient, a low wave reflection coefficient, and meets the functional requirements for effective wave attenuation.

3.1.2. Influence of the Relative Freeboard Height (Rc/Hm_0,i) on the Wave Transmission Coefficient (Kt)

Figure 3-5 illustrates the relationship between the wave transmission coefficient (Kt) and the relative freeboard height (Rc/Hm0,i). Due to the hollow structure breakwater body, when the structure in a submerged condition (Rc/Hm0,i<0), the Kt ranges from 0.6 to 0.8. In the range of 0≤Rc/Hm0,i<1, Kt decreases linearly from 0.6 to 0.5, indicating a gradual increase in wave attenuation efficiency (corresponding to 40–50% wave reduction). When Rc/Hm0,i>1 corresponding to an emerged breakwater the Kt coefficient stabilizes at approximately 0.34–0.4, showing only a slight decrease.

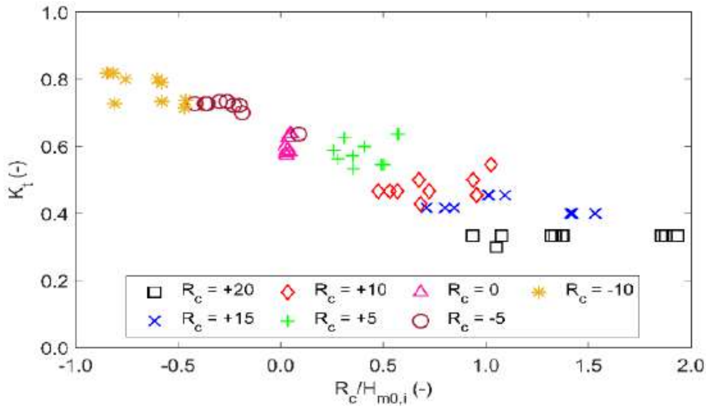

Figure 3-5. Effect of relative freeboard height (Rc/Hm0,i) on Kt.

3.1.3. Influence of relative width of dike (Beff/Lm0-1), Beff/d

The crest width is one of the key parameters influencing the wave attenuation performance of the structure. In this study, the crest width of the hollow breakwater is proposed as an "effective width" (Beff) for the calculation of the proposed trapezoidal cross-section. The influence of the relative effective crest width (Beff/Lm0−1) on the wave transmission coefficient (Kt) is illustrated in Figures 3-6.

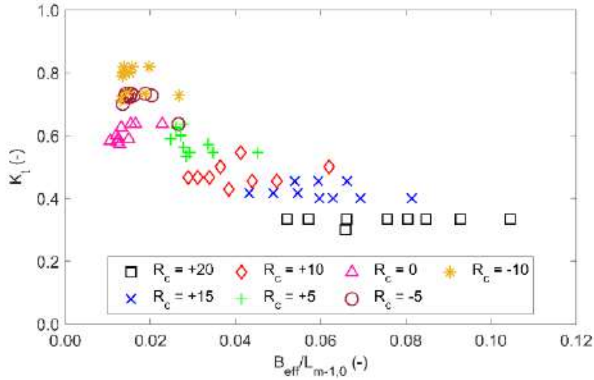

Figure 3-6. Effect of relative width Beff /Lm-1.0 on Kt

The influence of the relative effective crest width (Beff/Lm−1,0) on the wave transmission coefficient (Kt) becomes less significant when the breakwater in a submerged. At higher submergence levels (e.g., Rc=−5cm and Rc=−10cm), the effect of Beff/Lm−1,0 on Kt is minimal.

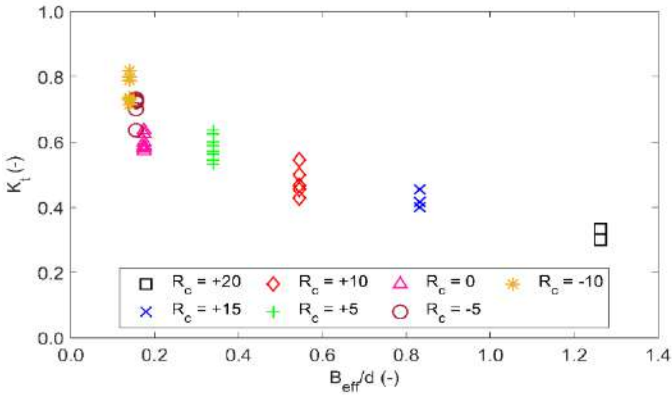

Figure 3-7. Effect of relative width Beff /d on Kt.

The influence of the relative width Beff/d on the wave transmission coefficient Kt exhibits a clear trend: as Beff/d increases, Kt decreases, indicating an inverse relationship. When the relative width is large

(Beff/d>0.8), it significantly affects the wave transmission coefficient, resulting in lower Kt values (ranging from 0.3 to 0.6). Conversely, when the relative width is very small (Beff/d<0.4), the wave transmission coefficient Kt becomes relatively high, typically ranging from 0.6 to 0.8.

3.1.4. Effect of wave slope (S_{0m})

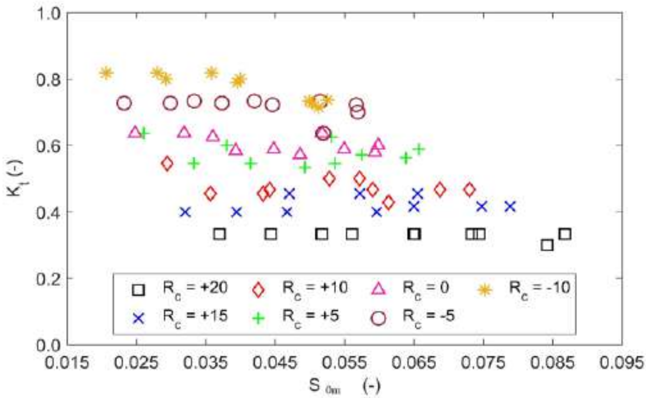

Figure 3-8. Relationship $S_{0m} \sim K_t$.

$$S_{0m} = \frac{2\ \Pi.H_{m0,i}}{gT_{m-1,0}^2} \quad (3\text{-}1)$$

Figure 3.8 illustrates the relationship between the wave transmission coefficient Kt and the incident wave steepness S_{0m} under different conditions. In general, the influence of S0m on Kt is relatively weak. When the structure in a submerged (Rc<0), an inverse trend is observed—particularly under deep submergence (Rc=−10), indicating that smaller wave steepness has minimal impact on the Kt. In contrast, when the structure emerged (Rc>0), this relationship becomes less pronounced.

3.1.5. Constructing the formula for the wave transmission coefficient through KCR TC1 from the results of physical model experiments

According to the dimensional analysis based on the Pi-Buckingham, the wave transmission coefficient for porous breakwaters follows a general formulation consistent with the findings of Angremond et al. (1996), Van der Meer et al. (2005), Thieu Quan Tuan et al. (2022), and Marcel R.A. van Gent et al. (2023). Therefore, this common formulation can be applied by the researcher to develop empirical equations for the KCR TC1 breakwater structure.

$$K_t = a_1 \frac{R_c}{H_{m0}} + a_2 \left(P_f \frac{B_{eff}}{L_{m-1,0}}\right)^{a_3} \left[1 - exp\left(\frac{a_4}{\sqrt{S_{0m}}}\right)\right] \quad (3\text{-}2)$$

$$K_t = a_1 \frac{R_c}{H_{m0}} + a_2 \left(P_f \frac{B_{eff}}{d}\right)^{a_3} \left[1 - exp\left(\frac{a_4}{\sqrt{S_{0m}}}\right)\right] \quad (3\text{-}3)$$

The empirical coefficients a1, a2, a3, a4 were determined through regression analysis based on data from 70 physical model experiments. The identified coefficients are: a_1 = –0.187, a_2 = 0.775, a_3 =- 0.025, a_4 = –0.41, R^2 = 0.9373, corresponding to Equation (3-2).

Accordingly, Equation (3-2) can be rewritten in the following form:

$$K_t = -0.187 \frac{R_c}{H_{m0}} + 0.775 \left(P_f \frac{B_{eff}}{L_{m-1,0}}\right)^{-0.025} \left[1 - exp\left(\frac{-0.41}{\sqrt{S_{0m}}}\right)\right] \quad (3\text{-}4)$$

With formula (3-3) The experimental constants are determined respectively as: a_1 = –0,112, a_2 = 0,765, a_3 = -0,11, a_4 = –0,485, R^2 = 0.9468.

Thus, the above formula (3-3) is rewritten as follows:

$$K_t = -0.112 \frac{R_c}{H_{m0}} + 0.765 \left(P_f \frac{B_{eff}}{d}\right)^{-0.11} \left[1 - exp\left(\frac{-0.485}{\sqrt{S_{0m}}}\right)\right] \quad (3\text{-}5)$$

Scope of application of the formula:

$\frac{R_c}{H_{m0,i}} = -1.07 \div 1.93;\ S_{0m} = 0.021 \div 0.087$

$\frac{B_{eff}}{d} = 0.14 - 1.263;\ K_t = 0.3 \div 0.80$*; P_1=20.7%; P_2=15.4%*

3.1.6. Validation of the formula with measurement data from wave basin

Using data from 24 scenarios of wave transmission experiments through the KCR TC1 structure in a wave basin, formulas (3-4) and (3-5) were validated. The comparison between the calculated Kt and the measured Kt, evaluated using the coefficient of determination R2 and root mean square error (RMSE), indicates a relatively good level of reliability (Table 3-1). However, formula (3-5) produced the best results, with the highest R2=0.8523 and the lowest RMSE = 0.057. Therefore, this formula was selected for calculating wave transmission through the TC1 structure.

Table 3-1. Correlation coefficient R^2 , RMSE

No	Formula	Evaluation indicators	
		R^2	RMSE
1	Formula (3-4)	0.8102	0.067
2	Formula (3-5)	0.8523	0.058

3.1.7. Validation of the formula with field measurement data

The field survey was conducted at Tan Thanh coast, Tien Giang Province. The layout of the monitoring stations is shown in Figure 3-9. Four measurement locations—ST1, ST2, ST3, and ST4—were established to collect hydrodynamic parameters, including current, wave characteristics, and suspended sediment concentrations.

Figure 3-9. Layout of Monitoring Stations at Tan Thanh Coast, Tien Giang Province.

To evaluate the proposed formula against field measurements, a dataset collected at the TC1 breakwater in Tan Thanh from January 13 to 15, 2021, was used. To assess the wave transmission coefficient Kt through the TC1 structure, the following formula was applied:

$$K_t = \frac{H_{m0,t}}{H_{m0,i}}$$

The wave transmission coefficient is determined as the ratio of the transmitted wave height behind the structure (Hm0,t) at station ST2 to the incident wave height in front of the structure (Hm0,i) at station ST1.

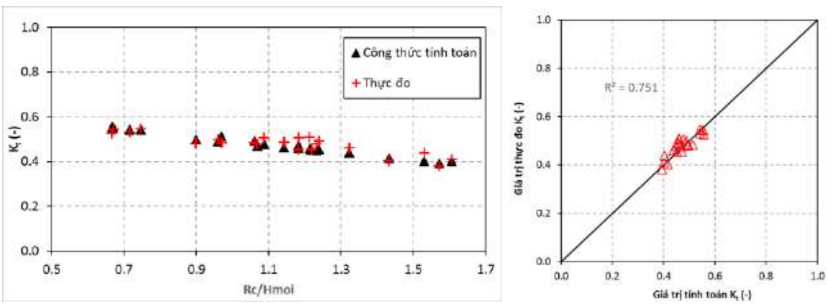

Figure 3-10. Comparison of the Kt Between Calculated and Measured

The comparison between the Kt calculated from the empirical formula and that derived from field measurements shows a reasonably good agreement, with a correlation coefficient of R2=0.751 and RMSE= 0.024. However, the R2 value obtained from field data is lower than that observed in wave flume experiments. This discrepancy indicates that conditions in laboratory wave flume models and actual field environments differ due to the influence of external factors such as wave and wind direction, topography, sediment concentration, salinity, wave diffraction, and refraction, model scale...

3.2. Velocity change through hollow structure dike TC1

The velocity transmission coefficient K_{Vmean} is defined as the ratio of the average velocity behind the structure to the average velocity in front of the hollow structure TC1: $K_{Vmean} = V_{mean,t} / V_{mean,i}$

The flow reduction efficiency ε_v % is determined by formula:

$$\varepsilon_v = (1 - K_{Vmean}) * 100\% = \left(1 - \frac{V_{mean,t}}{V_{mean,i}}\right) * 100\%$$

Với: K_{Vmean} The velocity transmission coefficient ($0 \le Ktv \le 1{,}0$)

ε_v The flow reduction efficiency ($0 \le \varepsilon_v \le 100\%$)

Vmean,i and Vmean,t are the average velocities in front and behind the hollow structure, respectively.

3.2.1. Average velocity variation process corresponding to the working states of the breakwater

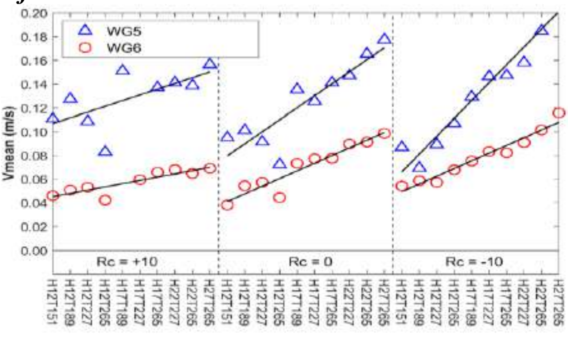

Figure 3-11. Variation of average velocity value at WG5, WG6.

To examine the influence of wave parameters on the process of changing the average velocity value before and after the construction at the measuring needle position WG5, WG6 (Figure 2-4). Figure 3-11 shows the change in average velocity very clearly, as the wave height increases, the velocity before and after the construction also increases accordingly, in which in the case of the emerged (Rc=+10) when the wave height increases from Hs=12cm to Hs=22cm, the average velocity before the construction (WG5) increases significantly from Vmean =0.115cm/s to 0.17cm/s, on the contrary, the velocity after the breakwater (WG6) increases very little from 0.045 to 0.055m/s, the flow reduction coefficient before and after the construction is up to ε_v = 50%.

3.2.2. Effect of relative crest (Rc/Hm0,i) on velocity transmission coefficient K_{Vmean}

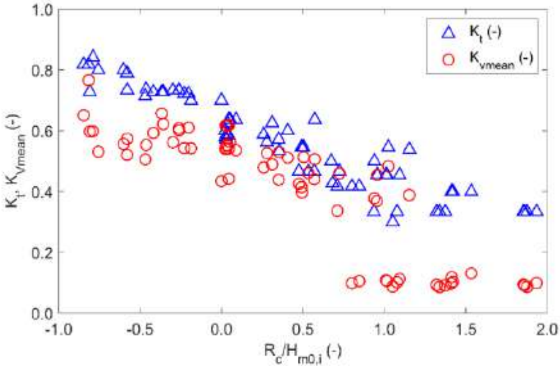

Figure 3-12.Relationship coefficient K_t, K_{Vmean} and relative crest Rc.

The average velocity transmission coefficient K_{Vmean} is calculated as the ratio between the velocity measured behind the structure (WG6) and the velocity measured in front of the structure (WG5). Figure 3-12 illustrates the trend that when the structure in an emerged state (Rc > 0), the K_{Vmean} value remains relatively low, K_{Vmean} =0.15 - 0.4. This corresponds to a velocity reduction efficiency ε_v = 60–85%. Conversely, when the structure in a submerged state (Rc < 0) and waves overtop the crest, K_{Vmean} increases significantly, K_{Vmean} = 0.4 - 0.7, equivalent to ε_v = 30–60%. This behavior is notably consistent with the trend of the wave transmission coefficient (Kt).

The wave transmission coefficient K_t and the average velocity transmission coefficient K_{Vmean} are hydraulic characteristics of the perforated hollow breakwater. When waves propagate through the structure, it does not completely block wave energy or flow velocity, but rather allows partial transmission. As a result, the flow velocity is reduced to a certain extent, with the velocity reduction efficiency ε_v = 30% - 85%.

3.3. Application of TC1 breakwater in Tan Thanh, Go Cong

3.3.1. Calculation of dike crest elevation

The dike crest elevation is calculated according to the wave reduction requirement determined by the following formula:

$$Z_đ = Z_{tp} + R_c \quad (3\text{-}6)$$

In which: - Z_{tp} is the design sea level elevation in monsoon conditions

- R_c is the clearance height from the top of the dike to the design water level, calculated experimentally from the established formula Kt;

$$K_t = -0{,}112\frac{R_c}{H_{m0}} + 0{,}765\left(P_f\frac{B_{eff}}{d}\right)^{-0{,}11}\left[1 - exp\left(\frac{-0{,}485}{\sqrt{S_{0m}}}\right)\right]$$

With wave conditions and water levels in the Tien Giang coastal area, the parameters for calculating and designing the dike crest elevation are shown in Table 3-2.

Bảng 3-2. Summary of breakwater design parameters

Design parameters	Value	Note
Design water level (m)	+1.55	the calculation appendix PL4
Water depth d(m)	1.7	Design water level - beach elevation
Wave height in deep water H_{mo} (m)	1.5	Northeast Monsoon Waves PL4
Wave period T_p (s)	5.0	
Design wave height H_{moi} (m)	0.9	Calculate the wave transmission from deep water to the structure PL4
Wave height max H_{max} (m)	1.38	H_{max} =1.53 H_{moi}
Wave height behind breakwater $H_{mo,t}$ (m) < [$H_{mo,t}$]	0.4	Wave reduction requirements for mangrove planting TCVN-10405-2020
Allowable transmission coefficient [K_t]	0.44	= Hmot/ Hmoi
Calculation results		
Effective dike crest width B_{eff}(m)	1.52	Calculation formula (2-6)
Height of the crest free space R_c (m)	+0.92	Calculation formula (3-7)
Wave height behind breakwater H_{mot} (m)	0.397	
Breakwater crest elevation (m)	**+2.47**	Calculation formula (3-6)

Based on the calculation the dike crest elevation selected is +2.5m

3.4. Evaluating the application of hollow structure breakwater through field measurements

3.4.1. The sediment formation

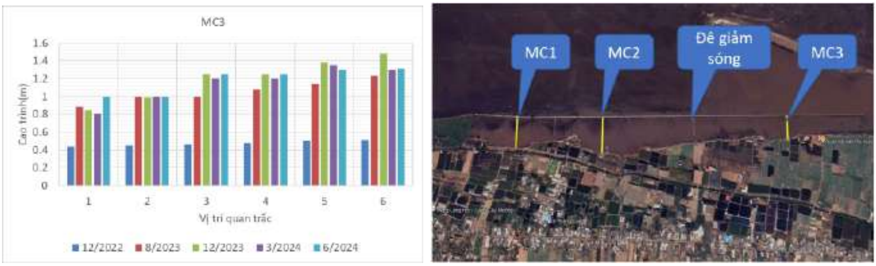

Figure 3-13. Beach elevation at the cross-section behind the wave-reducing dyke in Tan Thanh

Figure 3-13 illustrates the variation in beach elevation behind the structure at six monitoring points (Points 1 to 6, measured from the shoreline toward the Breakwater) cross-sections at Tan Thanh over five survey periods (from December 2022 to June 2024). The results show that beach elevation increased rapidly within the first year after construction and gradually stabilized in the following years, reaching levels between +0.8 and +1.2 meters. With this elevation, it is feasible to initiate mangrove planting and restoration, enhancing shoreline protection and wave attenuation.

3.4.2. Effectiveness of mangrove and ecosystem restoration

The results of mangrove restoration at Con Cong and Tan Thanh following the construction of the coastal structures indicate that the underwater ecosystem is gradually recovering. Various aquatic and marine species are beginning to thrive beneath the mangrove canopy. This is a positive indicator, demonstrating the effectiveness of the structures in supporting the restoration of the coastal ecosystem.

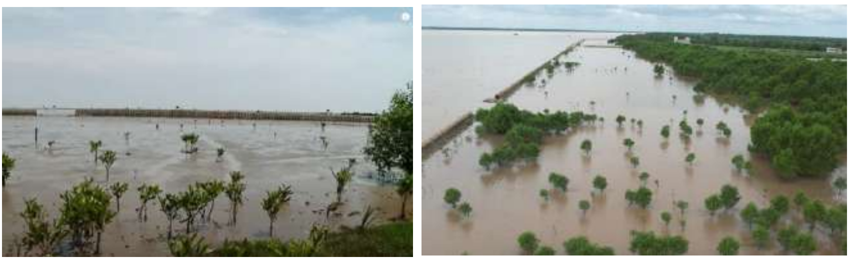

Figure 3-14. The process of restoring mangrove forests and ecosystems in Tan Thanh and Con Cong - Tien Giang after 4 years of construction.

CONCLUSIONS AND RECOMMENDATIONS

1. Conclusions

(1) The dissertation provides an overview of research achievements both globally and domestically on coastal protection solutions, with a focus on porous-structure breakwater. Based on this, the dissertation proposes an approach that delves into the study of wave transmission and hydraulic characteristics of the TC1-type porous breakwater.

(2) The dissertation established a formula calculating wave transmission through the TC1-type porous-structure. This was achieved through physical model experiments 2D, 3D, field measurements 1:1 scale.

(3) The research results analyzed parameters related to the wave transmission coefficient, including the geometric characteristics of the porous-structure TC1, wave parameters, and the variation in flow velocity before and after the TC1. The TC1 dike solution was applied to coastal areas of the Mekong Delta, and field measurements were conducted to evaluate the effectiveness of the structure in terms of wave attenuation, flow reduction, sediment deposition, and mangrove ecosystem restoration at Tien Giang Province. The findings are scientifically validated, reliable, and demonstrate the potential for practical application of the TC1 structure in coastal protection across the Mekong Delta region.

2. Recommendations

The wave transmission formula for the TC1 porous-structure dike was developed based on flume experiments with wave propagation perpendicular to the structure. However, waves impact the structure from various directions, accompanied by phenomena such as wave refraction and diffraction. Therefore, it is necessary to investigate the influence of oblique wave angles on the structure accounts for multiple incident wave directions.

The current study limited the arrangement of surface pores on the dike to circular holes aligned in rows. Therefore, further research is needed to investigate alternative pore shapes (triangular, rectangular, etc.) and different spatial configurations on the surface of the structural elements.

The study investigates the sedimentation morphology behind the TC1 porous breakwater, focusing on shoreline evolution and the formation of accretion zones after the structure's implementation.

The study evaluates environmental changes and the dynamics of aquatic flora and fauna ecosystems, as well as the mangrove forest ecosystem, before and after the construction of the structure. Based on these findings, a plan is proposed to implement mangrove reforestation and relocate the dike line seaward to allow for further expansion of the mangrove forest area.

THE LIST OF PUBLICATION

[1] **Le Xuan Tu**, Tran Ba Hoang, Le Manh Hung, 2023. Integrated solutions for coastal protection and mangrove forest restoration under climate change and sea level rise conditions in the coastal areas of the Mekong Delta. Scientific Research Compilation, Southern Institute of Water Resources Research, 2023.

[2] **Le Xuan Tu**, Tran Ba Hoang, Le Thanh Chuong, Le Manh Hung, Le Thi Hien. Application of porous-structure wave-reducing dikes TC1 and TC2 for coastal protection in the Mekong Delta region. Journal of Water Resources Science and Technology, No. 67 (August 2021).

[3] **Tu Le Xuan**, Hoang Thai Duong Vu, Peter Oberle, Thanh Duc Dang, Hoang Tran Ba, Hung Le Manh, 2024. Hydrodynamics and wave transmission through a hollow triangle breakwater, Estuarine, Coastal and Shelf Science,Volume 302, 108765.

[4] **Le Xuan Tu**, Le Manh, H., Ba, H.T., Do Van, D., Vu, H.T.D., Wright, D., Hieu, B.V., Anh, D.T., 2022. Wave energy dissipation through a hollow triangle breakwater on the coastal Mekong Delta. Ocean Eng. 245, 110419

[5] **Le Xuan Tu**, Ba, H.T., Thanh, V.Q., Wright, D.P., Tanim, A.H., Anh, D.T., 2022. Evaluation of coastal protection strategies and proposing multiple lines of defense under climate change in the Mekong Delta for sustainable shoreline protection. Ocean Coast Manag. 228, 106301.

[6] Water Security and Climate Change Conference (WSCC2022) - Adaptation for sustainable and resilient development". Presentation "Holistic coastal protection strategies with nature-based solution for climate change adaptation in coastal Mekong Delta". https://www.youtube.com/watch?v=BURR2Sm35NA

[7] Tran Ba Hoang, Dinh Cong San, Le Thanh Chuong, **Le Xuan Tu.** (2022). Coastal Erosion and Mitigation Solutions in the Mekong Delta. Monograph, Science and Technology Publishing House.

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