Effect of mangrove forest structures on wave attenuation in coastal Vietnam

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Tran Quang Bao

Vietnam Forestry University,
Xuan Mai, Chuong My, Ha Noi, Vietnam;

e-mail: baofuv@yahoo.com

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Abstract

This paper analyses wave attenuation in coastal mangrove forests in Vietnam. Data from 32 mangrove plots of six species located in 2 coastal regions are used for this study. In each plot, mangrove forest structures and wave height at different cross-shore distances are measured. Wave height closely relates to cross-shore distances. 92 exponential regression equations are highly significant with $R^2 > 0.95$ and P val. < 0.001. Wave height reduction depends on initial wave height, cross-shore distances, and mangrove forest structures. This relationship is used to define minimum mangrove band width for coastal protection from waves in Vietnam.

1. Introduction

Mangrove forests span the interface between marine and terrestrial environments, growing in the mouths of rivers, in tidal swamps, and along coastlines, where they are regularly inundated by saline or brackish water (Sterling et al. 2006). Mangrove forests play a vital role in coastline protection, mitigation of wave and storm impacts and mudflat stabilization, and protection of near-shore water quality. They also provide critical habitat for fish and wildlife. Many species new to science have recently been documented in mangrove forest areas in Vietnam (Thompson & Thompson 2008). The trunks and overground roots of mangrove forests have a considerable influence on the hydrodynamics and sediment transport within forests (Quartel et al. 2007). In 2002, Vietnam had approximately 155 290 ha of mangrove forests. More than 200 000 ha of mangrove forests have been destroyed over the last two decades as a result of conversion to agriculture and aquaculture (e.g. shrimp farming) as well as development for recreation (VEPA 2005). Mangrove forests are thought to play an important role in flood defence by dissipating incoming wave energy and reducing erosion rates (Hong & Son 1993, Wu et al. 2001). However, the physical processes of wave attenuation in mangroves are not widely studied, especially in Vietnam, because of the difficulties in analysing flow fields in vegetation and the lack of comprehensive data (Kobayashi et al. 1993).

Coastal mangrove forests can mitigate high waves, even tsunamis. By observing the casualties of the tsunami of 26 December 2004, Kathiresan & Rajendran (2005) highlighted the effectiveness of mangrove forest in reducing the impact of waves. Human death and loss of wealth were lower in areas of dense mangrove forests. A review by Alongi (2008) concluded that tsunami wave flow pressure was significantly reduced when the mangrove forest was 100 m wide. The wave energy spectrum and wave power are dissipated within a mangrove forest even over a small distance (Vo-Luong & Massel 2008). The magnitude of the energy absorbed depends strongly on the mangrove structures (e.g. density, stem and root diameter, shore slope) and the spectral characteristics of incident waves (Massel et al. 1999, Alongi 2008). The dissipation of wave energy inside mangrove forests is caused mostly by wave-trunk interactions and wave breaking (Vo-Luong & Massel 2006).

Mazda et al. (1997a) in their study in the Red River Delta, Vietnam, showed that wave reduction due to drag force on the trees is significant in high density, six-year-old mangrove forests. The hydrodynamics of mangrove swamps changes over a wide range, depending on their species, density and tidal condition (Mazda et al. 1997b). The high tree density and the overground roots in a mangrove forest present a much higher drag force to incoming waves than the bare sandy surface of a mudflat does. The wave drag force can be expressed as an exponential function (Quartel et al. 2007).

The general objective of this paper is to analyse the relationship between wave height and mangrove forest structures, and then to define minimum mangrove forest band width for coastal protection from waves for the coastline of Vietnam.

2. Material and methods

2.1. Study sites

The study was conducted in two coastal mangrove forests of Vietnam. The northern study site is located in the delta (the second largest in Vietnam) of the Red River, which flows into the Bay of Tonkin (Figure 1). Tides in the Bay of Tonkin are diurnal with a range of 2.6–3.2 m. Active intertidal mudflats, mangrove swamps and supratidal marshes in estuaries and along open coastlines characterize the coastal areas (Mathers & Zalesiewicz 1999, Quartel et al. 2007). The mangroves in the Red River delta are one of the main remaining large tracts of mangrove forest in Vietnam, which are important sites for breeding/stopover along the East-Asian or Australian flyways. In this northern region, four mangrove locations were selected for the research: Tien Lang, Cat Ba–Hai Phong, Hoang Tan–Quang Ninh and Tien Hai–Thai Binh. In each location, four mangrove forest plots were set up to measure mangrove structure and wave height at different cross-shore distances.

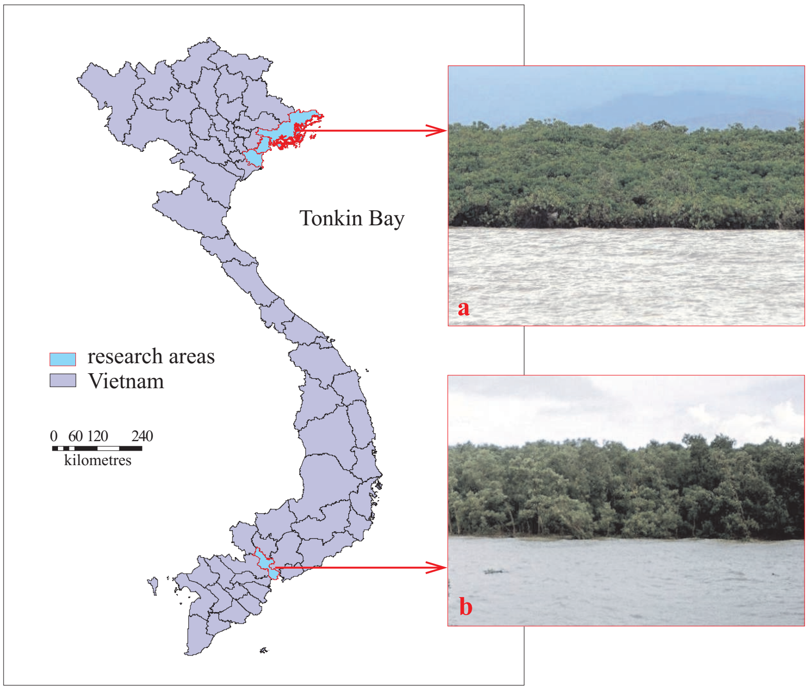

Figure 1. Map of Vietnam showing the locations of the study areas; a) *Sonneratia caseolaris* forest in Hai Phong, and b) *Rhizophora mucronata* forest in Ho Chi Minh City

The southern study site is the Can Gio mangrove forest. The first Biosphere Reserve in Vietnam, it is located 40 km southeast of Ho Chi Minh City and has a total area of 75 740 ha (Figure 1). Can Gio lies in a recently formed, soft, silty delta with an irregular, semi-diurnal tidal regime (Vo-Luong & Massel 2006). The major habitat types in Can Gio are plantation mangroves, of which there are about 20 000 ha, and naturally regenerating mangroves. The site is an important wildlife sanctuary in Vietnam as it is characterized by a wetland biosystem dominated by mangroves. The intertidal mudflats and sandbanks at Can Gio are an important habitat for migratory shorebirds. Eighteen mangrove forest plots were set up in Can Gio to collect data on mangrove structures and wave height. The selected plots are representative of the differences in mangrove structures in the region (e.g. age, species, height, tree density).

2.2. Data collection

A total 32 mangrove forest plots were set up in five locations of two regions along coastal Vietnam. In each plot of 4000 m^2 (20 m $\times$ 200 m), 2–5 transects were designed to measure wave height at different cross-shore distances (i.e. 0 m, 20 m, 40 m, 60 m, 100 m and 120 m) from the edge to the centre of the mangrove stand (Figure 2). In each measurement, wave height was measured by people standing at six cross-shore distances. The numbers of measurable replications on each route are from 2 to 10. Mangrove forest structures, such as breast-height diameter, height, tree density, canopy closure and species are collected in each plot. Wave attenuation is analysed in relation to distances, initial wave height and mangrove forest structures.

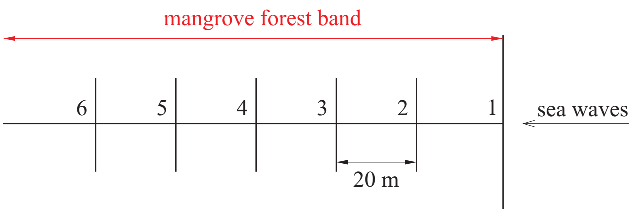

Figure 2. A diagram designed to measure wave height on a cross-shore transect

3. Results and discussion

3.1. Effects of mangrove structures on wave height

The structures of 32 mangrove forest plots in five coastal research areas are relatively simple. There are only six dominant species (*Rhizophora mucronata*, *Sonneratia caseolaris*, *S. griffithii*, *Aegiceras corniculatum*, *Avicennia marina*, *Kandelia candel*) with a high tree density (2000–13 000 trees ha^{-1}) and a canopy closure averaging $> 80\%$. Diameters and heights range from 7.5 to 12 cm and from 1.6 to 11.3 m respectively. Generally, the DBH and height of mangrove forests increases towards the south. This may be explained by the differences in resources: more mudflats and a warmer climate in the south. The average wave height observed in all plots ranged from 20 to 70 cm.

To the data on wave height [cm] measured at different distances [m] from the edge to the centre of the mangrove stand we applied regression models in order to examine the relationship between wave height and cross-shore distances to the forest. The results show that wave height decays exponentially and is significantly related to distance (Figure 3). All 92 exponential regression equations of five research areas with different mangrove forest species are highly significant with P values of < 0.001 and $R^2 > 0.95$. The exponential reduction of wave height in mangroves can be explained by the dense network of trunks, branches and above-ground roots of the mangrove trees, increasing bed roughness, causing more friction and dissipating more wave energy (Quartel et al. 2007).

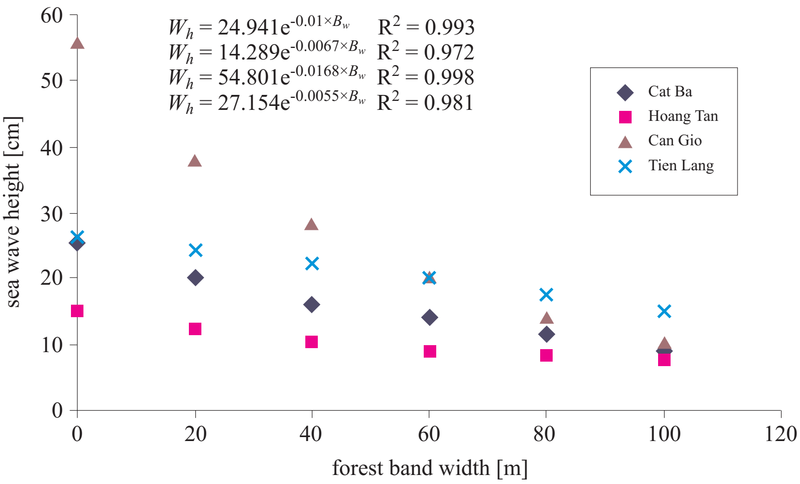

Figure 3. The reduction of wave height by cross shore distances. Examples from data measured on route 1 and the first replication of plots in Cat Ba, Hoang Tan, Can Gio and Tien Lang respectively

The effect of mangrove forest band width on wave height can be generalized in an exponential equation (1):

$$W_h = a \times e^{b \times B_w}, \tag{1}$$

where W_h is the sea wave height behind the forest band [cm], B_w is the forest band width [m], a is the intercept in log base e of equation (1), b is the slope coefficient in log base e of equation (1).

To establish a general equation for all measurements in five locations, from the data listed in the 92 regression coefficients of equation (1) we analyse the relation of these coefficients (i.e. intercept and slope) with different independent variables. We have found interesting relationships of regression coefficients to initial wave height and mangrove forest structures:

1) Intercept coefficient a is highly correlated with initial wave height (i.e. wave height at the edge of the mangrove forest, distance = 0), $R^2 = 0.989$, $P < 0.0001$. It is a linear equation, in which coefficient a is directly proportional to the initial wave height (Figure 4).

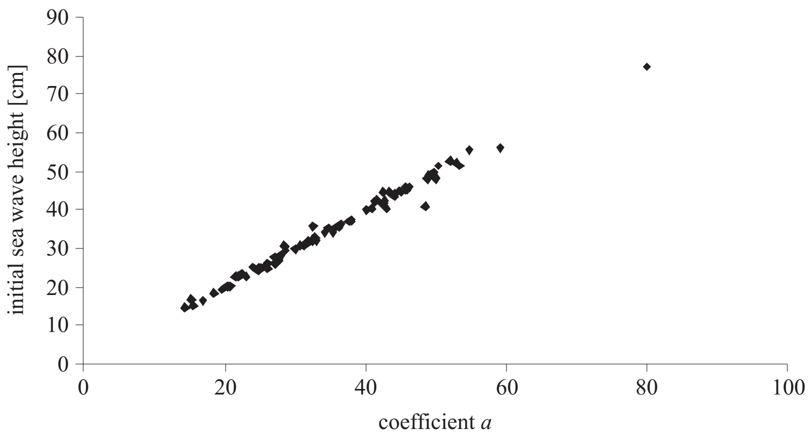

Figure 4. Bivariate plots of coefficient a in equation (1) and initial wave height [cm]

$$a = 0.9899 \times I_{wh} + 0.3526\,, \tag{2}$$

where a is the coefficient in exponential equation (1), and I_{wh} is the initial sea wave height [cm].

2) Slope coefficient b is in regression with the mangrove forest structure; about 71% of the total variations of coefficient b is associated with height, density and canopy closure ($R^2 = 0.713$, $P < 0.0001$). These independent variables are inversely related to the exponential coefficient of equation (1).

$$b = 0.048 - 0.0016 \times H - 0.00178 \times \ln(N) - 0.0077 \times \ln(CC)\,, \tag{3}$$

where b is the exponential coefficient in equation (1), H is the average tree height [m], N is the tree density [tree ha^{-1}], and CC is the canopy closure [%].

By inserting equations (2) and (3) into equation (1), we have an integrated equation (4) demonstrating the relationship of wave height reduction to initial wave height and mangrove forest structure.

$$W_h = (0.9899 \times I_{wh} + \\ +0.3526) \times e^{(0.048-0.0016\times H-0.00178\times\ln(N)-0.0077\times\ln(CC)\times B_w)} . \quad (4)$$

To validate the accuracy of model (4), the predicted values are compared with actual data. Figures 5a,b show a high correlation between predicted wave height and observed wave height at two cross-shore distances of 40 m and 80 m ($R^2 > 0.8$). The respective root squared mean errors (RSME) of the predictions are 2.54 cm and 3.93 cm.

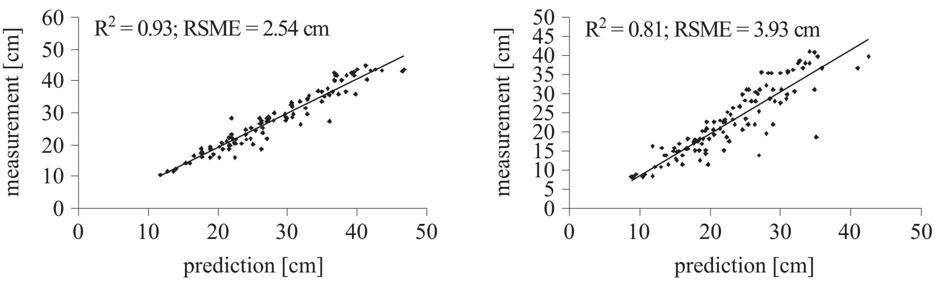

Figure 5. Bivariate plots of predicted and actual values of wave height [cm] at two distances from the edge to the centre of the forest, a) distance = 40 m; b) distance = 80 m

3.2. Minimum mangrove band width for coastal protection from waves

The integrated equation (4) is the prediction of wave height from cross-shore distance (i.e. mangrove band width), mangrove structures and initial wave height. Mangrove band width is identified by equation (5), derived from equation (4). In equation (5), for a given predicted wave height (i.e. safe wave height) and initial wave height, mangrove band width depends on mangrove forest structures:

$$B_w = \frac{\ln(W_h) - \ln(a)}{b} , \quad (5)$$

where B_w is the forest band width [m], W_h is the safe wave height behind the forest band [cm], a is a function of initial wave height (equation (2)), and b is a function of forest structure (equation (3)).

To identify the average initial wave height for equation (5), we collected maximum wave heights in different typical regions along the coastline of

Vietnam (Table 1). In the two years from 2004 to 2005, the maximum wave height approximately ranged from 1.25 m to 5.0 m. In reality, wave height depends on the characteristics of storm events. Wave height is caused by strong wind and heavy rain, whereas in normal weather wave height is usually low in Vietnam. We selected a threshold maximum wave height of 3 m for calculating the minimum mangrove band width for coastal protection.

Table 1. Maximum sea wave height in coastal Vietnam

Regions	Maximum sea wave height [m]		
	6^h30	12^h30	17^h00
Hai Phong	2.97	3.69	3.60
Quang Ninh	1.25	1.25	1.50
Vung Tau	1.25	125	1.50
Thanh Hoa	0.75	1.35	1.50
Da Nang	3.50	5.00	3.50

Sources: Department of Hydrometeorology, observed from 1 January 2004 to 31 December 2005.

The safe wave height behind the forest band in equation (5) is 30 cm: it is the averaged observed wave height, obtained by interviewing 50 people (e.g. farmers, peasants, managers) working in aquaculture and agriculture in the research areas.

By substituting the values of initial wave height (300 cm) and safe wave height (30 cm) into equation (5), we find that the required mangrove band width (B_w) is a function only of the forest structure index, depending on height, density and canopy closure (equation (3)).

$$\text{Let V} = -b = [-0.048 + 0.0016 \times H + \\ +0.00178 \times \ln(N) + 0.0077 \times \ln(CC)]\,, \tag{6}$$

where V is the index of mangrove forest structure. The theoretical line of minimum forest band width in relation to the vegetation index is shown in Figure 6.

The mangrove structure index is classified into 5 levels of wave prevention based on its relation to wave height (Figure 6; Table 2). The required mangrove band width decays exponentially with the vegetation index (V). When the mangrove forest is tall and dense, and the canopy closure high (i.e. a high V index), a narrower forest band is required. When the mangrove forest is short, the tree density and canopy closure low (i.e. a low V index), a wider mangrove band is required.

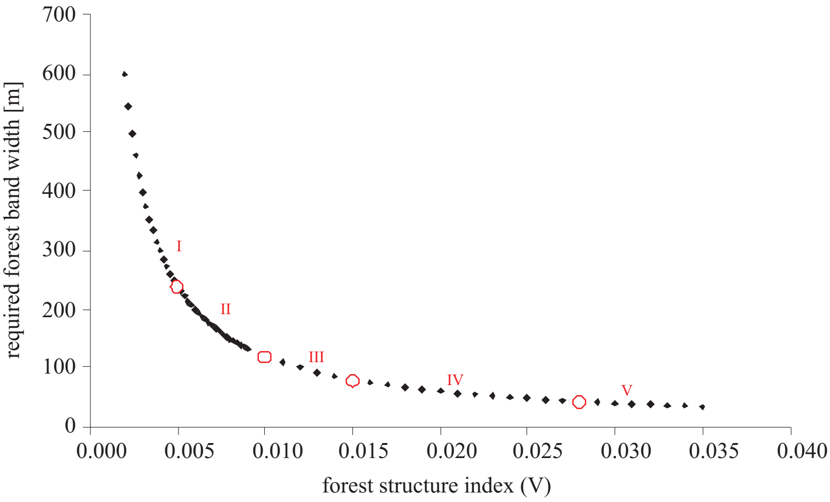

Figure 6. Theoretical curve showing the relationship between mangrove structure index (V) and mangrove band width [m]

Table 2. Classification of mangrove forests for prevention of sea waves

Levels	V index	Required band width [m]	Name of levels
I	< 0.005	> 240	very weak prevention
II	0.005–0.010	120–240	weak prevention
III	0.010–0.015	80–120	moderate prevention
IV	0.015–0.028	40–80	strong prevention
V	> 0.0280	< 40	very strong prevention

The maximum wave height is assumed to be 300 cm.

- Level I: the V index is less than 0.005. At this level when the V index is increasing, the minimum mangrove band width decreases rapidly quickly from 600 m to 240 m.
- Level II: the V index ranges from 0.005 to 0.015. At this level, an increase in the V index causes the minimum band width to decrease fairly quickly from 240 m to 120 m.
- Level III: the V index is from 0.010 to 0.015. At this level, an increase in the V index results in a gradual decrease in the minimum band width from 120 m to 80 m.
- Level IV: the V index lies between 0.015 and 0.028. An increase in the V index at this level results in a slow decrease in the minimum band width from 40 m to 80 m.

– Level V: the V index is greater than 0.028. An increase in the V index causes a minimal decrease in the minimum band width of always less than 40 m.

Applying the threshold V index in Table 3, we have identified the levels of wave prevention for 32 mangrove forest plots. The results show that the levels of wave prevention in the southern plots are higher than those of the northern plots. This indicates that the southern mangrove forest can protect the coastline better than the northern mangrove forest does (Table 3).

Table 3. Index of mangrove structures and corresponding level of wave prevention

No.	Locations	Dominant species	* V index	Level
1	Cat Ba	*Aegiceras corniculatum*	0.00484	I
2	Can Gio	*Avicennia marina*	0.01408	III
		Rhizophora mucronata	0.01631	IV
		Sonneratia caseolaris	0.01374	III
3	Hoang Tan	*Sonneratia caseolaris*	0.00587	II
		Avicennia marina	0.00474	I
		Aegiceras corniculatum	0.00318	I
4	Thai Binh	*Kandelia candel*	0.00749	II
		Aegiceras corniculatum	0.00242	I
5	Tien Lang	*Sonneratia caseolaris*	0.00504	II

*V: index of mangrove structure.

4. Conclusions

Mangrove forests are very important ecosystems located in the upper intertidal zones of the tropics. They are the primary source of energy and nutrients in these environments. They have a special role in stabilizing shorelines, minimizing wave damage and trapping sediments. However, in recent decades mangrove forests in Vietnam have been threatened by conversion to agriculture and aquaculture. The primary objectives of this study were to define a minimum mangrove band width for coastal protection from waves in Vietnam.

We set up 32 plots in 2 coastal regions of Vietnam to measure wave attenuation from the edge to the forest centre (distances). The results show that wave height is closely related to cross-shore distances in an exponential equation. All the single equations are highly significant with $P < 0.001$ and $R^2 > 0.95$.

We derived an integrated exponential equation applicable to all cases, in which coefficient a (the intercept in the log transformation of the exponential equation) is a function of initial wave height, and coefficient b (the slope in the log transformation of the exponential equation) is a function of canopy closure, height and density. The integrated equation was used to define appropriate mangrove band widths. On the assumption that the average maximum wave height is 300 cm and the safe wave height behind the forest band is 30 cm, the required mangrove forest band width associated with its structures was defined.

The mangrove structure index (V) is classified into 5 levels of protection from waves. As the southern mangrove forests of Vietnam protect waves better than the northern mangrove forests do, they have a higher V index.

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