

## Experimental Study on the Effectiveness of Emerged and Submerged Coastal Bio-Shield in Storm Surge Protection

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### Abstract

Surges and waves induced by cyclones and other severe storms can cause devastating damage of property and loss of life in coastal areas of Bangladesh. Bio-shield in wetlands can reduce the energy of storm surges and cyclones. To study the effectiveness of emerged and submerged coastal bio-shield in storm surge protection, a laboratory experiment was carried out in a 22 m long, 0.75 m wide and 0.75 m deep wave flume in the Hydraulics and River Engineering Laboratory of Bangladesh University of Engineering and Technology (BUET). Experiments were carried out for investigating the performance of the bio-shields in submerged as well as emerged conditions. Bio-shields were represented by cylindrical bamboo sticks as rigid bio-shield and polyethylene as flexible bio-shield whose diameter was 6 mm. There were a total of 51 experimental runs covering 3 different wave periods of 1.6, 1.8 and 2.0 seconds. Time-series of water surface elevations for vegetated (with bio-shield) and non-vegetated (without bio-shield condition) were compared to identify the influence of bio-shield on wave height reduction. It is found for emerged and submerged conditions of bio-shield that the maximum wave height reductions are 71% and 52% at a location which is 3.5 m away from the embankment for wave periods of 2.0 sec at bio-shield spacing of 50 mm c/c and 25 mm c/c respectively. These reductions of wave heights occur when bio-shield of 2 m width (1 m Rigid + 1 m Flexible) are placed at 4 m distance from the embankment. Hence, the most effective position for maximum wave height reduction by both emerged and submerged bio-shield of 2 m width is 4 m distance from the embankment. It is anticipated that these results will find broad application in coastal management and planning for areas with existing coastal bio-shield as well for bio-shield restoration and establishment efforts.

**Keywords:** Bio-shield; Storm surges; Rigid and flexible; Laboratory experiment; Emerged and submerged

### Introduction

Coastal bio-shield has been broadly considered as a low-cost and natural protection to reduce the energy of current and surge. Bangladesh has an area of about 144,000 square kilometers and a population of more than 150 million, of which 28% of the total population lives in the coastal region [1]. It has a coastal belt of about 710 km long from Raimongal River to the west and Teknaf to the Southeast. Almost the entire coastal belt is exposed to the potential danger of cyclones with associated storm surges. During the years of 1582 to 2007, Bangladesh has been hit by 72 severe cyclones, 34 of which were accompanied by storm surges [1,2]. A tropical cyclone forming in the Bay of Bengal has a lifetime of one week or longer. The height of the surges is limited to a maximum of 10 meters in the bay. The frequency of a wave (surge plus tide) with a height of about 8 m is approximately once per 20 years. A storm surge of approximately once in 5 years has a height of about 5 m. Waves of 3 m height may occur under unfavorable conditions in the coastal regions [3]. A cyclone in November 1970 hit the southern districts of Bangladesh forcing a 9 m high storm surge and killing approximately 300,000 people [4]. The cyclone of 1991 caused more than 145,000 lives [4]. In 2007, about 3,406 people were reportedly killed in the coastal areas of Bangladesh by the super cyclone SIDR [1]. In 2009, about 330 people were died by cyclone Aila in the southern coastal region of Bangladesh which hit the country with a wind speed of 110 km/h and 3.0 m of surge.

Now-a-days mangrove forests are increasingly being used or recommended as a part of broader coastal defense strategies [5]. A study by Danielsen et al. has revealed the significance of mangroves which have effective potential to mitigate damage in constructed areas and save human lives by acting as buffer

zones during extreme natural events like severe storm surges and cyclones [6]. Mangroves can also play a role in defending coasts from storm surges and from erosion [7,8]. Hiraishi and Harada conducted water flume experiments and numerical simulations based on the 1998 Papua New Guinea tsunami to estimate the attenuation of tsunami energy by mangroves [9]. A laboratory experiment conducted by Rahman and Rahman found that the wave height is reduced up to 46% behind the vegetation zone for wave period of 1.6 sec when the vegetation barrier is placed at 1m from embankment due to the buffering action of the vegetation barrier [10]. Field surveys in Sri Lanka and Thailand after the Indian Ocean tsunami showed that older *Casuarina equisetifolia* belts on the coast withstood the tsunami but failed to provide good protection [11]. Tanaka showed that tree growth and forest density can have a significant effect on tsunami mitigation because trees with larger trunk diameters require more space between them to grow [12]. This suggests that trunk diameter and density effects are important parameters for estimating vegetation drag. Tanaka reported that the relationship between the crown height and tsunami height is also important in terms of the drag characteristics of broad-leaved trees because they

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have branches with large diameters [12]. The studies by Tanaka and Sasaki and Tanaka et al. elucidated the breaking condition for a single tree when the scouring around the tree is not severe [5,13]. However, the breaking condition is not applicable for critical tree damage in the fringe area of a forest, especially the frontal vegetation on sand dunes where the substrate is not hard and severe scouring occurs.

The overall coastal area of Bangladesh has already protected by coastal embankment called polders. There are 139 polders in the coastal area most of which were constructed in the late sixties to protect the land from tidal and monsoon flooding and saline water intrusion [14]. The main focus was to enhance the crop production. The coastal areas can be protected in many ways by hard protection but it will be very costly that cannot be affordable for a developing country like Bangladesh. The ministry of Environment and Forest (MoEF) has a green belt project to protect the coastal areas of Bangladesh but it doesn't have proper plan for the protection. Protecting the coastal areas by bio-shield is a natural way which can be very effective for our country because it is cost effective and natural protection as well. Mangrove vegetation shield coastline from cyclone, storm surge and other natural disaster by reducing the wave energy and stabilizing sediment. In this study, a laboratory experiment was carried out in a two dimensional wave tank in the Hydraulics and River Engineering laboratory of Bangladesh University of Engineering and Technology (BUET) to investigate the effectiveness of emerged and submerged bio-shield of different scenarios such as different densities and stiffness as well as different locations from embankment and different wave periods for the reduction of storm surge energies.

### Methodology

The Figure 1 shows the details of the experimental set-up. The experimental set-up consisted of a relatively mild slope of 1:30, which had a length of 15 m and the bed was prepared by filling sand. The effective horizontal length of the flume was 20 m of the total flume length of 22 m. Bio-shields were represented by cylindrical bamboo sticks as rigid bio-shield and polyethylene as flexible bio-shield whose diameter was 6 mm, the densities of bio-shield were 780 and 390 sticks per square meter and the porosities were 0.9779 and 0.9889 for 25 mm c/c and 50 mm c/c spacing of bio-shields, respectively. The length

of bio-shield was 75 cm, same as the flume width, but its width was varied as 1 m (half meter flexible and half meter rigid) and as 2 m (one meter flexible and one meter rigid). The height of the submerged bio-shields was 40 cm and it was 75 cm for emerged condition. The bio-shields were placed at a distance of 2 m and 4 m from the embankment towards the foreshore. The depth of water was 50 cm in the flume for all the experimental run conditions. Figure 2 depicts a plan view of the arrangement of cylindrical bamboo and polyethylene sticks that were used as representative of bio-shield for this laboratory experiment. The bio-shields were placed on pre-drilled wooden planks.

To scale down the bio-shields for this laboratory experiment, one of the guiding parameter for this purpose is the Young's modulus,  $E$ . The common timber would have an  $E$  value in the range of 10.05 Gpa to 15 Gpa. The mangrove has one of the highest  $E$  values as 20.03 Gpa. In order to cover this wide range of  $E$ , a reference value of 15 Gpa has been assumed for the field which had to be modeled for laboratory tests. In order to scale down the prototype values and identify the model material, assuming that the flow is due to storm surges and tsunamis, and considering also the experimental ranges of flow including surge height, diameter of bio-shield, bio-shield spacing, bio-shield width and distances of bio-shield from the embankment, a guiding scale ratio of 1:40, i.e., a Scale Factor (SF) of 40 was adopted. This would mean that the  $E$  value for the experimental material should be about 0.375 Gpa, which is quite difficult to identify. The most practical option for achieving the above is to Consider  $EI$  as a single parameter and scaling the rigidity. For the present study the material considered are bamboo sticks as rigid and poly ethylene as flexible with an  $E$  value of about 0.75 Gpa and 0.1 Gpa respectively. The  $E$  value of bamboo is about two times that of the required value and that of poly ethylene is 150 times less. That's why poly ethylene is 75 times more flexible than bamboo sticks. Since the rigidity is used for calculation herein, the above said variation could be compensated with the variation in  $I$  of the material. Having chosen the experimental material, the typical prototype dimensions of vegetal stems are fixed in 6 mm. Moreover, the width of bio-shield was chosen as 1 m and 2 m as representative of 40 m and 80 m respectively in the field. The distances of bio-shield from the embankment were selected as 2 m and 4 m for 80 m and 160 m distance from polder respectively in reality. Finally, a mild slope of 1:30 was chosen for the laboratory experiment because the average slope of the sea beach in the coastal region of Bangladesh is in the range of

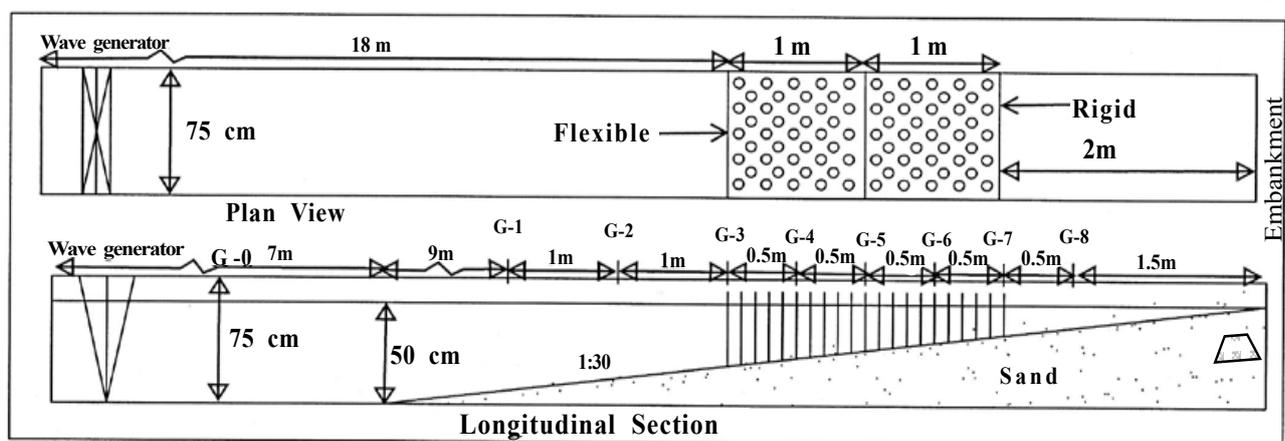


Figure 1: Details of laboratory experiment (Bio-shield at 2m away from the embankment and 1m Rigid + 1m Flexible).

1:20 to 1:50. In the laboratory experiment, the bed slope was fixed at 1:30 because of the length restriction of the wave flume.

Nine measuring tapes (G-0 to G-8) were deployed at nine specific locations to measure the temporal water surface elevation as shown in Figure 1. The wave periods for this experiment were 1.6 sec, 1.8 sec and 2.0 sec. Time series data was collected at 5 second interval for 60 sec at every measuring location.

The wave-generating system is capable of synthesizing sinusoidal small-amplitude long wave profile. In the wave flume, artificial wave was generated by wave paddle or wave generator. The wave generator was placed at one end of the experimental flume. Artificial wave of desired wave period and wave height was set with the help of this wave generator. Figure 3 shows the wave generator which was used in the laboratory. The wave generator was driven by an electric motor attached with the wave generator by a metal shaft.

Different lengths, densities, materials and submergence of bio-shield barrier had been used in the laboratory experiment. The bio-shield barrier was a combination of rigid and flexible bio-shields, 6 mm diameter of bamboo and polyethylene sticks were used as a representative of bio-shield in the laboratory experiment. The bio-shield barrier acts as buffering zone which neutralizes the waves during cyclonic storm surges. Figure 4 shows some photographs of bio-shield barrier that had been used in this study.

The two dimensional wave tank was prepared gingerly before the experiment. At first 4 wooden plank of 75 cm x 50 cm and thickness of 37.5 mm were collected and then 6.5 mm holes at 25 mm c/c are made by drill machine. After that 6 mm diameter of bamboo (as rigid bio-shield) and polyethylene (as flexible bio-shield) sticks were pushed into the pre drilled hole of the wooden planks. Finally sand was spreaded over the flume to prepare a 1:30 slope which is analogous to

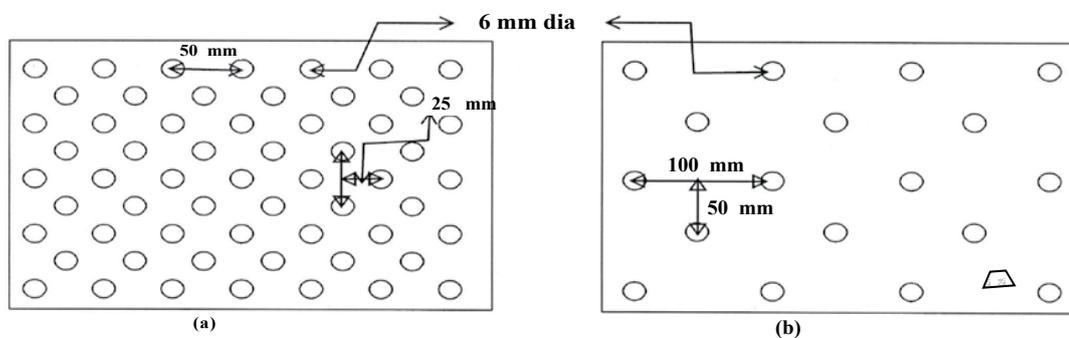


Figure 2: Two different types of arrangement of bio-shields (a) Spacing: 25 mm c/c (b) Spacing: 50 mm c/c.



Figure 3: Electric motor type wave generator used in laboratory experiment.



Figure 4: Photograph of bio-shield used in the laboratory experiment.

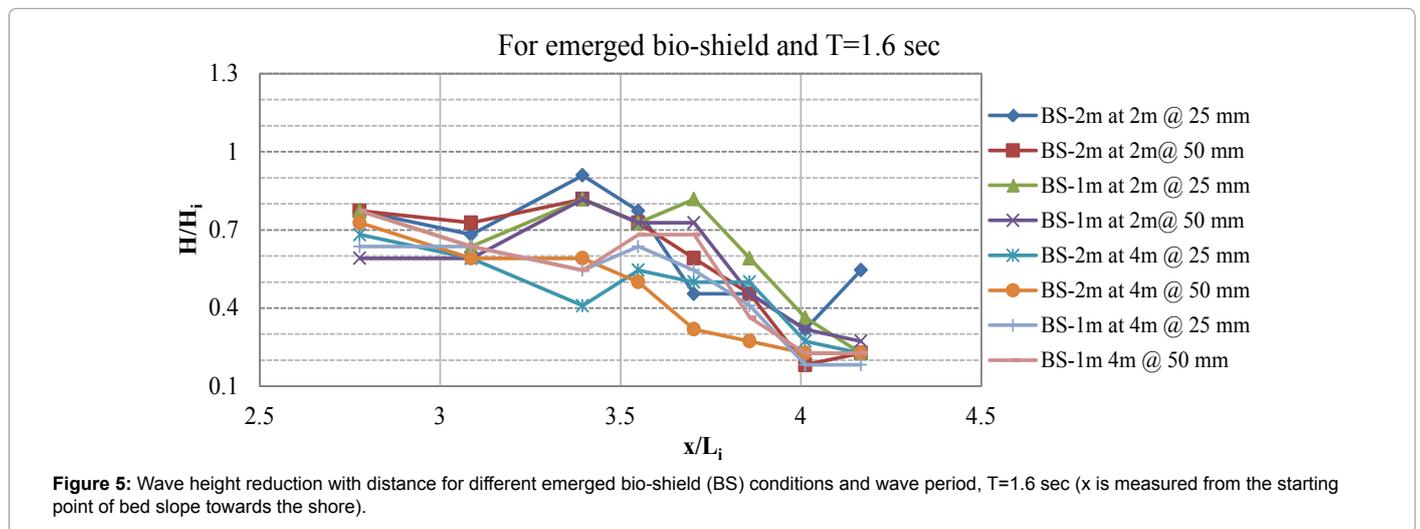
actual beach slopes of Bangladesh. The Figure 5 shows photographs of experimental flume after preparing for the test.

### Data Analysis and Results

A total of 51 experimental runs had been conducted using bio-shields of different materials, densities, different submergence conditions as well as different distances of bio-shield from embankment and for different wave periods. In this study, various combinations of bio-shields have been used to investigate the effectiveness of coastal bio-shields for the reduction of storm surge energies.

At measuring location G-3 (Figure 1) which is 4 m away from

the embankment shows that maximum wave height reduction occurs when bio-shield of 2 m width (1 m Rigid + 1 m Flexible @ 50 mm c/c) is placed at 4 m distance from the embankment for the wave period of 2.0 sec (Table 1). The maximum reduction of wave height is found to be 11 cm or 58% of the wave height of 19 cm for no bio-shield condition at the same measuring location. In this case the measuring location is situated just behind the bio-shield barrier. At measuring location G-4 (Figure 1) which is 3.5 m away from the embankment shows that maximum wave height reduction occurs when bio-shield of 2 m width (1 m Rigid + 1 m Flexible @ 50 mm c/c) is placed at 4 m distance from the embankment for the wave period of 2.0 sec (Table 2).



Emerged conditions		Wave height for T=1.6 sec (cm)	Wave height for T=1.8 sec (cm)	Wave height for T=2.0 sec (cm)	Comments
<b>No bio-shield</b>		<b>17</b>	<b>19</b>	<b>19</b>	
Bio-shield-2m at 2m @ 25 mm		20	18	15	
Bio-shield-2m at 2m @ 50 mm		18	19	19	
Bio-shield-1m at 2m @ 25 mm		18	23	17	
Bio-shield-1m at 2m @ 50 mm		18	22	23	
Bio-shield-2m at 4m @ 25 mm		9	10	10	
<b>Bio-shield-2m at 4m @ 50 mm</b>		<b>13</b>	<b>13</b>	<b>8</b>	
Bio-shield-1m at 4m @ 25 mm		12	11	12	
Bio-shield-1m at 4m @ 50 mm		12	13	14	
<b>Maximum Reduction of Wave Height</b>	cm	<b>8</b>	<b>9</b>	<b>11</b>	
	%	<b>47</b>	<b>52</b>	<b>58</b>	

Table 1: Wave height reduction for emerged conditions at location G-3 compared to no bio-shield condition.

Emerged conditions		Wave height for T=1.6 sec (cm)	Wave height for T=1.8 sec (cm)	Wave height for T=2.0 sec (cm)	Comments
<b>No bio-shield</b>		<b>19</b>	<b>20</b>	<b>21</b>	
Bio-shield-2m at 2m @ 25 mm		17	16	11	
Bio-shield-2m at 2m @ 50 mm		16	19	19	
Bio-shield-1m at 2m @ 25 mm		16	20	14	
<b>Bio-shield-1m at 2m @ 50 mm</b>		<b>16</b>	<b>19</b>	<b>19</b>	
Bio-shield-2m at 4m @ 25 mm		12	11	12	
Bio-shield-2m at 4m @ 50 mm		11	8	6	
Bio-shield-1m at 4m @ 25 mm		14	13	14	
Bio-shield-1m at 4m @ 50 mm		15	16	17	
<b>Maximum Reduction of Wave Height</b>	cm	<b>8</b>	<b>12</b>	<b>15</b>	
	%	<b>42</b>	<b>60</b>	<b>71</b>	

Table 2: Wave height reduction for emerged conditions at location G-4 compared to no bio-shield condition

The maximum reduction of wave height is found to be 15 cm or 71%. In this case the measuring location is situated 0.5 m away from the bio-shield barrier towards the embankment. From this comparison it is obvious that the percentage of wave height reduction is higher than the previous measuring location.

Again, at measuring location G-5 (Figure 1) which is 3 m away from the embankment shows that maximum wave height reduction occurs when bio-shield of 2 m width (1 m Rigid + 1 m Flexible @ 50 mm c/c) is placed at 4 m distance from the embankment for the wave period of 1.6 sec (Table 3). Here, the maximum wave height reduction is found as 4 cm or 36% of 11 cm of wave height for no bio-shield condition at the same measuring location. In this case the measuring location is situated 3 m away from the embankment.

Table 4 shows a comparison of wave height reduction for submerged bio-shield at measuring location G-3 which is 4 m away from the embankment with no bio-shield condition. The maximum wave height reduction occurs when bio-shield of 2 m width (1 m Rigid + 1 m Flexible @ 25 mm c/c) is placed at 4 m distance from the embankment for the wave period of 2.0 sec and the maximum reduction of wave height is found to be 7 cm or 36%. In this case the measuring location is situated just behind the bio-shield barrier.

At measuring location G-4 (Figure 1) which is 3.5 m away from the embankment shows that maximum wave height reduction occurs when bio-shield of 2 m width (1 m Rigid + 1 m Flexible @ 25 mm c/c) is placed at 4 m distance from the embankment for the wave period of 2.0 sec (Table 5). The maximum reduction of wave height found for this location is 11 cm or 52% of the wave height of 21 cm for no bio-shield condition at the same measuring location. In this case the measuring location is situated 3.5 m away from the embankment. From this

comparison it is obvious that the percentage of wave height reduction is higher than the previous measuring location.

At measuring location G-5 (Figure 1) which is 3 m away from the embankment shows that maximum wave height reduction happens when bio-shield of 2 m width (1 m Rigid + 1 m Flexible @ 25 mm c/c) is placed at 4 m distance from the embankment for the wave period of 2.0 sec (Table 6). Here, the maximum wave height reduction is found as 4 cm or 44% of 9 cm of wave height for no bio-shield condition at the same measuring location. In this case the measuring location is situated 1 m away from the bio-shield barrier towards the embankment.

A set of comparisons of wave height reduction for different emerged bio-shield conditions are shown in the Figures 5,6 and 7 for wave periods of 1.6 sec, 1.8 sec and 2.0 sec respectively. The distance x is measured from the starting point of bed slope towards the shore, the initial wave heights are 22 cm, 18 cm and 22 cm for wave period of 1.6 sec, 1.8 sec and 2.0 sec respectively. Moreover, the initial wave lengths are calculated as 3.24 m, 3.76 m and 4.25 m for wave period of 1.6 sec, 1.8 sec and 2.0 sec respectively. The figures show that the wave height is reduced most when bio-shields of 2 m width are placed at 4 m distance from the embankment. It is also obvious from the figures that the maximum wave height reduction occurs at measuring location G-3 and G-4 for two spacing of bio-shields such as 25 mm c/c and 50 mm c/c. The measuring location G-3 is situated just behind the bio-shield barrier and location G-4 is 3.5 m away from the embankment. At measuring location G-3, the wave height reductions are 47%, 52% and 58% for wave periods of 1.6 sec, 1.8 sec and 2.0 sec respectively (Table 1). At measuring location G-4, the wave height is reduced by 42%, 60% and 71% for wave periods of 1.6 sec, 1.8 sec and 2.0 sec respectively (Table 2). Hence, the most effective position for wave height reduction by emerged bio-shield condition is 4 m distance from the embankment when the bio-shield spacing is 50 mm c/c and wave period is 2.0 sec.

Emerged conditions		Wave height for T=1.6 sec (cm)	Wave height for T=1.8 sec (cm)	Wave height for T=2.0 sec (cm)	Comments
<b>No bio-shield</b>		<b>11</b>	<b>11</b>	<b>9</b>	Maximum reduction of wave height (11-7=4 cm) occurs when 2 m wide bio-shield at a distance of 4 m from embankment and T=1.6 sec
Bio-shield-2m at 2m @ 25 mm		10	11	10	
Bio-shield-2m at 2m @ 50 mm		13	13	14	
Bio-shield-1m at 2m @ 25 mm		18	15	12	
Bio-shield-1m at 2m @ 50 mm		16	17	12	
Bio-shield-2m at 4m @ 25 mm		11	10	10	
<b>Bio-shield-2m at 4m @ 50 mm</b>		<b>7</b>	<b>8</b>	<b>11</b>	
Bio-shield-1m at 4m @ 25 mm		12	10	12	
Bio-shield-1m at 4m @ 50 mm		15	19	17	
<b>Maximum Reduction of Wave Height</b>		<b>4</b>	<b>3</b>	<b>1</b>	
		<b>%</b>	<b>36</b>	<b>27</b>	<b>11</b>

Table 3: Wave height reduction for emerged conditions at location G-5 compared to no bio-shield condition.

Submerged conditions		Wave height for T=1.6 sec (cm)	Wave height for T=1.8 sec (cm)	Wave height for T=2.0 sec (cm)	Comments
<b>No bio-shield</b>		<b>17</b>	<b>19</b>	<b>19</b>	Maximum reduction of wave height (19-12=7 cm) occurs when 2 m wide bio-shield at a distance of 4 m from embankment and T=2.0 sec
Bio-shield-2m at 2m @ 25 mm		17	17	21	
Bio-shield-2m at 2m @ 50 mm		15	17	19	
Bio-shield-1m at 2m @ 25 mm		21	21	21	
Bio-shield-1m at 2m @ 50 mm		16	18	19	
<b>Bio-shield-2m at 4m @ 25 mm</b>		<b>14</b>	<b>15</b>	<b>12</b>	
Bio-shield-2m at 4m @ 50 mm		16	15	16	
Bio-shield-1m at 4m @ 25 mm		19	20	21	
Bio-shield-1m at 4m @ 50 mm		14	17	15	
<b>Maximum Reduction of Wave Height</b>		<b>3</b>	<b>4</b>	<b>7</b>	
		<b>%</b>	<b>18</b>	<b>21</b>	<b>36</b>

Table 4: Wave height reduction for submerged conditions at location G-3 compared to no bio-shield condition.

Submerged conditions		Wave height for T=1.6 sec (cm)	Wave height for T=1.8 sec (cm)	Wave height for T=2.0 sec (cm)	Comments
<b>No bio-shield</b>		<b>19</b>	<b>20</b>	<b>21</b>	
Bio-shield-2m at 2m @ 25 mm		17	16	16	
Bio-shield-2m at 2m @ 50 mm		17	19	16	
Bio-shield-1m at 2m @ 25 mm		14	12	18	
Bio-shield-1m at 2m @ 50 mm		18	17	17	
<b>Bio-shield-2m at 4m @ 25 mm</b>		<b>12</b>	<b>13</b>	<b>10</b>	
Bio-shield-2m at 4m @ 50 mm		15	16	14	
Bio-shield-1m at 4m @ 25 mm		15	15	17	
Bio-shield-1m at 4m @ 50 mm		19	18	15	
<b>Maximum Reduction of Wave Height</b>	<b>cm</b>	<b>7</b>	<b>8</b>	<b>11</b>	
	<b>%</b>	<b>36</b>	<b>40</b>	<b>52</b>	

Table 5: Wave height reduction for submerged conditions at location G-4 compared to no bio-shield condition.

Submerged conditions		Wave height for T=1.6 sec (cm)	Wave height for T=1.8 sec (cm)	Wave height for T=2.0 sec (cm)	Comments
<b>No bio-shield</b>		<b>11</b>	<b>11</b>	<b>9</b>	
Bio-shield-2m at 2m @ 25 mm		18	16	12	
Bio-shield-2m at 2m @ 50 mm		11	8	9	
Bio-shield-1m at 2m @ 25 mm		10	10	14	
Bio-shield-1m at 2m @ 50 mm		11	11	12	
<b>Bio-shield-2m at 4m @ 25 mm</b>		<b>14</b>	<b>14</b>	<b>5</b>	
Bio-shield-2m at 4m @ 50 mm		10	9	9	
Bio-shield-1m at 4m @ 25 mm		14	11	12	
Bio-shield-1m at 4m @ 50 mm		12	9	11	
<b>Maximum Reduction of Wave Height</b>	<b>cm</b>	<b>1</b>	<b>3</b>	<b>4</b>	
	<b>%</b>	<b>9</b>	<b>27</b>	<b>44</b>	

Table 6: Wave height reduction for submerged conditions at location G-5 compared to no bio-shield condition.

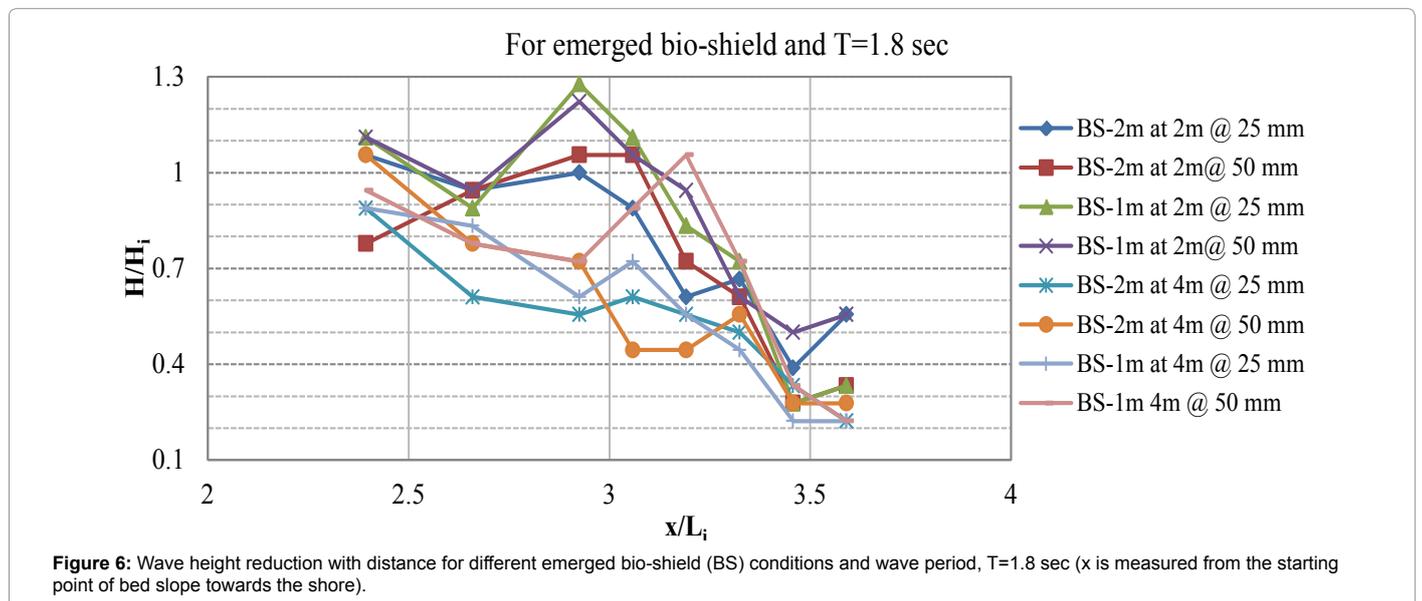
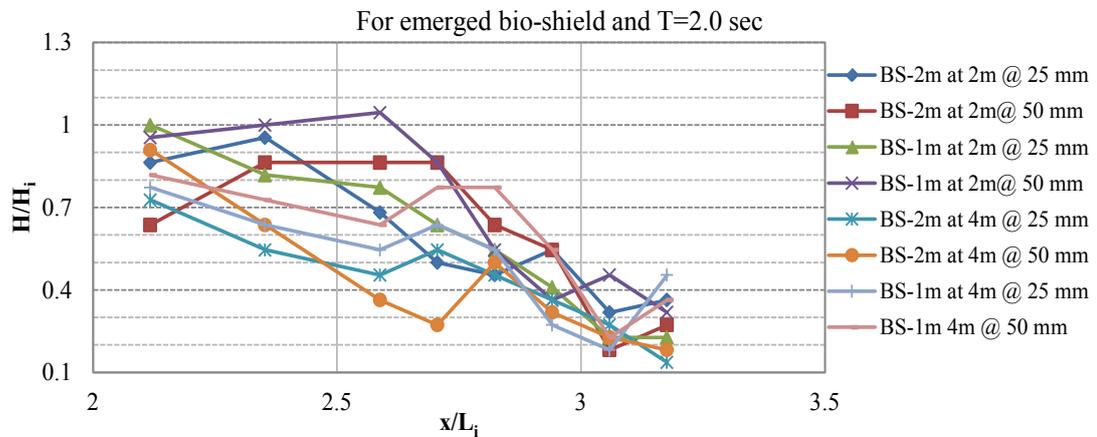


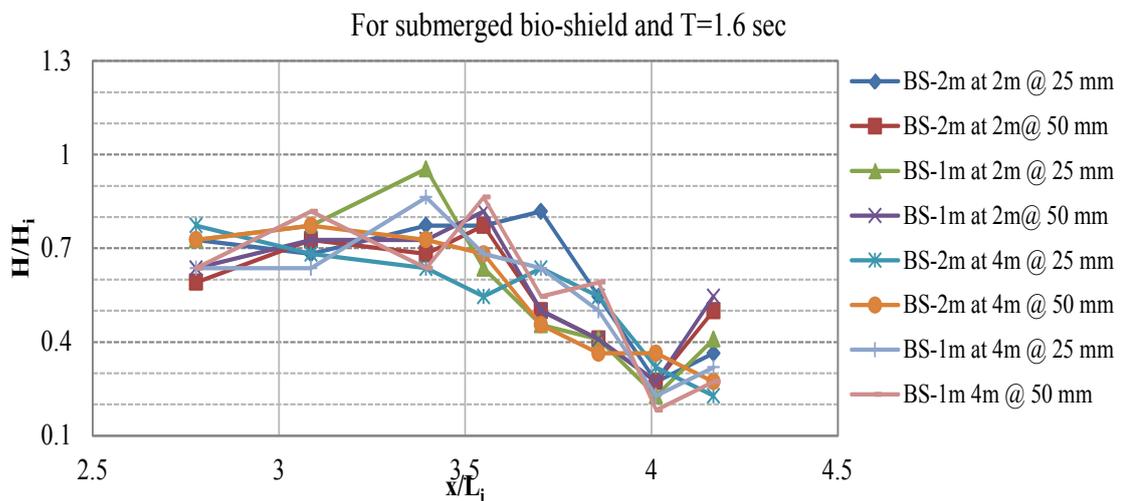
Figure 6: Wave height reduction with distance for different emerged bio-shield (BS) conditions and wave period, T=1.8 sec (x is measured from the starting point of bed slope towards the shore).

Another set of comparisons of wave height reduction for different submerged bio-shield conditions are shown in the Figures 8, 9 and 10 for wave periods of 1.6 sec, 1.8 sec and 2.0 sec respectively. The figures show the same result as before, that is, wave height is reduced most when bio-shields of 2 m width (1 m Rigid + 1 m Flexible) are placed at 4 m distance from the embankment. It is also obvious from the figures that the maximum wave height reduction occurs at measuring location G-3 and G-4 for bio-shield spacing of 25 mm c/c and 50 mm c/c. At

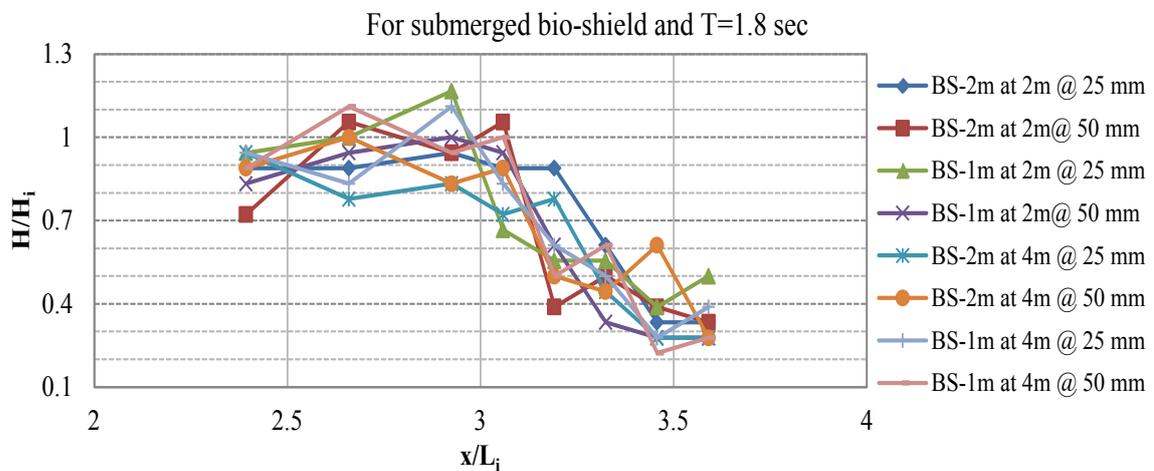
measuring location G-3, the wave height reductions are 18%, 21% and 36% for wave periods of 1.6 sec, 1.8 sec and 2.0 sec respectively (Table 4) and at measuring location G-4, the wave height reductions are 36%, 40% and 52% for wave periods of 1.6 sec, 1.8 sec and 2.0 sec respectively (Table 5). Hence, the most effective position for wave height reduction by submerged bio-shield condition is 4 m distance from the embankment when the bio-shield spacing is 25 mm c/c and wave period is 2.0 sec.



**Figure 7:** Wave height reduction with distance for different emerged bio-shield (BS) conditions and wave period, T=2.0 sec (x is measured from the starting point of bed slope towards the shore).



**Figure 8:** Wave height reduction with distance for different submerged bio-shield (BS) conditions and wave period, T=1.6 sec (x is measured from the starting point of bed slope towards the shore).



**Figure 9:** Wave height reduction with distance for different submerged bio-shield (BS) conditions and wave period, T=1.8 sec (x is measured from the starting point of bed slope towards the shore).

### Relationship between transmission coefficient and wave periods

From the experimental data analysis the best condition for maximum wave height reduction is determined for both the emerged and submerged bio-shield. For emerged and submerged condition of bio-shield, the maximum wave height reduction occurs when 2 m width of bio-shield is placed at a distance of 4 m from the embankment. To relate transmission coefficient with wave period, the wave height at measuring location G-7 is considered as it is always located behind the bio-shield barrier for all the experimental conditions. The Figures 11,12 show the relationship between the transmission coefficient ( $K_T = \frac{H_{G7}}{H_G}$ ) and wave periods for emerged and submerged condition of bio-shield respectively. The trend line for both the conditions show a negative slope which indicates that as the wave period increases the transmission coefficient decreases causing greater reduction in wave height.

It is also revealed from the experimental study that the waves with longer period are reduced most by bio-shield barrier. Since the storm surges and tsunami waves are long wave with higher wave periods, the energy of these types of waves will be reduced most if bio-shield protection is available as per requirement. It is also found that maximum wave height reduction (71%) occurs for emerged conditions of bio-shields when 2 m width of bio-shield at 50 mm c/c is placed at 4 m distance from the embankment but for submerged condition of bio-shield the maximum reduction (52%) occurs at 25 mm c/c spacing of bio-shield (Table 7).

### Conclusions

Coastal forests and trees can, under certain conditions, act as bio-shields to protect lives and valuable assets against coastal hazards, including: tsunami, cyclone, wind and coastal erosion. However, there

is limited knowledge and few models that address the effectiveness of coastal bio-shield on storm surges. Hence, the main objective of this study was to conduct laboratory experiments to quantify the reduction of storm surge energies by emerged and submerged bio-shields. From the laboratory experiment, it is revealed that the wave height is reduced most when bio-shield of 2 m width (1 m Rigid + 1 m Flexible) is placed at a distance of 4 m from the embankment. It is also obvious from Tables 2,5, and Figures 7,10 that the maximum wave height reduction occurs at a measuring location which is 3.5 m away from the embankment for two spacing of bio-shields such as 50 mm c/c and 25 mm c/c for emerged and submerged bio-shields, respectively. For emerged bio-shield, the wave height reductions are 42%, 60% and 71% (Table 2) for wave periods of 1.6 sec, 1.8 sec and 2.0 sec respectively at 3.5 m away from the embankment. Hence, the most effective position for wave height reduction by emerged bio-shield is 4 m distance from the embankment and the bio-shield spacing is 50 mm c/c for wave period of 2.0 sec. For submerged bio-shield, the wave height reductions are 36%, 40% and 52% (Table 5) for wave periods of 1.6 sec, 1.8 sec and 2.0 sec respectively at 3.5 m away from the embankment. Hence, the most effective position for wave height reduction by submerged bio-shield is 4 m distance from the embankment and the bio-shield spacing is 25 mm c/c for wave period of 2.0 sec. It is also conspicuous from the relationship of transmission coefficient and wave period that waves with higher wave period, especially longer waves such as storm surges and tsunamis will be reduced most in wave height by both emerged and submerged bio-shield protection.

From this study, it is suggested that bio-shields of 1-2 m c/c spacing should be preserved as wide as possible not less than 200 m in front of the coastal sea facing polders to reduce the effect of cyclonic storm surges for protecting the hinterland. Sundri, Gewa and coconut

Conditions	Width of Bio-shield (R+F) (m)	Distance from Embankment (m)	Measuring location	Maximum wave height reduction	Spacing, mm c/c	Time periods (sec)
Emerged	2	4	G-3	58 %	50	2
	2	4	G-4	71 %	50	2
	2	4	G-5	36 %	50	1.6
Submerged	2	4	G-3	36 %	25	2
	2	4	G-4	52 %	25	2
	2	4	G-5	44 %	25	2

Table 7: Comparison of wave height reductions by emerged and submerged bio-shield.

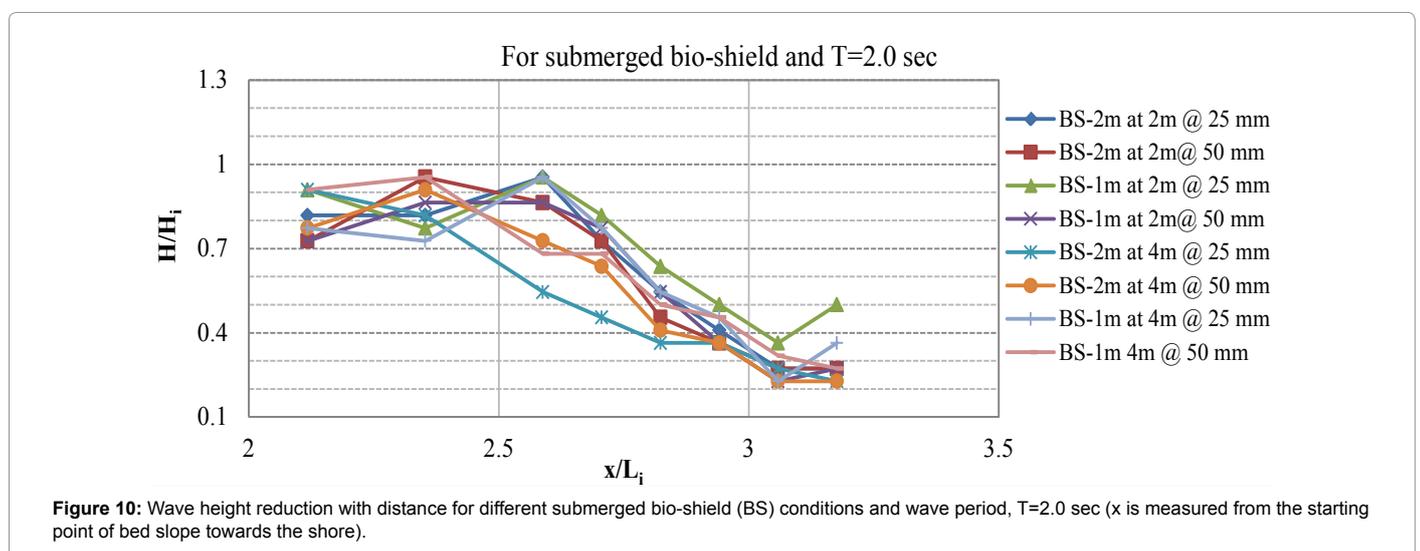


Figure 10: Wave height reduction with distance for different submerged bio-shield (BS) conditions and wave period, T=2.0 sec (x is measured from the starting point of bed slope towards the shore).

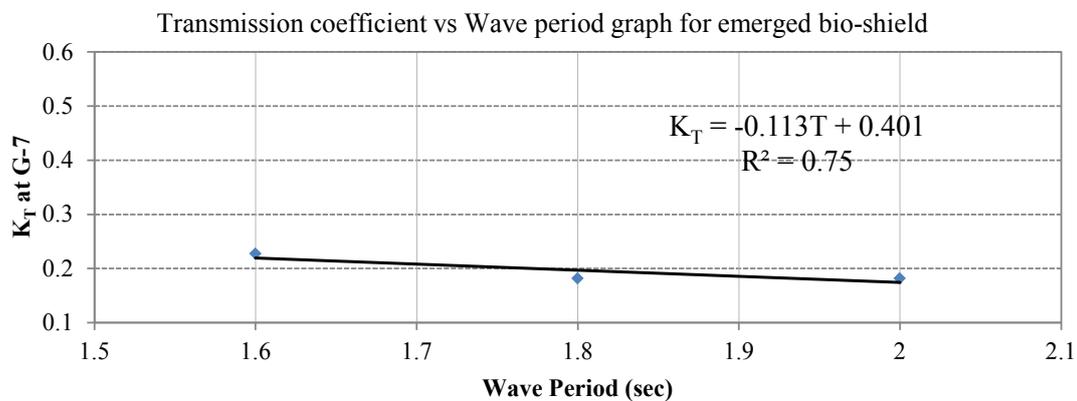


Figure 11: Relationship between the transmission coefficient and the wave periods for emerged bio-shield (BS).

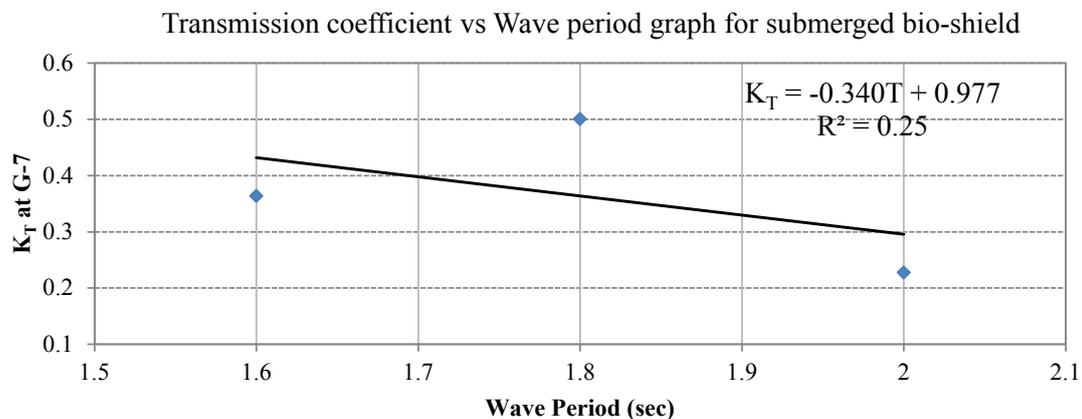


Figure 12: Relationship between the transmission coefficient and the wave periods for submerged bio-shield (BS).

trees are the specific species that are available in the coastal areas of Bangladesh which can be used as bio-shield protection to save the coastal areas from natural disasters.

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