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PHAM DUC HUNG

PROPOSING A HORSE-HOOF-SHAPED HOLLOW PILE BREAKWATER TO PROTECT THE WESTERN COAST OF THE MEKONG DELTA

Field of engineering: Hydraulic Construction Engineering

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SUMMARY OF ENGINEERING DOCTORAL THESIS

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INTRODUCTION

1. Problem Statement

Viet Nam has a coastline of approximately 3,260 kilometers, making it one of the countries with significant potential for developing a maritime economy. However, in recent years, the impacts of climate change and rising sea levels have led to increasingly complex coastal erosion issues. These issues are intensifying in both scope and severity, posing serious threats to the livelihoods of coastal communities, infrastructure in coastal areas, and significantly affecting socio-economic development.

The Mekong Delta is currently the most severely impacted region, experiencing the erosion of tens of kilometers of coastline each year. In many areas, the loss of protective mangrove forests along the coast has significantly heightened risks to the safety of sea dikes, vital infrastructure, and the livelihoods of communities residing behind these dikes.

With the proactive support and attention of the Government, central ministries, and the dedicated efforts of local authorities, numerous projects have been implemented, achieving certain positive outcomes. However, due to the distinctive hydrographic conditions and the soft soil foundation of the Mekong Delta, it remains imperative to “conduct research and apply advanced scientific and technological solutions, with a priority on environmentally friendly, innovative, easily constructible, reusable, and cost-effective technologies, while integrating traditional methods.”

Accordingly, this dissertation focuses on the topic: " ***Proposing a horse-hoof-shaped hollow pile breakwater to protect the western coast of the Mekong Delta***" which holds significant scientific and practical value in the field of contemporary coastal protection.

2. Objectives

- To propose a new type of breakwater with a horse-hoof-shaped hollow piles to protect the Western coast of the Mekong Delta.

- To develop an experimental formula for calculating the wave transmission coefficient of the horse-hoof-shaped hollow piles breakwater.

- To create an envelope diagram and establish a method for determining the maximum wave pressure on the wave-facing surface of the horse-hoof-shaped hollow pile breakwater.

3. Subject and scope

- Subject of the study:

+ Interaction between waves and the horse-hoof-shaped hollow pile breakwater under the hydrodynamic conditions of the western coast of the Mekong Delta.

- Scope of the study:

+ Study on wave transmission through the horse-hoof-shaped hollow pile breakwater in the natural conditions of the western coast of the Mekong Delta.

+ Analysis of maximum wave pressure on the wave-facing surface of the horse-hoof-shaped hollow pile breakwater in the natural conditions of the western coast of the Mekong Delta.

4. Research contents

- Provide an overview of global and national research on wave interaction with various breakwaters, leading to the identification of the research problem addressed in this dissertation.
- Investigate the scientific foundation and propose new structure solutions for coastal protection, followed by experimental testing on a physical model to study the interaction between waves and the proposed structure.
- Analyze the determination of wave transmission coefficients and wave pressure on the horse-hoof-shaped hollow pile breakwater.
- Apply the research findings to the design of a breakwater in the Western coastal area of Ca Mau Province.

5. Methodologies

The dissertation employed the following primary research methods: theoretical research methods, experimental research methods, and expert consultation methods.

6. The scientific and practical significances

- Scientific significances:

The dissertation introduced a new type of breakwater called the horse-hoof-shaped hollow pile breakwater (HPB) to protect the western coast of the Mekong Delta. It also developed an experimental formula to calculate the wave transmission coefficient, analyzed the pressure distribution, and proposed a method to estimate the maximum wave pressure on the wave-facing surface of the HPB. These findings contribute to advancing research on breakwaters, particularly hollow piles breakwaters.

- Practical significances:

The dissertation's findings provide practical guidance for investors and design consultants in evaluating and designing breakwaters for the western coast of the Mekong Delta and similar regions.

7. Outline of the dissertation

In addition to the introduction, conclusions and recommendations, the dissertation consists of 4 chapters as follows:

Chapter I: Overview of studies on wave interaction with breakwaters,

Chapter II: Scientific foundations and research methodology,

Chapter III: Determination of wave transmission coefficients and wave pressure on the horse-hoof-shaped hollow pile breakwater

Chapter IV: Application of research findings in the design of breakwater for the western coastal area of Ca Mau province.

8. New contributions

1) Propose a new type of breakwater with a horse-hoof-shaped hollow piles to protect the Western coast of the Mekong Delta.

2) Develop experimental formula (3.6) to calculate the wave transmission coefficient of the proposed structure.

3) Construct an envelope diagram for the maximum wave pressure acting on the proposed structure.

Chapter I. OVERVIEW OF STUDIES ON WAVE INTERACTION WITH BREAKWATERS

1.1. Overview of global studies on wave interaction with breakwaters

1.1.1. Rubble mound breakwaters

The sloped rubble mound breakwater is the most commonly used type of breakwater worldwide. Notable studies on wave interaction with sloped rubble mound breakwaters include those by Van der Meer (1991), Van der Meer and Daemen (1994), and D'Angremond et al. (1996). Among these, the empirical formula developed by D'Angremond for determining the wave transmission coefficient (Kt) is considered highly reliable and has been widely applied in practice.

1.1.2. Caisson breakwaters

Gűnaydın and Kebdaşlı (2004; 2007) experimentally studied the hydraulic performance of the U-type and П-type barriers under regular and irregular waves. Brossard et al. (2003) developed a Ш-type barrier. Research results indicated that the reflection coefficient (Kr) of a submerged box without a wave absorption chamber is approximately 0.9, whereas for a submerged box with a wave absorption chamber, Kr varies between 0.5 and 0.6.

1.1.3. Semicircular breakwaters

Studies on semicircular breakwaterswere first conducted by Tanimoto and his research team in the 1980s. Later, Dhinakaran and colleagues proposed that a surface porosity ratio of 11% for SBWs (Submerged Breakwater Structures) would optimize both wave transmission reduction and wave reflection. However, the authors did not develop an empirical formula to determine the wave transmission coefficient through the structure for design application purposes

1.1.4. Quarter circular breakwater

The quarter circular breakwater (QBW) was first proposed by Xie and colleagues in 2006. The structure of this breakwater includes a wave-facing surface in the shape of quarter of a circle, with a flat bottom and rear surface. Notable studies on this type of structure include those by Balakrishna K, Arkal Vittal Hegde, and Binumol S (2015), as well as Binumol S, Subba Rao, and Arkal Vittal Hegde (2017). However, these studies have only been conducted with a surface porosity ratio of 12%, focusing on evaluating the reflection coefficient of the structure, without addressing its wave reduction capacity.

1.1.5. Hollow pile breakwater

The hollow pile breakwater has been studied since 1994 in Japan, with a practical installation carried out at the Sakaiminato breakwater. K. Sankarbabu, S.A. Sannasiraj, and V. Sundar (2008) experimentally tested dual cylindrical hollow piles and proposed an optimal ratio between the inner and outer pile diameters of 0.5. Previously, Rao et al. (1999) demonstrated that the wave energy dissipation capacity of perforated piles (with perforations) is 10% to 15% greater than that of solid piles. Norzana Mohd Anuar and Faridah Jaffar Sidek (2010, 2012) compared the wave transmission characteristics of single and double rows of perforated piles with different hole area ratios: 6.25%, 14%, 28%, and 48%. The authors also developed an empirical equation to predict the wave transmission coefficient based on independent governing parameters.

1.2. Studies on wave interaction with breakwaters in Viet Nam

Nguyen Trung Anh (2007) conducted a study on the submerged box structure with a wave absorption chamber (BTS). The author recommended selecting a wave absorption chamber width of B/L = 0.1 to 0.2, with a maximum width of 10 meters, and a wave penetration hole ratio of 20% to 30%. The shape of the holes should be circular.

Thieu Quang Tuan et al. (2018) conducted a study to assess the wave dissipation capacity of a double-sided hollow structure (with a hole area ratio of 17.7%) and analyzed the changes in the wave spectrum before and after the installation of the structure.

Le Thanh Chuong et al. (2020) studied the wave dissipation capacity and energy absorption of two types of breakwaters (an open quadrilateral pyramid-shaped structure with a surface hole ratio of 17.6%, and a closed crescent-shaped structure with a front hole ratio of 19.7%) based on physical modeling.

Nguyen Anh Tien (2019) studied the wave reduction effectiveness of a complex hollow breakwater structure. The breakwater consists of a hollow submerged base and a system of piles above, designed to dissipate wave energy. Phan Dinh Tuan (2021) proposed a type of breakwater in the form of a ¼ cylindrical hollow shape placed on top of a sea dike.

Le Xuân Tu and Do Van Duonng (2020, 2021) studied the wave transmission characteristics through double- row pile breakwaters. The study highlighted that the wave transmission process is influenced by two key factors: the relative free board and the wave steepness.

Nguyen Nguyet Minh (2022) conducted experiments using a physical wave flume to assess the reflection, transmission, and wave energy dissipation characteristics of various wave-reducing structures, including CLT, ĐTR, and TC1.

1.3. Overview of studies on wave pressrure on breakwaters

1.3.1. Some key research findings worldwide

Hiroi (1919) developed a formula for calculating wave pressure acting on vertical breakwaters in relatively shallow waters, assuming a uniform distribution of wave pressure in the vertical direction. Sainflou (1928) proposed a formula for determining the vertical wave pressure on breakwaters, which has been widely adopted and applied globally for many years

Goda (1985) proposed a method for calculating wave pressure for vertical breakwaters. Later, Takahashi (1992, 1994) further developed this approach by incorporating the impact of wave shock pressure into Goda's formula. This method remains widely used to this day

El-Hafid Tabet-Aoul and Eloi Lambert (2003) assessed the distribution and wave pressure acting on the surfaces of perforated submerged caisson. The Dalian University of Technology (DUT), China (1998), proposed a method for calculating the total wave force on perforated submerged boxes, which was incorporated into the Chinese Breakwater Design and Construction Code (JTS-154-1-2011).

Xuefeng Chen, Yucheng Li, and Liu Yong (2010) used the RANS model and k-ε equations to study the wave pressure acting on submerged box structures with a perforated rectangular wave-facing surface (with hole ratios $\varepsilon = 20\%$ and 40%), a sealed wave-ward surface, and a wave energy dissipation chamber filled with rubble stone. Alf Tørum, Annette Jahr, and Øivind Arntsen (2012) conducted physical model experiments to determine the wave pressure acting on cylindrical submerged boxes.

1.3.2. Some key research findings in Viet Nam

Nguyen Viet Thanh (2014) presented three detailed methods for calculating wave pressure on half-circular hollow structures, referred to by the author as "semi-circular breakwaters." Nguyen Van Dung (2017) conducted experiments and developed an empirical formula for calculating the wave pressure acting on the crest wall.

Tran Văn Thai (2018) developed a method for calculating the stability of the "Hollow circular breakwater" on the softsoil foundations. Le Hai Trung, Nguyen Thai Hoang (2020) studied the distribution of wave pressure on seawalls using the ANSYS model and physical model experiments. The results identified the pressure distribution charts representing the maximum wave pressure acting on different types of seawalls.

Commentary: Research on wave pressure acting on breakwater structures (ĐGS) in Vietnam is still limited, with only a few studies measuring wave pressure on crest walls and seawalls. These studies have a limited number of experiments and their results are in the preliminary stages. The types of ĐGS currently being tested are primarily based on global references, and there is a lack of comprehensive scientific data to assess their suitability under the specific conditions in Vietnam.

1.4. Conclusion of Chapter I

There are many types of breakwaters; however, no studies have been proposed internationally or domestically for structures in the form of hollow piles with a horse-hoof-shaped cross-section.

For any coastal protection project, developing a formula to determine the wave transmission coefficient is crucial for selecting an appropriate scale and size for the structure based on the requirements.

Research on determining wave pressure on wave-reduction structures is still limited, and accurately determining wave pressure remains a complex challenge. Currently, most studies focus on methods for calculating wave pressure for various types of breakwater structures, based on the framework proposed by Goda (1985). In Vietnam, while several new types of breakwater structures have been proposed, there is very little research on the wave pressure acting on each specific structure type.

Chapter II. SCIENTIFIC FOUNDATIONS AND RESEARCH METHODOLOGY

2.1. Basis for proposing the horse- hoof-shaped Hollow pile breakwater

2.1.1. Solutions currently applied and tested in the Mekong delta and limitations

To cope with coastal erosion, many solutions have been applied or tested, such as: Pile-rock breakwaters, Busadco breakwaters, hollow circular breakwaters, and TC1 and TC2 breakwater (see Figure 2.1).

(Pile-rock breakwater)

(Busadco # 1)

(Busadco #2)

(Hollow circular breakwater)

(TC1 breakwater)

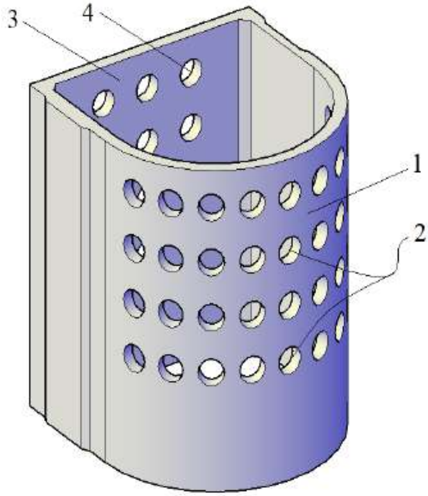
(TC2 breakwater)

Figure 2.1. Some types of breakwaters applied and tested in the Mekong delta

The existing issues with the pile-rock breakwaters are as follows: it cannot be reused, it limits the process of nutrient exchange and sediment transport along the shore, rubble stones tend to subside due to weak soil foundations, construction faces numerous challenges, and investment costs remain relatively high. The hollow circular breakwater is limited when applied in deepshore areas and large water depths. The Busadco non-metallic core breakwater has modest wave reduction and sedimentation capabilities, and its durability has not been thoroughly tested.

2.1.2. Proposing a horse-hoof shaped hollow pile breakwater

The proposed HPB has a horse-hoof-shaped cross-section, cast as a hollow block made of reinforced concrete, formed by the seaward surface (1) and the landward surface (3) (see Figure 2.2). The area of the hollow openings accounts for 15% to 25% of the seaward surface, while on the landward surface, this ratio is approximately 12%.



(1) seaward surface, (2) perforations of seaward surface; (3) landward surface; (4) perforations of landward surface

Figure 2.2. Hollow pile breakwater component

The breakwater structure is formed by assembling HPB components, which are interconnected using male and female grooves to increase the horizontal contact area. Additionally, the components are partially embedded into the foundation to enhance stability

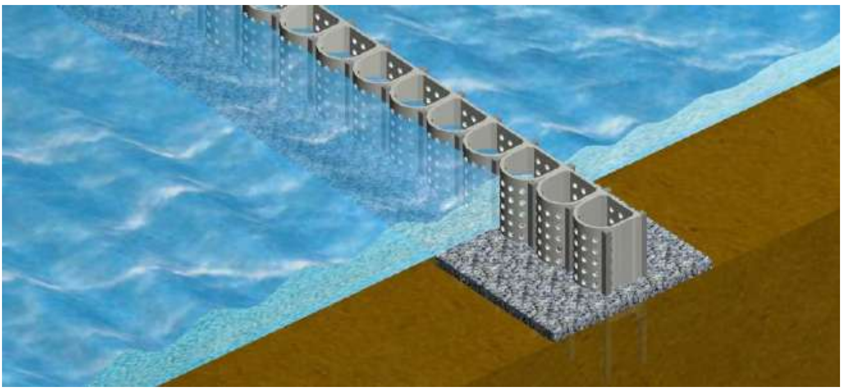


Figure 2.5. The completed hollow pile breakwater

2.2. Basis for evaluating the functionality of the breakwater structure

When waves interact with a breakwater structure of any shape, part of the energy is reflected back toward the sea, part is dissipated due to the energy transformation process caused by the structure, and the remaining energy is transmitted to the wave-shadowed side of the breakwater. In theory, this hydrodynamic problem follows the law of conservation of energy and can be mathematically represented in the form of an energy balance equation.

$$E_i = E_t + E_r + E_l \tag{2.1}$$

In which Ei, Et, Er, and El represent the incident wave energy, transmitted wave energy, reflected wave energy, and dissipated wave energy, respectively. Equation (2.1) is expressed in terms of wave height as follows:

$$E_i = \frac{\rho g H_i^2}{8} = \frac{\rho g H_t^2}{8} + \frac{\rho g H_r^2}{8} + E_l \tag{2.2}$$

or:

$$1 = K_t^2 + K_r^2 + K_l^2 \tag{2.4}$$

Where Kt, Kr, and Kl are the transmission coefficient, reflection coefficient, and wave energy dissipation coefficient, respectively, and Hi, Ht, and Hr are the incident wave height, transmitted wave height, and reflected wave height, respectively.

$$K_t = \frac{H_t}{H_i} \quad (2.5); \qquad K_r = \frac{H_r}{H_i} \quad (2.7); \qquad K_l^2 = 1 - K_r^2 - K_t^2 \quad (2.9)$$

The determination of the coefficients Kt, Kr, and Kl to assess the functionality of the breakwater structure is the objective of the studies.

2.3. Theoretical basis for physical model experiment to evaluate wave interaction with HPB

2.3.1. Theory of similarity

The physical model is established based on the theory of similarity. The model factors must satisfy the following conditions: geometric similarity, kinematic similarity, and dynamic similarity of the flow with the prototype.

2.3.2. Dimensional analysis to establish the relationship between key parameters, wave transmission coefficient, and wave pressure on the HPB

Using the Pi-Buckingham method to establish general equations that express the relationship between the key governing parameters and the characteristics of wave transmission and wave pressure acting on the HPB

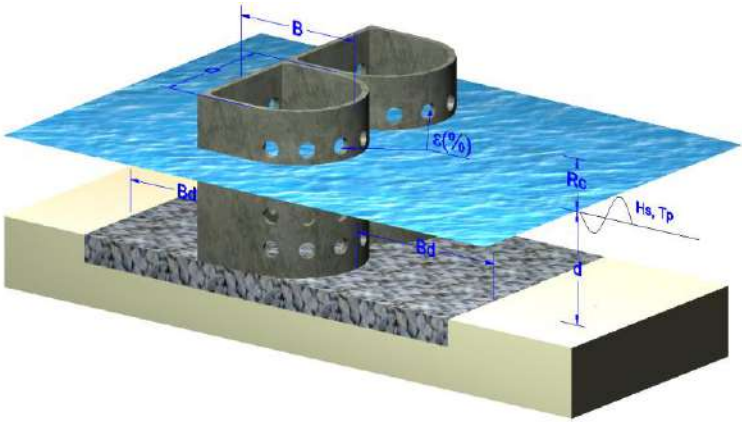


Figure 2.7. Diagram of the key governing parameters affecting the wave interaction characteristics with the HPB

The governing parameters can be expressed as a functional relationship as follows:

$$f\left(\rho, \mu, g, V, H_{m0,i}, H_{m0,t}, L_{m-1,0}, T_{m-1,0}, \beta, d, R_c, B, D, B_d, \varepsilon, i\right) = 0 \qquad (2.14)$$

The result for determining the wave transmission coefficient through the HPB structure is typically expressed as:

$$K_t = \frac{H_{m0,t}}{H_{m0,i}} = f\left(s_{m-1,0}, \frac{R_c}{H_{m0,i}}, \frac{B}{H_{m0,i}}, \varepsilon\right) \qquad (2.23)$$

The result for determining the wave pressure acting on the wave-facing surface of the HPB structure is typically expressed as:

$$\frac{p}{\rho.g.H_{m0,i}} = f\left(\frac{R_c}{H_{m0,i}}, \frac{B}{H_{m0,i}}, s_{op}, \varepsilon\right) \qquad (2.32)$$

2.4. Determining and selecting experimental boundary conditions

Wave height: According to existing research results, in the Western Sea area, waves have a height of Hs≤0.5 (~70%) and 0.5 m<Hs<2.0 (~30%). Therefore, the thesis selects the experimental wave height range as 0.5 m<Hs<2.0 m.

Wave period: The wave period is determined from the wave height values using the relationships from the research of Thiều Quang Tuan, Nguyen Xuan Hung, and the SPM method (1984). For wave heights in the range of 0.5 m<Hs<2.0 m, the selected wave period range is 3.5 s<Tp<7.0 s.

Beach slope: According to the survey results from the Southern Institute of Water Resources, the area has an average beach slope of i≤1/500. The thesis selects a typical beach slope of i=1/500

Water depth: The water depth in this area ranges from 2.1m to 3.5m. To ensure a broader coverage, the selected experimental water depth range is d=2.0m to 3.6m.

2.5. Design of the physical model experiment

2.5.1. Experimental equipments

The experiment will be conducted in the wave tank of the National Key Laboratory for River and Coastal Dynamics.

The wave generator in the tank can produce both regular and random waves, following Jonswap and Moskowitz spectra, with a maximum water depth of 0.7 meters in front of the wave maker. The maximum wave height that can be generated in the tank is 0.25 meters, and the wave period Tp ranges from 0.5s to 3.0s.

The wave flume is constructed on 1/6 of the width of the wave tank, using a steel frame system with box dimensions of 80x100mm and reinforced glass walls with a thickness of 10mm. The total length of the flume is 35 meters, with an effective length of 30 meters, a width of 1.2 meters, and a height of 1.0 meter.

Wave measurement is carried out using DHI Wave Gauge Type 102E, and pressure sensors from Pico, with a sampling frequency of up to 1000Hz.

2.5.2. Model scale and Experimental setup

Based on the spatial scope of the model and the capabilities of the wave generator, in order to meet the research objectives and minimize errors, a model scale ratio of 1/12 is selected.

With the capacity of the available experimental equipment, the experimental layout is as follows (see Figure 2.10):

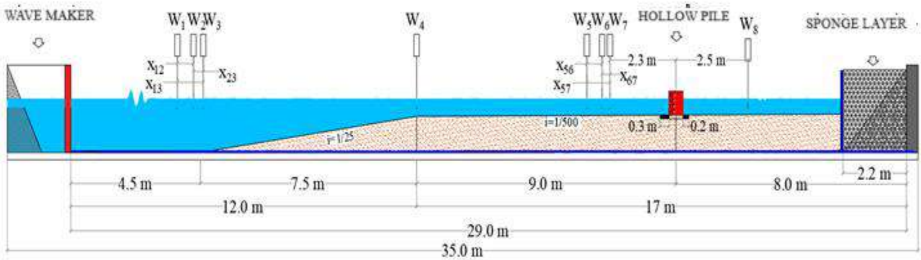


Figure 2.10. Experimental layout on the wave flume

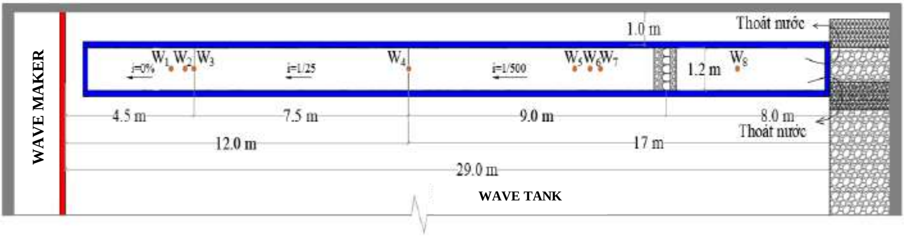


Figure 2.11. Experimental plan

Arrange 8 wave gauges ($W_1 \div W_8$) of the resistance type to record wave heights at different positions in the wave flume. The spacing between the gauges W_5, W_6, and W_7 is determined according to the method of Mansard and Funke (1980). Gauge W_8 is placed behind the HPB structures at a distance of (0.5 ÷ 1) L_p to measure the wave height propagating behind the structure.

The pressure gauges are arranged as follows:

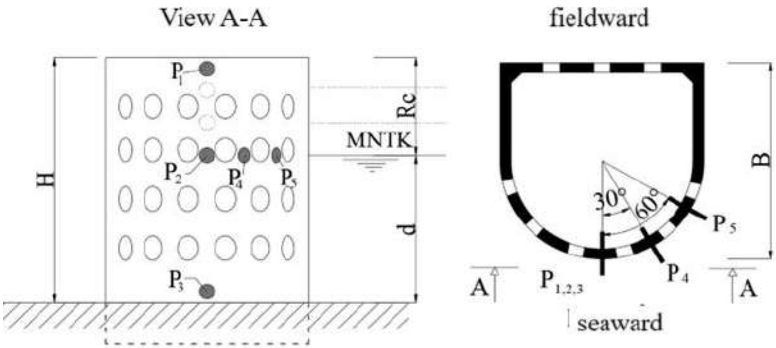


Figure 2.12. Arrangement of wave pressure gauges

2.5.3. Structure and experimental scenarios

The HPB structures designed for the experiment have a curved surface diameter of 0.24 m, with the width of the structure along the wave propagation direction varying as B = 0.24 m, 0.30 m, and 0.36 m. The surface of the structures is perforated with 3 cm diameter holes, where the wave-facing surface (curved surface) has porosity ratios of 0%, 15%, 20%, and 25%, and the wave-sheltered surface (flat surface) has a porosity ratio of 11.78%. The total number of experimental scenarios is summarized in Table 2.5.

Table 2.5. Experimental scenarios

Name of scenarios	Baseline B0	Scenario with varying structure width and porosity ratios												Water depth
		B=0,24 (m)				B=0,30 (m)				B=0,36 (m)				
		ε=0%	ε=15%	ε=20%	ε=25%	ε=0%	ε=15%	ε=20%	ε=25%	ε=0%	ε=15%	ε=20%	ε=25%	
H7T11	x	x	x	x	x	-	x	x	x	-	x	x	x	0,18; 0,22; 0,26; 0,30
H7T13	x	x	x	x	x	-	x	x	x	-	x	x	x	
H10T13	x	x	x	x	x	-	x	x	x	-	x	x	x	
H10T15	x	x	x	x	x	-	x	x	x	-	x	x	x	
H13T15	x	x	x	x	x	-	x	x	x	-	x	x	x	
H13T17	x	x	x	x	x	-	x	x	x	-	x	x	x	
H16T17	x	x	x	x	x	-	x	x	x	-	x	x	x	
H16T19	x	x	x	x	x	-	x	x	x	-	x	x	x	
Tổng số	**32**	**32**	**32**	**32**	**32**	**0**	**32**	**32**	**32**	**0**	**32**	**32**	**32**	**352**

2.6. Conclusion of Chapter II

Based on the analysis of the characteristics of the study area and a comprehensive evaluation of the wave-reducing dike structures currently employed in the Mekong Delta, the researcher has provided an in-depth explanation and proposed a wave-reducing dike structure in the form of hollow piles with a horse-hoof-shaped cross-section. This design aims to address the existing limitations and shortcomings of the currently applied structural forms.

To achieve the research objectives of the dissertation, the PhD candidate employs the physical wave flume model experiment method. A total of 352 experimental scenarios were designed (32 scenarios without structures and 320 scenarios with structures), following the Froude scale. The measurement devices were calibrated and verified to ensure their reliability.

Chapter III. DETERMINATION OF WAVE TRANSMISSION COEFFICIENT AND WAVE PRESSURE ON THE HORSE HOOF SHAPED HOLLOW PILE BREAKWATER

3.1. Evaluation of the wave attenuation capability of the horse hoof shaped hollow pile breakwater

3.1.1. Characteristics of wave reflection

When the relative width increases, the wave reflection coefficient of the HPB structure tends to decrease significantly in all experimental scenarios. The relationship between $B/H_{m0,i}$ and K_r is inversely proportional.

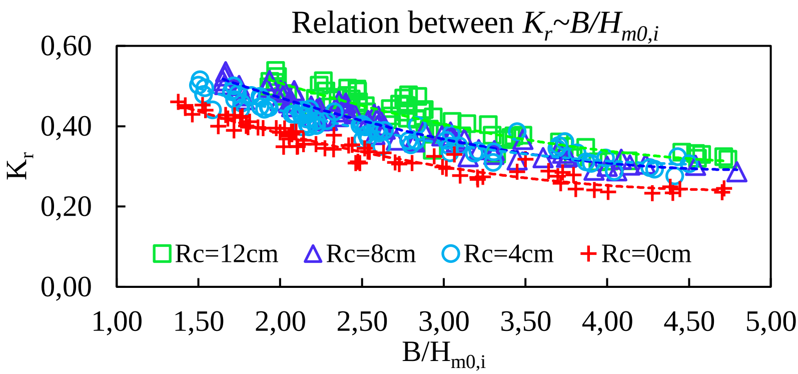


Figure 3.1. Relation between K_r ~ $B/H_{m0,i}$

As the water depth increases, the wave reflection coefficient tends to decrease, showing a clear inverse relationship in all cases where the HPB dike's crest width is perforated.

The reflection coefficient has a direct correlation with the wave period, meaning that longer-period waves cause a greater reflection compared to shorter-period waves.

There is also a significant difference in the reflection coefficient between perforated and non-perforated wave-facing surfaces. The reflection coefficient ranges from Kr = 0.84 to 0.58 for non-perforated surfaces and from Kr = 0.23 to 0.54 for perforated surfaces

3.1.2. Wave energy dissipation effectiveness

In the case of a closed wave-facing surface of the HPB (non-perforated), the dissipation coefficient Kl ranges from 0.5 to 0.66. This means that, if the incoming wave energy is 100%, after interacting with the HPB, the energy dissipation corresponds to 25% to 44% of the total energy (Figure 3.5).

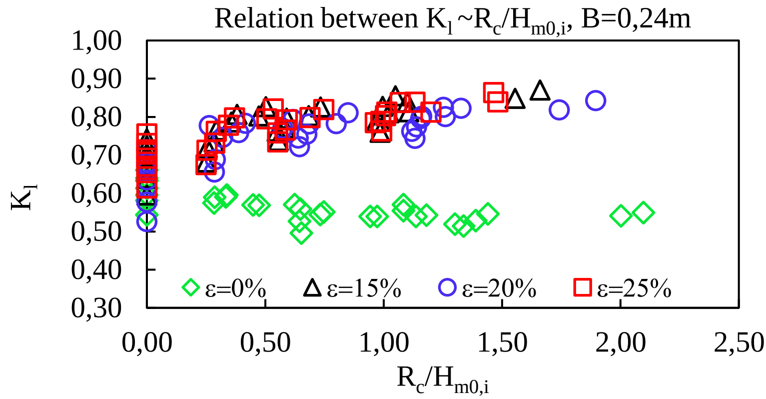


Figure 3.5. Relation between K_l ~$R_c/H_{m0,i}$

In the case where the wave-facing surface of the HPB is perforated with a porosity ratio ε = 15% to 25%, the dissipation coefficient Kl ranges from 0.53 to 0.87. This corresponds to 28% to 76% of the total incoming wave energy being dissipated.

3.1.3. Evaluation of wave forces acting on the structure

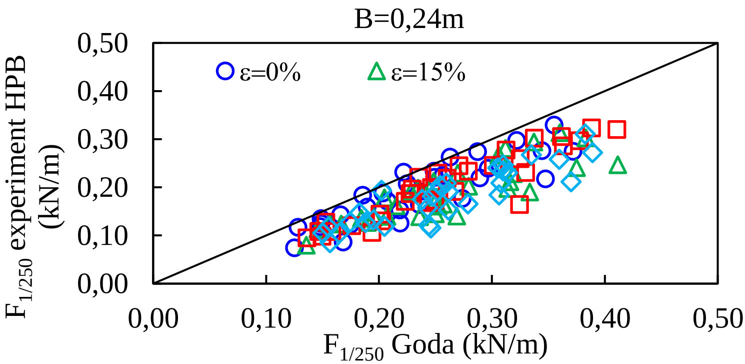


Figure 3.10. S Comparison of maximum horizontal wave forces based on HPB experimental results and Goda's calculation formula (for B = 0.24 m)

When the wave-facing surface of the HPB is closed (ε = 0%) (see Figure 3.10), the horizontal wave force acting on the HPB is approximately 82% of the horizontal force calculated using Goda’s method. When the wave-facing surface is perforated (ε = 15%, 20%, 25%), the horizontal wave force on the HPB is only 68% to 78% of the force calculated for a vertical solid wall using Goda’s formula.

3.2. Determining the wave transmission coefficient through the HPB

3.2.1. Characteristics of wave transmission

Similar to other traditional breakwater types, the relative freeboard crest ($R_c/H_{m0,i}$) has a significant influence on K_t. As the relative freeboard crest increases, Kt tends to decrease.

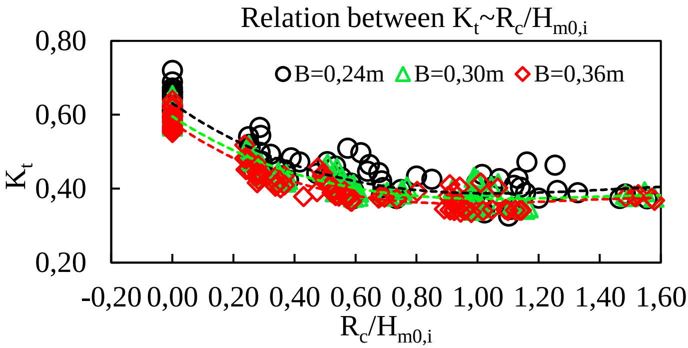


Figure 3.13. Relation between K_t ~$R_c/H_{m0,i}$

The experimental results shown in Figure 3.13 indicate that the wave transmission coefficient (K_t) tends to decrease rapidly when the relative freeboard height $0<R_c/H_{m0,i}<1$, reaching its minimum value when $R_c/H_{m0,i} \approx 1$. When $R_c/H_{m0,i} > 1$, Kt levels off and remains relatively constant.

Influence of relative crest width ($B/H_{m0,i}$): In general, as the relative crest width ($B/H_{m0,i}$) increases, Kt tends to decrease. This indicates an inverse relationship between the crest width and wave transmission.

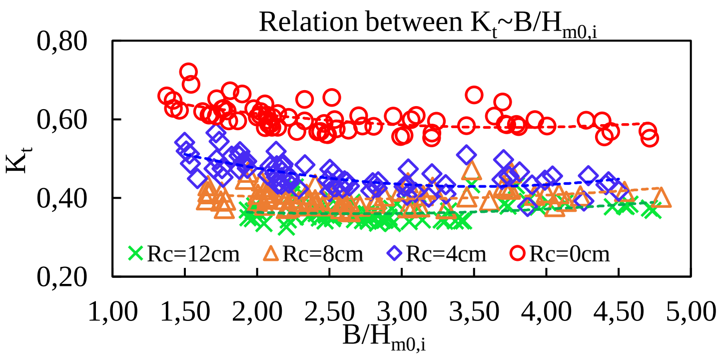


Figure 3.14. Relation between K_t ~ $B/H_{m0,i}$

In addition, it can be observed that when $B/H_{m0,i}$ continues to increase up to $B/H_{m0,i}$ ~ 3, Kt) tends to level off.

Influence of perforation ratio on surface: For a crest width of B = 0.24m, Kt max observed for non-perforated structures (no holes) is 0.53, which is only 73.6% of the maximum Kt max = 0.72 observed for structures with perforated surfaces.

3.2.2. Developing a formula for calculating the wave transmission coefficient through the HPB

Waves propagating through HPB follow the general principles of breakwaters and, specifically, those of hollow structures. Therefore, the empirical formula of d'Angremond (1996) can be used, while also considering the influence of the surface porosity ratio to develop a formula for determining Kt for HPB. The general expression for determining Kt is as follows:

$$K_t = a.\min(1;\frac{R_c}{H_{m0,i}}) + b.\left(\frac{1}{1-\varepsilon}\right)\left(\frac{B}{H_{m0,i}}\right)^{c_1}\left[1-\exp\left(\frac{c_2}{\sqrt{s_{m-1,0}}}\right)\right] \tag{3.4}$$

Where: a, b, c1, c2 are constants. The determination of these constants in formula (3.4) is carried out using the least squares method. The results build the formula for different integrated cases as follows:

In the case not considering the boundary value $R_c/H_{m0,i}$ =1:

$$K_t = -0,17.\frac{R_c}{H_{m0,i}} + 0,62.\left(\frac{1}{1-\varepsilon}\right)\left(\frac{B}{H_{m0,i}}\right)^{-0,01}\left[1-\exp\left(\frac{-0,31}{\sqrt{s_{m-1,0}}}\right)\right] \tag{3.5}$$

In the case considering the boundary value $R_c/H_{m0,i}$ =1:

$$K_t = -0,23.\min(1;\frac{R_c}{H_{m0,i}}) + 0,59.\left(\frac{1}{1-\varepsilon}\right)\left(\frac{B}{H_{m0,i}}\right)^{-0,03}\left[1-\exp\left(\frac{-0,38}{\sqrt{s_{m-1,0}}}\right)\right] \tag{3.6}$$

\+ With $B/L_{m-1,0}$:

$$K_t = -0,23.\min(1;\frac{R_c}{H_{m0,i}}) + 0,52.\left(\frac{1}{1-\varepsilon}\right)\left(\frac{B}{L_{m-1,0}}\right)^{-0,03}\left[1-\exp\left(\frac{-0,44}{\sqrt{s_{m-1,0}}}\right)\right] \tag{3.7}$$

\+ With B/d:

$$K_t = -0,21.\min(1;\frac{R_c}{H_{m0,i}}) + 0,52.\left(\frac{1}{1-\varepsilon}\right)\left(\frac{B}{d}\right)^{-0,08}\left[1-\exp\left(\frac{-0,52}{\sqrt{s_{m-1,0}}}\right)\right] \tag{3.8}$$

The analysis shows that formula (3.6) provides the best results with an R^2 coefficient of 0.80, where the 95% confidence interval for the coefficients a and b is: a = [-0.24, -0.21], b = [0.48, 0.69]. The limits of the parameters are as follows: $R_c/H_{m0,i}$ = 0 ÷ 2.10; $B/H_{m0,i}$ = 1.375 ÷ 4.794; $s_{m-1,0}$ = 0.036 ÷ 0.076; Porosity ratio: seaward surface: 0% ÷ 25%, landward surface: 11.78%; K_t = 0.14 ÷ 0.72.

3.3. Determining the envelope diagram of the maximum wave pressure on the HPB

3.3.1. Envelope diagram of the maximum wave pressure distribution on the vertical face with respect to water depth.

In general, the distribution of the maximum wave pressure on the wave-facing surface of the HPB shows a trend similar to the pressure distribution diagram for vertical wall-type designs proposed by Goda (1985). A comparison of the measured values from the experiments with the calculated wave pressure distribution based on Goda's formula at three measurement positions results in the following relationship:

Table 3.4 Comparing the measured wave pressure distribution values with the calculated values based on Goda's formula

Vertical positions	$p_{meas}/\ p_{Goda}$	
	unperforated seaward	perforated seaward
Crest of HPB	0,60	0,57
Still water level	0,79	0,68
Toe of HPB	0,74	0,60

3.3.2. Envelope diagram of the maximum wave pressure along the curved surface

The measurement and calculation results show that the wave pressure distribution along the curved surface of the HPB is uneven and follows a curve. The maximum wave pressure distribution values are mainly observed at the measurement point P4 (where the wave direction makes an angle of 30° with the surface).

The correlation between the magnitude and the distribution pattern of the wave pressure at the positions p0°, p30°, and p60° on the curved surface of the HPB is shown in Figure 3.36 below:

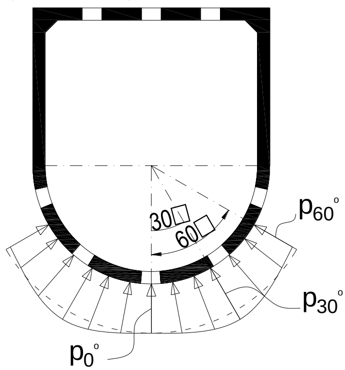


Figure 3.36. Diagram of the maximum wave pressure along the curved surface

A summary comparison of the maximum wave pressure distribution values at various positions on the curved surface of the HPB is presented in Table 3.6 below:

Table 3.6. Comparison of the maximum wave pressure distribution values at various positions on the curved surface of the HPB

Positions on the curved surface	Cases	
	unperforated seaward	perforated seaward
Angle 30° (p_{30^o}/p_{0^o})	1,15	1,16
Angle 60° (p_{60^o}/p_{0^o})	0,87	0,90

3.3.3. Determining the envelope diagram of the maximum wave pressure on the HPB

In general, assuming the wave pressure is evenly distributed along the curved surface, the envelope diagram of the maximum wave pressure acting on the HPB structure is proposed as shown in the figure 3.39:

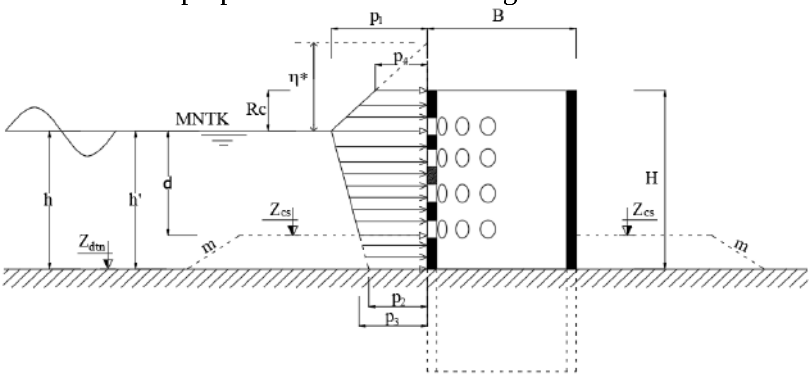


Figure 3.39. the envelope diagram of the maximum wave pressure on the HPB

The wave pressure values at the crest, static water level, and base of the HPB in the envelope diagram of the maximum wave pressure distribution on the HPB (Figure 3.39) are determined based on the calculated wave pressure values using Goda's formula and the corresponding scaling factors, as shown in Table 3.7 below:

Table 3.7. Comparison of the maximum wave pressure values with the calculated values of Goda's formula at various vertical positions of the HPB

Vertical positions	$p_{HPB}/\ p_{Goda}$	
	unperforated seaward	perforated seaward
Crest of HPB	0,60*1,15=0,69	0,57*1,16=0,66
Still water level	0,79*1,15=0,91	0,68*1,16=0,79
Toe of HPB	0,74*1,15=0,85	0,60*1,16=0,70

3.4. Conclusion Chapter III

The dissertation has established several empirical formulas to determine the wave transmission coefficient through the HPB, among which formula (3.6) is selected as the formula for determining the wave transmission coefficient for the HPB structure.

In general, the envelope diagram of the maximum wave pressure on the HPB structure is proposed in the form shown in Figure 3.39. The wave pressure values at various positions are calculated using Goda's original formula multiplied by the pressure reduction scaling factors summarized in Table 3.7.

Chapter IV. APPLICATION OF RESEARCH FINDINGS IN THE DESIGN OF BREAKWATER STRUCTURES IN THE WESTERN COASTAL AREA OF CA MAU PROVINCE

4.1. Application location

The spatial scope of the thesis is the Western coast of the Mekong Delta. Therefore, the chosen application site is the coastal area of Khanh Binh Tay commune, Tran Van Thoi district, Ca Mau province.

4.2. Application of research findings in the design of the cross-section of the breakwater

4.2.1. Determination of the design boundary conditions

The boundary condition parameters for the design are determined as shown in Table 4.3

Table 4.3 Parameters for the design

Parameters	Symbol	Unit	Value
Grade			IV
Design frequency	P	%	3,33
Design wave hight	H_s	m	1,40
Design wave period	$T_{m-1,0}$	s	5,6
Climatic wave height	H_{skh}	m	1,0
Climatic wave period	T_p	s	6,44
Sea level	Z_{tkp}	m	+0.76
Natural seabed	Z_{dtn}	m	-1.40

4.2.2. Structure and cross-section of the HPB for the application Area

The geometric dimensions of the HPB must be calculated and selected to ensure that the wave transmission through the structure is less than 0.4m under normal conditions (subject to climatic waves). The wave conditions are as follows: wave height 0.5m < Hs = 1.4m < 2m; wave period 3.5s < Tp = 6.44s < 7s, which satisfy the experimental range of the thesis. Therefore, the wave transmission coefficient through the HPB is calculated using formula (3.6). The thesis proposes several scenarios for calculations with: B = 2.5m ÷ 4m; ε = (0% ÷ 25%), and determines the geometric parameters of the cross-section and HPB that ensure wave reduction and stability as follows:

Table 4.5. Geometric dimensions of the HPB

TT	Geometric dimensions	Symbol	Unit	Value
1	Length	Lc	m	5
2	Crest width	B	m	2,5
3	Seaward surface diameter	D	m	2,5
4	Shell thickness	t	m	0,15
5	Number of perforations on the seaward surface	n_t		24
6	Number of perforations on the landward surface	n_s		9
7	Hole diameter	d_r	m	0,33

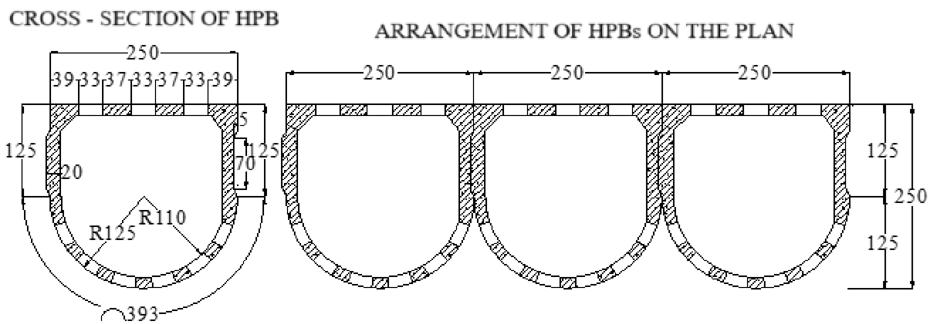


Figure 4.6. Cross-section of the HPB and the connections on the plan

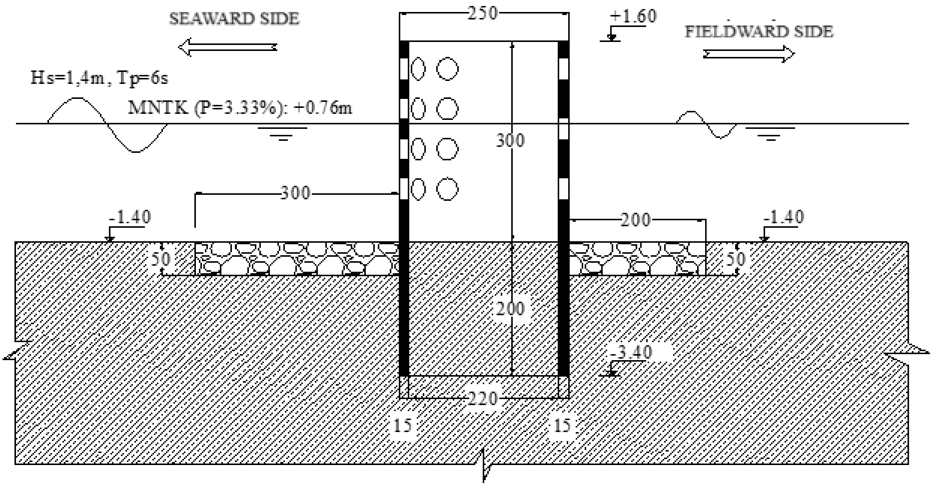


Figure 4.7. Typical design cross-section of the breakwater

4.3. Conclusion of Chaprer IV

The thesis has applied the research findings from Chapter III to the design of breakwater structures in the Khanh Binh Tay commune, Tran Van Thoi district, Ca Mau province. The dimensions of the HPB components were determined based on the wave reduction requirements to ensure mangrove forest planting and the stability of the structure. A comparison with other solutions shows that, under the same working conditions, the HPB components exhibit relatively good wave reduction capability and leverage the advantages of both hollow circular breakwaters and pile - rock breakwaters in terms of load-bearing capacity and stability.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The dissertation has proposed a type of breakwater structure in the form of a horse-hoof-shaped hollow piles, capable of attenuating waves to protect the area behind the structure and creating favorable conditions for mangrove growth in the Western coast of the Mekong Delta.

Based on the results of the physical model experiments, the dissertation has clarified the wave transmission and reflection characteristics through the HPB and developed an empirical formula (3.6) to determine the wave transmission coefficient for the proposed HPB

The dissertation has proposed an envelope curve for the distribution of the maximum wave pressure on the HPB both vertically and along the plan view on the curved surface of the HPB. To determine the wave pressure values on the HPB, the dissertation recommends using Goda's (1985) diagram and formula, combined with the attenuation ratio coefficients compiled in Table 3.7, for the positions at the crest, still water level, and toe of the HPB.

The dissertation has applied the research results to calculate and design a nearshore breakwater work in the Western Coastal region of the Mekong Delta. The structure meets both stability requirements and the wave reduction criteria necessary for mangrove forest cultivation.

Recommendations

The research results of the dissertation serve as a scientific basis for designing offshore breakwater structures in the Western coast of the Mekong Delta, as well as in other areas with similar conditions.

Outstanding issues and areas for further research

+The dissertation has not specifically evaluated the impact of the curvature radius of the seaward surface on wave reduction effectiveness and wave pressure;

+The influence of the scour protection layer on both the upstream and downstream sides has not been considered, and the effect of the supporting piles on wave reduction and structure stability has been neglected;

+The wave pressure on the landward surface has not been assessed.

The proposed directions for future research are:

+ Further studies in a 3D wave basin, with waves obliquely approaching the breakwater, to evaluate the wave pressure on the HPB on the landward surface and the pressure along the curved surface of the HPB.

+ Further research should be conducted to include additional influencing parameters of the HPB cross-section, such as: (1) The width and height of the scour protection layer; (2) The slope of the front beach; (3) The water level above the crest of the breakwater; (4) Structures with varying percentages of holes on the landward surface; (5) The presence of a rubble mound layer within the structure.

LIST OF PUBLISHED PAPERS

1. **Pham Đuc Hung**, Tran Đinh Haa, Nguyen Ngoc Nam (2021): "Horse-hoof-shaped Hollow Piles Breakwaters – New technological solutions for coastal protection". *Journal of Water Resources Science and technology, Vietnam academy for water Resources. Special publication, (ISSN:1859-4255),* No 69, December, 2021, p 1-6.
2. **Pham Duc Hung**, Tran Dinh Hoa (2022): "Numerical study on the effect of perforations on the wave dissipation characteristics of "Horse-hoof-shaped Hollow Piles Breakwaters". *Journal of Water Resources Science and technology, Vietnam academy for water Resources. Special publication, (ISSN:1859-4255),* No.2, December, 2022, p11-18.
3. **Pham Đuc Hung**, Tran Đinh Hoa, Nguyen Manh Linh (2023): "Design of physical model experiment for wave interaction with Horse hoof-shaped Hollow Piles Breakwaters". *Journal of Water Resources Science and technology, Vietnam academy for water Resources. Special publication, (ISSN:1859-4255),* No 77, April, 2023, p 1-6.
4. **Pham Đuc Hưng**, Tran Đinh Hoa, Phan Đinh Tuan (2023): "Study of the reflection characteristics of a Horse hoof-shaped Hollow Piles Breakwaters on a physical model". *Journal of Water Resources Science and technology, Vietnam academy for water Resources. Special publication, (ISSN:1859-4255),* August, 2023, p 34-40.
5. **Pham Duc Hung**, Tran Dinh Hoa (2023): "Wave pressure distribution on Horse-hoof-shaped Hollow Piles Breakwaters". *Journal of Water Resources Science and technology, Vietnam academy for water Resources. Special publication, (ISSN:1859-4255),* No.4, December, 2023, p2-10.
6. Thai Van Tran, **Hung Duc Pham**, Ha Hai Nguyen & Tam Thanh Nguyen (2019): "Study on the reflection, transmission, and wave energy dissipation characteristics of perforated hollow pile breakwaters. *Proceedings of the 10th International Conference on Asian and Pacific Coasts (APAC 2019) Hanoi, Vietnam, September 25-28, 2019*, pp 1021–1025, https://doi.org/10.1007/978-981-15-0291-0_140.