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Coastal Protection in Cu Lao Dung Mangroves (Soc Trang Province, Vietnam): Quantifying Wave Energy Dissipation

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ABSTRACT

Mangrove forest is always considered an effective barrier to protect habitats from high waves, especially tsunami. Therefore, the estimation of wave energy dissipation is required for disater warning. The aim of this study is to calculate wave attenuation in mangrove areas by combining field survey method and mathematical modeling method. The application area is Cu Lao Dung mangrove forest, Soc Trang, Vietnam. From data measurements of hydrodynamics and mangrove characteristics, the wave attenuation coefficient r, the drag coefficient C_d were determined in mud area, mud-mangrove area and mangrove area. In addition, using WAPROMAN model, the attenuation of wave height is simulated in different cases such as without mangrove, with mangrove, breaking wave effect and wave trunk interaction effect. Both the results from the measured method and the model method show the role of mangroves in reducing wave energy. The results from modeling are smaller than the calculated results. However, both methods tend to be suitable. Such difference required more considerations not only on calculation formulas but also on modeling adjustment. The research clearly demonstrated the effectiveness of mangroves in coastal protection, with wave-trunk interaction becoming the dominant factor in energy dissipation deeper into the forest. For future, extending the study to different mangrove forests and longer time scales could provide a more comprehensive understanding of the role of mangroves in coastal protection across various geographical and temporal contexts.

Keywords: Mangroves; Wave Energy Dissipation; Waproman Model; Cu Lao Dung (Soc Trang, Vietnam)

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1. Introduction

Mangroves are one of the most productive ecosystems. They have a variety of useful ecological, biophysical, and socio-economic functions [1]. In particular, the role of coastal protection against natural hazards such as storms, typhoons, tsunamis and coastal erosion has been widely acknowledged. Mangroves are clearly able to efficiently reduce wave energy [2, 3].

The most important factors affecting wave height attenuation coefficient with distance into the forest are water depth and mangrove tree characteristics. Different types of mangroves exhibit varying resilience to wave energy due to several factors, including their physical characteristics, root structures, and ecological adaptations. As waves travel through the forest, different parts of mangrove tree will resist waves in varying rates depending on the density and size of the species. At low water levels, the roots will attenuate waves more, while at high water levels it is the stems and leaves [4]. The studies of Mazda et al. [5] in Vietnam showed that at a high water depth, due to the spreading of branches and leaves, the density is greater, so the wave energy is reduced more, and at the same time when the water level reaches the height of the branches and leaves, the larger wave, the more attenuated [5]. The tree's age also plays an important role in wave reduction because it relates to the size, shape and density of the trunks, branches, and roots [6]. The research by Zhou et al. [7] in the Nanliu Delta, China found that younger mangroves were particularly effective in reducing wave heights by up to 80% along 1,000 meters.

Many methods have been applied to calculate and predict wave attenuation. For the measurement method, a study in the mangroves along Thailand's Andaman coast found that wind waves lose energy significantly, while swell waves maintain or even increase energy [8]. The ability to reduce high wave attenuation during storms can be up to 75–83% according to research in Hai Phong, Vietnam [9]. Studies by Cao et al. [10] in the Leizhou Bay mangrove forest area (China), Bao [11] in Hai Phong and Can Gio (Vietnam) also showed the role of wave energy dissipation of the mangrove forest system. In addition, Le Nguyen et al. [12] analyze energy spectral density by using Blackman-Tukey and Fast Fourier Transform methods in order to analyze the wave energy dissipation as well as the nonlinear effects in mangrove areas in Cu Lao Dung (Soc Trang, Vietnam).

For the modeling method, Massel et al. [13] developed a theoretical prediction model for attenuation of wind induced random surface waves, in case of constant water levels. The applied results in Townsville (Australia) and Iriomote Island (Japan) show that mangrove density, diameter of mangrove roots and trunks and the spectral characteristics of the incident waves are the factors affecting the rate of wave energy reduction. Then, the model was developed by Vo Luong and Massel (named WAPROMAN model). In which, the wave-trunk interaction and wave breaking are considered the dominant dissipation mechanisms, and wave breaking plays an important role in the sparse mangrove areas [14]. The SWAN model can be applied to calculate wave attenuation by considering the interaction of mangroves and random wave breaking [15], or in combination with hard infrastructures such as seawalls [16]. The WAVEWATCH III (WW3) model, incorporating wave-mud interaction physics, was used to analyze wave energy dissipation by mudbanks [17]. Studies can also use the Delft 3D model to evaluate the wave height reduction role of mangrove forests in coastal areas as in the case study in Hai Phong (Vietnam) [18].

In addition, physical models are also applied to calculate the wave energy attenuation when passing through mangrove forests. A case study of a 1:6 scale *Rhizophora* mangrove forest showed that water depth, wave height, and mangrove frontal area significantly affect wave attenuation and drag forces [19]. A study using a 10-meter-long mature *Rhizophora* forest model proposed a general empirical formula expressing the correlation between the bulk drag coefficient and the vegetation drag coefficient [20]. Laboratory experiments with regular waves examined hydrodynamic variations influenced by different mangrove morphologies by Zhang et al. [21]. Zhang et al. [22] integrated the prediction of drag on individual plants with measurements of wave decay across a plant meadow to create a wave-damping model.

This study aims to calculate wave attenuation in the Cu Lao Dung mangrove forest, Soc Trang province, Vietnam, using both field measurements and the WAPROMAN model. By combining these approaches, we seek to provide a comprehensive understanding of wave energy dissipation in mangrove areas and validate the effectiveness of the WAPROMAN model in simulating these processes.

2. Methodology

2.1. Data Collection

2.1.1. Study Site

Cu Lao Dung is the easternmost district of Soc Trang province, located at the end of the Hau river, with Dinh An and Tran De estuaries flowing into the East Sea (**Figure 1**). The area experiences two distinct wind seasons: Northeast monsoon from November to April and Southwest monsoon from June to September. **Figure 2** shows that the dominant wind directions are West and East, in which East tends to be more dominant (52% for East, East Northeast or East Southeast directions and 30% for West, Southwest or West Northwest West directions). (Source: The Southern Region Hydro-Meteorological Centre SRHMC). This seasonal change in wind direction significantly affects the wave regime in Cu Lao Dung. The Northeast monsoon brings higher waves from the East-Northeast, while the Southwest monsoon generates smaller waves from the West-Southwest. This difference directly influences coastal erosion and accretion.

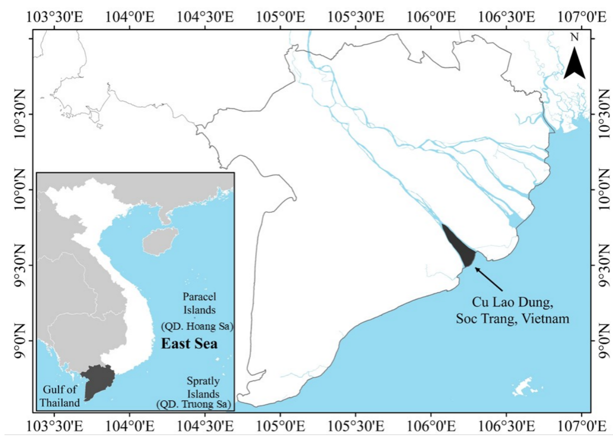


Figure 1. Study site: Cu Lao Dung, Soc Trang, Vietnam.

The water level at Tran De station in 2018 (source: SRHMC) shows that the coastal area of Cu Lao Dung as well as Soc Trang province has an irregular semi-diurnal tidal regime, with an average tidal range of about 1.5–2 m. The tidal water level also changes throughout the months of the year, being lower during the rainy season (Southwest monsoon season, **Figure 3a**) and higher during the dry season (Northeast monsoon season, **Figure 3b**).

The mangrove forests in Cu Lao Dung are primarily protective forests, dominated by species such as *Sonneratia* caseolaris, *Avicennia* alba, and *Rhizophora* apiculata. In the mangrove forests, *Avicennia* and *Sonneratia* are the two pioneer species advancing into the sea, followed by *Rhizophora*. *Rhizophora* is also a species of high economic value in mangrove forests, so it is often chosen for reforestation.

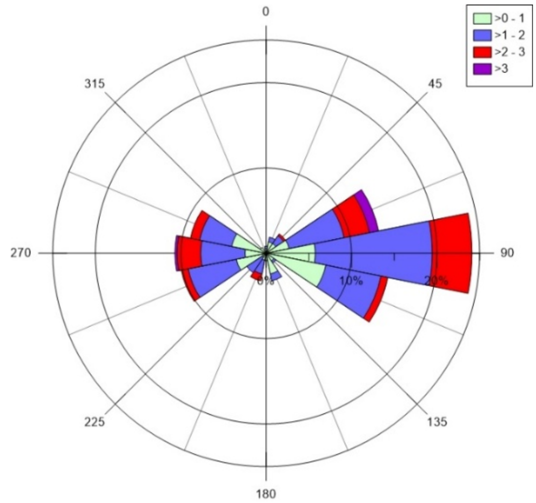


Figure 2. Wind rose in Soc Trang in 2018.

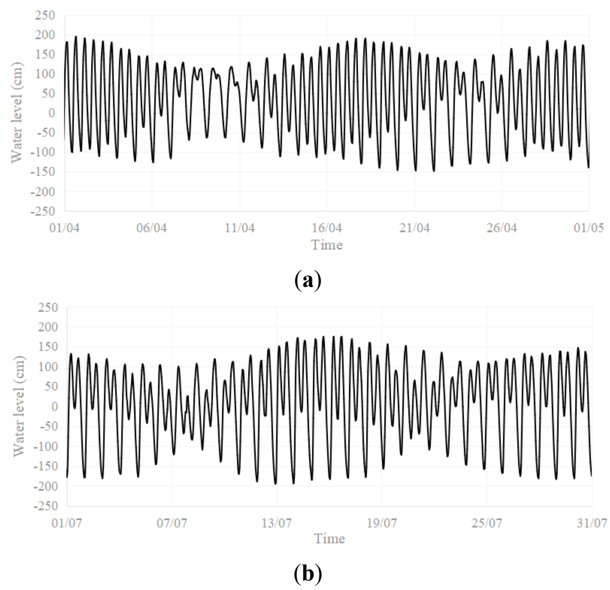


Figure 3. The tidal water level in Soc Trang. (**a**) in the dry season; (**b**) in the wet season.

The aim of the measurement is to calculate the wave energy dissipation in mangrove forests, mainly *Sonneratia* and *Avicennia*.

2.1.2. Instrument Settings

Hydrodynamic data (water depth, waves, currents, SSC) and mangrove characteristics in Cu Lao Dung, Soc

Trang were extracted from two research projects:

- Ministry of Science and Technology project: Study on the impact of hydrolithodynamic factors in erosion and accretion in mangrove areas of Vietnam, Project NCCB-DHUD 2012-G/10, NAFOSTED (Vo Luong Hong Phuoc, 2012).
- Vietnam-US cooperation project: Hydrodynamics and sediment flux through the Cu Lao Dung mangrove forest (Vo Luong Hong Phuoc, 2014).

The survey and measurement process were carried out by the Department of Oceanology, Meteorology and Hydrology, University of Science, Vietnam National University Ho Chi Minh City. Two survey campaigns were conducted in two seasons: SW monsoon season (from September 19, 2014 to October 5, 2014) and NE monsoon season (from March 2, 2015 to March 16, 2015). Specific information of instrument settings for wave measurements is shown in **Table 1**. For observing the wave propagation from shallow water to mangrove forest, the transect for instrument deployment was set up with four stations: one in the shallow water, one in mud flat and two inside the mangrove forests. The locations of four stations are shown in **Figure 4**.

Figure 4. Location of measuring stations in the Cu Lao Dung.

Table 1. List of measuring equipment and measurement parameters at stations in Cu Lao Dung.

Stations	Instruments	Setting Up	Parameters
ST0 (outer) 9°28′47.9″ N; 106 °17′37.7″ E	Valeport MIDAS DWR 27111	-Sampling frequency 4Hz - Wave Burst: 30 minutes - Wave Samples: 2048 -Tide burst: 60 seconds	Currents, Waves, Turbidity
ST1 (mud flat) 9°30′32.0″ N; 106°16′25.7″ E	Valeport MIDAS DWR 27110	-Sampling frequency 4Hz - Wave Burst: 30 minutes - Wave Samples: 2048 -Tide burst: 60 seconds	Waves, Turbidity
ST2 (near mangrove edge) 9°30′52.8″ N; 106°16′14.8″ E	AWH-USB	- Wave Burst: 30 minutes - Sampling frequency 10 Hz- Wave Samples: 4800	Waves
ST3 (mangrove inside) 9°30′54.4″ N; 106°16′11.9″ E	RBRduo 052561	- Wave Burst: 10 minutes - Sampling frequency 6 Hz - Wave Samples: 4800	Waves, Turbidity

The instrumental deployments in mudflat (ST2) and in mangroves (ST3) were shown in **Figure 5**.

Figure 5. The instruments at mudflats and mangroves stations in Cu Lao Dung.

2.1.3. Mangrove Characteristics and Topography

Wave dissipation in mangrove forest depends strongly on density of mangrove trees, water level and topography [23]. Therefore, besides hydrodynamic factors, mangrove characteristics and topography are required to measure.

Sonneratia sp. and *Avicenia* sp. are dominant in Cu Lao Dung and inside mangrove forest, some *Rhizphora* sp. growing.

Measurement of mangrove density: The study area consists of 10 large cells, each measuring 30 m × 60 m (**Figure 6**). Based on the position of instrumental deployments and the distribution of mangrove trees, the calculated area is divided into four zones: 1, 2, 3, and 4, with respective lengths of 10 m, 30 m, 140 m, and 100 m (**Figure 7**). The correspondence between the four zones and ten mangrove density measurement cells can be described as follows: Zone 1 corresponds to Cell 10 (30 m long); Zone 2 corresponds to Cell 9 (30 m long); Zone 3 includes Cells 5, 6, 7 and 8, with the forest-side end of Zone 3 being the position of station ST2; therefore, Zone 3 is chosen to be 140 m; Zone 4 includes Cells 1, 2, 3 and 4 with the forest-side end of Zone 4 being the position of station ST3. Given the 100 m distance between ST3 and ST2, Zone 4 has been chosen to be 100 m long. In summary, the lengths of zones 1, 2, 3, and 4 are 10 m, 30 m, 140 m and 100 m, respectively.

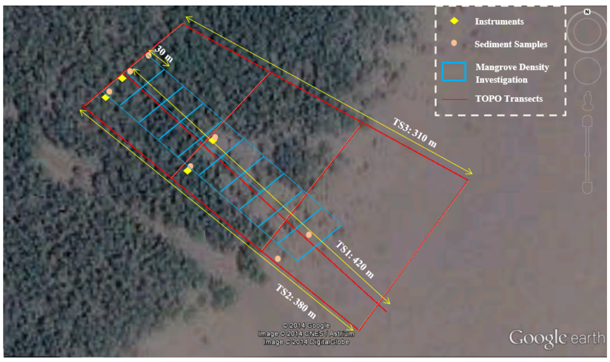


Figure 6. Distribution of cells for mangrove characteristic, instruments collected in Cu Lao Dung.

Data collection on mangrove characteristics: after zoning the survey area, the characteristics of the mangrove forest were determined by counting the number of trees and measuring the distinctive features of the mangrove trees and roots. The survey characteristics include the number and density of trees, trunk diameter, number and density of roots, root height, and root diameter. These characteristic parameters provide insights into the mangrove forest at the survey area and are also used as input data for wave propagation models in the mangrove forest.

The main mangrove species in the survey area are Sonneratia and *Avicennia*.

- Tree density is measured as the number of trees per area, with the unit being trees/m² (**Figure 8a**).
- Root density is measured as the number of roots per m² (**Figure 8b**).

In addition, to calculate for the WAPROMAN model, trunk diameter, root diameter, and root height (**Figure 8c**) are also measured to calculate the linear coefficient f_e, which will be mentioned in Section 2.3.

Topography is measured along the transect in every meter by using theodolite (**Figure 9**). These typical parameters will indicate the characteristics of mangroves in the study area and will also be used as input data for the model of wave propagation into the mangrove area.

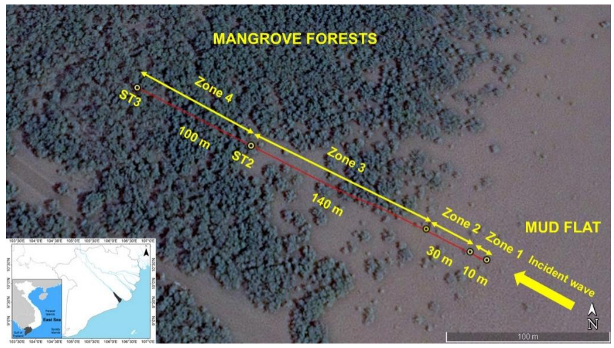
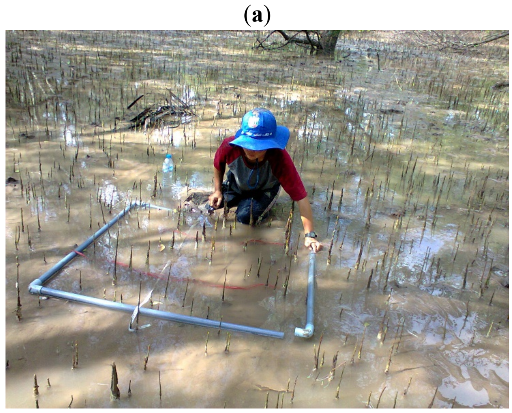


Figure 7. Four zones: from mud flat, forest edge to mangrove forest.

(**a**)



(**b**)

Figure 8. *Cont.*

(**c**)

Figure 8. Data collection on mangrove characteristics. (**a**) tree density; (**b**) root density; (**c**) tree diameter.

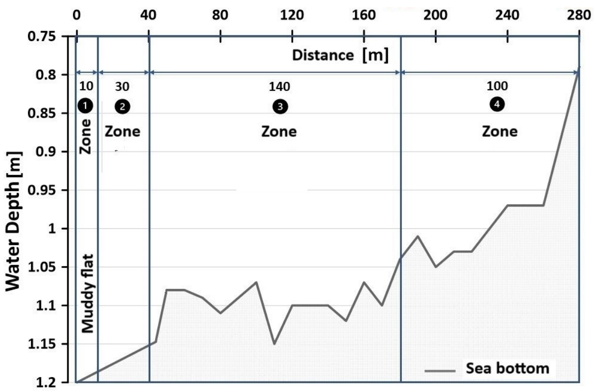


Figure 9. Topography in Cù Lao Dung (on Sept., 2014)

2.2. Calculating Wave Dissipation

To assess the phenomenon of wave attenuation as waves propagate through different locations, particularly in mangrove environments, researchers commonly employ the wave attenuation coefficient formula (1) developed by Mazda et al.[5]:

$$r = \frac{(H_{in} - H_{trans})}{H_{in}} \tag{1}$$

The formula provides a quantitative measure of how wave energy dissipates over distance. In this equation, r symbolizes the wave attenuation coefficient, a crucial parameter that indicates the rate at which wave height decreases. H_{in} represents the incident wave height, typically measured at an initial point, while H_{trans} denotes the transferred wave height after traveling a distance x between two observation points. The formula's versatility allows for its application in various coastal scenarios, particularly in studying the wave-dampening effects of mangrove forests.

2.3. Application of WAPROMAN Program

WAPROMAN model (WAve PROpagation in MANgrove forest) is a predictive model of wave propagation through non-uniform forest in water of arbitrary depth[14]. In the theoretical model, wave energy dissipation due to wave−trunk interaction and wave breaking were considered as the dominant dissipation mechanisms. A modified mild-slope equation including dissipation is applied for wave model over changing water depth within the mangrove forest. The non-linear governing equations for wave−trunk interactions are linearised using the concept of stochastic minimalisation.

In the model, the computational domain is divided into three distinct zones, and the solution to the boundary value problem for the entire fluid domain is constructed from separate solutions in each zone: Zone I: area before entering the mangroves; Zone II: area within the mangroves; and Zone III: area behind the mangroves. The water depth in Zones I and III is considered as a constant. In Zone II, the water depth h(x) has arbitrary values.

The input parameters of the model include Water depth along the cross-section; Initial wave parameters in Zone I: wave height H, wave period T, wave spectrum; Characteristics of trees in mangroves: number of layers, number of areas; number and diameter of tree trunks or roots in each layer and each area. From the model, the following wave output parameters can be calculated such as: Wave height values along the cross-section in mangroves; Values of wave transmission and reflection coefficients; Distribution of wave spectrum along the transect; Vertical profile of average wave amplitude of horizontal and vertical velocity components at different cross-sections.

For calculating the linear coefficient f_e in the case of a mixed mangrove forest, the number of species, species characteristics, and the water level in the forest being considered and the thickness from the forest floor to the average water level can be divided into multiple layers. **Figure 10** illustrates a simple example of a mixed mangrove forest consisting of *Avicennia* sp. and *Rhizophora* sp. Suppose the water level is high enough to be divided into three layers: Layer 1 includes the pneumatophores of *Avicennia* sp. and the roots of *Rhizophora* sp.; Layer 2 consists of the roots of *Rhizophora* sp. and the trunks of *Avicennia* sp.; and Layer 3 includes the trunks of both *Rhizophora* sp. and *Avicennia* sp.

In each layer, the number of trunks or roots, as well as the average trunk and root diameter, will be calculated. In this case, the linear coefficient f_e will be (2):

$$f_e = \frac{1}{\omega_p}\sqrt{\frac{2}{\pi}}\sum_{i=1}^{M}\frac{\int_0^l\int_{L_i}\bar{D}_i N_i C_d^{(m)}(Re,x,z)\,\sigma_{u_2}^3 dzdx}{\int_0^l dx\int_{-h_2(x)}^0 \sigma_{u_2}^2 dz} \quad (2)$$

where M is the number of layers, L_i is the thickness of layer i, and N_i and D_i represent the number of trunks/roots and the average trunk/root diameter in layer i, respectively.

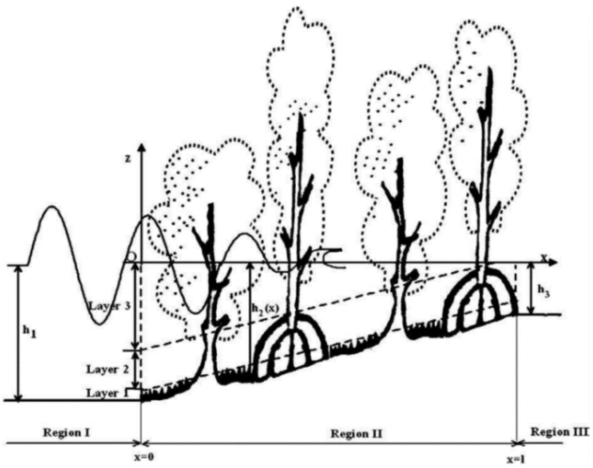


Figure 10. Coordinate system in mixed mangrove forest[14].

Based on measured data of mangrove characteristics (density of trunks and roots, trunk diameter, root diameter, and root height, the linear coefficient fe can be determined.

3. Wave Energy Dissipation in Cu Lao Dung Mangrove Forest

3.1. Distribution of Roots and Trunks in Mangroves

Table 2 presents a detailed of mangrove forest characteristics across four zones, focusing on trunk and root properties. Zone 1 appears to be the outer edge of the mangrove forest. It has the lowest trunk density, suggesting a sparser distribution of trees. The trunk and root diameters are relatively small, indicating younger or smaller species. In Zone 2, it can be seen an increase in both trunk density and diameter. This suggests a transition to a more mature or denser part of the forest. The root characteristics remain like Zone 1, but with a measurable diameter, indicating slightly more developed root systems. Zone 3 marks a significant change in forest structure. The trunk density dramatically increases, nearly tripling from Zone 2. However, the average trunk diameter decreases slightly, suggesting a dense growth of smaller trees. The most striking change is in root density, which jumps to 75.63 roots/m². This could indicate a species with extensive aerial root systems, like *Rhizophora* mangroves. The innermost zone shows a slight decrease in trunk density compared to Zone 3, but these trunks have the largest diameter of all zones. This suggests mature, well-established trees. The root density reaches its peak here, further indicating a well-developed, complex root system typical of mature mangrove forests. The progression from smaller, sparser trees in Zone 1 to larger, more densely rooted trees in Zone 4 may indicate a gradient of forest maturity from the coastal edge inward. In general, there is no much difference of the density of mangrove trees and roots in two seasons.

Table 2. Mangrove Forest characteristics across four zones.

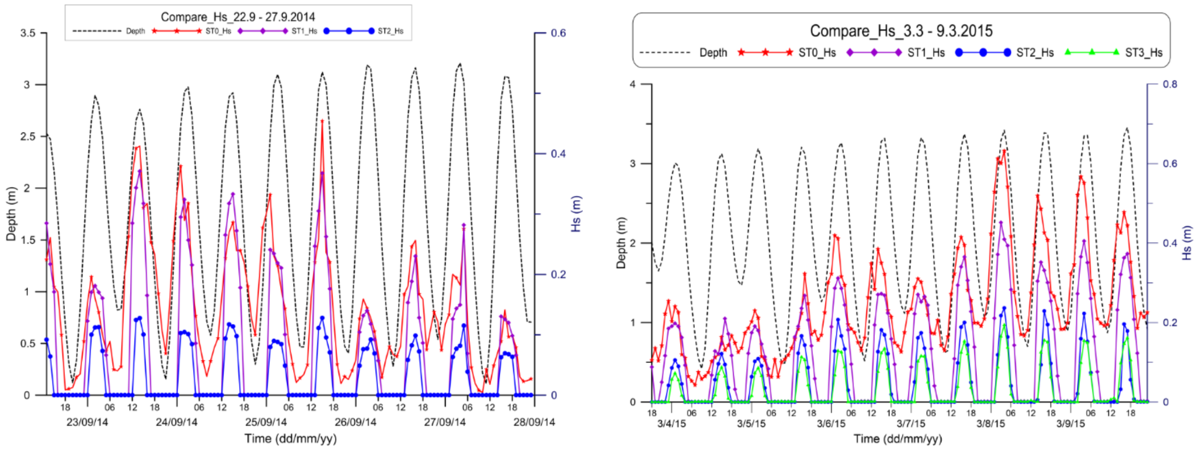
Zone	Trunk Density (Trunks/m^2)	Trunk Diameter (m)	Root Density (Roots/m^2)	Root Diameter (m)
1	0.28	0.127	0.009	0.003
2	0.42	0.223	0.012	0.01
3	1.17	0.156	75.63	0.007
4	0.84	0.285	114.88	0.012

3.2. Wave Measurements in Two Seasons

Statistical data on the maximum values, and values of significant wave height during the Northeast and Southwest monsoon seasons in the Cu Lao Dung area (Soc Trang) are shown in **Figure 11** and **Table 3**.

In general, the dynamics of the northeast monsoon are significantly stronger. Waves during the northeast monsoon in offshore areas can reach a maximum height of 0.8 m, reducing to 0.55 m at the mud flat area and 0.2 m when entering the forest. Meanwhile, during the southwest monsoon season, waves decrease significantly, reaching a maximum of only 0.45 m offshore and 0.1 m when entering the forest.

It can be seen that there is a significant difference in wave dynamics between the Northeast and Southwest monsoon seasons. The Northeast monsoon shows stronger overall dynamics compared to the Southwest monsoon. Both seasons show a clear pattern of wave attenuation as waves move from offshore areas towards the forest. The attenuation effect is more pronounced during the Northeast monsoon due to higher initial wave heights.



(**a**) (**b**)

Figure 11. Significant wave height in two monsoon seasons in the Cu Lao Dung area (Soc Trang). (**a**) in Northeast; (**b**) in Southwest.

Table 3. Statistics of significant wave height at stations in the mangrove area of Cu Lao Dung (Soc Trang) during the Northeast and Southwest monsoon seasons.

Seasons	**Northeast Monsoon Season**				**Southwest Monsoon Season**			
Stations	ST0	ST1	ST2	ST3	ST0	ST1	ST2	ST3
Mean H_s (m)	0.25	0.15	0.05	0.04	0.1	0.15	0.07	-
Max H_s (m)	0.8	0.55	0.2	0.25	0.45	0.4	0.1	-

ST0: offshore station; ST1: mud flat station; ST2 and ST3: forest station.

3.3. Wave Energy Dissipation in Different Areas

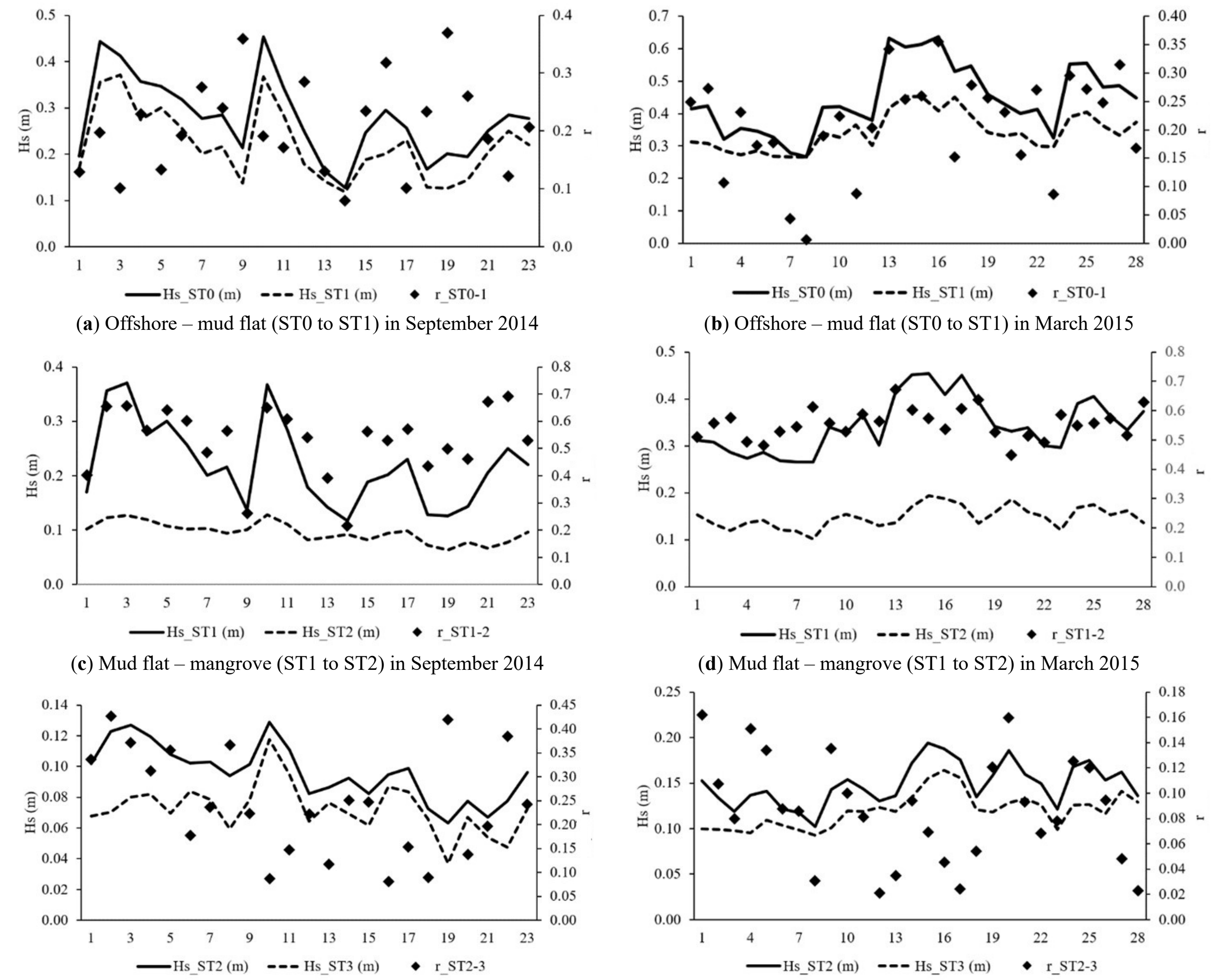
Based on Equation (1), the results of calculating the wave attenuation coefficient r are shown in **Table 4** and **Figure 12**.

From offshore to mud flat, the average r is about 0.21 in both September 2014 and March 2015, reducing wave height by over 20% (**Table 4** and **Figure 12a**,**b**). When waves enter the mangrove forest from the mud flat, r increases significantly to around 0.53–0.56, resulting in over 50% wave height reduction (**Table 4** and **Figure 12c**,**d**). Within the forest, r averages 0.24 in September 2014 but drops to 0.09 in March 2015 (**Table 4** and **Figure 12e**,**f**).

In summary, it is obvious that the wave attenuation coefficient r in mangrove forest is also 10–40 times larger than in areas without mangrove trees. This hightlights the important role of mangorve forest in wave attenuation.

Table 4. Wave attenuation coefficient r in September 2014 and March 2015.

Stations	**ST0–ST1**		**ST1–ST2**		**ST2–ST3**	
	Outer Station–Mud flat (no mangroves)		Mud flat–Mangroves		Sparse mangrove forests - Dense mangrove forests	
Distance	3,900 m		720 m		100 m	
	September 2014	**March 2015**	**September 2014**	**March 2015**	**September 2014**	**March 2015**
Range of r	0.08–0.37	0.01–0.36	0.22–0.69	0.45–0.67	0.08–0.43	0.02–0.16
Average r	0.21	0.21	0.53	0.56	0.24	0.09
Wave Attenuation (%)	20%	20%	50%	50%	20%	10%



(**a**) Offshore – mud flat (ST0 to ST1) in September 2014

(**b**) Offshore – mud flat (ST0 to ST1) in March 2015

(**c**) Mud flat – mangrove (ST1 to ST2) in September 2014

(**d**) Mud flat – mangrove (ST1 to ST2) in March 2015

(**e**) In mangrove forest (ST2-CLD to ST3-CLD) in September 2014

(**f**) In mangrove forest (ST2-CLD to ST3-CLD) in March 2015

Figure 12. Significant wave heights at stations and wave attenuation coefficient r results in September 2014 ((**a**) From offshore to mud flat, (**c**) From mud flat to mangrove forset, (**e**) From ST2 to ST3 in mangrove forest) and March 2015 ((**b**) From offshore to mud flat, (**d**) From mud flat to mangrove forset, (**f**) From ST2 to ST3 in mangrove forest).

4. Wave Propagation in Cu Lao Dung Mangrove Forest Based on WAPROMAN Model

4.1. Input Data and Calibration Procedure

Based on the field measurements at Cu Lao Dung, it can be divided the calculations into three diferrent cases. The selection of input wave data for the model is based on statistical analysis and grouping of data points with similar water depths and significant wave heights. The calculation cases are shown in **Table 5**.

The WAPROMAN model is applied to calculate with input data obtained from actual surveys. In reality, there are many different factors affecting the results, and actual conditions are always more complex than the assumed conditions in the wave model[25]. Thererefore, to achieve good compatibility between the wave model and the measured data, some adjustments need to be made in the wave model[14, 24]. The WAPROMAN model uses two wave energy dissipation mechanisms: wave breaking and trunk-root interaction of mangroves. However, the calculation results of wave propagation according to this hypothesis give lower wave heights compared to actual measurement data. Therefore, calibration was made to make the results consistent with the measured wave height results in the Cu Lao Dung mangrove area, Soc Trang province. After calibration, the results of the numerical model are quite compatible with the measurement results if the total energy dissipation coefficient γ has the form as Equation (3)[24]:

$$\gamma = \gamma_b + 0.1 * \gamma_i \quad (3)$$

where γ_b và γ_i represent the dissipation coefficient by wave breaking and the dissipation due to the interaction of flow and mangroves, respectively.

Table 5. Input data for water depth h and significant wave height H_s in mangrove edge.

Cases	Water Depth h (m)	Significant Wave Height H_s (m)	Periods T (s)
1	0.9	0.2	2.3
2	1.0	0.3	3.2
3 [24]	1.2	0.4	4.0

4.2. The Calculation Results of Wave Height Reduction

The calculation results of wave height reduction from the forest edge into the forest for the three calculation scenarios are shown in **Table 6**, **Table 7**, **Figure 13** (with water depth of 0.9 m); **Figure 14** (with water depth of 1.0 m). The calculation results from the model show good agreement with the measured data in the study area.

The results show that under the impact of topographic changes, wave breaking, and mangrove trunk/root interaction, the wave height has decreased when moving from the forest edge into the deep forest. In general, all three cases show that waves almost break in zone 1–10 m from the forest edge; under the influence of mud flat, the wave height begins to decrease; continuing into the inner zones, under the impact of mangroves, the wave height continues to decrease.

Table 6. Average value of wave height H_s in three calculation cases.

Zone	H_s - Total Energy Dissipation (m)	H_s - Energy Dissipation Due to Wave Breaking (m)	H_s - Energy Dissipation Due to Wave-Trunk Interaction (m)	Main Factor
Case 1: Water depth at mangrove edge = 0.9 m; H_s at mangrove edge = 0.2 m				
Mangrove edge	0.20	0.20	0.20	
1	0.14	0.14	0.20	Wave breaking
2	0.11	0.11	0.18	Wave-trunk interaction
3	0.10	0.11	0.15	Wave-trunk interaction
4	0.08	0.11	0.12	Wave-trunk interaction
Case 2: Water depth at mangrove edge = 1.0 m; H_s at mangrove edge = 0.3 m				
Mangrove edge	0.30	0.30	0.30	
1	0.24	0.26	0.30	Wave breaking
2	0.20	0.26	0.27	Wave-trunk interaction
3	0.17	0.26	0.20	Wave-trunk interaction
4	0.13	0.26	0.14	Wave-trunk interaction
Case 3: Water depth at mangrove edge = 1.2 m; H_s at mangrove edge = 0.4 m				
Mangrove edge	0.40	0.40	0.40	
1	0.33	0.37	0.40	Wave breaking
2	0.26	0.37	0.36	Wave-trunk interaction
3	0.21	0.37	0.24	Wave-trunk interaction
4	0.16	0.37	0.16	Wave-trunk interaction

Table 7. Wave attenuation ratio in three cases due to the influence of each factor.

Zone	Wave Attenuation Ratio (%)		
Water depth	h = 0.9 m	h =1.0 m	h =1.2 m
Due to wave breaking			
Zone 1	30.0	13.3	7.5
Due to wave-trunk interaction			
Zone 2	10.0	10.0	10.0
Zone 3	25.0	33.3	40.0
Zone 4	40.0	53.3	60.0

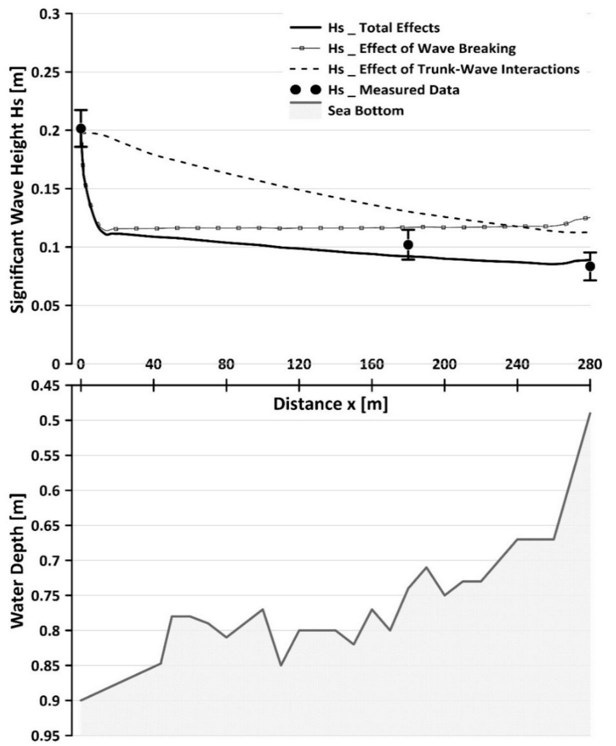


Figure 13. Comparison between model results and measured data at water depth 0.9 m.

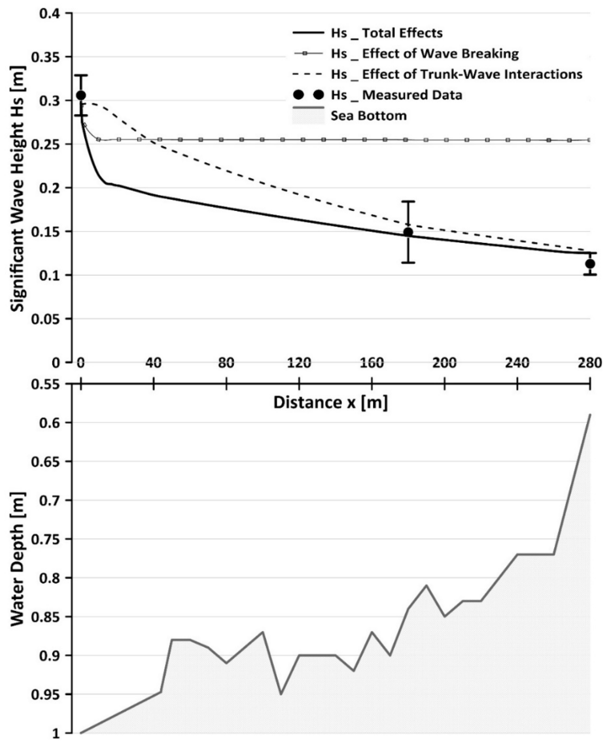


Figure 14. Comparison between model results and measured data at water depth 1.0 m.

In zone 1, the main factor affecting wave reduction is wave breaking. When waves begin to enter zone 2 and into the forest, the results show that the wave height is reduced due to the interaction of mangrove trunks/roots. Compared with the characteristic data of mangroves (**Table 2**), zones 2 - 3 - 4 have higher tree/root density than zone 1, and the deeper into the forest, the larger trunk diameter and root diameter also get. Therefore, the wave reduction role of mangroves is more clearly shown in these zones. When the water depth and wave height are larger, the wave reduction role of mangroves is most clearly shown (case 3).

The impact results of each individual factor on wave reduction are shown in **Table 7**. The results show that the wave reduction rate due to wave breaking in zone 1 tends to decrease as the water depth increases, with ratios of 30% : 13.3% : 7.5% corresponding to water depths of 0.9 m : 1.0 m : 1.2 m. Meanwhile, the rate of wave height reduction due to mangrove trunk/root interaction is the opposite, the reduction rate increases as the water level increases, except for zone 2, this rate is the same (in all three cases) reaching 10%. In general, mangroves have contributed an important role to wave reduction, with a reduction rate of 50%–60% when waves propagate from the forest edge into the deep forest.

4.3. Discussions

In addition, the comparison results of total wave reduction (both wave breaking and tree interaction factors) from the mathematical model and the reduction coefficient r show that the wave height reduction rate from the model is consistent with the results of measured data analysis, although the rate from the model is lower than the measured results. It can be seen that the wave dissipation from mud flat to mangroves due to wave breaking, wave-trunk interaction and both effect when wave height got 0.4 m with 1.2 m of water level in the mangrove edge. Result shows that only 17.5% energy dissipation was due to wave breaking in the mangrove edge where few mangroves existed. Therefore, it can be considered that the simulated 17.5% energy dissipation is due to water level, topography with no mangrove trees. The result is suitable with the calculation of 21% energy dissipation in mud area. From 10 m from the mangrove edge, the effect of wave - trunk interaction is dominant in wave energy dissipation. About 40.5% wave energy was dissipated in ST2 and 20% in ST3. The results from modeling are smaller than the calculated results. Such difference required more considerations not only on calculation formulas but also on modeling adjustment.

5. Conclusions

Based on the study's findings, it is evident that mangrove forests play a crucial role in dissipating wave energy as waves propagate from shallow water into the forest. The extent of this dissipation is significantly influenced by mangrove characteristics, initial wave height, and topography. Both data analysis and WAPROMAN modeling provided valuable insights into the wave attenuation process, with results from the model generally aligning with, slightly lower than, the calculated results from field measurements. The research clearly demonstrated the effectiveness of mangroves in coastal protection, with wave-trunk interaction becoming the dominant factor in energy dissipation deeper into the forest. For future, extending the study to different mangrove forests and longer time scales could provide a more comprehensive understanding of the role of mangroves in coastal protection across various geographical and temporal contexts.

Author Contributions

Field experiment, T.X.D. and V.L.H.P.; data process and analysis, L.N.H.T. and T.X.D.; results interpretation and discussion, L.N.H.T. and V.L.H.P.; manuscript design, V.L.H.P.; manuscript revision, T.X.D. and L.N.H.T.; submission steps, T.X.D. and L.N.H.T. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

The data supporting the findings of this study have been generated but are not currently available in a public repository. The data can be made available by the corresponding author upon reasonable request.

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Conflict of Interest

The authors declare no conflict of interest.

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