

Laboratory study on tsunami erosion and deposition under protection of rigid emergent vegetation

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Abstract Devastating tsunami waves can change the coastal morphology considerably. The effects of vegetation to coastal morphodynamics have been of primary interest for decades, because of their role in coastal protection and ecological environment. The damping of wave and impact of beach evolution are the two significant contributions on emerged vegetation. However, the laboratory study of tsunami erosion and deposition under protection of coastal vegetation was less understood compared to tsunami run-up and tsunami inundation. A set of laboratory experiments were reported in this study on changes of size-selective sandy beach profile under the protection of rigid emergent vegetation. The total of fifteen experiments was carried out in a wave flume including two initial profiles (with vegetation and none vegetation), three different wave conditions and four forest densities. The experiments show that rigid emergent vegetation changes the depth and location of tsunami deposition and erosion in sandy beach. The dimensionless numbers were derived to characterize the cross-shore beach profile response under the protection of rigid emergent vegetation. These parameters were written as a dimensionless group, and based upon this present experimental datum, the empirical equations were developed. The study reveals the internal connection among tsunami deposition and erosion, wave height and forest density. The findings of this study have the potential to assist the tsunami hazards prevention and mitigation.

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1 Introduction

Tsunami erosion and deposition has received increasing attention over the past decade, given that it produces significant erosion in affected coastal areas, and in particular the wide scale damage to the infrastructure resulting from the 2004 Indian Ocean Tsunami. Devastating 2004 Indian Ocean Tsunami wave mobilized substantial amount of coastal sediments, resulting in a significant morphological changes in attacked coastal areas along the Indian Ocean. Some engineering protections on tsunami erosion and deposition, such as emergent breakwater and submerged breakwater, have thus been studied (Chen et al. 2016). For the last 10 years or so, there has been a growing interest in studies which coastal vegetation had an important function in preventing erosion due to wave attack. Coastal vegetations, such as mangroves, which frequently grow in estuaries, floodplains and places near coastal water, not only could restore or improve the cleanliness of the water, provided fish and wildlife habitats, and supported recreational activities, but also could reduce wave energy, protected the coastline and prevented erosion. This surge of interest is a new approach to a concept which tries to solve coastal engineering problems taking ecological balance into account.

There are some observational evidences suggesting that mangrove forests might have served as tree belt to attenuate tsunami energy and saved several villages from tsunami damage in the 2004 Indian Ocean Tsunami (Danielsen et al. 2005; Iverson and Prasad 2007). The USD 62 million program with the financial support has been endorsed to restore and preserve the coastal vegetation in 12 Asian and African countries for coastal protection against future tsunamis. It is very vital to understand tsunami erosion and deposition under protection of coastal vegetation to mitigate tsunami hazards and reduce potential economical losses in the future.

Several published papers have presented limited flume laboratory studies in an effort to understand tsunami erosion and deposition. Kobayashi and Lawrence (2004) performed to examine the cross-shore sediment transport processes under breaking solitary waves on a fine sandy beach. Moronkeji (2007) conducted physical experiments on the run-up and drawdown of solitary and cnoidal waves over a movable bed at two different beach slopes. Tsujimoto et al. (2008) measured the beach profile changes under solitary waves alone and in combination with regular waves. Young et al. (2010) performed a large-scale experimental study to examine the cross-shore sediment transport by breaking solitary waves. Recently, Chen et al. (2012a, b) performed laboratory experiments to investigate the changes of beach profile and mean sand grain size by tsunami-like waves. The sandy beach sorting and sedimentary characteristic induced by wave action were explored by Jiang et al. (2015a, b). Daghighi et al. (2015) investigated sediment transport, bed formation and sustainability of sandy beaches with different grain sizes under tsunami attack. The above experimental results all show that the tsunami wave is capable of causing sediment motion in both the uprush and backwash phases, producing significant erosion in the affected coastal areas. It is worth focusing on this serious damage. Meanwhile, the above experimental results reveal spatial patterns of tsunami erosion and deposition for sandy beach. One of the primary motivations of present studies is to further understand how coastal vegetation changes the spatial patterns of tsunami erosion and deposition for sandy beach.

In the current literature, it has been generally agreed that vegetation increases flow resistance, reduces wave energy, controls the mean and turbulent flow structure in channels and coastal regions and thus modifies sediment transport and deposition (Nepf and Vivoni 2000; Türker et al. 2006; Natale and Ciarmiello 2011). Hydrodynamic processes play a major role in morphodynamic processes. Firstly, a number of studies on the flow resistance and drag coefficient of rigid emergent vegetation are carried out (Mazda et al. 1997; Huang et al. 2011). On the other hand, several studies have already been performed to analyze wave attenuation in rigid emergent vegetation (Massel et al. 1999; Mazda et al. 2006; Augustin et al. 2009). The current studies provide insight into the details of hydrodynamic in and around the vegetation and, nevertheless, pay less attention to morphodynamic around the vegetation.

The role that vegetations play in the geomorphology of wetland and coast has been acknowledged for more than a 100 years (Cowles 1899). The hypothesis of the protective role of coastal vegetation during storm was mentioned after a catastrophic storm in Bangladesh (Fosberg and Chapman 1971). Then, various laboratorial studies have already addressed. Türker et al. (2006) experimentally explored the protection performance of the emergent vegetation on the morphological changes of a coastal zone under regular or irregular waves. Chen et al. (2012a, b) experimentally investigated the effects of submerged vegetation on the characteristic of flow and the formation of a scour hole. Follett and Nepf (2012) described the sediment patterns formed in a sand bed around a patch of reedy emergent vegetations by laboratory study. Tang et al. (2013) investigated the incipient motion of sediment in open channel covered with emergent rigid vegetations. Lately, Silva et al. (2016) studied the effects of four densities of vegetation cover on the movement of sediment along two beach-dune profiles under three storm conditions. A few mechanistic studies on the role of vegetation in beach profile change have found the situation to be complex. In spite of the relevant information generated in such studies, the role of mangrove forest, or coastal vegetation in general, in protection and decreasing tsunami-induced erosion and deposition is still limited and yet to be investigated.

In conclusion, it is worth focusing on tsunami wave's serious damage, which produces significant erosion in the affected coastal areas. This study pays attention to morphodynamic around the coastal vegetation and wants to further understand how coastal vegetation protects and decreases the tsunami erosion and deposition for sandy beach and to mitigate tsunami hazards and reduce potential economical losses in the future. To achieve these, a total of 15 experiments were carried out in a wave flume including two initial profiles (with vegetation and none vegetation), three different wave conditions and four forest densities. The objectives of this study are summarized to examine (1) the protection performance of the rigid emergent vegetation on tsunami erosion and deposition; (2) the patterns of cross-shore beach profiles affected by rigid emergent vegetation under tsunami wave; (3) the relationships among wave height, forest density and beach evolution.

2 Experimental setup and test procedure

The principal physical mechanism of coastal vegetation must be described in order to model the related changes on a coastal zone. To achieve this, it is necessary to study the beach profile evolution under different wave climates and vegetation densities. However, to establish cause-and-effect relationship between the governing factors and the beach profile response, it should be possible to clearly delineate these relationships. Use of field

actual data as a basis for developing a physical model is extremely difficult due to the complexity of naturally occurring conditions and restriction in experimental conditions. Laboratory facilities provide a well-controlled environment where such investigations may be carried out efficiently at a temporal scale. The similarity and suitability for scaled flume tests with a moving bed under tsunami wave action is also extensively discussed by Chen et al. (2012a, b, 2013, 2016) and Jiang et al. (2015a, b).

Following Chen et al. (2012a, b, 2013, 2016), further experiments were conducted in a 2-dimensional glass-walled wave flume in the Key Laboratory of Water-Sediment Sciences and Water Disaster Prevention of Hunan Province, P. R. China. The dimensions of the wave flume were 40.0 m long \times 0.5 m wide \times 0.8 m deep. A piston-type wave maker was installed at one end of the flume, and a size-selective sandy beach was constructed on the other side of the flume.

For the convenience of describing the sandy beach and the arrangement of the measuring devices, we define a Cartesian coordinate as follows: the x -axis points toward the sand beach with its origin being located at the toe of the sand beach; the z -axis points upward with its origin at the flume bottom; and the y -axis is perpendicular to the side wall of the flume with its origin at the inner surface of the front side of the flume.

Referring to Fig. 1, the slope of the size-selective sand beach changed from 1/10 to 1/20 at $x = 3.5$ m, and the 1/20 slope was 4.0 m long. The sand beach was constructed using the well-sorted natural sand. Sieve analysis was performed on the three different random sand samples. The grading curve of the soil sample obtained from the test is shown in Fig. 2. The sand beach was constructed using a mixture of grain sizes: 0.025% in diameter of 1.20 mm, 9.939% in diameter of 0.6 mm, 59.692% in diameter of 0.30 mm, 23.177% in diameter of 0.15 mm, 6.669% in diameter of 0.075 mm, 0.498% of sand which was finer than 0.075 mm. The sand had a mean median diameter $d_{50} = 0.377$ mm. The mean coefficient of uniformity ($C_u = d_{60}/d_{10}$) for this sand was calculated as 2.33, and the mean coefficient of curvature ($C_c = d_{30}^2/(d_{10} \cdot d_{60})$) was calculated as 1.183. The specific gravity of the sand was 2.51.

Coastal vegetations are generally not homogeneous. They occur in different environmental settings and differ in types of forests. In most of studies, the coastal vegetation was simulated by a group of cylinders of the same height and diameter at a regular spacing (Huang et al. 2011, etc.). The rigid emergent coastal vegetation models were made of polyvinyl chloride tubes with a uniform outer diameter d_t of 1.0 cm. The model was placed on the slope from $x = 2.0$ m to $x = 2.5$ m during the experiment. Four types of cylinder arrangements as shown in Fig. 3 were examined. The model block center space l is 2.50 cm as shown in Fig. 3. The forest density is the so-called solid volume portion of a forest (Tanino and Nepf 2008), which is defined by

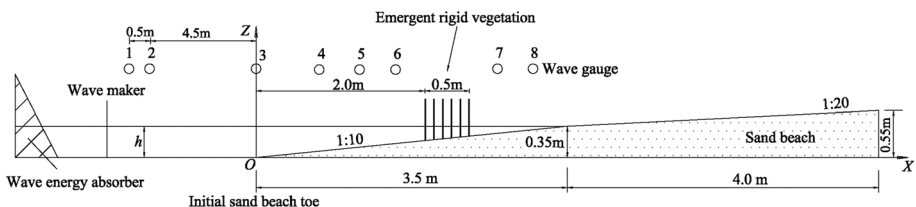


Fig. 1 Experimental setup

Fig. 2 Grading curve of the soil sample

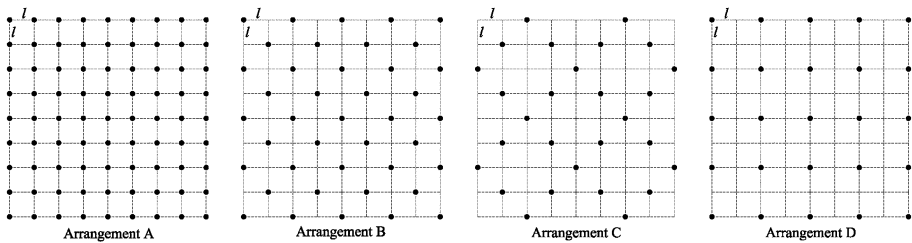
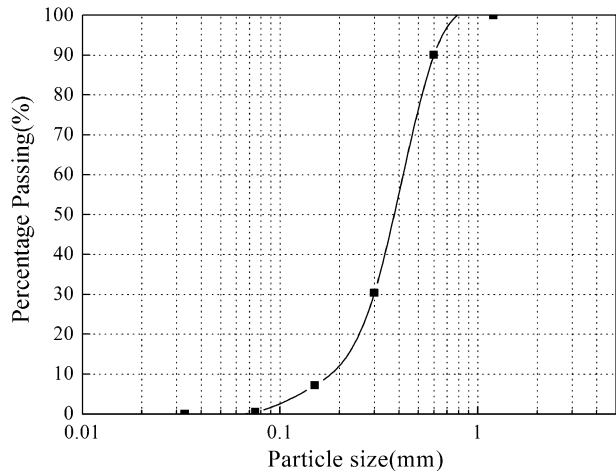


Fig. 3 Vegetation models used in the experiments

$$\varphi = \frac{V_s}{V} \tag{1}$$

with V_s being the volume occupied by solid objects in a control volume V . For these four types of cylinder arrangements, the forest density $\varphi = 0.1243$ for the arrangement A, $\varphi = 0.0621$ for the arrangement B, $\varphi = 0.0475$ for the arrangement C, and $\varphi = 0.0311$ for the arrangement D. The vegetation width was 0.50 m. The vegetation models examined in this study are summarized in Table 1.

Freshwater (from the city tap) was used in the experiment. A series of solitary waves were selected as incident wave in the flume. The water depth was fixed at $h = 0.35$ m, and the solitary wave height varied from 6.0 to 12.0 cm. Fifteen tests were performed. The test conditions examine in the experiment are listed in Table 1.

Six WG-50 capacitance wave gauges (WG, Canadian RBR Limited Liability Company) and two AWMS ultrasonic water level gauges (UWLG, Beijing Sinfotek Science and Technology Co., Ltd) were used to measure the wave surface elevations at selected locations as shown in Fig. 1. The surface elevations were sampled at 50 Hz. The water levels were sampled at 20 Hz. The beach profile change after wave run was measured using the URI-III ultrasonic-impedance topographic meter (UITM, Wuhan University Electronic Information Institute, China), which has measurement accuracy up to ± 1.0 mm. One camera (Logitech C910 HD Webcam with a resolution of 1MP) was located at one side of the wave flume to provide a side view of such processes as wave

Table 1 Summary of test conditions

Case	Wave type	Wave height H (cm)	Vegetation model arrangement	Forest density ϕ
1	Solitary wave	6.0	None vegetation	–
2		9.0		
3		12.0		
4		6.0	Arrangement A	0.1243
5		9.0		
6		12.0		
7		6.0	Arrangement B	0.0621
8		9.0		
9		12.0		
10		6.0	Arrangement C	0.0475
11		9.0		
12		12.0		
13		6.0	Arrangement D	0.0311
14		9.0		
15		12.0		

attenuation in vegetation and beach profile changes. The frame rate of camera was fixed at 15 Hz.

A detailed description of the preparation and measurement of wave surface elevations and bed profiles can be found in Chen et al. (2012a, b), only the key steps are summarized in the following for completeness. Series preparatory experiments were carried out including solitary wave generating, preparation of initial beach profile and beach profile change under the same wave condition before the experiment begins. The repeatability of wave maker in the experiment was satisfactory, and the maximum deviation was less than 3%. The maximum deviation of twice beach profile changes in the same situation was less than 0.2 cm. The overall agreement in the experiment was satisfactory.

The size-selective sandy beach was leveled, and the location of the vegetated area was checked to ensure identical condition during all the experiment stages. Before starting each test, the wave flume was first filled slowly with water to the desired water depth, and then, the sandy beach was allowed to soak for more than 12 h. The initial beach profile was measured using a URI-III ultrasonic-impedance topographic meter. Since the beach profile was almost exactly two-dimensional, the profile measurement was done in the center of the beach. The beach profiles were measured along the center cross section twice to minimize possible random measurement error. Each test started as soon as the wave was generated toward the sandy beach, and the primary result of each test was the final beach profile accomplished as long as the dynamic stability was attained.

Using solitary wave to reproduce tsunami wave itself is not realistic especially when using it to study sediment transport. It is need to generate multiple solitary waves to achieve the measurable amount of bed elevation change, because one solitary wave is not strong enough to move enough sand (Kobayashi and Lawrence 2004; Young et al. 2010; Chen et al. 2012a, b, 2013, 2016; Jiang et al. 2015a, b). The identical solitary wave was run six times for each test condition in Young et al. (2010) and Chen et al. (2012a, b). According to our preparatory experimental results, running identical solitary waves six

times also allow us to study the evolution of the sand beach under wave attacks in the present study. After each trial, the water was allowed to calm for approximately 5 min before another solitary wave run. After collecting datum in one test condition, the sand beach was rebuilt with the same size-selective sand.

3 Experimental analysis

The change of cross-shore beach profile under the protection of rigid emergent vegetation is the function of combination of wave, sediment, vegetation and beach profile parameters. As a result, a general functional expression representing an event related to the effect of rigid emergent vegetation on tsunami erosion and deposition is

$$f(A_e, A_d, d_{e \max}, d_{d \max}, H, d_{50}, \varphi, \tan \alpha, \gamma_s, \gamma_w) = 0 \tag{2}$$

where A_e and A_d are the area of tsunami erosion and deposition in center cross section, respectively; $d_{e \max}$ and $d_{d \max}$ are the maximum depth of tsunami erosion and deposition in center cross section, respectively; H is the incident wave height; d_{50} is the mean median diameter of the sandy beach; φ is the forest density of rigid emergent vegetation; $\tan \alpha$ is the initial slope of the beach profile; γ_s is the specific weight of sediment; γ_w is the specific weight of water.

Because of the larger number of parameters in Eq. (2), it is necessary to simplify the analysis by making use of the dimensional properties of the various parameters; this results in

$$\Pi(\underbrace{A_e/H^2, A_d/H^2, d_{e \max}/H, d_{d \max}/H}_{\text{Tsunami erosion and deposition}}, \underbrace{H/d_{50}}_{\text{Wave}}, \underbrace{\varphi}_{\text{Vegetation}}, \underbrace{\tan \alpha}_{\text{Slope}}, \underbrace{\gamma_s/\gamma_w}_{\text{Sediment}}) = 0 \tag{3}$$

In the above equation, A_e/H^2 and $d_{e \max}/H$ are dimensionless tsunami erosion parameters, respectively; A_d/H^2 and $d_{d \max}/H$ are dimensionless tsunami deposition parameters, respectively; H/d_{50} is dimensionless tsunami wave parameter; φ is the dimensionless vegetation parameter; $\tan \alpha$ is the initial beach slope; $s_d = \gamma_s/\gamma_w$ is dimensionless sediment parameter.

Keeping the beach slope constant and using the same size-selective sand in all experiments bring about an uncertainty in their effect on the beach profile change. The dimensionless wave parameter H/d_{50} indicates the dominance of wave height and grain size on the cross-shore transport processes. Türker et al. (2006) defined a dimensionless parameter named vegetation parameter and use a single indicator for distinguishing beach profile change named as Number of Vegetated Profile in their experiments, which is consider initial beach slope and specific weight parameter, together with the dimensionless vegetation parameter. It is inconvenient to get the spacing between two adjacent polyvinyl chloride tubes parallel and perpendicular to incident wave direction in vegetation parameter for vegetation model arrangement B and arrangement C in this paper. The initial beach slope $\tan \alpha$ and specific weight $s_d = \gamma_s/\gamma_w$ are constant in the present study. Consequently, the forest density of rigid emergent vegetation φ defines the dimensionless vegetation parameter.

4 Results and discussions

The initial bed profile and those after running six solitary waves (wave height $H = 12.0$ cm) under the protection of rigid emergent vegetation are plotted in Fig. 4a–d, and the comparisons of without vegetation are also given in Fig. 4a–d. For cases 1–3 without vegetation model, erosion on the shore face and deposition offshore are found. The sand erosion and deposition patterns are consistent with results of Kobayashi and Lawrence (2004), Young et al. (2010) and Chen et al. (2012a, b), who found in their experiments that the strong backwash water could cause erosion on the foreshore and a deposition seaward of the shoreline. For case 4–case 15 under the protection of vegetation, erosion on the shore face and deposition offshore are also found. The only differences are that the depth and location of deposition and erosion change. The experimental results show that the rigid emergent vegetation could change spatial patterns of erosion and deposition for sandy beach and effectively reduce the beach scouring. The reason for such reduction is that vegetation dissipates substantial wave energy due to friction and drag force; thus, the solitary wave loses its energy, which is necessarily used to erode the beach profile.

The solitary wave height variations on the sandy beach are shown in Fig. 5a–d for case 4–case 15. Based on the datum collected by WG and UWLG, as well as video recordings in camera, the solitary wave propagates on the slope, influenced by shoaling as the depth of water decreases, the wave height augments. In the front of vegetation model, the solitary wave height reaches maximum. When wave propagates over the vegetation model, the solitary wave height decreases rapidly. The wave energy is dissipated, while waves transmit through the vegetation. Then, solitary wave plunging on the thin layer of water

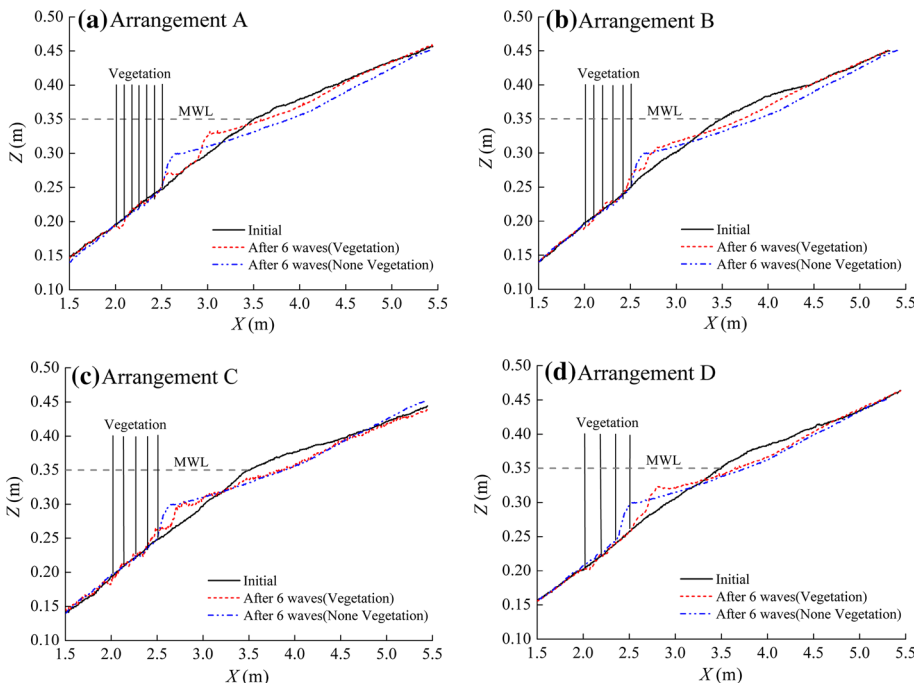


Fig. 4 Experimental results of center cross-section beach profiles under $H = 12$ cm solitary waves attack

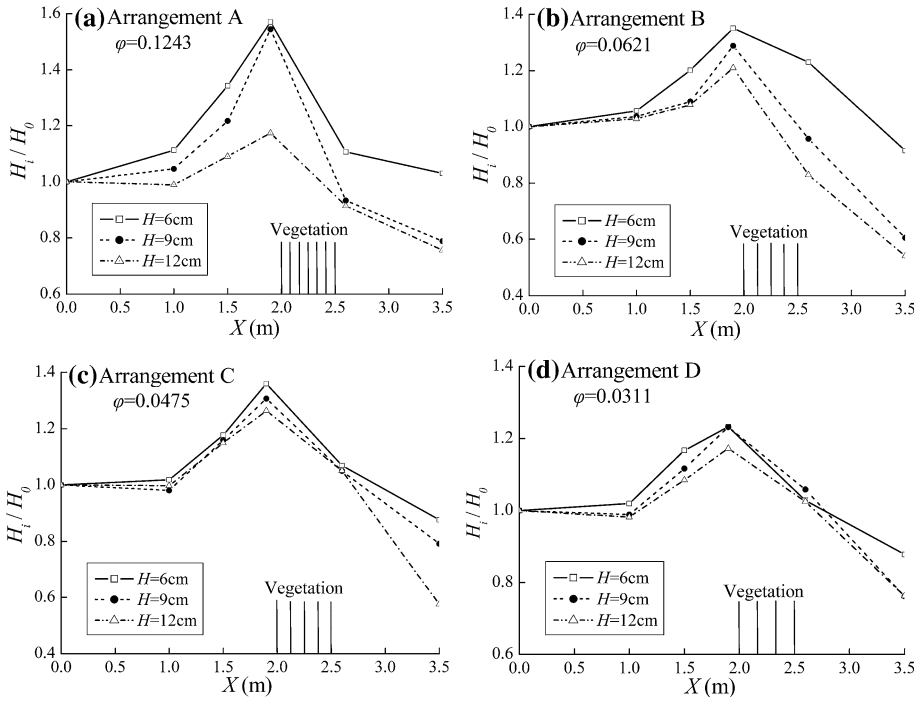


Fig. 5 Experimental results of the solitary wave height variation on the beach (case 4–15)

prior to reaching the shoreline not entrains much sediment. The waves uprush to the maximum and then downwash toward seaward. The backwash flow velocity is high and the water depth is shallow with high sediment concentration, which is resulted in net erosion of this region. As the flow with high concentration of sediment injects into the bottom of the rundown jump, a large recirculation region is formed by the same process which leads to the rundown jump. The sudden deceleration of the sediment-rich seaward flow, as well as the long particle residence time caused by the recirculation region, allows the sediments to deposit in this region. Consequently, an offshore bar is observed in the recirculation region.

The changes of center cross-section bed elevation in different wave parameters H/d_{50} under solitary wave actions are given in Fig. 6a–d. The experimental results show that the height of deposition sand bar and depth of scouring hole increase, as wave parameter H/d_{50} increases. Meanwhile, the location of maximum deposition sand bar moves to seaward and the location of maximum scouring depth moves to shoreward as wave parameter H/d_{50} increases. The experimental analysis shows that the amount of erosion and deposition is directly proportional with the wave height and inversely proportional with the sediment particle diameter. Therefore, predefined dimensionless erosion and deposition parameters can be related to the number of wave parameter H/d_{50} .

The changes of center cross-section bed elevation in different forest densities vegetation under solitary wave actions are given in Fig. 7a–c. The experimental results show that the height of deposition sand bar and depth of scouring hole decrease, as forest density of rigid emergent vegetation ϕ increases. Huang et al. (2011) found that the reflection and transmission coefficients are strongly depend on vegetation density ϕ . Less dense vegetation gives out a smaller reflection coefficient. The transmission coefficient increases with

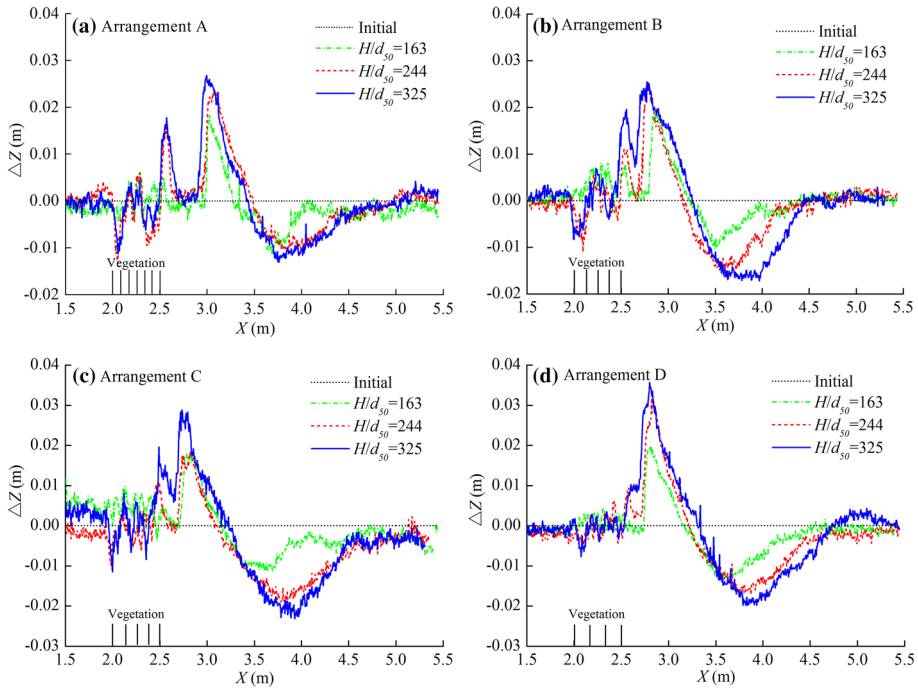


Fig. 6 Experimental results of center cross-section bed elevation changes in different wave parameters under solitary wave attack

decreasing vegetation density. Dense vegetation may decrease the wave transmission and also reduce the height of deposition and depth of scouring. The experimental analysis shows that the amount of erosion and deposition is directly proportional with vegetation density. Therefore, predefined dimensionless erosion and deposition parameters can be related to the number of vegetation density φ .

The tsunami erosion and deposition parameters are finally defined in terms of the above dimensionless parameters. Hence, the final empirical relation that defines the amount of erosion under the protection of rigid emergent vegetation in present experimental conditions is

$$A_e/H^2 = 54.570(H/d_{50})^{-0.890}(\varphi)^{-0.408} - 0.150 \tag{4}$$

$$d_{e\max}/H = 0.574(H/d_{50})^{-0.260}(\varphi)^{-0.184} - 0.088 \tag{5}$$

The linear relation between the empirical equation and the dimensionless erosion parameters is given in Fig. 8. The coefficients of determination between the dimensionless parameters are 0.878 and 0.855, respectively. The effects of solitary wave on beach profile deposition under the protection of rigid emergent vegetation yield in present experimental conditions an empirical equation given as

$$A_d/H^2 = 752.959(H/d_{50})^{-1.704}(\varphi)^{-0.550} + 0.362 \tag{6}$$

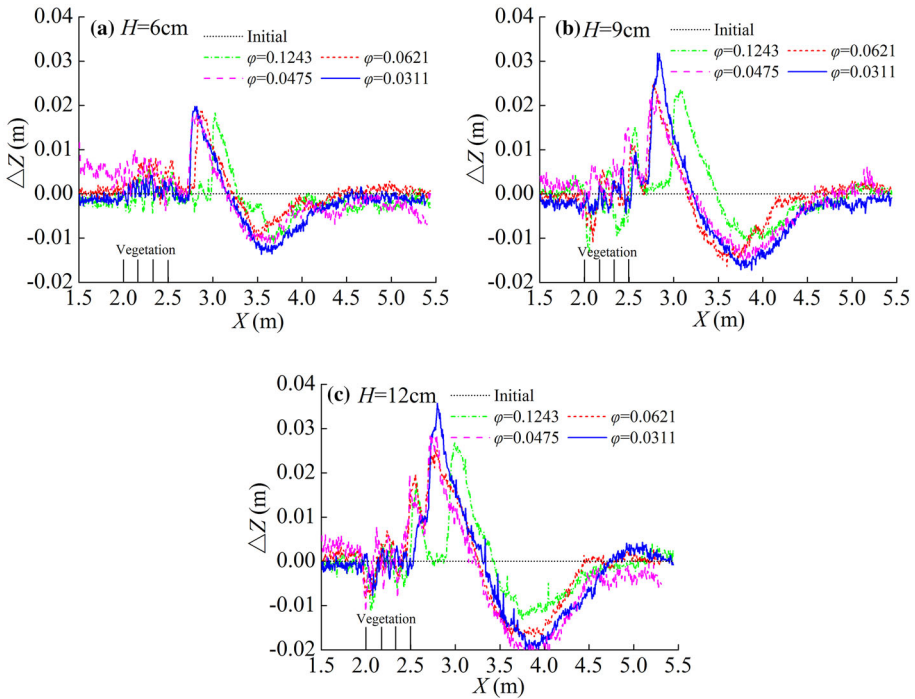


Fig. 7 Experimental results of center cross-section bed elevation changes in different forest density vegetations under solitary wave attack

$$d_{d \max}/H = 5.097(H/d_{50})^{-0.016}(\varphi)^{-0.011} - 4.566 \tag{7}$$

Above empirical definition also follows the linear relationship possessing good trend between the dimensionless parameters as shown in Fig. 9. The determination coefficients are 0.829 and 0.824, respectively. The results show that dimensionless erosion parameters A_e/H^2 and $d_{e \max}/H$ and dimensionless deposition parameters A_d/H^2 and $d_{d \max}/H$ are affected by wave parameter H/d_{50} and forest density φ . The A_e/H^2 , $d_{e \max}/H$, A_d/H^2 and $d_{d \max}/H$ increase, as H/d_{50} and φ decrease.

The depths of erosion and deposition are one of the main factors leading to describe beach evolution. According to Eqs. (5) and (7), the theoretical maximum depth of erosion $d_{e \max}$ is 1.8 cm and the theoretical maximum depth of deposition $d_{d \max}$ is 3.1 cm for case 15 (solitary incident wave height $H = 12.0$ cm; forest density $\varphi = 0.0311$), as shown in Fig. 10. The experimental results show that the experimental maximum depth of erosion $d_{e \max}$ is 1.9 cm, and the experimental maximum depth of deposition $d_{d \max}$ is 3.5 cm for case 15 according to Fig. 6d. The predicted results are in good agreement with the experimental datum. As shown in Fig. 10, the results indicate that the maximum depth of erosion $d_{e \max}$ and deposition $d_{d \max}$ decreases as incident wave height H decreases and forest density φ increases. Meanwhile, the same variation law for the area of erosion A_e and deposition A_d is found according to Eqs. (4) and (6).

Türker et al. (2006) presented the two segments (static stability and dynamic stability) of beach profiles under the protection of emergent vegetation according to his fourteen groups of experimental datum. A criterion to distinguish static and dynamic stability was

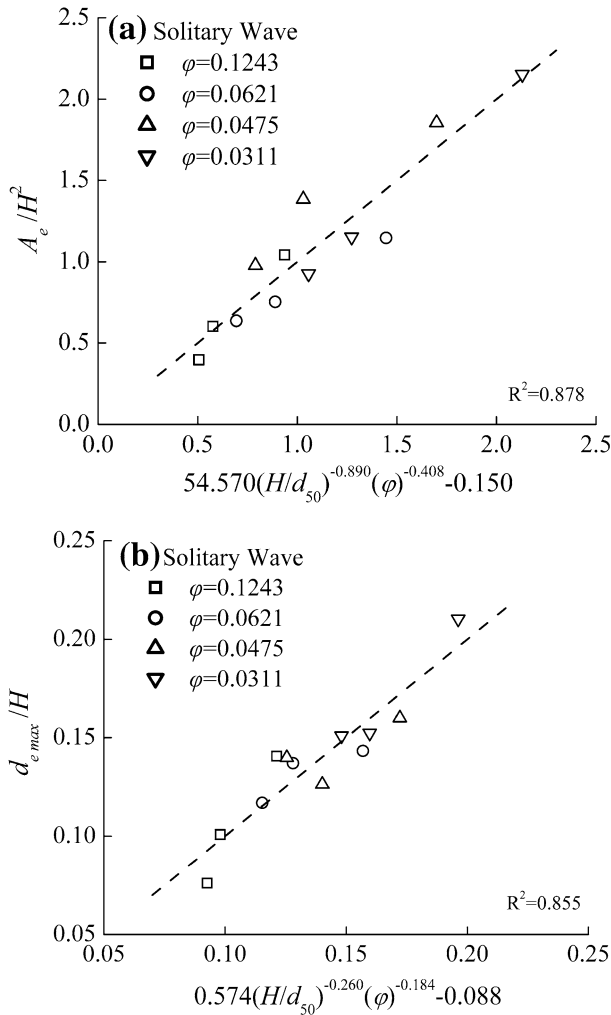


Fig. 8 Dimensionless trend of beach erosion under solitary waves attack

proposed in his paper, considering the above two segments. The dimensionless parameter named ‘vegetation parameter’ Ψ represents the magnitude of vegetated area defined by the amount of reeds per unit grid area, $\Psi > 40$; static stability of the beach profile was predicted, whereas the condition $\Psi < 40$ indicates dynamic stability.

Meanwhile, the two segments are also presented in this paper. As shown in Fig. 10a, b, when the forest density $\varphi < 0.05$, the gradually declining curve facing to the origin develops to a vertical asymptote, and the vegetation could quantitatively reduce beach evolution with increasing its density. If the forest density $\varphi > 0.2$, the linearly sloping face along the horizontal axes can be approximated into a linear equation which occurs as the change in $d_{e\max}$ and $d_{d\max}$ asymptotes to horizontal axes; further reduction in beach evolution is not significant. Consequently, beach profile of static and dynamic stability could be presented in this experimental condition. For the case of static stability, within

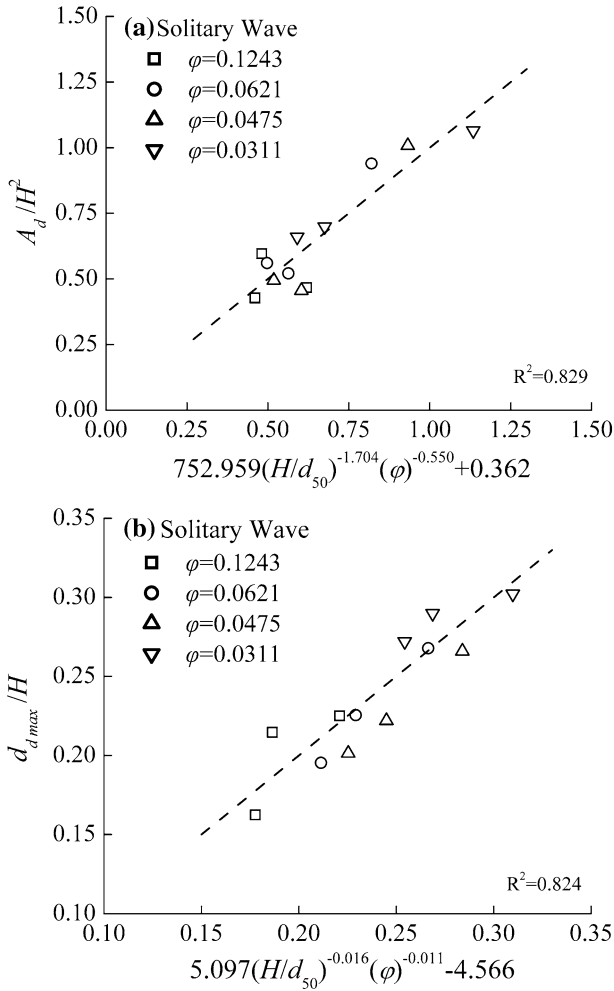


Fig. 9 Dimensionless trend of beach deposition under solitary waves attack

forest density $\phi > 0.2$, the change in beach profile is negligibly small, which compared with the change when dynamic stability is dominating. There is the transition between dynamic stability and the static stability of beach profile for forest density $0.05 < \phi < 0.2$.

5 Concluding remarks

The tsunami erosion and deposition under the protection of rigid emergent vegetation was studied experimentally. Hence, a size-selective sandy beach under solitary wave actions was conducted. The rigid emergent vegetation changes the spatial patterns of erosion and deposition for sandy beach and effectively reduces the beach scouring. The most important governing parameters on tsunami erosion and deposition under the protection of rigid emergent vegetation, tsunami wave parameter H/d_{50} and vegetation density ϕ were

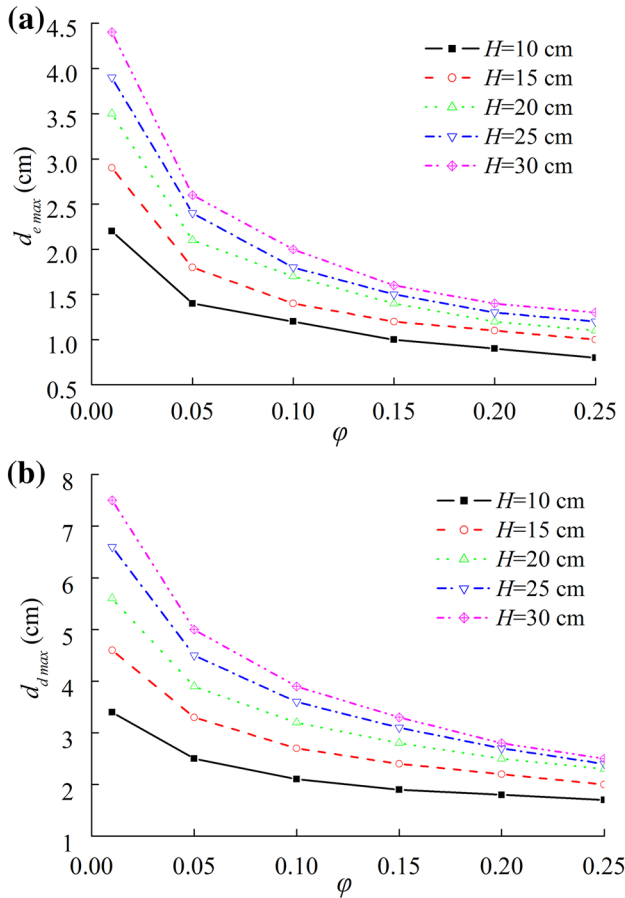


Fig. 10 Variations of maximum depth of erosion and deposition with incident wave height of solitary wave and forest density

defined. These parameters were written as a dimensionless group, and based upon this present experimental datum the empirical equations were developed. The study reveals that dimensionless tsunami erosion and deposition parameters A_e/H^2 , $d_{e\max}/H$, A_d/H^2 and $d_{d\max}/H$ increase as tsunami wave parameter H/d_{50} and vegetation density ϕ decrease. The dynamic stability and static stability of beach profiles under the protection of rigid emergent vegetation are presented in this experimental condition. The forest density plays the opposite effect in variations of maximum depth of erosion and deposition. In present experimental conditions, the results show that coastal vegetation could quantitatively reduce beach evolution with increasing its density when the forest density $\phi < 0.05$; if the forest density $\phi > 0.2$, the further reduction in beach evolution is not significant. That means we should plant coastal vegetations with reasonable density for coastal protection against future tsunamis.

In the present study, the coastal vegetation was simplified to a group of rigid cylinders with the same height and diameter at a regular spacing, while the root and canopy were ignored in laboratorial models. Coastal vegetations, such as mangroves, generally are with

thick trunk, flourishing roots, luxuriant foliage and spreading branches. Further research is needed to relate the more real coastal vegetation model with roots, leaves, stems and foliage.

One of the difficulties in studying tsunami-induced sediment transport under laboratory conditions lies in downscaling the tsunami flows and sand grains in physical modeling. Meanwhile, there are too many influencing factors in this topic, such as wave height, water depth, beach slope, sediment particle size, vegetation stem size, plant width and forest density. These experimental studies were restricted by many factors, such as the performance of the wave maker, size of wave flume and scaling. Hence, more vegetation stem sizes, plant widths, sediment particle sizes, wave conditions and beach slopes should be considered in future experimental design. The most promising approach to prediction of beach profile change under the protection of vegetation seems to conduct in big wave flume to better solve the scaling of wave, sediment and vegetation in future laboratorial research.

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