

APPLICATION OF VEGETATION ON MITIGATING RIVERBANK EROSION CAUSED BY BOAT-GENERATED WAVE ATTACKS

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ABSTRACT

Bank erosion by boat-generated waves is an increasingly severe issue on navigable channels and rivers causing serious damage. A field study designed to elucidate how boat-generated waves threaten riverbank stability, was conducted in Ca Mau Province, Vietnamese Mekong Delta. The characteristics of soil of riverbanks as well as waves were measured in-situ at a number of sites over a range of flow conditions for analysis. In addition, both vegetated and non-vegetated riverbanks were considered. The results from numerical simulation demonstrate that for the bare banks (without vegetation protection), the boat-induced shear stresses acting on the riverbed exceeded the critical shear stress of soil and bank erosion therefore is occurring. In the case of riverbank covered with vegetation, no bank erosion was observed. This brings out an idea of applying vegetation as countermeasure to protect riverbank from wave attacks. Thus, a relationship between vegetation width and percentage of wave height reduction was established taken into account the effect of ground slope condition on the performance of vegetation towards wave attenuation.

KEYWORDS: Bank erosion, vegetation, ground slope, boat-generated wave.

1. INTRODUCTION

Streambank erosion processes may be responsible for land loss and the delivery of large volumes of sediment with associated sedimentation hazards in the downstream reaches of a fluvial system. Therefore, it is not surprising that bank erosion is often considered as a significant problem in river management. The reasons causing bank erosion are various, either by nature or anthropical activities. It is noticeable that in recent years, navigation has been developing rapidly to serve for human demands. The participation of different types of boats/ships nowadays has been suspected to accelerate the bank erosion rate because of the waves generated by ships/boats. Previous studies showed that waves generated by boats contain a massive amount of energy that can erode seriously the riparian and coastal environment (Bonham, 1983; Coops et al., 1996; Belibassakis, 2003). Once bank erosion occurs, it may adversely affect on not only human livelihood but also the ecosystem. However, little work has been done on the influence of waves, although they induce high energy events. Kirkegaard et al. (1998) showed that waves generated by high-speed boat in shallow water are substantially different from the waves generated by conventional ships as a consequence of the higher speed and the size of these modern vessels. Tanimoto et al. (2000) found out that the

ship waves in a shallow and narrow channel such as a canal are greatly different from those in a deep open sea. Surprisingly, most damage is not caused by the large ships, which often move slowly and relatively far from the banks. Small, high-speed boats with powerful engines passing near the bank actually do more harm (Schiereck, 2005). Moreover, study of Nascimento et al. (2010) reported that in heavily navigated channels, the combination of two or more wave trains, generated by boats moving either in the same direction or in opposite directions, causes much more damage. Such studies were largely based on computational simulations and improved algorithms of wave transformation over shoaling seabed. Although this approach is able to support a large amount of calculations, there are always some certain limitations due to initial assumptions for simplicity and therefore cannot reflect exactly the happening in the real field with the effects of complex internal and external factors. There are just a few studies on ship/boat waves based on field investigation, although these studies have not yet included enough information to compare the theoretical results with the field data. Velegrakis et al. (2007) conducted a field observation of waves generated by passing ships and compared how influence the wave, induced by conventional ferry and fast ferry, on beach sediment dynamics. Their results

demonstrated that the fast ferry could generate a much more energetic event, which not only did include much higher waves, but it was also an order of magnitude longer. Therefore it might affect both beach sediment dynamics and nearshore benthic ecosystem. Nanson et al. (1994) tried to link bank erosion rates with measured wave characteristics, conducted on the lower Gordon River, Tasmania, with the aim of river management. McConchie and Toleman (2003) carried-out a field investigation along the Waikato River, New Zealand to determine the main reason causing bank erosion and bed elevation change. They found out that the wakes induced by boat were more effective at suspending and transporting sediment than wind-generated waves, particularly in the cases of shallow water. To deal with boat/ship-generated wave attacks, Bonham (1983) conducted hydraulic experiments and field tests about the attenuation of ship waves in well-surviving beds of emergent river plants. In his study, both wave type and vegetation characteristics were considered. His results showed that any of those species could dissipate almost two-third of the boat wash ship wave energy and inhibit wave-break. Coops et al. (1996) by conducting an experimental study in a wave tank; found out a positive impact of emergent vegetation characteristics on both sediment reinforcement and wave attenuation. While small waves (10 cm) could cause considerable alteration to the slopes in the unplanted sections, such waves did not greatly affect slopes under vegetation cover. Moreover, due to more finely distributed root structure into the soil, *Phragmites australis* (Cav.) Trin. ex Steudel could withstand the attacks of 23 cm waves while *Scirpus lacustris* L. was uprooted, followed by increased erosion of the soil. Therefore, in order to complement more information regarding ship wave attack obtained from the field observation, it is necessary to study boat-generated wave characteristics and its impacts on riverbank stability in the real field in the cases of bare and vegetated riverbanks. The objectives of this study are to 1) clarify the relationship between the shear stress induced by boat waves and bank erosion rate based on a field investigation and 2) establish a relationship between vegetation width and percentage of wave height reduction taken into consideration the effect of ground slope condition by numerical simulation. A vegetation field can be designed based on this relation for wave attenuation.

2. STUDY AREA

In the Vietnamese Mekong Delta, due to specifically geographical condition, the road traffic systems are not able to be developed properly. Instead, with a dense river network, inland waterways have been built to support the demands of passages among areas. Recently, due to rapidly

socioeconomic development in the Vietnamese Mekong Delta, there has been a remarkable increase of transportation in order to meet the demands of passage among areas. The width of river and channel does not much change whereas the waterway density becomes too dense due to the presence of a large number of boats joining in the transportation. Considering as the most populated waterway in Vietnam, the transport in Ca Mau Province is diversified in terms of type of means as engine-driven boats, canoes, high-speed boats, etc...In recent years, it is noticeable that together with the remarkable increase in both quantity and speed of boats, the more and more severe bank erosions have been occurring. According to the statistics from the Board of River Traffic Management, Ca Mau Province, there are great increases of ships/boats demand from 1995-2004 (10 years: 29,837 boats) to 2005-July of 2011 (6.5 years: 57,535 boats). The constant attacks of boat-generated waves are suspected as one of the main reasons causing this problem.

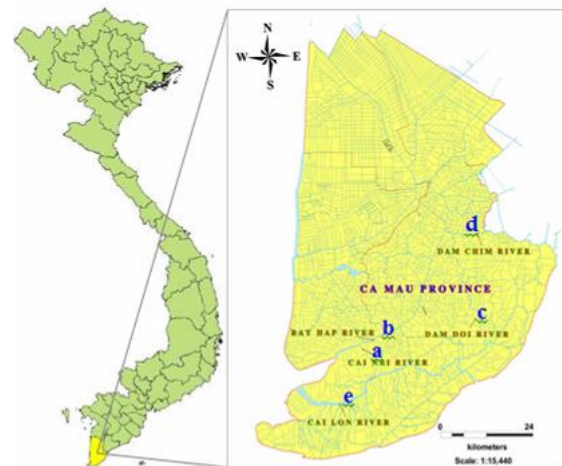


Fig. 1 Study area (a) Cai Nai River, (b) Bay Hap River, (c) Dam Doi River, (d) Dam Chim River, and (e) Cai Lon River.

The field investigation was conducted in Ca Mau Province, the end point of the Vietnamese Mekong Delta in February, 2013 (Fig. 1). Five sites were selected including Cai Nai River, Bay Hap River, Dam Doi River, Dam Chim River, and Cai Lon River which are all under the effect of semi-diurnal tide with a range of 0.9-1.4 m. At the first four rivers, the measurements were conducted at 3 transects in each river. These locations were selected based on three conditions 1) heavy transport of boat traffic, 2) similar soil characteristics of river bank and 3) no vegetated protection. Thus, the total damage causing by boat-generated waves on a bare riverbank can be determined. As for the last river, i.e. Cai Lon River, the measurement was conducted at 2 transects where has the appearance of vegetation. (Fig. 2)

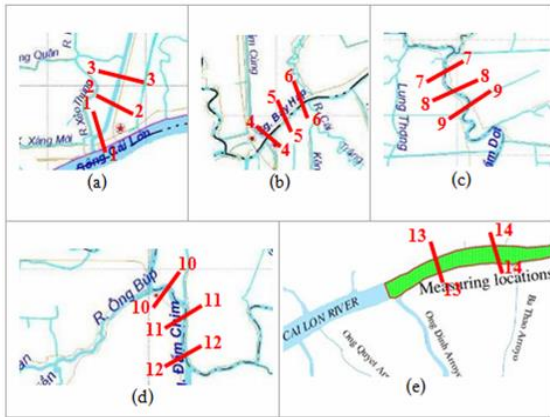


Fig. 2 The location of each transect where the field measurements were conducted.

The aim was to test that under the presence of vegetation how it would affect the wave energy dissipation. According to the field observation, *Rhizophora apiculata*, belonging to mangrove family, is dominated and covers along the riverbank (Fig. 3). *R. apiculata* has a special root structure including a tap-root that is small but grows deep into the soil and many secondary prop roots that are big and adhere strongly to the muddy soil layer



Fig. 3 The characteristics of *Rhizophora apiculata* observing at Cai Lon River, transect 14-14.

The vegetation characteristics were noted at the site. The vegetation width l is the same at both transects, which is 16 m. The average tree trunk diameter D_t is 0.08 m. Vegetation density N varies from 0.77 to 1.32 trees/m². The average prop root density n_r is 72 roots/tree. The ratio of L_l/d is 2.2 where L_l is the space between neighboring mangrove roots and d is the average diameter of a root which is 0.023 m. Table 1 below shows the characteristics of each site including the river width, average bank slope, vegetation condition, and current bank erosion situation.

Table 1 Summary of sites characteristics

Site	Trans.	River width (m)	Ave. bank slope (%)	Bank vegetated	Bank erosion rate
Cai Nai River	1-1	80	1/50	No	3.05
	2-2	77	1/25	No	2.78
	3-3	68	-	No	N/A
Bay Hap River	4-4	82	-	No	N/A
	5-5	75	1/20	No	2.68
	6-6	80	-	No	N/A
Dam Doi River	7-7	62	1/7	No	2.57
	8-8	60	-	No	N/A
	9-9	60.5	1/8	No	2.15
Dam Chim River	10-10	70	1/6	No	4.18
	11-11	70	-	No	N/A
	12-12	70	-	No	N/A
Cai Lon River	13-13	200	1/80	Yes	0.00
	14-14	205	1/80	Yes	0.00

3. METHODOLOGY AND CASES

3.1 Boat-generated wave characteristics

The measurements of boat-generated wave characteristics were conducted under calm weather condition twice per day in order to get the best result.



Fig. 4 Wave measurement equipment (a) Boat used for wave generation, (b) Staff gauge and, (c) Electromagnetic velocity device.

The first time was at 10.00 AM when the tide was the highest and the second time was at 4.00 PM when water level was the lowest. At each transect, three hydraulic parameters including wave height, wave velocity and still water depth were measured in-situ and repeated three times for the precision. Two boats were used for the measurement; one was berthed securely with all

equipment in it while the other which is 5.5 m long, 2.1 m wide and 0.7 m draft deep was served for wave generation. This engine-driven boat is very common and can be seen everywhere in this region (Fig. 4a). Waves were controlled by boat speed, which are 8.3 and 15.3 m/s. When getting the signal (whistle), the boat driver would increase and control the boat speed to the designating rate and started the run towards the measuring point. While the still water depth was directly obtained by using staff gauge (Fig. 4b) when water surface was calm, the wave height and wave velocity were determined synchronously by using digital camera recording (Olympus μ Tough) and electromagnetic velocity device (Kenek LP1100), respectively (Fig. 4c). The obtained water surface elevation in time series' recordings were then analyzed by video technical software (Corel Video Studio ProX3). Even though the entire wave train may give a better measure of its erosive potential, it is difficult to determine the exact length of the wake train at some sites, particularly the point at which the effect of the boat ceased. Moreover, according to the previous study of Nanson et al. (1994), the erosive energy of the wave train is concentrated in a small part of the train (with the maximum peak in it), with the remaining waves having little effect. Therefore, in this study, the maximum wave heights were used for analysis. In addition, number of boats transporting in each river was counted during the monitoring time, from 8.00 AM to 5.00 PM because it reflects the frequency of wave attack towards the riverbank.

3.2 Soil characteristics analysis

A device so-called 16-T0174/A (Controls Testing Equipment Ltd.) was used to measure in-situ the shear strength of soil (Fig. 5). Consisting of a cylindrical body containing a torsional spring and three interchangeable vanes of different size, T174 is peculiarly suitable for soft and medium cohesive soil. The procedure of the measurement includes 5 steps. Firstly, the most suitable vane is selected for the probable shear strength value of the soil to be tested and screw into the body of the instrument, use spanners for the final tightening. To test an undisturbed zone, the vane is pressed 5-6 cm into the soil axially and regularly, and remember to align the reference line on the venire with the zero of the scale (the two lugs are to be in contact) by rotating the scale-ring anti-clockwise. The instrument then is rotated slowly clockwise, at a constant rate until the lower part of the body follows the upper part of the body. At this moment the soil has been failed and the maximum value of shear strength can be read. Finally, allowing the spring to return to the zero position by releasing applied torque slowly without touching the scale-ring. At each transect, three soil samples were collected and measured for precision. Particle size

distribution of soil was analyzed by sieve screening method.

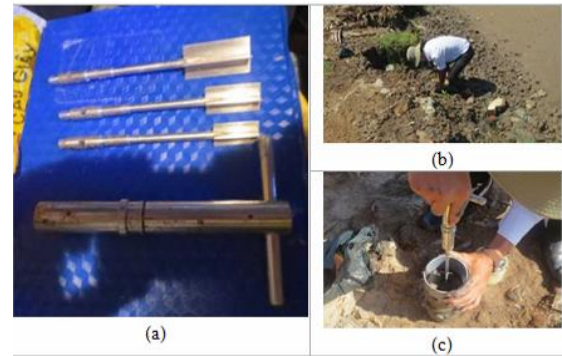


Fig. 5 Soil experiment at site. (a) Equipment for in-situ measurement, (b) Collecting soil sample and, (c) Measurement

3.3 Cases

According to the tidal condition and speed of boat, four cases of hydraulic conditions were set including high tide – high wave, high tide – low wave, low tide – high wave and low tide – low wave. Herein, the high wave and low wave were managed by boat speed, i.e. 8.3 and 15.3 m/s, respectively while high tide and low tide were corresponding with the maximum spring-tide and minimum ebb-tide. Hence, with 14 transects at 5 rivers, 56 measurements were conducted in total.

3.4 Numerical simulation

To clarify the relationship between the shear stress induced by boat waves acting on the bed and erosion rate at each site as well as the role of vegetation in terms of riverbank protection from boat-generated wave attacks, the simulation method was used to solve numerically Boussinesq-type equations (Madsen and Sørensen, 1992) with a moving ship boundary (Chen and Sharma, 1995). Dam et al. (2006) added the effect of energy dissipation due to wave breaking modeled by introducing eddy viscosity terms (R_{bx} and R_{by}). In this study, the drag forces (f_x and f_y) due to vegetation were added into the momentum equations. Takemura and Tanaka (2007), Tanaka and Yagisawa (2010) established the relationship between the drag coefficient C_D and G/D and L/D . In their studies, G is the space between cylinders in the cross-stream direction, L is the space between neighboring cylinders, and D is the diameter of a cylinder. According to their results, because L/d in this study is 2.2, the C_D value is 1.65 and was used for the calculation in the model.

The governing equations are shown as below:
Continuity equation:

$$b \frac{\partial \eta}{\partial t} + \frac{\partial Q_x}{\partial x} + \frac{\partial Q_y}{\partial y} = 0 \quad (1)$$

Momentum equation in x direction

$$\begin{aligned} & \frac{\partial Q_x}{\partial t} + \frac{\partial}{\partial x} \left(\frac{Q_x^2}{A} \right) + \frac{\partial}{\partial y} \left(\frac{Q_x Q_y}{A} \right) + gA \frac{\partial \eta}{\partial x} - R_{bx} \\ & + \frac{\tau_{bx}}{\rho} + \frac{f_x}{\rho} = \left(\beta + \frac{1}{3} \right) h^2 \left(\frac{\partial^3 Q_x}{\partial t \partial x^2} + \frac{\partial^3 Q_y}{\partial t \partial x \partial y} \right) \\ & + h \frac{\partial h}{\partial y} \left(\frac{1}{6} \frac{\partial^2 Q_y}{\partial t \partial x} \right) + h \frac{\partial h}{\partial x} \left(\frac{1}{3} \frac{\partial^2 Q_x}{\partial t \partial x} + \frac{1}{6} \frac{\partial^2 Q_y}{\partial t \partial y} \right) \\ & + \beta g h^3 \left(\frac{\partial^3 \eta}{\partial x^3} + \frac{\partial^3 \eta}{\partial x \partial y^2} \right) \\ & + \beta g h^2 \left\{ \frac{\partial h}{\partial x} \left(2 \frac{\partial^2 \eta}{\partial x^2} + \frac{\partial^2 \eta}{\partial y^2} \right) + \frac{\partial h}{\partial y} \frac{\partial^2 \eta}{\partial x \partial y} \right\} \end{aligned} \quad (2)$$

Momentum equation in y direction

$$\begin{aligned} & \frac{\partial Q_y}{\partial t} + \frac{\partial}{\partial x} \left(\frac{Q_x Q_y}{A} \right) + \frac{\partial}{\partial y} \left(\frac{Q_y^2}{A} \right) + gA \frac{\partial \eta}{\partial y} - R_{by} \\ & + \frac{\tau_{by}}{\rho} + \frac{f_y}{\rho} = \left(\beta + \frac{1}{3} \right) h^2 \left(\frac{\partial^3 Q_x}{\partial t \partial x \partial y} + \frac{\partial^3 Q_y}{\partial t \partial y^2} \right) \\ & + h \frac{\partial h}{\partial x} \left(\frac{1}{6} \frac{\partial^2 Q_x}{\partial t \partial y} \right) + h \frac{\partial h}{\partial y} \left(\frac{1}{3} \frac{\partial^2 Q_y}{\partial t \partial y} + \frac{1}{6} \frac{\partial^2 Q_x}{\partial t \partial x} \right) \\ & + \beta g h^3 \left(\frac{\partial^3 \eta}{\partial x^2 \partial y} + \frac{\partial^3 \eta}{\partial y^3} \right) \\ & + \beta g h^2 \left\{ \frac{\partial h}{\partial y} \left(2 \frac{\partial^2 \eta}{\partial y^2} + \frac{\partial^2 \eta}{\partial x^2} \right) + \frac{\partial h}{\partial x} \frac{\partial^2 \eta}{\partial x \partial y} \right\} \end{aligned} \quad (3)$$

where η is the water surface elevation, Q_x and Q_y are the depth-integrated velocity components in x and y directions, respectively, t is the time, β is the correction factor of the dispersion term, b is the porosity for the permeable layer of the river bed, and A is the cross-sectional area of flow in unit width under the water surface. The eddy viscosity terms in x and y directions R_{bx} and R_{by} were calculated by using the Eq. (4) and (5).

$$R_{bx} = \frac{\partial}{\partial x} \left(v_e \frac{\partial Q_x}{\partial x} \right) + \frac{1}{2} \left\{ \frac{\partial}{\partial y} \left(v_e \frac{\partial Q_x}{\partial y} \right) + \frac{\partial}{\partial y} \left(v_e \frac{\partial Q_y}{\partial x} \right) \right\} \quad (4)$$

$$R_{by} = \frac{\partial}{\partial y} \left(v_e \frac{\partial Q_y}{\partial y} \right) + \frac{1}{2} \left\{ \frac{\partial}{\partial x} \left(v_e \frac{\partial Q_x}{\partial y} \right) + \frac{\partial}{\partial x} \left(v_e \frac{\partial Q_y}{\partial x} \right) \right\} \quad (5)$$

τ_{bx} and τ_{by} are the shear stresses acting on the bed in x and y directions and given by Eq. (6)

$$(\tau_{bx}, \tau_{by}) = \frac{\rho g n^2}{A^{7/3}} \sqrt{Q_x^2 + Q_y^2} (Q_x, Q_y) \quad (6)$$

where n ($= 0.02$) is the Manning roughness coefficient. Considering the vegetation density N and the diameter of tree D_t , the drag forces f_x and f_y were calculated by Eq. (7)

$$(f_x, f_y) = \frac{1}{2} \rho C_D N D_t \left(\frac{Q_x |Q_x|}{A dx}, \frac{Q_y |Q_y|}{A dy} \right) \quad (7)$$

4. RESULTS AND DISCUSSIONS

4.1 The hazard of erosion by navigation

It is well-accepted that the erosion rate of riverbank depends on the frequency of wave impacts as well as the balance between the energy in the waves and the resistance of the bank sediment. Therefore, these factors were all taken into account and analyzed. In the Vietnamese Mekong Delta in general and in Ca Mau Province in particular, because the waterways are the most convenient transportation served for all types of activities such as household demand, business, passenger and cargo shipping, etc...the boats joining in the transport are always heavy everyday. As far as in concern, the frequency of boats at each site is high as can be seen in Table 2, especially in Cai Nai and Cai Lon River.

Table 2 Frequency of boat at each transect during the monitoring time (8.00 AM-5.00 PM)

Site	Transect	Average boat counts/hr
Cai Nai River	1-1	110
	2-2	81
	3-3	58
Bay Hap River	4-4	60
	5-5	57
	6-6	60
Dam Doi River	7-7	39
	8-8	40
	9-9	40
Dam Chim River	10-10	76
	11-11	77
	12-12	76
Cai Lon River	13-13	125
	14-14	125

It is understandable because they are the life-lines of transportation and shipping for not only within this province but also the whole Southern region. Even though the common boats used in this area are small size, they have powerful engine and usually run relatively close to the bank line. Due to heavy navigation, boat-generated waves constantly appear and attack towards riverbank that puts the bank stability under high threat of being eroded. Furthermore, because there is no rule regarding the speed limit, boats run as fast as possible which generates great wave energy and makes the bank erosion become worse. Especially, if the soil of riverbank is not strong enough, the erosion process will happen quicker. It is, therefore, urgently necessary to promulgate such a limited speed of boat in these rivers. Table 2 below summarizes the

soil characteristics collected at 5 sites in this study as well as those in the study of Watts et al. (2003).

Table 2. Summary of soil characteristics at each transect of this study and Watts et al. (2003)

Site	Transect	Shear strength τ_f (kPa)		Average particle size distribution (%)		
		Max	Min	Sand	Silt	Clay
Cai Nai	1-1	92	22	7.5	39.7	52.8
	2-2	120	52			
	3-3	123	43			
Bay Hap	4-4	135	40	15.7	33.0	51.3
	5-5	128	45			
	6-6	122	32			
Dam Doi	7-7	110	45	6.3	49.7	44.0
	8-8	100	30			
	9-9	88	26			
Dam Chim	10-10	118	40	12.8	38.8	48.4
	11-11	115	25			
	12-12	120	40			
Cai Lon	13-13	127	42	10.5	42.8	46.7
	14-14	126	42	10.2	43.0	46.8
Blackwater (Watts et al., 2003)	Plot 5	10	-	7.0	49.0	44.0
	Plot 4	0.52	-	7.0	42.0	51.0
	Plot 3	0.33	-	6.0	42.0	52.0
	Plot 3g	10	-	6.0	45.0	49.0
	Plot FL	228	-	6.0	39.0	55.0
	Plot SM	25	-	4.0	47.0	49.0

It can be seen that the shear strength of soil ranges from 88 to 135 kPa which is classified as medium value. According to the average particle size distribution, it can be concluded that the soil texture is similar at all sites and it is a combination of silty clay and sand.

Both shear strength and critical shear stress can express the soil resistance to shear. Watts et al. (2003) established the correlation between shear strength and critical shear stress as following

$$\tau_c = 2.145 + 0.52 \ln(\tau_f) \quad (8)$$

where τ_c is the critical shear stress (N/m^2) above which erosion is initiated and τ_f is the shear strength of soil (kPa).

In their study, shear strength ranges from 0.33 to 228 kPa. Because the soil shear strength measured in this study ranges between 88 and 135 kPa, the Eq. (8) can be applied.

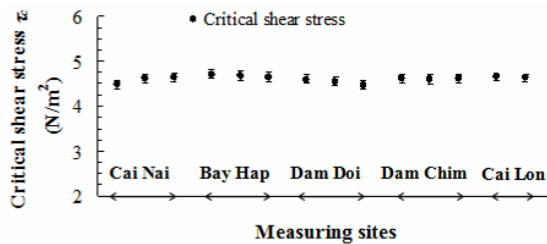


Fig. 6 Calculated critical shear stress of soil at each transect

Fig. 6 shows the critical shear stress of soil from the soil shear strength measured in-situ at the study sites. The soil analysis indicates that the critical shear stresses are quite similar among sites and the critical shear stress ranges between 4.5 and 4.7 N/m^2 . Yet again, this range is classified as medium value.

4.2 Numerical model validation

To ensure that the numerical model is able to simulate the wave propagation, it is necessary to validate the model. Fig. 7a shows the comparison between the time series of wave height calculated by numerical simulation and the observed one obtained at a representative transect (10-10, Dam Chim River). It can be seen that the numerical calculation can simulate well the wave propagation including the timing when the big wave heights occur, the shape of wave propagation as well as the duration of boat-generated wave.

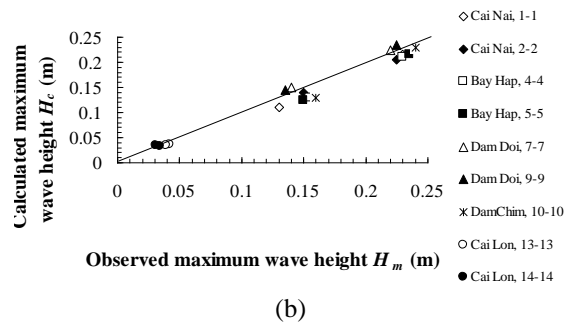
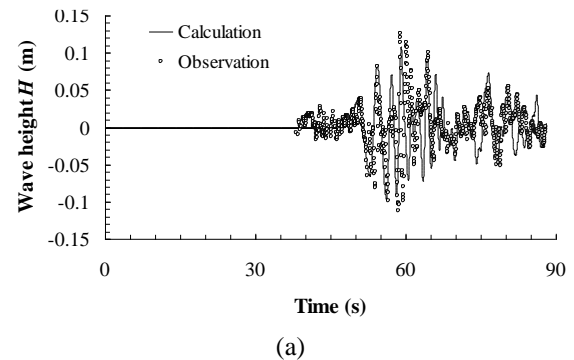


Fig. 7 Validation of numerical simulation used in this study: (a) Comparison between the time series of wave propagation calculated by numerical simulation and the observed one obtained at transect 10-10, Dam Chim River, (b) Comparison between observed and calculated maximum wave height at some representative transects

In addition, the results in Fig. 7b indicate that the values of the maximum wave height calculated by numerical simulation match well with those observed at the field in both cases of being with and without vegetation. Therefore, this model can be used for determining the shear stress acting on the bed induced by boat-generated waves.

4.3 Assessment of bank erosion situation

Even though the erosion and/or deposition can be determined more accurately based on the difference of sediment budget fluxing in and out of a calculated volume, such a method of using a threshold value for qualitative erosion assessment can be acceptable (Nanson et al., 1994). Based on the critical shear stress calculated from soil shear strength at each transect, the average critical shear stress is determined and defined as threshold value at which bank stability is under the highest risk of being eroded. Once the wave-induced shear stress acting on the riverbed is excessive this threshold, the process of bank erosion will trigger. From the wave characteristics measured at the field, numerical simulation was used to calculate the shear stress acting on the riverbed. The results show that at most of the transects (except Cai Lon River), the shear stresses are greater than the threshold value and therefore, the riverbanks are under the hazard of erosion. Additionally, the relationship between the shear stress acting on the bed and erosion rate obtained from the field is established as shown in Fig. 8.

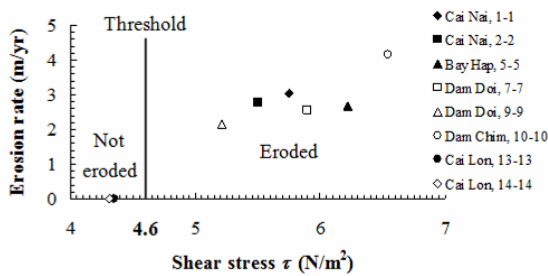


Fig. 8 The relationship between the wave-induced shear stress acting on the river bed and the erosion rate

It is clearly seen that the erosion rate increases with the increase of shear stress. Interestingly, although the boat-generated wave and soil characteristics are quite similar among those observed locations, shear stresses acting on the bed are distinct. The reason should be related to riverbank slope as the milder the slope is, the less damage the surface of riverbank suffers by the wave attacks. For instant, at transect 10-10, Dam Chim River, the average slope is about 1/6, which is the steepest compared to other transects. Therefore, under the attacks of boat-generated waves, the shear stress acting on the bed is also the greatest. Another issue should be taken into account is the frequency of boat as the heavier navigation is, the more waves are generated attacking riverbank. As mentioned in the earlier section, there are a large number of boats transporting along Cai Nai River everyday. This accounts for the higher erosion rate at transects 1-1 and 2-2, Cai Nai River compared to that at transects 5-5, Bay Hap River and 7-7, Dam Doi

River even though their shear stresses are smaller. At transect 13-13 and transect 14-14 of Cai Lon River, the shear stress is smaller than threshold value, and therefore there is no bank erosion as observed in the field.

4.4 Vegetation design for mitigating wave attacks

The field investigation and results from numerical simulation indicate that in spite of having heavy navigation as well as being under the attacks of similar boat-generated waves compared to other rivers, there is no erosion occurring at transect 13-13 and 14-14, Cai Lon River. More interestingly, the frequency of boat counted at these transects are evenly the highest. The crucial factor should be the presence of *Rhizophora apiculata* along the bank of Cai Lon River acting like a natural filter which absorbs effectively boat-generated waves attacking towards the banks. The previous studies of Kobayashi et al. (1993), Luong and Massel (2008), Zhang et al. (2012) indicated that vegetation, especially the intricate root structure as of *Rhizophora apiculata*, could dissipate the wave energy and therefore diminish or even prevent the riverbank from erosion. Moreover, the performance of wave attenuation by vegetation is influenced by the ground slope condition (Nandasena et al., 2008). Therefore, in order to design a reasonable width vegetation belt for obtaining an expected percentage of wave height reduction, the ground slope must be considered.

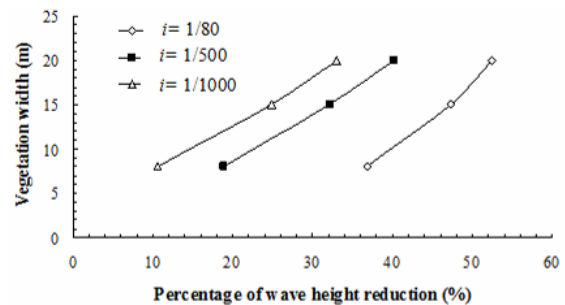


Fig. 9 Correspondence between vegetation width and ground slope condition

Fig. 9 shows that in spite of the same vegetation width, higher percentage of wave height reduction in the case of steep slope compared to mild one. Here the percentage of wave height reduction was calculated using the Eq. (9) below:

$$P = \frac{(wave\ reduction)_{with\ veg.} - (wave\ reduction)_{no\ veg.}}{(wave\ reduction)_{with\ veg.}} \% \quad (9)$$

It is because not only vegetation but also the ground interact and reduce wave energy. For instant, with the vegetation width of 20 m, percentage of wave height reduction is 32%, 40%, and 52.5% under the slope $i = 1/1000$, $1/500$, and

1/80, respectively. This relationship is useful and can be applied for river management.

5. CONCLUSIONS

The field investigation shows that motor boats in spite of small size but high speed can be considered as one of the main reasons causing bank erosion in the rivers, especially where the waterways are heavy. Such a strict rule therefore is needed for river management to reduce the number of motor boats navigating daily as well as a limit for boat speed. The erosion rate not only depends on the correlation between waves and the resistance of soil but also the frequency of boat traffic and ground slope condition. The relationship between vegetation width and percentage of wave height reduction shows that in order to get an expected wave reduction, bigger vegetation width is needed in the case of mild slope compared to steep one. This relationship is useful for engineering field and can be applied for river management.

ACKNOWLEDGEMENT

The study was partially funded by JSPS Asia-Africa Science Platform Program. The authors would like to thank the Thuyloi University (the second base), Service of Agriculture and Rural Development, Ca Mau Province, Vietnam for their great supports during the field investigation.

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