Experimental Investigations of Wave Height Attenuation by Submerged Artificial Vegetation

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Abstract Coastal populations around the world are at a greater risk of damage from coastal hazards due to the unprecedented rise of global climate change characterized by sea-level rise, longer and frequent droughts and floods, heightened cyclonic and storm surge activities. The narrow fringe of vegetated coastal habitats along the shores of continents mainly acts as a buffer for the impacts of rising sea levels and wave action. The losses from natural disasters like the 2004 Indian Ocean tsunami, Hurricane Katrina, and others have reached an all-time high, and the decision-makers now realize that coastal habitats have an important role to play in risk reduction. Though coastal vegetation, as a shore protection method, is sustainable, environment friendly, and cost-effective, its behavior with wave is very complex, especially because of the coupling between the waves and vegetation motion and is therefore, not completely understood. Numerical modelling approach, having based on more assumptions and field study, being uneconomical fomented the need for the study in the form of physical modelling. This paper focuses on figuring out the effect of vegetation on wave attenuation through an experimental approach. The wave flume of length 50 m, height 1 m, and width 0.71 m is used to study the characteristic behavior of submerged heterogeneous vegetation of varying width for wave heights ranging from 0.08 to 0.16 m with an increment of 0.02 m and wave periods 1.8 and 2 s in water depths of 0.40 and 0.45 m. Measurements of wave heights at locations along the vegetation were observed to quantify wave attenuation and its trend.

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Introduction

Coasts are dynamic environments which are subjected to continuous and extensive changes in response to winds, waves, sea levels, and currents. These changes can become large and catastrophic during extreme events like cyclones, storm surges, and tsunami. High waves can result in erosion of beaches and inundation of low-lying lands. The forces of waves and currents can cause landward displacement of the shoreline which can in turn cause coastal erosion. An unprotected shoreline can easily be taken away by the sea. Man has continuously evolved methods to keep his settlements protected from the onslaught of the advancing sea. Hard methods of coastal protection including massive constructions was prevalent during the nineteenth and twentieth centuries, but alternative approaches harnessed from nature or natural resources have gained acceptance in the recent past (Charlier et al. 2005). The world's oceans are home to an abundance of important habitats ranging from seagrasses, coral reefs, and kelp forests to salt marshes and mangrove forests. Coastal vegetation aids in shoreline protection by damping the incoming waves and dissipating the energy. However, the hydrodynamics of vegetated coastal zones and the mechanism of wave attenuation through vegetation are still not fully understood (Massel 1999).

Pioneering studies on interactions between submerged vegetation and wave-induced flows include analytical solution of wave height attenuation due to a kelp farm, with kelp plants modelled as rigid cylinders (Dalrymple et al. 1984); experimental study on wave damping using artificial seaweed (Asano et al. 1988); effect of submerged or subaerial vegetation on wave activity expressed in terms of drag resistance against the fluid motion (Kobayashi et al. 1993); interaction between waves and vegetation motion with the analysis for the flow field and the swaying motion of an individual vegetation stand (Asano et al. 1992); and analytical solution for the vegetation motion of kelp fronds and kelp plant models (Dubi and Torum 1994).

Numerous experimental, numerical, and field studies have been conducted to investigate the effect of seagrasses (Gambi et al. 1990; Fonseca and Cahalan 1992; Ciraolo et al. 2006; Stratigaki et al. 2011; Koftis et al. 2012; Zeller et al. 2014), kelp forests (Dubi and Torum 1994; Elwany et al. 1995; Lovas and Torum 2001; Rosman et al. 2013), salt marshes (Bouma et al. 2005; Ozeren et al. 2013), and mangroves (Struve et al. 2003; Husrin et al. 2012; Strusinska-Correia et al. 2013) on wave activity. Gedan et al. (2011) presents a literature review and meta-analysis of wave attenuation data, which suggests that salt marsh and mangrove vegetation provides protection from erosion, storm surge, and potentially small tsunami waves. An experimental project which evaluated the wave energy attenuation associated with living shorelines (which included intertidal oysters and cordgrass) revealed that the living shoreline stabilization could attenuate a significant amount of wave energy produced by boat wakes (Manis et al. 2015).

The 2004 Indian Ocean tsunami which wreaked devastation across the Indian Ocean coastline, including the southeastern coast of India, marked a critical turning point for the scientists and administrators in India. The vulnerability of coasts to sudden catastrophic events gained importance, and measures to protect our coastline have become a prime concern. Kathiresan and Rajendran (2005), in their study of tsunami-hit regions, reported that agricultural fields suffered enormous loss due to intrusion of seawater in regions not protected by mangroves and other coastal vegetation and reiterated that mangroves prevent the entry of seawater inland, thus protecting the underground water systems essential for drinking water supply. Post-tsunami reconnaissance investigations along the most affected coastal stretches of India revealed that the thick forest of interwoven mangrove vegetation along the backwater canals of Pichavaram decelerated the gush of tsunami shoreward, thus greatly protecting the hamlet from the impact of tsunami (NIO 2005). Jayakumar et al. (2005) carried out a post-tsunami survey to ascertain the inundation limits at different locations along the tsunami-affected coastline. It was observed that the inundation values were lower at places where the coast is protected by dunes. However, the inundation values were higher wherever openings were found in dunes, as these openings provided a gateway for the water mass to travel through them to the hinterland. With reference to the Tamil Nadu coast (Southeast of Indian Peninsula), field observations with relevant measurements revealed that sand dunes and casuarina forests could aid in dissipating powerful waves (Mascarenhas and Jayakumar 2008). The soft measures of coastal protection thus gained importance in India during the post-tsunami years. Some of the early experimental works which shot up from this need were conducted in the 72 m long, 2 m wide, and 2.7 m deep wave flume at the Department of Ocean Engineering, Indian Institute of Technology Madras, India, by Sundar et al. (2011), Lakshmanan et al. (2012).

Sundar et al. (2011), from IIT Madras, India, in their detailed experimental investigations, studied the effect of vegetation in reducing the wave run-up and the variation of pressure on a wall fronted by different arrangements of vegetation, by varying the vegetative parameters such as diameter of stem, spacing between the stems, width of the green belt, and their rigidity. Lakshmanan et al. (2012) presented the variation of forces on a model building mounted over a slope, positioned at different distances from the vegetation belt, and subjected to the action of Cnoidal waves as a function of flow and vegetation parameters. The authors also studied the hydroelastic interaction of flow with vegetal stems and the resulting wave run-up on beach slopes (Noarayanan et al. 2012). The present paper aims to determine the wave height attenuation through varying widths of submerged artificial heterogeneous vegetation acted upon by varying wave parameters.

Methods

Experimental Setup and Instrumentation

The two-dimensional wave flume of Marine Structures Laboratory of the Department of Applied Mechanics and Hydraulics, National Institute of Technology Karnataka, Surathkal, is used to test the physical models of submerged artificial vegetation. The flume is 50 m long, 0.71 m wide, and 1.1 m deep. Figure 1 shows a schematic diagram of the setup of the present experiment.

The flume has a 6.3 m long, 1.5 m wide, and 1.4 m deep chamber with a bottom-hinged flap at one end which generates waves. The wave filter consists of a series of vertical asbestos cement sheets spaced at about 0.1 m center-to-center and parallel to length of the flume. A flywheel and bar-chain link the motor with the flap. By changing the eccentricity of bar chain on the flywheel, the wave height can be varied for a particular wave period. By changing the frequency through inverter, waves of desired wave period can be generated. The flap is controlled by an induction motor of 11 kW power at 1450 rpm, which in turn is regulated by an inventor drive (0–50 Hz), rotating in a speed range of 0–155 rpm. Monochromatic waves of heights 0.08–0.24 m and periods of 0.8–4.0 s in a maximum water depth of 0.5 m can be generated in this flume. In order to reduce reflection from the end of the flume, a rubble-mound wave absorber is in place at the other end of the flume. Four capacitance-type wave probes along with amplification units are used for data acquisition in the present experimental study. The spacing between probes is adjusted approximately to one-third of the wave length to ensure accuracy (Isaacson 1991). A MATLAB program based on the Isaacson's three-probe method is employed for separating the incident and reflected components of the signals recorded by the wave probes. Signals from wave probes are recorded by the computer through the data acquisition system.

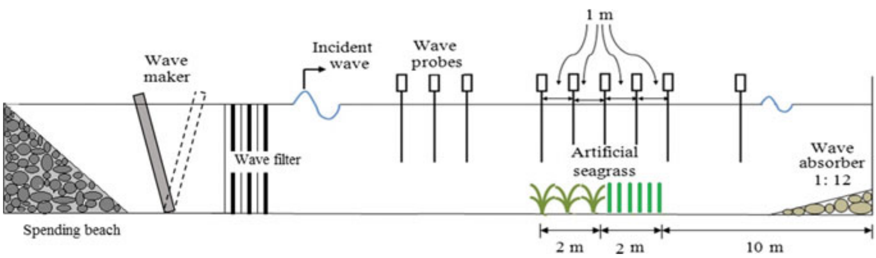

Fig. 1 Schematic diagram of experimental setup with submerged artificial vegetation

Test Models

To investigate the effect of width of vegetation on wave attenuation, two model scenarios are of interest in the present paper. The model scenarios include two cases of varying width of vegetation. The first case, represented by model 1, is a submerged artificial vegetation meadow of 3 m width, placed on the horizontal part of the flume bed. This is a combined heterogeneous model comprising of a 2 m wide seagrass meadow followed by a 1 m wide rigid vegetation meadow (rigid in the sense that the vegetation considered here is a submerged stem which may vibrate under the influence of passing waves, but this is very much less compared to the swaying motion of the seagrass leaves or kelp fronds). Model 2 is defined by a submerged artificial vegetation meadow of width 4 m; which also is a combined heterogeneous model, comprising of a 2 m wide seagrass meadow followed by a 2 m wide rigid vegetation meadow.

The submerged artificial seagrass is prepared from 0.1 mm thick polyethylene plastic sheets, whereas the submerged rigid plant model is made of nylon rods of diameter 0.010 m. In order to replicate the original vegetation in the field, a suitable material for the model is selected based upon the Young's modulus of natural vegetation. This is a measure of stiffness of the elastic material and is used to characterize the material property. The value of Young's modulus for seagrass is in the range 0.4–0.8 GPa (Folkard 2005), and that for common timber is in the range 10.05–15 GPa. In order to cover this range of *E*, a reference value of 0.7 and 11.5 GPa is assumed for the seagrass and the rigid vegetation, respectively, for the field condition. A reference value of 0.7 and 11.5 GPa, which falls in the above-mentioned range, is assumed for the seagrass and the rigid vegetation, respectively, for the field condition. A model scale of 1:30 is adopted in this experiment to scale down the prototype values. This would mean that the value of Young's modulus of the model material should be about 0.023 and 0.383 GPa, respectively. A material corresponding to this value is quite difficult to be identified for this type of vegetation model. Therefore, the stiffness property, *EI*, is modelled as a single parameter, instead of separately modelling Young's modulus, *E*, and the second moment of area, *I*. Thus, the appropriate material chosen for simulating seagrass leaves and the rigid vegetation trunks for this study is polyethylene with an *E* value of about 0.6 GPa and nylon with an *E* value of about 3 GPa, respectively. Accordingly, the prototype dimensions of seagrass leaves as well as the diameter of the rigid vegetal stems are fixed. The artificial vegetal models used for the experiments are shown in Fig. 2.

The seagrass model consists of a stipe of height 0.01 m, leaves of length 0.21 m, and placed at a spacing of 0.005 m. Each simulated plant is composed of 4–5 polyethylene leaves and is attached to 1 m $\times$ 0.73 m $\times$ 0.02 m concrete slabs in a staggered distribution. The rigid plant model is constructed by fixing rigid nylon

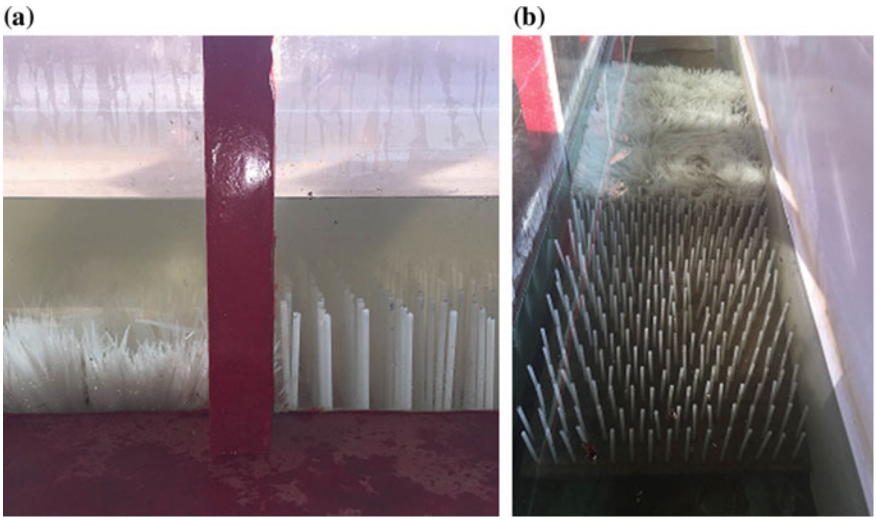

Fig. 2 Photo of model setup to study wave attenuation over a submerged heterogeneous artificial vegetation. **a** side view, **b** plan view

rods in holes drilled in 1 m × 0.73 m × 0.04 m concrete slabs. The rods are 0.010 m in diameter and 0.21 m long. Model scenario I of meadow width 3 m and model scenario II of width 4 m are placed over the flume bed, 30 m away from the wave flap and tested separately. Figure 2 illustrates a 1:30 scaled artificial heterogeneous vegetation model placed on the horizontal part of the flume bed.

Test Procedure

The models designed as submerged artificial vegetation are tested for the wave height attenuation when subjected to varying wave heights and wave periods in a water depth of 0.40 and 0.45 m in a two-dimensional wave flume. The vegetation test sections are subjected to normal attack of waves of characteristics as described in Table 1. The incident wave height, wave heights at locations within the meadow, and the wave transmission are recorded during the physical model investigation.

The wave flume is filled with ordinary tap water to the required depth. Before starting the experiment, the flume was calibrated to produce the incident waves of different combinations of wave height and wave periods. These models were tested for wave height attenuation in water depths (d) of 0.40 and 0.45 m with varying waves of heights (H) of 0.08–0.16 m, with an increment of 0.02 m and wave periods (T) of 1.8–2 s.

Table 1 Vegetation characteristics and experimental conditions

Artificial plant type	Vegetation model characteristics		Wave height (m)	Wave period, T (s)	Water depth, d (m)	Relative plant height (h_s/d)
Seagrass	Modulus of elasticity	0.6 GPa	0.08, 0.10, 0.12, 0.14, 0.16	1.8, 2	0.40, 0.45	0.525, 0.47
	Thickness of leaf	0.0001 m				
	Length of leaf	0.21 m				
	Width of leaf	0.004 m				
	Plant density	10,000 shoots/m^2				
Rigid vegetation	Modulus of elasticity	2–4 GPa	0.08, 0.10, 0.12, 0.14, 0.16	1.8, 2	0.40, 0.45	0.525, 0.47
	Length of rod	0.21 m				
	Diameter of rod	0.010 m				
	Rod spacing	0.05 m				

Results

In this section, the variation of wave heights within the submerged vegetation meadow as well as the influence of relative plant height (h_s/d) on wave attenuation is analyzed for the two model scenarios, I and II.

Wave Height Attenuation

The measured wave heights at locations within the 3 m wide artificial submerged heterogeneous vegetation model (h_s/d = 0.525, 0.47) corresponding to wave periods, T = 1.8, 2 s are illustrated in Fig. 3.

It is observed that wave height attenuation along the meadow follows exponential decay, and the exponential curves obtained falls one below the other in decreasing order of wave heights. The percentage wave height at the exit point of the 3 m wide meadow for h_s/d = 0.525 is 44.8% and for that of h_s/d = 0.47, it is 53.3%. Figure 4 represents wave heights at locations within the 4 m wide meadow (h_s/d = 0.525, 0.47) corresponding to wave periods, T = 1.8, 2 s. The percentage wave height at the exit point of the 4 m wide meadow for h_s/d = 0.525 is 41.5% and that of h_s/d = 0.47 corresponds to 46%.

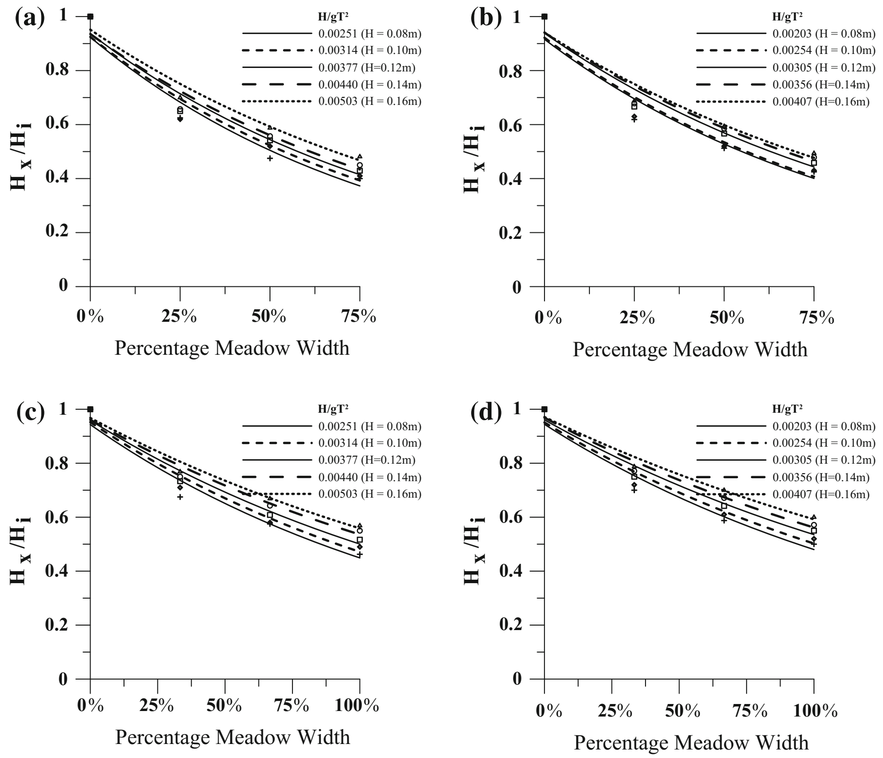

Fig. 3 Relative wave heights (H_x/H_i) at locations within the submerged heterogeneous vegetation model for **a** $w = 3$ m, $T = 1.8$ s, $h_s/d = 0.525$, **b** $w = 3$ m, $T = 2$ s, $h_s/d = 0.\ 525$, **c** $w = 3$ m, $T = 1.8$ s, $h_s/d = 0.47$, **d** $w = 3$ m, $T = 2$ s, $h_s/d = 0.\ 47$

Effect of Relative Plant Height ($\mathbf{h_s/d}$) *on Wave Attenuation*

The relative plant height represents the height of submergence of the vegetation with respect to the depth of water. An increase in relative plant height results in higher attenuation of incident wave height along the vegetated meadow. For the submerged vegetation model of 3 m width, the percentage wave height at the exit point of the meadow is nearly 44.8% for the case of higher relative plant height ($h_s/d = 0.525$) and 53.3% for $h_s/d = 0.47$; whereas, for the same vegetated meadow of width 4 m, it is nearly 41.5% for $h_s/d = 0.525$ and 46% for $h_s/d = 0.47$ (Fig. 5).

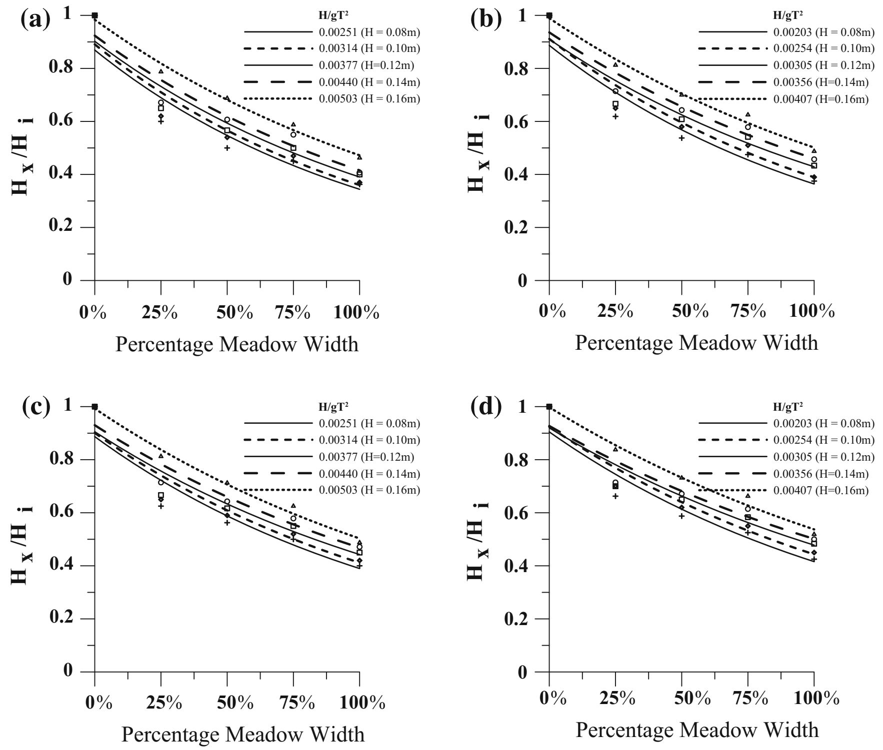

Fig. 4 Relative wave heights (H_x/H_i) at locations within the submerged heterogeneous vegetation model for **a** $w = 4$ m, $T = 1.8$ s, $h_s/d = 0.525$, **b** $w = 4$ m, $T = 2$ s, $h_s/d = 0.\ 525$, **c** $w = 4$ m, $T = 1.8$ s, $h_s/d = 0.47$, **d** $w = 4$ m, $T = 2$ s, $h_s/d = 0.\ 47$

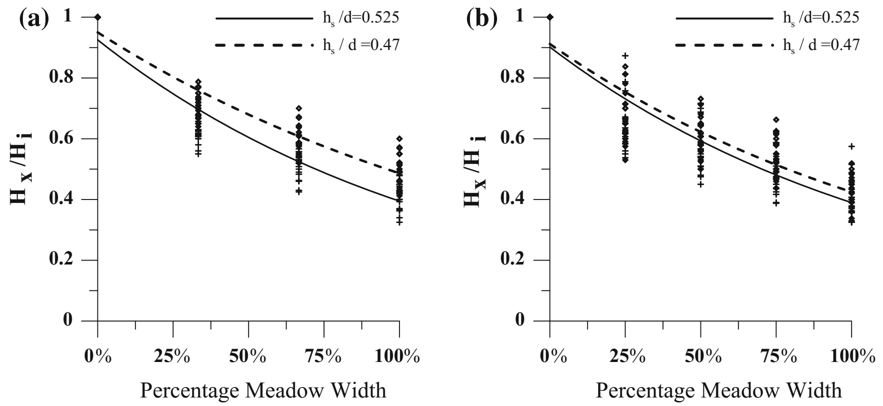

Fig. 5 Effect of relative plant height on wave attenuation for submerged heterogeneous vegetation model of width **a** $w = 3$ m, **b** $w = 4$ m

Conclusions

Wave heights decay exponentially as the wave propagates through the submerged vegetation. The wave orbital velocities are intercepted by the vegetation which results in increased turbulence, which in turn gives rise to loss of energy and reduction in wave heights.

As the relative plant height (h_s/d) increases from 0.47 to 0.525, both the model scenarios of width 3 and 4 m exhibit increased efficiency in wave height reduction. The percentage wave heights at the exit point of the meadow are 53.3 and 46% for a lower relative plant height of 0.47, when compared to 44.8 and 41.5% for a higher relative plant height of 0.525.

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