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Bamboo Fences as a Nature-Based Measure for Coastal Wetland Protection in Vietnam

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Climate change has induced sea-level rise and a high intensity of storms, which create high nearshore waves. These caused severe mangrove degradation and erosion along the coastal wetland areas in the Mekong Delta in Vietnam. Mangroves in the coastal wetland foreshore can withstand only some certain design storm waves and grow under several certain submerged conditions. Therefore, reducing waves and shallowing wetland elevation for recovering mangroves and protecting them in an early birth state is important. Bamboo or melaleuca fences have been used as a nature-based solution to reduce waves and currents approaching the shore for these above purposes along Vietnamese Mekong deltaic coasts. This paper investigates wave transmission through the bamboo fence system and assesses its effectiveness in protecting the mangroves. Waves were simultaneously measured at two locations for comparison: in front of and behind the fences. The result shows that the wave reduction by the fences is considerable, and sedimentation occurs rapidly in the shelter areas behind the fences, which is highly favorable for the recovery and growth of mangroves. Next, the empirical formulae have been proposed for relationships between the wave transmission coefficient of the fence and the dimensionless wave-structures parameters, such as the relative water depth, the wave steepness, and the fence freeboard. The findings create a basic technical reference for designing a naturally friendly-based solution by using bamboo and/or wooden fences in coastal protection generally and protecting mangroves specifically. The outcome of the research contributes to narrowing an existing gap in Vietnamese design guidelines for coastal wetland protection and also facilitates the use of locally available eco-friendly materials for coastal management along the Vietnamese Mekong delta coasts.

Keywords: wave transmission, wooden fence, coastal protection, Mekong delta coast, nature based solution, bamboo fence

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INTRODUCTION

Coastal regions are historically the most densely populated areas globally, which benefit from the open ocean and provide inputs for economic development, such as navigation, coastal industries, tourism, and recreation. However, coastal regions are increasingly threatened by the sea-level rise and coastal hazards, such as intense storm surges and hurricanes. Church and White (2006) stated that the sea level might rise about 19 cm in the past century and estimate to rise at least 28 cm to

34 cm by 2100. Along with the sea-level rise, the alert from increased coastal hazards is noticeable, with more than 66% of storm and hurricane events happening in the 21st century (ICCP, 2007). Most of the low-lying land is vulnerable if these estimations are taken seriously. To protect valuable lands, hard solutions to prevent coastlines sensitive to the sea-level rise become more prevalent. The implementation of coastal protection, e.g., breakwaters, groins, revetments, and sea dikes (Schoonees et al., 2019), brings a certain safety level for the inland from flooding incidents during storm surges or increased sedimentation to a particular area.

The hard solution is the action of human intervention that always interrupts the balance of natural coasts. In principle, the presence of permanent coastal structures changes the hydrodynamics of the coasts, including wave regimes and flow dynamics (Dugan et al., 2011). Consequently, the gradients in sediment transport and depositional processes will be changed, leading to an imbalance of sediment and morphology changes, including acceleration at the updrift side and erosion at the downdrift side of the structure (Schoonees et al., 2019).

Mangroves, known as the natural coastal defenses, are the coastal vegetation that usually lives in the intertidal areas, including along shorelines, rivers, and estuaries (Duke and Schmitt, 2015). Mangroves mostly grow in tropical or subtropical regions where the warm temperature is designed for them to withstand (Alongi, 2008, 2009). Mangroves can be easily recognized by the complex systems of their body, e.g., roots, stems, and canopies. Unfortunately, mangroves are extremely sensitive to surrounding environments, such as economic activities and especially, the presence of coastal structures. The sensitivity of mangroves becomes more significant than before, especially in the era of the sea-level rise, making mangroves as the most vulnerable ecosystems in the world. Moreover, the increase in fish farming and aquaculture resulting in an estimation of about 2% of mangroves loss annually, and about 40% of mangrove forests lost in the next two decades (Gilman et al., 2008). Furthermore, the coastal structures, such as seawall, sea dikes, or revetments, are recognized as a fixed boundary between mangrove forests and the intertidal land, which become an obstruction for a natural retreat of the mangroves themselves under a sea-level-rise situation.

In the Mekong deltaic coast, the reduction of mangrove forests has been even more serious/severe since the combination of sea dikes and aquaculture, such as shrimp ponds, is presented along the coastal area. From 2009 to 2010, severe erosion occurred along about 30 km of coastline, resulting in about 8 km of eroded earthen dikes (Duke et al., 2010). Moreover, according to a report of SIWRR (2019), about 80 km of the total 744 km of the Mekong deltaic coastline was protected by sea dikes and revetments to prevent erosion and flooding. As a result, nearly 50% of mangrove forests vanished in the past decade (Christensen et al., 2008; Joffre and Schmitt, 2010; Nguyen et al., 2013).

There are many studies to find solutions for protecting the coastline from erosion due to waves and currents. These solutions could be hard-structure solutions (U. S. Army Corps of Engineers, 1992; Van Rijn, 2013) and eco-friendly structure measures (Hegde, 2010; MFF, 2010; Albers et al., 2013; Wetland International, 2014). Nowadays, soft solutions that are friendly with the environment have been prioritized over hard solutions. Soft solutions are also more convenient and less cost-effective than hard structures, especially to apply in coastal areas formed by silt and wetland because of an unstable foundation. One of the most eco-friendly and sustainable structure solutions, which have been developed and expanded, is mangrove planting. The mangrove belt systems used for reducing waves and currents to protect coastlines and sea dykes were investigated and presented in Mazda et al. (1997). In severely eroded and affected by large waves and high-tides coastal areas, mangroves cannot grow due to the inundation time. Therefore, reducing waves and rising wetland elevation for planting mangroves during the planting period is very necessary. Moreover, wooden (bamboo or melaleuca) fences have been used to reduce wave energy to shore and to increase sedimentation along coastlines in Vietnam (Reeve and Fleminget, 2004; Albers, 2011; Chu and Brown, 2012; Dao et al., 2018).

Additionally, Dao et al. (2020) carried out experiments to obtain the resistance of the wooden fence that mimicked the one in the field. In this study, the fence samples with porosity varying from 62 to 90% in both a model- and a full-scale set-up in inhomogeneous and staggered arrangements were investigated by using the hydraulic pressure gradient method. The flow resistance was determined by measuring the hydraulic gradient under stationary flows. The experimental results demonstrated that the bulk drag coefficient has a strongly dependent relationship with the Reynolds number. This coefficient increases quickly with the increase of the Reynolds number and becomes stable at the value exceeding 1,000. The finding from this study then was applied in another study in Dao et al. (2021). In the latter study, the bulk drag coefficient is the main parameter for controlling wave-fence interaction in the numerical model, SWASH. The numerical results determined the strong dependence of wave transmission coefficient on the wooden fence thickness. However, only wave-fence interaction was investigated, while the determination of sediment transport through wooden fences has been developed.

This paper analyzes the observed data from a practical model for mangrove planting to understand the efficiencies of a wooden fence on waves reduction and transmission at the coastal area in Nha Mat ward, Bac Lieu city, Vietnam. Wave data in the front and at the rear of the fence have been measured (**Figure 1**). In addition, sedimentation in the researched area has been observed and will be analyzed and presented in this paper.

METHODOLOGY

A prototype experimental model with a scale of 1:1 was built in the coastal area in Nha Mat ward, Bac Lieu City (**Figure 1**) in February 2016. The longitude and latitude of the tested model were 105°44’46.86”E and 9°12’10.98”N, respectively. The bamboo fence was composed of three main rows of bamboo poles with a diameter of 0.06 m and a height of 1.6 m and an additional row with a height of 0.9 m as a frame. The spacing between rows of the frame is 0.4 m and filled with bundles of bamboo. Thus, the total working width of the fence is 0.8 and is 1.2 m with the additional row. The detailed structure of

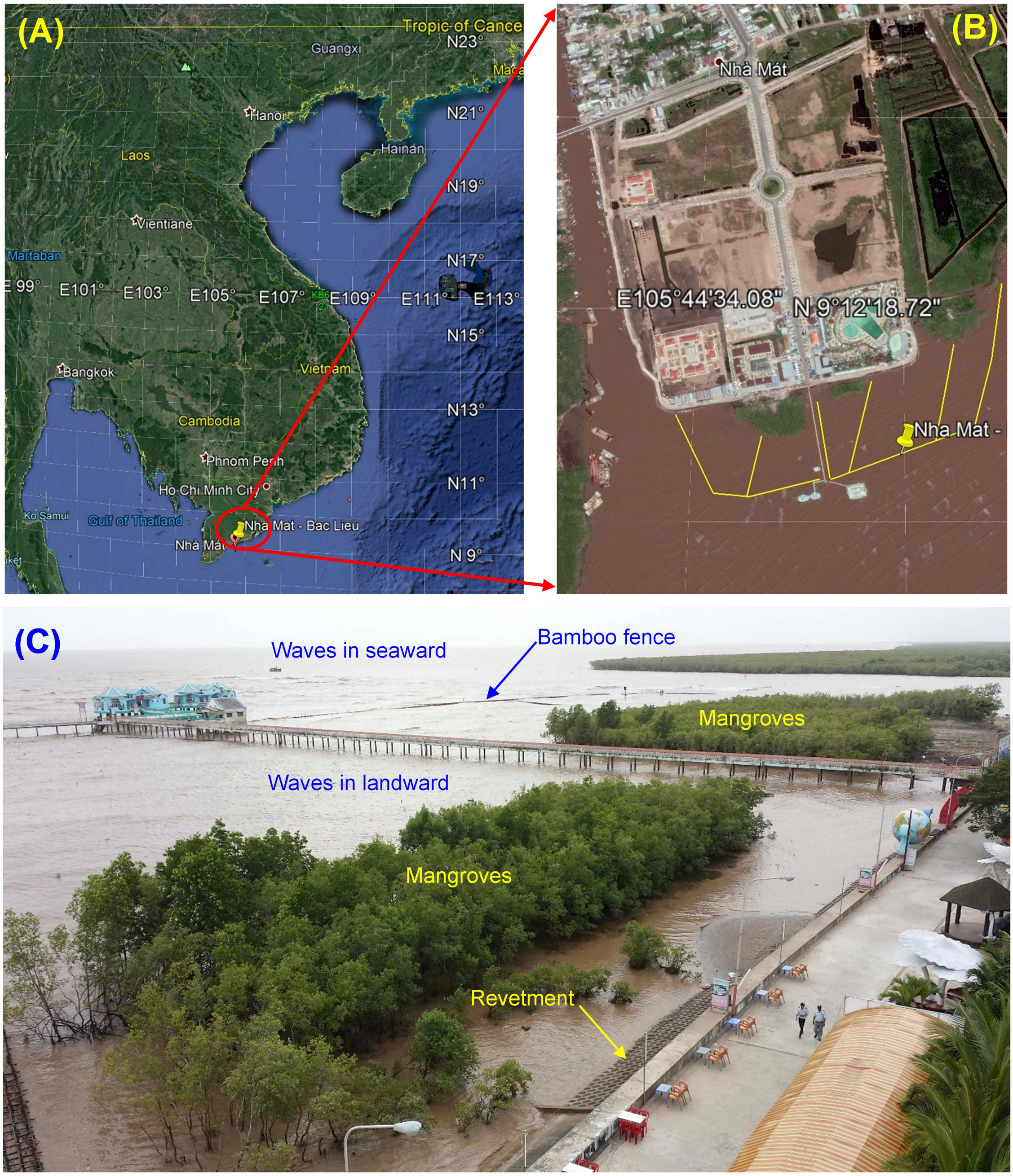

FIGURE 1 | The study area in Nha Mat ward, Bac Lieu City in Vietnam: **(A)** Vietnamese coast; **(B)** Nha Mat coast; **(C)** A photo taken at Nha Mat coast.

the fence is shown in **Figure 2**, along with a photo taken from the field.

Wave gauges TGR-1050-P and TWR-2050, which are operating based on the water column pressure method, were used to synchronistically measure waves in the upstream and downstream of the fence in this research. These wave gauges were tested in the laboratory under freshwater conditions before the measurements in the field. The details of this experiment were introduced by Mai et al. (2018). In addition, the influence of sampling frequency on wave characteristics has been analyzed and detailed in a study by Ellis and Sherman (2005) and resulted in the significant wave height H_s and peak wave period T_p at 1. Hz as same as at 50 Hz frequency for wave measurements at Galveston, based on wave spectral analysis. However, at Huntington Beach, the wave height and the wave period from 1 Hz sampling frequency data resulted in varying percentages from 0.3 to 2.5%, compared with the results at 50 Hz frequency. Therefore, Ellis and Sherman (2005) recommend tuning the

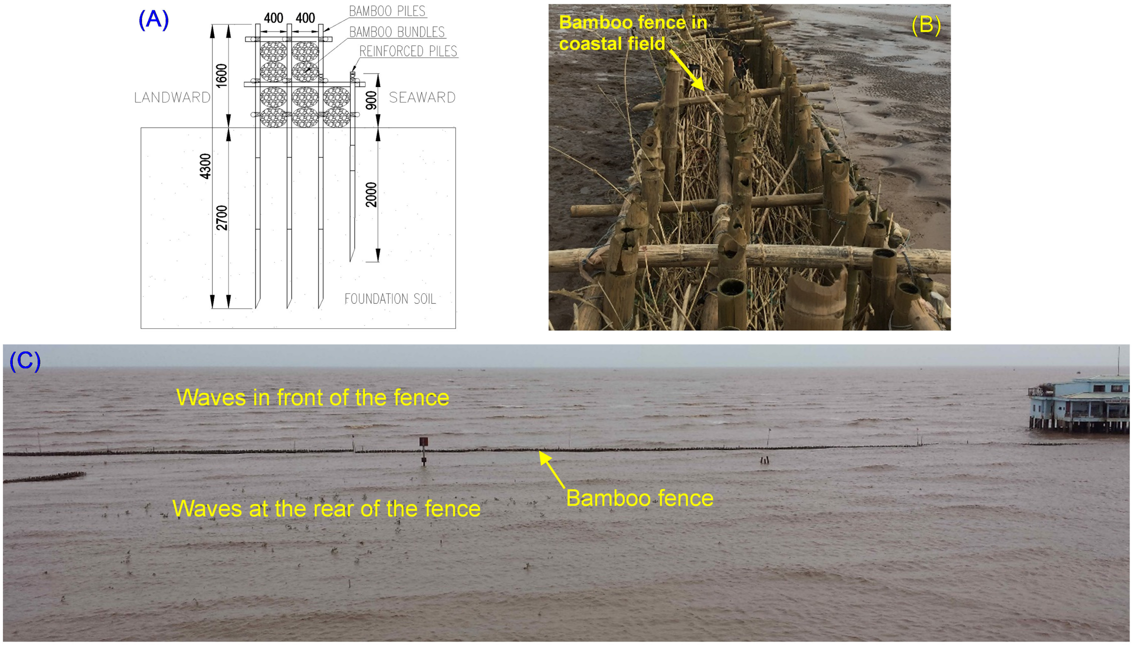

FIGURE 2 | Cross-section of bamboo fences **(A)**, bamboo fences at the coastal site **(B)**, and incident and transmitted waves at the coastal site **(C)**.

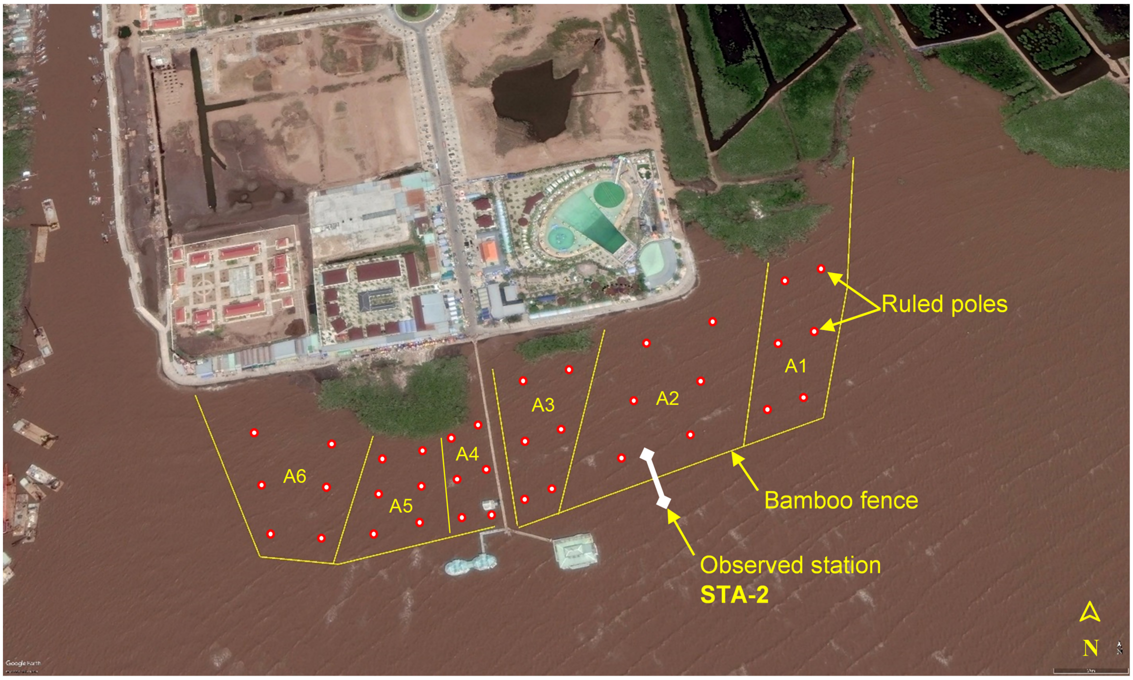

FIGURE 3 | Locations of the wave observing station (STA-2) and the sedimentation areas A1-A6 at the site.

measurement frequencies ≥0.5 Hz to measure field waves. Thus, the sampling frequency of data in this research was initially selected as 1 Hz. This study analyzes and presents the 2016 southwest and northeast monsoons results at the observed station STA-2 (**Figure 3**). The distance between two measuring devices is 25 m that is equivalent to one wavelength.

The Nha Mat coast is characterized by a very gentle bathymetry with an average slope of about 1/500 at the observed

TABLE 1 | Sediment grain size at the Nha Mat coast.

Sediment grain size (mm)	0.5–0.25	0.25–0.1	0.1–0.063	0.063–0.02	0.02–0.006	0.006–0.002	<0.002
Content (%)	0	3.6	88.52	3.88	2.16	1.84	0

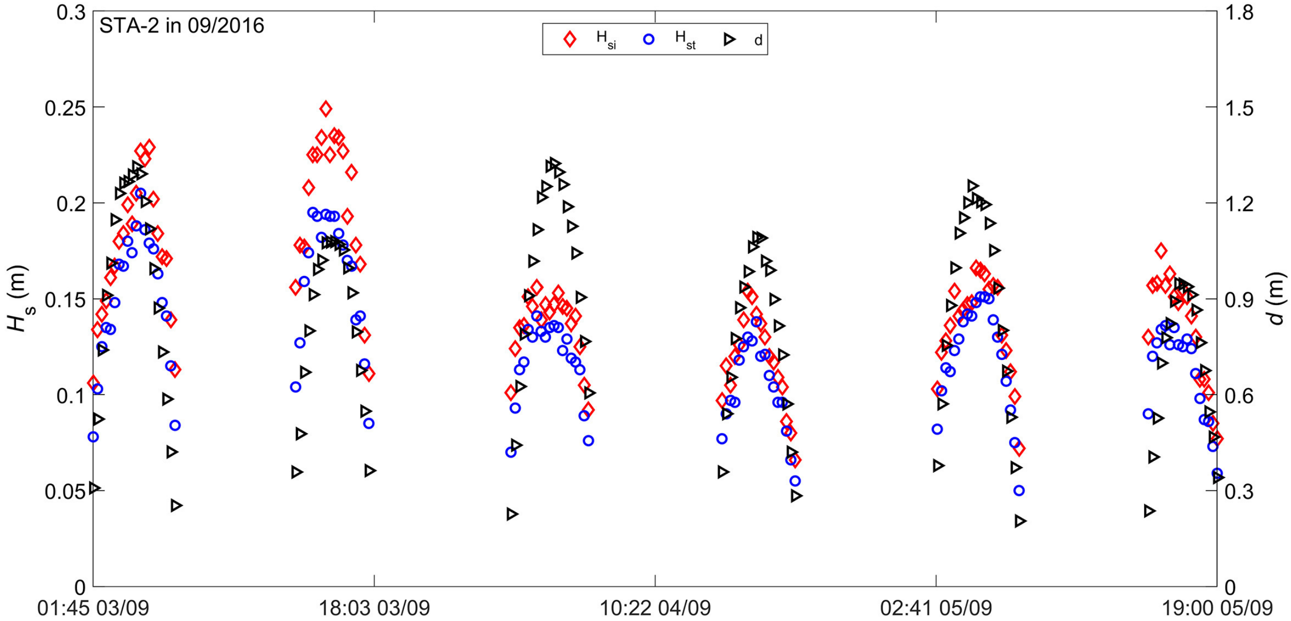

FIGURE 4 | Significant wave heights (H_{si} and H_{st}) and water depth at station STA-2 in 09/2016.

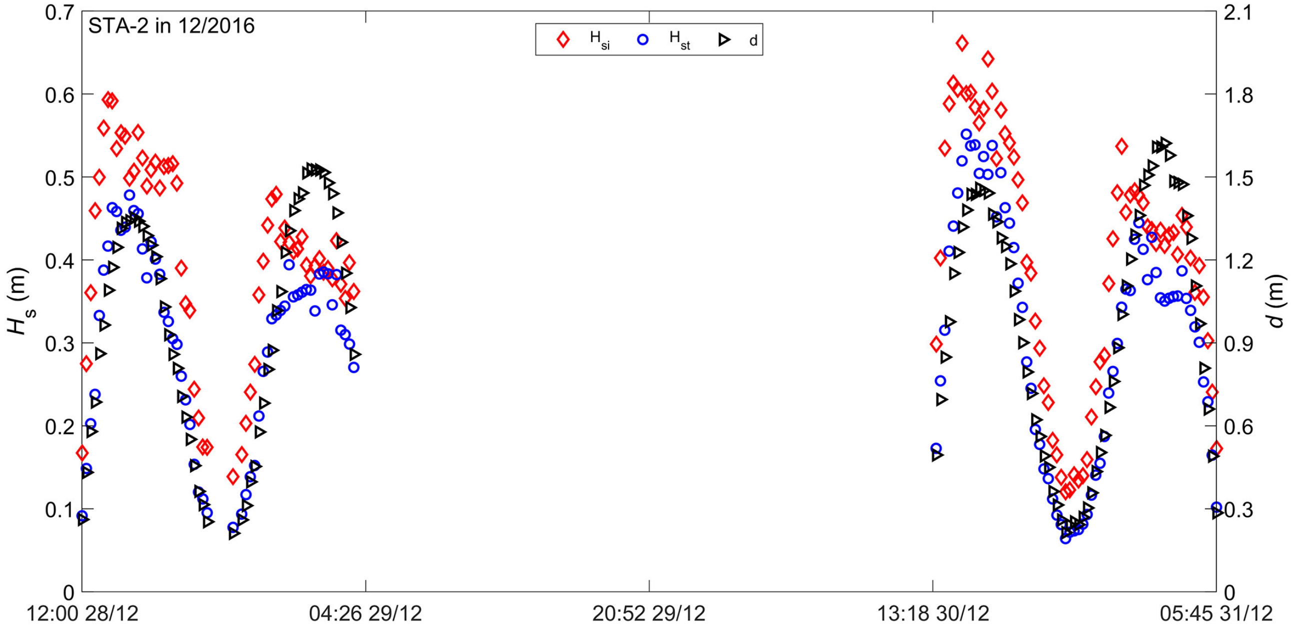

FIGURE 5 | Significant wave heights (H_{si} and H_{st}) and water depth at station STA-2 in 12/2016.

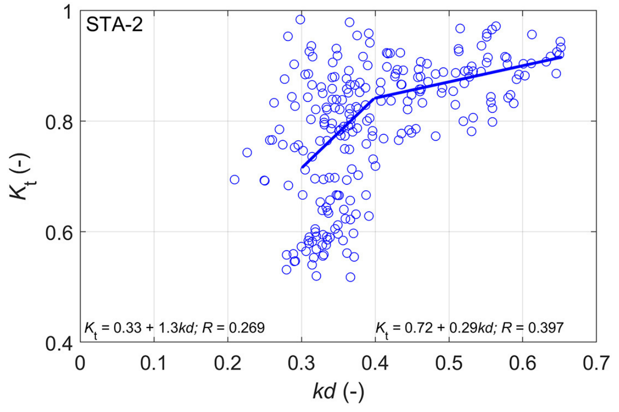

FIGURE 6 | The relationship between the wave transmission coefficient K_t and the relative water depth kd.

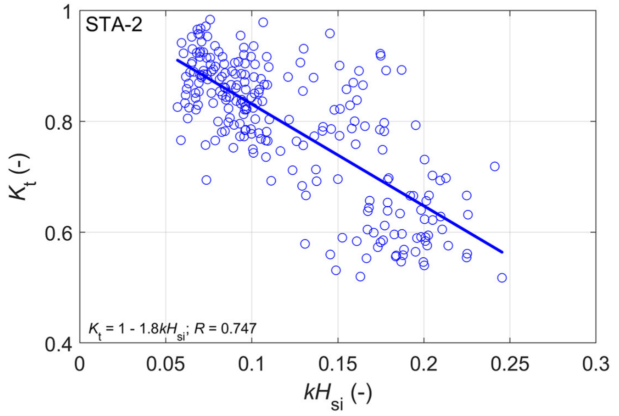

FIGURE 7 | The relationship between the wave transmission coefficient K_t and the wave steepness kH_{si}.

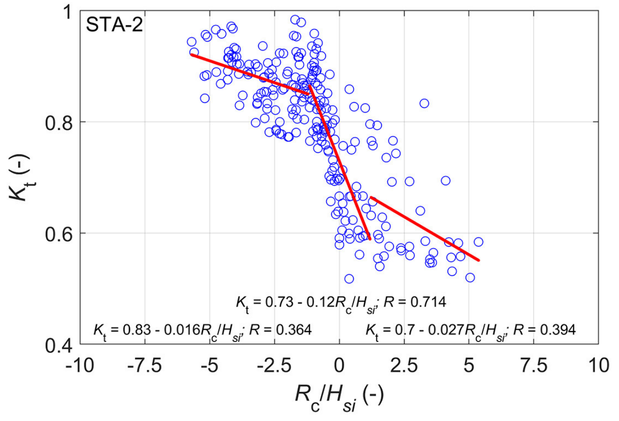

FIGURE 8 | The relationship of the wave transmission coefficient K_t and the relative fence freeboard R_c/H_{st}.

TABLE 2 | Empirical coefficients of the Equation (5).

a	*b*	Conditions
−0.016	0.83	$R_c/H_{si} < -1.2$
−0.12	0.73	$-1.2 \le R_c/H_{si} \le 1.2$
−0.027	0.70	$R_c/H_{si} > 1.2$

time in March 2016. The semidiurnal tide is the typical water level variation at the Nha Mat coast. The tidal range in the researched area varies from 1 to 1.6 m. Currents at this site were observed during the experiment and varied from 0.4 to 0.6 m/s. Sediment grain sizes at the Nha Mat coast were also observed in March 2016, as shown in **Table 1**.

Sedimentation in the study area has been observed in six zones by installing six ruled poles in each zone to read the wetland surface elevation every 20 days (**Figure 3**).

RESULTS AND DISCUSSIONS

The result of wave measurements at the front and the rear of the bamboo fence and the depth of water is presented in **Figures 4**, **5** at station STA-2 in 09/2016 and 12/2016, respectively. In **Figures 4**, **5**, H_{si} is the significant incident wave height (the red diamond symbol); H_{st} is the significant transmitted wave height (the blue circle symbol), and d is the water depth at the location of the measuring station (the black triangle symbol). The data were filtered out with conditions that waves were measured in water depth $d \geq 0.2$ m to remove the affected data due to too-shallow water depth. Preliminary assessments show that the significant incident wave height has been significantly reduced by the bamboo fence (**Figures 4**, **5**).

The transmission coefficient is determined according to Equation (1):

$$K_t = \frac{H_{st}}{H_{si}} \quad (1)$$

where: H_{si} is the significant incident wave height, and H_{st} is the significant transmitted wave height.

The wave transmission coefficient of the fence in 2016 in the study area is presented in **Figures 6–8**. The relationship between the wave transmission coefficient and nondimensional parameters, such as the relative water depth kd, wave steepness kH_{si}, and the relative freeboard R_c/H_{si} where k is the incident wave number, and R_c is the freeboard of the fence. The freeboard of the fence (R_c) is the distance between the crest level of the fence (Z_f) and the water level (WL), expressed as $R_c = Z_f\text{-}WL$. Thus, R_c is positive if the crest level of the fence is higher than the water level. In contrast, R_c is negative if the crest level of the fence is lower than the water level; this means that the fence is submerged in water for this case.

Figure 6 shows the relationship between wave transmission coefficient and the relative water depth (kd). It can be seen that the wave transmission coefficient K_t increases with the increase of the relative water depth (kd). Therefore, if the water depth increases, the wave height reduction due to the fence decreases.

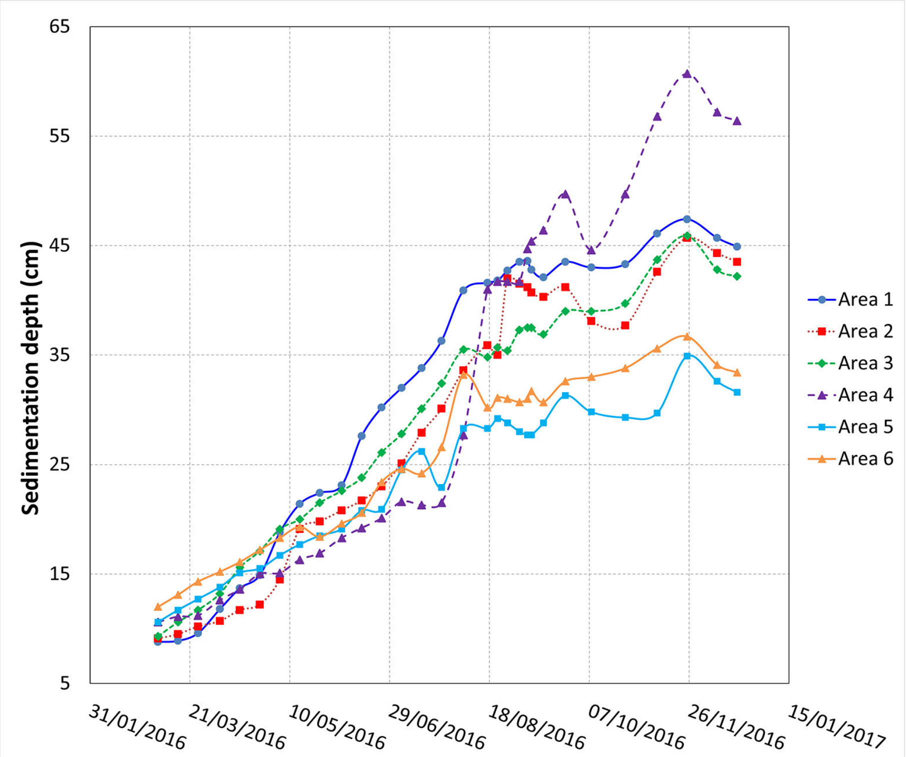

FIGURE 9 | Sediment accumulation in the study area after the presence of bamboo fences.

That is reasonable due to the fact that, in a higher water depth (same as the water level), the waves could be easy to transmit through the fence. The empirical relationship between the wave transmission coefficient K_t and the relative water depth (kd) is proposed as Equation (2) and (3):

$$K_t = 0.33 + 1.3kd \text{ if } kd < 0.4 \tag{2}$$

$$K_t = 0.72 + 0.29kd \text{ if } kd \geq 0.4 \tag{3}$$

The relationship between the wave transmission coefficient and the wave steepness kH_{si} is shown in **Figure 7**. In contrast to the relationship of K_t and kd presented in **Figures 6**, **7** shows that, as the wave steepness (kH_{si}) is increasing, the wave transmission coefficient decreases. The proposed empirical formula for K_t and kH_{si} is presented in Equation (4):

$$K_t = 1 - 1.8kH_{si} \tag{4}$$

Figure 8 presents a relationship between the wave transmission coefficient K_t and the relative fence freeboard R_c/H_{si}, showing the dependence of the wave transmission coefficient on the freeboard. It is shown that the relative freeboard R_c/H_{si} varies from −5.7 to +5.4 for the fence used at station STA-2 according to the measurements. The results also show that the wave transmission coefficient decreases with the increase of the relative fence freeboard R_c/H_{si}. This result is similar to previous studies done by Albers et al. (2013) and Schmitt et al. (2013) for the fence system built in the Soc Trang coast, Vietnam. In addition, the relative freeboard of the fence becomes zero, i.e., $R_c/H_{si} = 0$; the wave transmission coefficient is still relatively high, $K_t = 0.73$.

The relationship between the wave transmission coefficient (K_t) and the relative fence freeboard R_c/H_{si} is determined based on the best fit line in **Figure 8**. This relationship is expressed as Equation (5):

$$K_t = a\frac{R_c}{H_{si}} + b \tag{5}$$

where a and b are the empirical coefficients obtained from the analysis of the data in this study, and their values are presented in **Table 2**.

The observed sedimentation depths are presented in **Figure 9**. It is shown that the sedimentation depth has been increased about 30–60 cm after 10 months (from March 5, 2016, to December 20, 2016) from the time the bamboo fences were installed in the study area. Consequently, the new wetland surface could be used to start planting young mangroves. Note that sediment transport can be closely linked to wave actions, including short and long waves, especially long waves play a vital role as the controlling factor in the net sediment transport (Baldock et al., 2010). Additionally, this net transport relatively links to the odd moment $<u|u|^2>$ (Bosboom and Stive, 2012), where u is the time-averaged velocity, insisting a high-frequency oscillatory motion of short waves and low-frequency motion at wave-group scale (long waves). The term u^2 can be related to the sediment concentration stirred up by the oscillatory wave motion and is relatively proportional to the wave height in the shallow water. As shown in **Figure 8**, waves reduce about 40% of their heights at relatively shallow depths, resulting in estimation for the remaining long waves energy propagated through the fences. Furthermore, the incident wave and wave group related to long-wave propagation could correspond to sediment concentrations in the shoaling wave conditions (Pang et al., 2020). Because the measured sedimentation level behind the fence shows an increasing trend, the sediment induced by long-wave motions might contribute a vital role in the increase of the sedimentation level.

CONCLUSIONS AND RECOMMENDATION

The incident and transmitted waves during the southwest and northeast monsoons in 2016 in Nha Mat have been analyzed and presented in this paper. The measured wave data were filtered with the condition that those waves were measured in the water depth $d \geq 0.2$ m. This paper also presents the results including the relationships between the wave transmission coefficient (K_t) and the relative water depth (kd), the wave steepness (kH_{si}), and the relative fence freeboard (R_c/H_{si}). Furthermore, sedimentation in the wetland area was observed and presented in this study.

Based on the results of data analysis, several conclusions are given as follows: (i) the wave transmission coefficient (K_t) decreases as increasing the wave steepness (kH_{si}), but in contrast, the wave transmission coefficient K_t is increasing as the relative water depth (kd) increases; (ii) As the relative fence freeboard R_c/H_{si} increases, the wave transmission coefficient decreases and reaches $K_t = 0.73$ when $R_c/H_{si} = 0$ (the crest fence level at the water level); (iii) Preliminarily formulation of the empirical formulae for calculating the wave transmission coefficient K_t in terms of the relative water depth kd, the wave steepness kH_{si}, and the relative fence freeboard R_c/H_{si}; (iv) Sedimentation depth could be increased up to 0.60 m, which is significant for planting new mangrove belt for eco-friendly coastal protection.

Findings from this research create a technical basic reference for the design of a nature-based solution by using bamboo and/or wooden fences for coastal protections, which currently, is a gap in existing Vietnamese design guidelines. This facilitates, also, the use of the local available eco-friendly materials for coastal protection and management along the Vietnamese Mekong delta coasts instead of applying many concrete structures presently.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

CM: conceptualization, methodology, formal analysis, visualization, and writing—original draft. AN: conceptualization and writing—review and editing. TM: conceptualization, investigation, and writing—review and editing. HD: writing—review and editing. All authors contributed to the article and approved the submitted version.

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