

STUDY ON EFFECTIVENESS OF COASTAL BIO-SHIELD FOR REDUCTION OF THE ENERGY OF HIGH FREQUENCY SURGES

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**Study on Effectiveness of Coastal Bio-Shield for Reduction of the
Energy of High Frequency Surges**

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By

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Bangladesh University of Engineering and Technology
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Certification of Thesis

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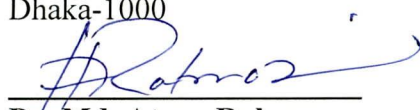
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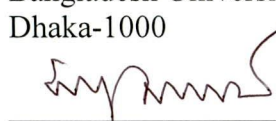
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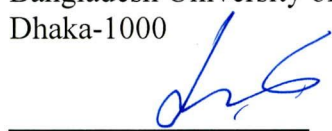
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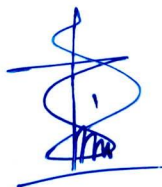
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ABSTRACT

Storm surges generated by cyclones 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. In this study, historical storm surges are analyzed and existing bio-shield protection is evaluated along the coastal belt of Bangladesh. Moreover, a laboratory experiment has been carried out and the result of a numerical model has been used to study the effectiveness of coastal bio-shield in reducing the energy of high frequency surges.

In this study, wind speed of 25 cyclones that hit the country from 1960 to 2007 has been analyzed and found that the wind speed of cyclonic storm surges increases by 0.83 km/h each year. But the human death toll caused by storm surges shows a decreasing rate of 500 people per year because of the present growing successful institutional arrangement for disaster management. It is also found that there are only 60 km or 6% of forest belts of the 957 km total length of embankment of 49 sea-facing polders, much of which is already degraded.

To study the effectiveness of coastal bio-shield in reducing the energy of high frequency surges, a laboratory experiment is 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. Bio-shields are represented by cylindrical bamboo sticks as rigid bio-shield and polyethylene (Polyethylene is 75 times more flexible than bamboo sticks) as flexible bio-shield whose diameter is 6 mm. The densities of bio-shield are 780 and 390 sticks per square meter and the porosities are 0.9779 and 0.9889 for spacing 25 mm c/c and 50 mm c/c of bio-shields, respectively. It is found for emerged conditions of bio-shield that the maximum wave height reduction is 71 % for bio-shield spacing of 50 mm c/c and that for submerged condition of bio-shield is 52 % for spacing of 50 mm c/c. 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 for wave period of 2.0 sec.

Moreover, a two-dimensional numerical model named Bay of Bengal model developed by Institute of Water Modeling is used to simulate the effect of coastal bio-shield in reducing the energy of storm surge SIDR along the Kuakata beach of Bangladesh. In this modeling, four simulations are performed for four different conditions including 74 cm of SLR. Surge levels and current speeds are measured at three specific locations on the Kuakata beach (polder-48). The model results demonstrate that up to 2 cm of surge height and 0.48 m/s or 62 % of current speed are reduced by 200 m width of bio-shield when SLR is not considered. Again, the surge height and current speed are reduced by 3 cm and 0.46 m/s or 59 % respectively by 200 m width of bio-shield when 74 cm of SLR is considered for the year 2100 according to 5th IPCC report.

It is anticipated that these results will find broad application in coastal management and planning for areas with existing coastal bio-shield as well as for bio-shield restoration and establishment efforts.

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List of Notations and Acronyms

p	flux in x directions ($\text{m}^3/\text{s}/\text{m}$)
q	flux in y directions ($\text{m}^3/\text{s}/\text{m}$)
x	Longitudinal Cartesian Co-ordinate (m)
y	Lateral Cartesian Co-ordinate (m)
t	time (s)
h	water depth (m)
g	acceleration due to gravity ($9.81 \text{ m}^2/\text{s}$)
ε	Sea surface elevation (m)
τ	Bed shear stress ($\text{kg}/\text{m}/\text{s}^2$)
ρ_w	water density (kg/m^3)
ρ_a	Air density (kg/m^3)
C_w	wind friction factor
W	wind speed (m/s)
Ω	Carioles' parameter
P_a	Atmospheric pressure ($\text{kg}/\text{m}/\text{s}^2$)
P_c	Central pressure ($\text{kg}/\text{m}/\text{s}^2$)
P_n	neutral pressure ($\text{kg}/\text{m}/\text{s}^2$)
A	Horizontal area of the Mangrove forest (m^2)
D	Diameter of the trunk (m)
S	Bed slopes
T	Wave period (s)
E	Eddy viscosity ($\text{kg}/\text{s}/\text{m}$)
R_m	Radius of maximum winds (km)
Re	Reynold's number
K_m	Geostrophic correction factor
f	Friction factor
M	Manning's number ($\text{m}^{1/3}/\text{s}$)
n	Number of trees
F	Force from the trunk on the water body ($\text{kg}.\text{m}/\text{s}^2$)
V	Depth averaged flow velocity (m/s)
V_f	Cyclone track forward speed (km/h)

V_{10}	Near-surface wind (m/s)
V_m	Maximum wind speed (m/s)
V_r	Rotational wind speed (rad/s)
V_g	Rrotational wind gradient speed (rad/s)
K_N	Nikuradses roughness height

BIWTA	Bangladesh Inland Water Transport Authority
BoBM	Bay of Bengal Model
BMD	Bangladesh Meteorological Department
BWDB	Bangladesh Water Development Board
BUET	Bangladesh University of Engineering and Technology
CERP	Coastal Embankment Rehabilitation Project
CSPS	Cyclone Shelter Preparatory Study
DHI	Danish Hydraulic Institute
DEM	Digital Elevation Model
FAP	Flood Action Plan
GoB	Government of Bangladesh
IPCC	Intergovernmental Panel on Climate Change
IWM	Institute of Water Modeling
JTWC	Joint Typhoon Warning Center
MES	Meghna Estuary Study
MSL	Mean Sea Level
NAPA	National Adaptation Programme of Action
PWD	Public Works Datum
SLR	Sea Level Rise
WRE	Water Resources Engineering

CHAPTER ONE

INTRODUCTION



1.1 Background and Present State of the Problem

Bangladesh has an area of about 144,000 square kilometres and a population of more than 150 million, of which 28% of the total population lives in the coastal region (Paul, 2009). 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 cyclone with associated storm- surge. During the years of 1582 to 2007, Bangladesh has been hit by 72 severe cyclones, 34 of which were accompanied by storm surges (Islam, 2004; Paul, 2009). 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 (surge plus tide). Waves of 3 m height may occur under unfavorable conditions in the coastal regions (Rana et al., 2010). A cyclone in November 1970 hit the southern districts of Bangladesh forcing a 9 m high storm surge and killing approximately 300,000 people (Haider et al., 1991). The cyclone of 1991 caused more than 145,000 lives (Haider et al., 1991). In 2007, about 3406 people were reportedly killed in the coastal areas of Bangladesh by the super cyclone SIDR (Paul, 2009). 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. In most recent years, however, number of deaths caused by the cyclones with severe intensity has declined due to the growing successful institutional arrangements for disaster management (Haider et al., 1991).

Bangladesh is one of the top vulnerable countries to the climate change (Ali, 1999). Due to climate change and sea-level rise, the country is likely to be affected by more intense cyclonic events in the foreseeable future. The consequences of climate change lead to an increase in the cyclone-prone area and put a large number of people at risk. According to the 5th IPCC report

(IPCC, 2013) a global sea level rise (SLR) would be 28 cm to 98 cm up to 2100, but the rise up to the mean over 2081-2100, from a baseline of the mean over 1985-2005. The mean sea level rise (MSL) will be 74 cm up to the year 2100 (IPCC, 2013) and if emissions continue to track at the top of IPCC scenarios, global temperature could rise by between 3.2°C and 5.4°C by the end of the century relative to a 1850-1900 baseline. If emissions track along the lowest scenario, then global average temperature could rise from 0.9-2.3°C by the end of the century relative to a 1850 -1900 baseline (IPCC, 2013). Again according to the 4th IPCC report (IPCC, 2007) the intensity and frequency of the cyclonic storm surge will be increased in the near future in the Bay of Bengal. It is plausible from various researches (IPCC, 2007; NAPA, 2005; Ahmed et al., 2009) that the frequency and magnitude of cyclones and storm surges will be increased perpetually in future due to climate change effects. The cyclones and storm surges of high magnitude associated with future climate change effect can be faced by green belt bio-shield protection along the coastal areas to save the hinterland against future severe natural disasters (Rahman and Rahman, 2013).

Coastal bio-shield has been considered as a low-cost and natural protection to reduce the energy of current and surge. Now-a-days mangrove forests are increasingly being used or recommended as a part of broader coastal defence strategies (Tanaka, 2009). A study by Danielsen, et al. (2005) 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. Mangroves can also play a role in defending coasts from storm surges (Kathiresan and Rajendran, 2005) and from erosion (Vo-Luong and Massel, 2008). A laboratory experiment conducted by Rahman and Rahman (2013) found that the wave height is reduced up to 46% behind the vegetation zone, 43% within the vegetation barrier and 41% in front of vegetation for wave period of 1.6 sec when the vegetation barrier is placed at 1m from embankment due to buffering action of the vegetation barrier.

Hiraishi and Harada (2003) conducted water flume experiments and numerical simulations based on the 1998 Papua New Guinea tsunami to estimate the attenuation of tsunami energy by mangroves. The model output suggested a more than 90%

reduction in maximum tsunami flow pressure by a 100-m-wide forest belt when the tree density is very high (30 tree trunks per 100 m²). Takemura and Tanaka (2007) investigated by numerical model study on coastal vegetation that the maximum water depth and current velocity reduced to 1.4 m (22% reduction) and 1.2 m/s (49% reduction), respectively, behind the vegetation in comparison with the case without vegetation and wide coastal vegetation belt with mild slope might be suitable for storm surge energy reduction; however, a doubling or tripling of forest width (from 100 m to 200 m or 300 m) did not produce two-fold or three-fold increase of wave reduction with negligible additional velocity reduction. To study the effectiveness of mangrove against cyclonic storm surge, Hasan (2009) used three types of widths of mangrove (200 m, 400 m and 600 m) in the Bay of Bengal model which was applied on Sandwip island of Bangladesh and found that mangrove reduced the surge height by 10 cm to 20 cm and current speed to its one third. Kabir et al. (2006) in Bangladesh carried out a modeling study to assess the impact of afforestation on cyclone surge level considering 1970 cyclone for simulation and found a maximum reduction of storm surge height 0.45 m with 600 m strip of mangroves. Storm surge height of 1970 cyclone was significantly higher (10.6 m) compared with storm surge height of Sidr-2007 (6 m) in Bangladesh (Karim and Mimura, 2008).

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 (GOB, 2013). 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 will be 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 coastal bio-shield of different scenarios such as emerged and submerged condition of bio-shield as well as different densities and stiffness for the reduction of storm surge energies. Moreover, the Bay of Bengal (BoB) model developed at IWM will be used to evaluate the effectiveness of coastal bio-shield of different scenarios for the reduction of cyclonic storm surge energy along the Kuakata beach of Bangladesh.

1.2 Objectives

The specific objectives of this study are:

- (i) To analyze the historical storm surges and to assess the existing coastal bio-shields along the coastal belt of Bangladesh.
- (ii) To evaluate the effectiveness of coastal bio-shield of different scenarios for reduction of storm surge energy through experimental study.
- (iii) To evaluate the effectiveness of coastal bio-shield of different scenarios for reduction of storm surge and cyclone energy along a selected beach of Bangladesh using numerical model results.

1.3 Scope of the Study

Coastal bio-shield such as mangroves acts as buffering zone for cyclone induced storm surges. The country, like Bangladesh needs bio-shield protection along the coast line to reduce the magnitudes of deadly storm surges and cyclones that hit the country almost every year. The main purpose of this study is to find out the effectiveness of coastal bio-shield in reducing the energy of high frequency surges and cyclones. In this study, the effectiveness of coastal bio-shield in reducing the energy of high frequency surges and cyclones has been evaluated through laboratory experiment and numerical modeling.

A laboratory experiment is carried out to study the effectiveness of coastal bio-shield of different scenarios such as different submergence of bio-shields, different stiffness, densities as well as different width and different locations of bio-shields from the defined embankment for the reduction of high frequency surge energy. Basically the cyclone induced storm surges are long waves but due to limited facilities in the laboratory flume the surge waves have been considered as high frequency surges.

Moreover, modeling software named MIKE21 is used to develop the Bay of Bengal (BoB) model that is applied to the Kuakata beach (polder-48) of Bangladesh to investigate the behavior of severe storm surges and cyclones on current speed and wave height reduction.

1.4 Outline of the Report

The report is organized as follows: Chapter one contains the introduction. In chapter two, different types of literatures relevant to this study are reviewed. In chapter three, theories and methods of the study are discussed. The historical, experimental and numerical data are analyzed and results are discussed in chapter four. Finally, chapter five gives the conclusions and the recommendations of the study. Appendix A, Appendix B, Appendix C and Appendix D are also attached as addendum in last section of this report.

CHAPTER TWO

LITERATURE REVIEW

2.1 General

A considerable research effort has been devoted to conduct the laboratory experiments and simulate attenuation of surges and waves by bio-shields. A comprehensive literature review is presented in the following sections to highlight these studies over the last few decades.

Coastal protection typically involved construction of hard structures, such as levees, floodgates, jetties and breakwaters. These measures may alter nearshore hydrodynamic and circulation patterns, disrupt regional and local morphodynamic processes, and cause unintended ecosystem consequences. The latest trends in coastal engineering are focusing more and more on sustainable, non-intrusive forms of coastal protection, such as natural wetland vegetation. Vegetation known as bio-shield plays an important role in the sustainable development of aquatic environment. Aquatic vegetation can help to dissipate incoming wave energy, regulate water levels, enhance deposition of sediment near coastal zones, improve water quality, reduce flood and storm damages, provide important fish and wildlife habitats, and support recreational activities.

2.2 Cyclones and Storm Surges

2.2.1 Definition, Classification and Causes

Typhoons are tropical revolving storms. They are called 'Cyclones' in English, when they occur in the Indian Ocean area. The coastal regions of Bangladesh are subject to damaging cyclones almost every year. They generally occur in early summer or pre-monsoon (April-May) or late rainy season or post-monsoon (October-November). Cyclones originate from low atmospheric pressures over the Bay of Bengal. Figure 2.1 shows a typical cyclone structure formed in the tropics of the northern hemisphere.

Most of the coastal areas of the world are at risk from natural hazards created by geological or meteorological disturbances. The hazards are classified (Crater, 1988) as:

(1) Short term (minutes, hours, or days) events associated with storms or earthquakes (tsunamis), and (2) Long-term events (decades, millennia) related to changes in rise of sea level caused by secular eustatic (atmospheric, cryospheric, geoidal) or isostatic (tectonic) processes. Tropical cyclones or hurricanes are common within latitude 30° north and south. These intense storms move across shallow shelf seas; the water is being piled-up along the coast as a surge. In most cases the mixture of these effects creates most dreadful effects in the coastal regions; a gradual rise in the regional sea level produces enhanced landward penetration of surges and storm waves.

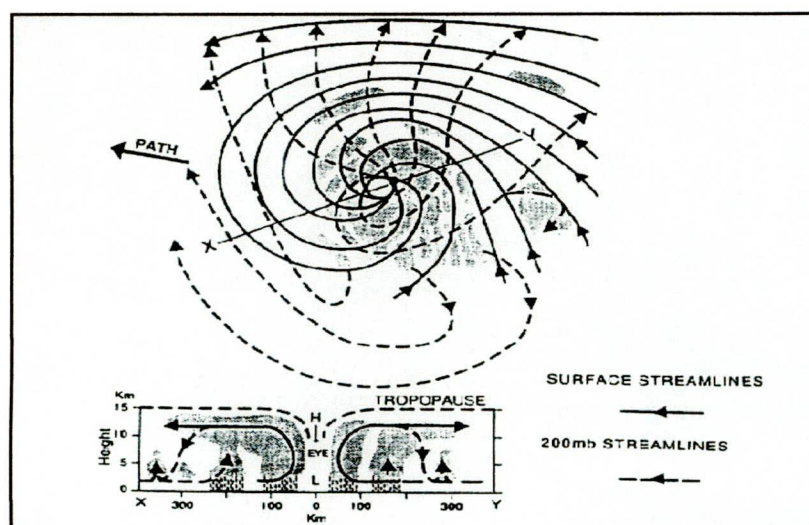


Figure 2.1: A model of the aerial and vertical structure of a tropical cyclone. The areas of rainfall are indicated in the vertical section X-Y across the system (after Barry and Chorley, 1992).

Cyclones in the South Asian Sub-Continent are presently classified according to their intensity and the following nomenclature is in use (Choudhury, 1992):

Table 2.1: Classification of storms based on wind speed

Depression	Winds up to 62 km/h
Cyclonic Storm	Winds from 63-87 km/h
Severe Cyclonic Storm	Winds from 88-118 km/h
Severe Cyclonic Storm of Hurricane Intensity	Winds above 118 km/h

2.2.2 Storm Surge Flooding and Causes of Severity in Bangladesh

Storm surges are generated by two principal factors: pressure drop and wind stress. Atmospheric pressure drop below normal raises the water through "inverted barometer effect" (which is also called "sucking effect") by a nominal amount, i.e. about 1 cm per 1 Mb drop of pressure. Wind is the main force for the generation of storm surges. Wind exerts tangential as well as normal (downward) stresses on the water underneath. Water being almost incompressible, the normal stress cannot generate any noticeable motion in water. The tangential stress generates long water waves or storm waves i.e. storm surges. The amplitude of the wave depends directly on the strength of the wind. The wind stress is approximately proportional to the square of the wind speed. Flooding by storm surge in Bangladesh can be classified as follows:

- (a) Normal coastal flooding - no damage on crops.
- (b) Moderate coastal flooding - very limited damage on crops.
- (c) Moderately high coastal flooding - high damage on crops but relatively low damage on properties and lives.
- (d) High coastal flooding - large scale damage on crops, properties and lives.
- (e) Severe coastal flooding - severe damage on crops, properties and lives.

Table 2.2 shows the approximate percentage of storm-surge impact in various regions on the globe. Storm surges generated by tropical cyclones are most common in the Bay of Bengal and the Gulf of Mexico.

Table 2.2: Approximate percentage of storm surge impact

Region	Percentage
Bangladesh	40
Asia (excluding Bangladesh)	20
North America	20
Europe	10
Africa and South America	5
Australia and New Zealand	5

(Source: Murty and El-Sabh, 1992)

The reasons for this disproportional large impact of storm surges on the coast of Bangladesh are the followings:

- (1) The phenomenon of recurvature of tropical cyclones in the Bay of Bengal
- (2) Shallow continental shelf, especially in the eastern part of Bangladesh
- (3) High tidal range
- (4) Triangular shape at the head of the Bay of Bengal
- (5) Almost sea-level orography of the Bangladesh coastal land
- (6) High density of population and coastal defence system

2.2.3 Storm Surge SIDR

In November, 2007, the category 4 cyclonic storm surge SIDR with a wind speed of 250 km/hr hit the south coast of Bangladesh. Figure 2.2 shows the track and propagation of SIDR. The impact of the storm surge was severe: over 3000 people died, and extensive damage occurred to roads, bridges, houses, livestock, and crops.

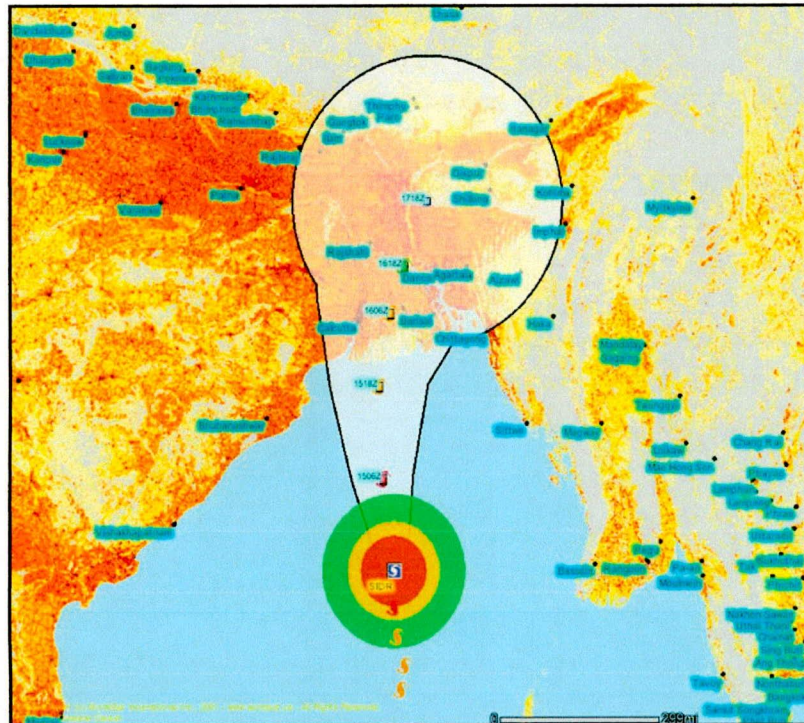
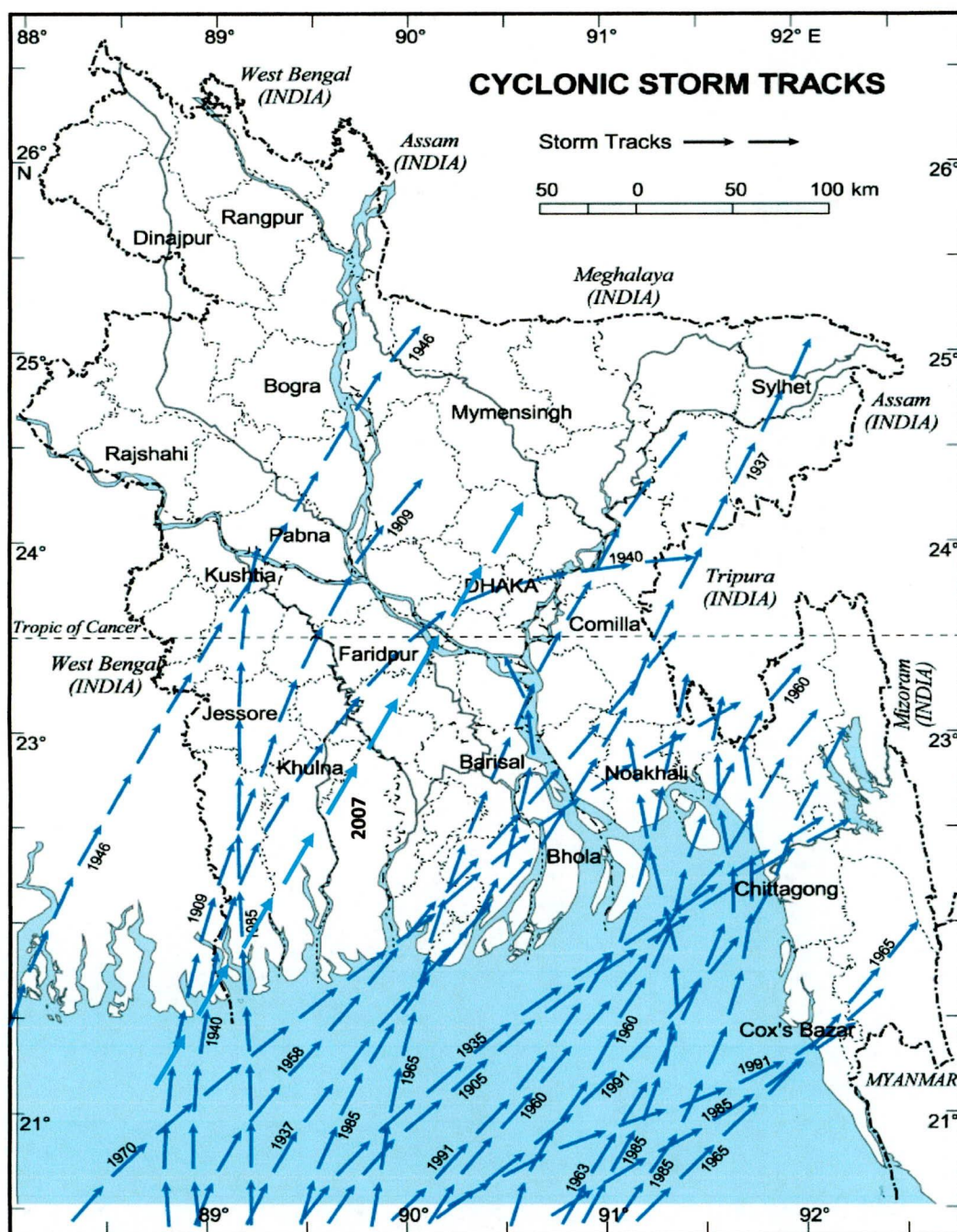


Figure 2.2: Track of storm surge SIDR (2007)

Most of the cyclonic storm surge hit the coasts of Bangladesh with north-eastward approaching angle. Tracks of various storm surges and cyclones are shown in the following Figure 2.3.



Tracks of various storm surges passed over the southern part of Bangladesh

2.3 Previous Studies

According to the 4th IPCC report (2007) future tropical cyclones and storm surges will become stronger, with faster wind speeds (Alley et al., 2007). Also known as hurricanes and typhoons, these massive storm systems combine the effects of heavy rainfall, high winds, and storm surge and sea-level rise. Warmer ocean temperatures will increase the frequency and intensity of such storms (Williams, 2002). Storm routes are also predicted to move poleward, which will mean changes in wind, precipitation and temperature patterns (Alley et al., 2007).

During the last 30 years total power released by storms in the Atlantic has more than doubled and so has the number of Category 4 and 5 hurricanes/typhoons worldwide and these are expected to increase due to warmer seas and oceans (EEN, 2005). According to Stern (2006), infrastructure damage costs will increase substantially from even small increases in sea temperatures because: (1) peak wind speeds of tropical storms are a strongly exponential function of temperature, increasing by about 15 -20% for a 3°C increase in tropical sea surface temperatures; and (2) damage costs typically scale as the cube of wind-speed or more. Storms and associated flooding are already the most costly natural disaster today, making up almost 90% of the total losses from natural catastrophes amounting to US\$184 billion from windstorms alone, particularly from tropical cyclones during 2005.

Different types of bio-shield along coasts can protect the shoreline from cyclone, storm surge and wave attacks during severe hydrological conditions. Unraveling dissipation of wave energy in coastal mangroves by field and laboratory studies has only gained attention recently (Alongi, 2009). Due to the inaccessibility of (natural) mangrove forests, a limited number of field studies have been executed in mangroves in Vietnam, Australia and Japan mainly (Brinkman et al., 1997; Mazda et al., 1997a; Mazda et al., 2006; Vo-Luong and Massel, 2006; Brinkman, 2006; Quartel et al., 2007; Bao, 2011). Wave attenuation by mangroves can be parameterized by calculating a bulk roughness parameter comprising both vegetation induced drag forces and bottom friction (Mazda et al., 1997b; Quartel et al., 2007). Recent modeling studies are directly taking account of the vegetation induced drag forces, calculated by simplifying mangrove vegetation into

one or several layers of cylinders (Vo-Luong and Massel, 2008; Suzuki et al., 2012). This approach requires site specific information on vegetation characteristics such as stem and root diameters, distinct vegetation layers, densities and (bulk) drag coefficients.

There are numerous examples showing the importance of bio-shield on shoreline stability: the harvesting of Kelp the Norwegian coast (Dubi and Torum, 1995; Mork, 1996), seagrass meadows of *Posidonia oceanica* along the Mediterranean coast (Gacia and Duarte, 2001), the *Spartina canopies* (Möller et al., 1999). Magi et al. (1996) and Mazda et al. (1997) studied the quantitative effects of vegetation species, *Rhizophora stylosa* and *Kandelia candel*, respectively, on the reduction of sea waves, based on field observations. Massel et al. (1999) discussed the effect of *Rhizophora* species on the reduction of sea waves. Camfield (1983) considered vegetation as a high friction area and studied wind-wave growth over shallow flooded regions. Numerous models predict wave attenuation using time-averaged conservation equation of wave energy and account for vegetation effects in an energy dissipation term (Dalrymple et al., 1984; Mendez and Losada, 2004), while others use the conservation of momentum approach (Kobayashi et al., 1993; Lima et al., 2006). These models were expressed in terms of a wave shear stress friction coefficient (Teeter et al., 2001) or the drag force acting on the vegetation (Dalrymple et al., 1984; Kobayashi et al., 1993).

Tanaka and Sasaki (2007) have examined the height at which *P. odoratissimus* and *C. nucifera* trees were broken in two tsunamis (the 2004 Indian Ocean and 2006 Java tsunamis) and found that the threshold of tsunami water depth at which a tree trunk broke was about 80% of the tree height for *P. odoratissimus*. *C. nucifera* was seldom damaged except for small trees, but when it was toppled, the critical tsunami height was about 80%, the same as *P. odoratissimus*. Because the breaking point of *P. odoratissimus* is 1–2 m high, the moment by drag at that point is smaller than that of a tree without aerial roots. Although the threshold tsunami water depth for breaking *P. odoratissimus* is similar to that for *C. nucifera*, the trunk strength of *P. odoratissimus* is not as great and it receives a large drag force from the tsunami current when the tsunami water depth is greater than the height of its aerial roots.

Dengler and Preuss (2003) investigated the disaster caused by the 1998 Papua New Guinea tsunami and found that *Casuarina* trees presented relatively greater resistance than palm trees. However, they pointed out the need to conduct further research in understanding the interaction of trees, roots and high flow water regimes in order to utilize vegetation as a tsunami-abatement measure because significant scouring occurred in the areas where the root systems were undermined and in some cases, trees caused additional damage to their surroundings in the fast moving water. This demerit was also pointed out by Shuto (1987). Kathiresan and Rajendran (2005) concluded that the presence of mangroves reduced the human death toll along the Tamil Nadu coast of southeast India, although Kerr et al. (2006) argued that this is an over simplification of a complex scenario. However, the buffering behavior of mangroves has been examined in many other post-tsunami investigations. Dahdouh-Guebas et al. (2005) showed by cluster analysis that the man-made structures located directly behind the most extensive mangroves were less damaged.

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 (Tanaka et al., 2006). Tanaka et al. (2007) 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. This suggests that trunk diameter and density effect, important parameters for estimating vegetation drag. Tanaka et al. (2007) 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 have branches with large diameters.

The United Nations Food and Agriculture Organization (FAO) (2007) stated that active forest management is required to produce variously aged stands of trees with a range of sizes and with branches at all levels to enhance the potential for mitigation, particularly in smaller tsunamis because the mitigation potential of *Pinus* species and *Casuarina* species declines with age. The studies by Tanaka and Sasaki (2007) and Tanaka et al. (2009) elucidated the breaking condition for a single tree when the scouring around the tree is not severe. 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.

Different types of bio-shield offer different amount of resistance to the shoreward propagating waves. There are a significant number of laboratory experiments and field measurements on different bio-shield species by many investigators over time. The laboratory and field measurements are used to understand the physical processes and to validate mathematical models. Some examples are given below. Asano et al. (1988) conducted experiments on wave attenuation due to vegetation in a 27 m long, 0.5 m wide and 0.7 m deep flume using flexible polypropylene strips of 0.25 m in length as model vegetation. Gambi et al. (1990) studied flow speed reduction by *Zostera marina* in a seawater flume, with the seagrass bed occupying only 20 percent of the width of the flume. Dubi (1995) and Dubi and Torum (1997) presented laboratory experiments to investigate wave energy dissipation in a coastal kelp field of artificial *Laminaria hyperborean*, analyzing the sensitivity of the damping rate to several parameters. Li and Yan (2007) conducted experiments on wave-current-vegetation interaction in a flume of 15 m in length, 0.31 m in width, and 0.4 m in height, using semirigid rubber rods as model vegetation. Schutten et al. (2004) measured the hydraulic forces on submerged aquatic vegetation by waves. The experiments were carried out in a wave-flume (5 m long, 0.6 m wide and 1 m deep), and replicas and real plants were used.

Augustin et al. (2009) conducted laboratory experiments on wave attenuation using synthetic vegetation under a range of wave conditions and plant stem densities. The bulk drag coefficient was determined using linear wave theory and the friction factor using a nonlinear Boussinesq model (COULWAVE). The drag coefficient obtained using linear theory showed a higher dependence on Reynolds number during emergent conditions than during near-emergent conditions. However, drag coefficients during near-emergent conditions exhibited somewhat higher correlation with the Keulegan-Carpenter number. The experiments proved that emergent conditions lead to a higher amount of wave attenuation compared to near-emergent conditions. Elwany et al. (1995) carried out experiments on *Macrocystis pyrifera* forest on the propagating waves at Carlsbad, California to measure wave reduction. The measurements were continued for about 67-day period. Their study concluded that when the average vegetation density is about 10

plants per 100 m², the vegetation does not have a significant effect on waves. Such information can be important for mathematical models and as indication of limitation using coastal vegetation to protect shorelines.

The energy dissipation due to vegetation is often used in the wave energy equation as a sink term. Such models have been used in many coastal hydrodynamic models that compute current and waves separately with either considering or ignoring the interactions of current and waves. For example, Meijer (2005) implemented a capability of simulating wave attenuation by vegetation in the 2-D nearshore model SWAN. The effects of mangrove forests on the flow structure in estuaries was studied by Wu et al. (2001) using a two-dimensional depth-integrated model. The hydrodynamic model was modified to include both the effects of drag force induced by mangrove trees and the blockage effects on the mass fluxes through mangrove forests. Two idealized tests were considered and it was found that the velocities were significantly reduced by mangroves in the forested area, and correspondingly a significant increase occurred in the velocities in the main channel. The model developed by Wu et al. (2001) was enhanced by Struve et al. (2003). They conducted experiments in a laboratory flume and further validated the numerical model considering additional resistance and blockage created by mangrove model trees. Teo et al. (2009) applied the two-dimensional numerical model of Wu et al. (2001) to an idealized estuary to study the impact of mangroves on tsunami waves. The vegetation was represented by rigid circular cylinders.

The numerical experiments showed that the vegetation significantly impacted the wave height and velocity inside the vegetated area. Harada and Imamura (2005) performed numerical simulations, including an evaluation of the quantitative effects of coastal forests in controlling tsunami reduction and damage. They found that an increase in forest width can reduce not only inundation depth, but also the currents and hydraulic forces behind the coastal forest. Thuy et al. (2010) also applied a depth-averaged 2-D shallow water model for simulating tsunami wave runup on a vegetated beach, and explored the influence of coastal forest gap on tsunami inundation. Erduran and Kutija (2003) introduced a quasi-three-dimensional model, which coupled the finite volume solution of the two-dimensional shallow water equations with a finite difference solution of Navier–Stokes equations for the vertical velocity distribution. The drag forces were included in

both sets of equations, and a cantilever beam theory was used to deal with flexible vegetation.

Tanaka (2008) developed a different approach to numerically model the storm surge from Cyclone Sidr, which made landfall in Bangladesh in 2007. He modeled the passage of short period wind waves (wave period 1 or 2 minutes) and a longer period storm surge (wave period 1 or 2 hours) through trees; both types of waves were modeled separately and in combination. The modeled vegetation characteristics were based on the non-mangrove tree species *Casuarina equisetifolia*; trees were modeled as cylinders, 10 m high and 16 cm in diameter, with 0.35 trees per m² in a triangular arrangement. He used a one-dimensional non-linear long wave differential equation to explore different short wave and long wave storm surge conditions and wind conditions, in the presence or absence of a 150 m wide band of vegetation. The underlying topography and vegetation measurements matched those seen in transects in Mathbaria, Bangladesh, and the model results were compared with observations of how this area was affected by Cyclone Sidr. Using his model, Tanaka (2008) found that a 150 m band of vegetation had a small effect on the wind's ability to raise water levels (assuming wind speeds of 60 m/s, but not including wind waves); the water level was 4 cm lower behind the vegetation than would be expected with no vegetation present. Vegetation had no effect on the water depth caused by the long wave component (i.e. the storm surge) although the vegetation slightly decreased the velocity of water inside the vegetation zone and the arrival time of the peak of the storm surge. When wind waves were included on top of the storm surge as short waves with a period of 1 or 2 minutes, the water depth behind the vegetation was reduced by 12 or 28 cm respectively (compared to no vegetation being present). This supports the idea that the largest effect of vegetation on storm surge water levels may be through their effect on the short-period wind waves on top of the surge.

Additionally Tanaka (2008) explored the effect of changing the ground slope. He found that when the gradient of the land was 1 in 500 (as opposed to 1 in 100, as used in the previous model runs), and with a long wave with a period of 2 hours and short waves with a period of 2 minutes, water depth behind the vegetation was 80 cm lower than it would have been without the vegetation. Tanaka concluded that the vegetation had a larger effect on reducing water depths (i.e. storm surge water levels) when the storm

surge was passing over a lower angle slope (i.e. closer to horizontal). The results from Tanaka's model broadly match observations: Tanaka (2008) reported that during cyclone Sidr in Bangladesh in November 2007, a 150 m band of river-side vegetation near Mathbaria may have caused a 0.5 to 1.0 m difference in water level (including the effects of wind and swell waves) behind the trees. The observed reduction in water level was based on interviews with local people about where the water reached. Tanaka's model demonstrates that a relatively narrow band of trees (150 m) may result in a fairly large reduction in water levels (0.8 m), when the effect of vegetation on wind waves is also taken into account. Further research is needed to verify this result for mangroves.

The global climate is changing and it is likely to change further over coming decades due to increasing concentrations of 'greenhouse gases' in the earth's atmosphere caused largely by human activities. This will result in greater variations in weather patterns, a greater frequency of extreme weather events such as floods, droughts and tropical storms, and gradual rises in average temperatures and sea-levels. Bangladesh is extremely vulnerable to climate change impacts because of its geographical location, high population density, high levels of poverty, and the reliance of many livelihoods on climate-sensitive sectors.

A number of studies on the impact of climate change in Bangladesh exist. Notable among them are those of Mahtab (1989), BCAS (1994), BUP (1994), and Bangladesh Climate Change Country Study Program (1997). Most of the climate change impacts in Bangladesh are likely to come from the south — that is, the Bay of Bengal and the adjoining North Indian Ocean. These waters are the sources of tropical cyclones and storm surges, coastal erosion, monsoon wind, evaporation for monsoon rainfall, floods, and droughts. Considering these, the present study concentrates on the tropical cyclones and storm surges along the coastal belt of Bangladesh considering future climate change effects.

According to IPCC's Fourth Assessment Report (2007) all of Asia is likely to warm this century and warming in South Asia is likely to be above the global average at around 3.3°C and According to the 5th IPCC report (2013) a global temperature could rise by between 3.2°C and 5.4°C by the end of the century. Other studies (Alley et al., 2007;

Stern, 2006; Hasan, 2009) have also predicted all seasons to get warmer within the Ganges-Brahmaputra-Megna Basins, with an increase in extreme temperatures. Temperatures are expected to warm slightly slower in Bangladesh than for other areas in the Ganges-Brahmaputra-Megna basin which is estimated to be 1.2 °C warmer by the 2020s and up to 2.4 °C by the 2050s. But warming is still predicted to be significant from 0.9 °C to 1 °C by the 2020s and 1.6 °C to 2 °C by the 2050s (Hasan, 2009). This warming is predicted to be more pronounced from December to May, with for example average winters in the 2050s being around 1.9-2.4 °C warmer compared to summers in the 2050s being 1.4-1.8 °C warmer in Bangladesh (Tanner et al., 2007).

Extreme weather events have also been observed to be increasing in South Asia and can exacerbate mortality. In 2003 heat waves that killed 1539 Indians and cold waves that killed 1156 Indians are suspected to be linked to climate change (Akhtar, 2007). In the last 10 years severe cold waves have become common in Bangladesh (Roach, 2005), temperatures as low as 5°C were recorded in January 2007 which were the lowest in 38 years in Bangladesh and also affected the north of India and Nepal killing over 130 people (Reid et al, 2007). However, many more people could be affected by climate change's impact on disease, and a number of diseases in South Asia may become more common due to hotter weather and changing rainfall patterns (Kovats & Alam, 2007).

Global warming has raised and will continue to raise sea level due to thermal expansion of the oceans as warmer water takes up more space and the melting of ice stored in glaciers or ice sheets since floating sea ice being lighter than water sits on the sea surface and when it melts it increases the seas volume causing sea level rise. The consequences of sea level rise include more frequent and more devastating flooding and loss of coastal land. For in coastal situations, a 50 cm rise normally results in a 50 m loss of land (Artic Climate Impact Assessment In: EEN, 2005b).

According to the information from the 4th IPCC report global sea levels will rise by at least 18 cm, but in the worst case scenario as much as 59 cm by the year 2100 (Alley et al., 2007) and the 5th IPCC report (2013) has predicted that a global average sea level rise would be 74 cm by the end of the century. As half of the world's population is living in coastal regions, flooding due to storm surges already affects around 46 million people a

year, mostly in developing countries. But with a 50 cm sea-level rise, this figure could double to 92 million. Indeed, it is estimated based on the IPCC reports, that by 2025 over half of all people living in developing countries will be highly vulnerable to floods and storms (La Trobe, 2002). However, these predictions from the IPCC excluded the melting of ice caps as scientists have been finding it difficult to assess their impact on sea levels (Hodson & Hodson, 2008). Melting of the Greenland Ice Sheet is expected to continue to contribute to sea level rise beyond 2100, as melting ice adds water to the sea. If ice sheet melting continues as global warming increases, eventually that would lead to virtually complete elimination of the Greenland Ice Sheet and a resulting contribution to sea level rise of about 7 m (Alley et al., 2007).

Rising sea levels will cause livelihoods to be lost and people displaced as land permanently goes under water, while the costs of sea defenses will rise. Coastal areas are amongst the most densely populated areas in the world and support several important ecosystems on which local communities depend. Critical infrastructure is often concentrated around coastlines, including oil refineries, nuclear power stations, port and industrial facilities. Currently, more than 200 million people live in coastal floodplains around the world, with 2 million Km² of land and \$1 trillion worth of assets less than 1 m elevation above current sea level. Many of the world's major cities (22 of the top 50) are at risk of flooding from coastal surges, including Tokyo, Mumbai, Calcutta, New York, and London (Stern, 2006).

2.4 Summary

A considerable number of research papers have been studied on the coastal areas of Bangladesh as well as other coastal areas all over the world to understand the effectiveness of coastal bio-shields for the reduction of cyclonic storm surges. From the reviewed research it has been found that there is a very few studies on the coastal bio-shields for reduction of surge energy considering future climate change effects. There are a limited number of laboratory experiments related to this topic. As the coastal areas are very much exposed to the sea, they are more vulnerable to storm surges and sea level rise than other areas. So the literature review has been very much helpful to select this topic for study.

CHAPTER THREE

METHODOLOGY

3.1 General

This study has been performed to find out the effectiveness of coastal bio-shields for reduction of the energy of cyclonic storm surges along the coastal belt of Bangladesh considering future climate change effects. This study comprises the analysis of historical storm surges as well as assessment of the existing coastal bio-shields along with an experimental and numerical study for the reduction of storm surge energies along the coastal belt of Bangladesh. The theories and methods of the analysis have been described in this chapter.

3.2 Data Collection of Historical Storm Surge and Existing Bio-shields

Almost all the available data on cyclonic storm surge has been collected from IWM, Wikipedia and different reports that have been included in the reference section. The track data of SIDR has been collected from BMD. The track data covers position of the eye, maximum wind speed, radius and center of pressure. The historical cyclonic storm surge data has been presented in the Appendix A. The existing bio-shields data has been collected from reports of Bangladesh Forestry Department and Arannayk Foundation, 2013 and websites.

3.3 Laboratory Experiment

A two-dimensional experimental study was carried out in the Hydraulics and River Engineering Laboratory of Bangladesh University of Engineering and Technology to analyze the effects of coastal bio-shield in reducing the energy of high frequency surges. The laboratory experiment was performed on a 22 m long, 0.75 m wide and 0.75 m deep rectangular wave flume. Water was allowed to enter the flume by pipes from the main water supply system. In the wave flume artificial waves were generated by mechanically driven wave paddle. The frequency of the wave paddle was set before each run which is related to the desired wave period. A total of 51 experimental runs were conducted using bio-shield of different materials and densities as well as different submergence conditions and wave periods.

3.3.1 Selection of Scale for the Laboratory Experiment

To scale down the bio-shields for 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 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.

3.3.2 Experimental Setup

The following Figure 3.1 and Figure 3.2 show the details of the experimental set-up that was fixed in a flume. The experimental set-up consisted of a relatively mild slope of 1:30, which had a length of 15 m and the flume 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 material and polyethylene (polyethylene is 75 times more flexible than bamboo) as flexible material whose diameter were 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 spacing 25 mm c/c and 50 mm c/c of bio-shields, respectively. The width of bio-shield was fixed at 75 cm as the flume width was 75 cm but the length varies from 1 m to 2 m. There were two combinations of length of the bio-shield, i.e. (i) one meter flexible and one meter rigid and (ii) half meter flexible and half meter rigid. The flexible bio-shields were placed always on the rear side and rigid bio-shields were placed on the front side of the embankment. The experiments were conducted for two distances of bio-shield from the embankment such as 2 m and 4 m. The water level was always fixed at 50 cm throughout the flume. The next Figure 3.3 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 fixed carefully on pre drilled wooden plank.

The wave-generating system (electric motor type) was capable of synthesizing sinusoidal small-amplitude long wave profile. In the wave flume, artificial waves were generated by wave paddle or wave generator. So, wave generator was a very important part of the experiment. 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 3.1 and Figure 3.2. 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 at every measuring location.

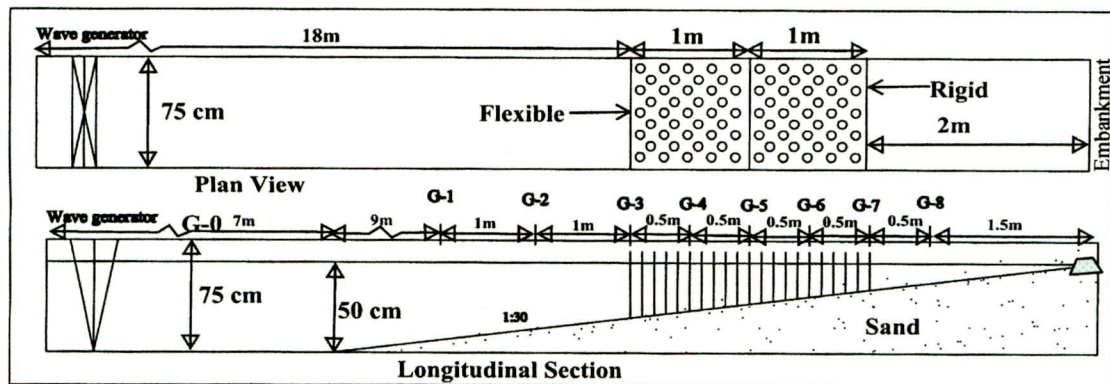


Figure 3.1: Details of laboratory experiment (Bio-shield at 2m from the embankment and 1m Rigid + 1m Flexible)

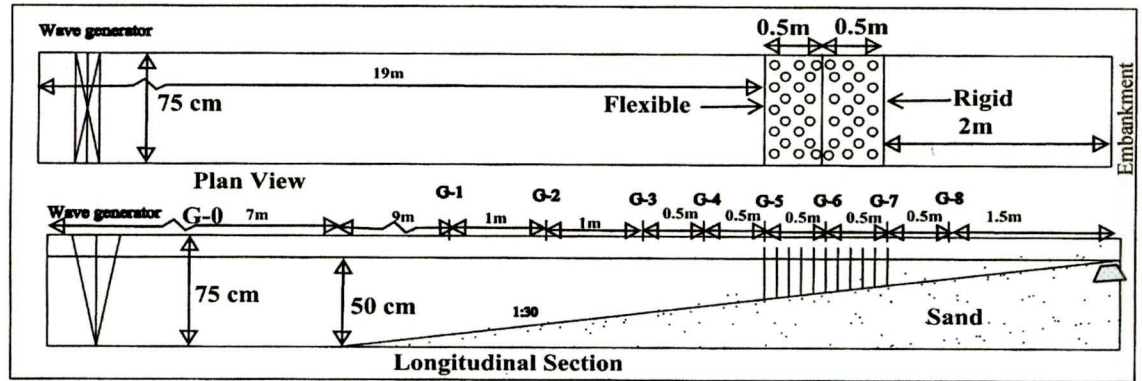


Figure 3.2: Details of laboratory experiment (Bio-shield at 2m from the embankment and 0.5m Rigid + 0.5m Flexible)

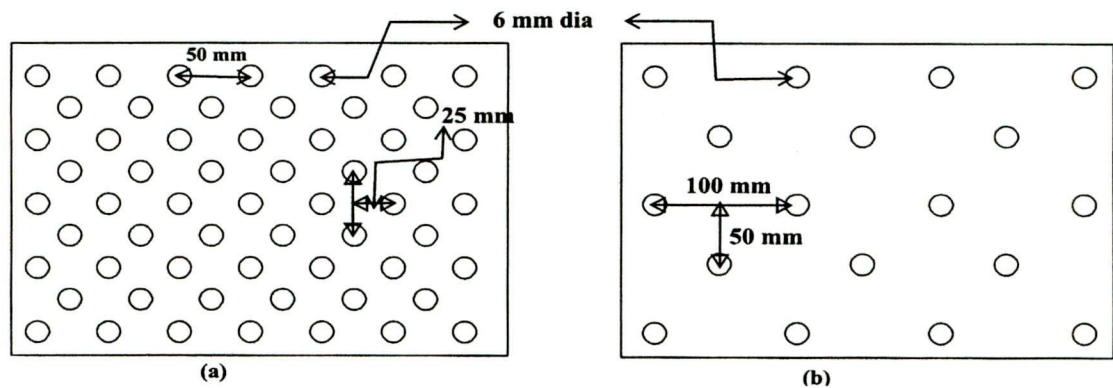


Figure 3.3: Two different types of arrangement of bio-shields (a) Spacing: 25 mm c/c (b) Spacing: 50 mm c/c

3.3.3 Wave Generator

The wave generator is fixed one of the experimental flume. Artificial wave of desired wave period and wave height was set with the help of this generator. Figure 3.4 shows the wave generator which was used in the laboratory.



Figure 3.4: Electric motor type wave generator used in laboraotory

3.3.4 Setting of Wave Generator

To set the wave generator at a certain wave period, the flume needed to be emptied before setting the wave generator. Then the mean position of wave paddle was marked by a permanent marker on the glass. For doing this, the cooling fan cover of the driving motor was being removed and the fan was being rotated by hand until the wave paddle was vertical. This was checked by a spirit level. Then a line was drawn along the wave paddle which indicated the mean position of wave paddle.

Three different wave periods were used in this experiment. They were 1.6, 1.8 and 2.0 sec. The water level was kept constant at 50 cm for all the run conditions. For setting the wave periods there are some calculations which had to be done every time. Suppose when the wave period is 1.6 sec

So, $T=1.6$ sec, $H=50$ cm

$$\text{Then, } \frac{\omega^2 h}{g} = \left(\frac{2\pi}{T} \right)^2 * \frac{h}{g} = \frac{4\pi^2}{1.6^2} * \frac{50}{980} = 0.7868$$

From the graph (Figure 3.5), we found $e = 0.50$ and $f = 0.74$ So, $e+f = 0.50 + 0.74 = 1.24$

$$\frac{e+f}{f} = \frac{1.24}{0.74} = \frac{1.24*100}{0.74*100} = \frac{124}{74} = 1.68$$

So, we found that the ratio was 1.68. Now, it was the time to adjust the cradle arm. When the cradle arm was vertical, there was rotational motion. So, the arm was set in such position that $\frac{e+f}{f} = 1.68$. By taking the measurement from mean line, arm was set in desirable position. Then the wave period was adjusted to 1.6 sec. Then, the flume was again filled and experiment was done for wave period 1.6 sec. Similarly The experiment was done for 1.8 and 2.0 sec.

For wave period 1.8 and 2.0 sec the $\frac{e+f}{f}$ ratio were 1.48 and 1.36 respectively.

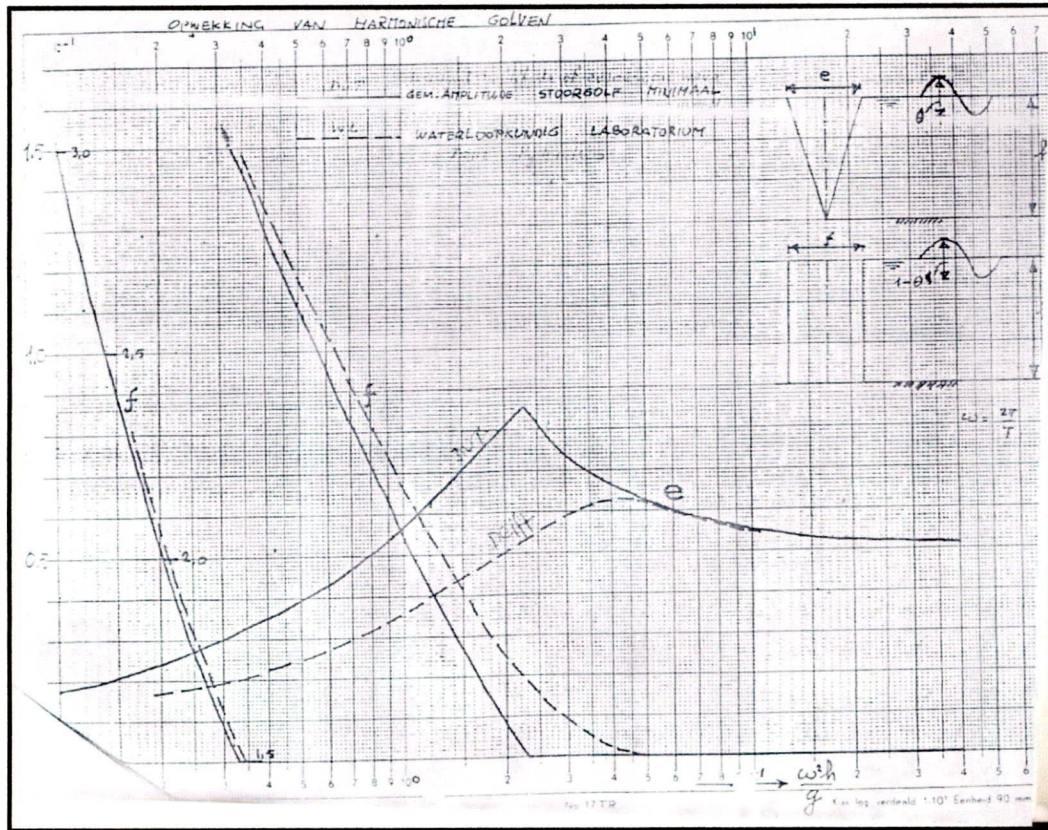


Figure 3.5: Graph for setting the wave periods

3.3.5 Bio-shield Barrier Used in the Laboratory Experiment

Different lengths, densities, materials and submergence of bio-shield barrier has been used in this laboratory experiment. The bio-shield barrier was a combination of rigid and flexible materials, 6 mm diameter of bamboo and polyethylene sticks were used in the laboratory experiment. 0.75 m long and 2 m wide bio-shield barrier has been used to study the effect of vegetation in reducing the energy of high frequency surges. The vegetation barrier acts as buffering zone which neutralizes the waves during cyclonic storm surge. The barrier was placed at two different positions i.e. 2 m and 4 m from embankment. Figure 3.6 shows the pictures of vegetation barrier that has been used in this study.

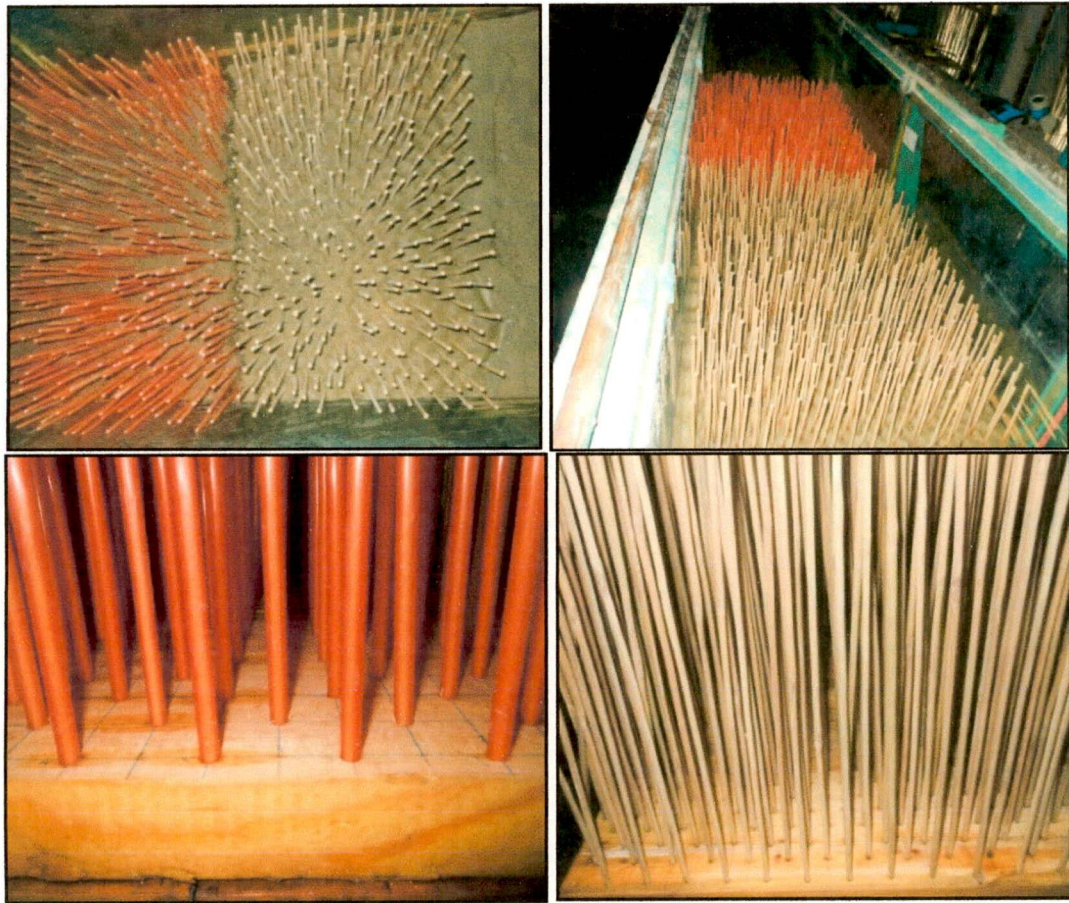


Figure 3.6: Photograph of bio-shield used in the laboratory experiment

3.3.6 Flume Preparation

The two dimensional wave tank was prepared very dexterously before the experiment. At first 4 wooden plank of size 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. The polyethylene or flexible sticks were always placed towards the down side of the slope and bamboo sticks were placed on the up side of the slope. Finally sand was scattered over the flume to prepare a 1:30 slope. Then the flume was ready for the experiment. Figure 3.7 shows some photographs of flume preparation.



Figure: 3.7: Photographs showing preparation of experimental wave flume

3.3.7 Experimental Run Conditions

A total of 51 experimental runs have been conducted using bio-shields of different materials, densities and different submergence conditions as well as different distances of bio-shield from embankment and wave periods. To investigate the water surface profile, wave heights were measured before and after passing the vegetation barrier at nine different locations. Nine measuring tapes were deployed at nine measuring locations on the glass surface of the flume to measure the water level at nine desired locations. The measuring location G-0 was placed at 16 m, measuring location G-1 at 6 m, measuring location G-2 at 5 m, measuring location G-3 at 4 m, measuring location G-4 at 3.5 m, measuring location G-5 at 3 m, measuring location G-6 at 2.5 m, measuring location G-7 at 2 m, measuring location G-8 at 1.5 m from the embankment. The measuring location G-8 was always placed behind the bio-shield zone, location G-1 was always placed in front of the bio-shield barrier and the position of the rest of the measuring locations were changing depending on the experimental run conditions. The run conditions are presented in Table 3.1.

Table 3.1: Laboratory Experimental Run Conditions

Run No	Submergence condition	Distance from embankment, (m)	Length of bio-shield, (F+R) (m)	Spacing of bio-shield, (mm)	Wave periods, T(sec)	Still water depth, H (cm)	Bed slope, S
1	Emerged	2	1+1	25	1.6	50	1:30
2	Emerged	2	1+1	25	1.8		
3	Emerged	2	1+1	25	2.0		
4	Emerged	2	1+1	50	1.6		
5	Emerged	2	1+1	50	1.8		
6	Emerged	2	1+1	50	2.0		
7	Emerged	2	0.5+0.5	25	1.6		
8	Emerged	2	0.5+0.5	25	1.8		
9	Emerged	2	0.5+0.5	25	2.0		
10	Emerged	2	0.5+0.5	50	1.6		
11	Emerged	2	0.5+0.5	50	1.8		
12	Emerged	2	0.5+0.5	50	2.0		
13	Emerged	4	1+1	25	1.6		
14	Emerged	4	1+1	25	1.8		
15	Emerged	4	1+1	25	2.0		
16	Emerged	4	1+1	50	1.6		
17	Emerged	4	1+1	50	1.8		
18	Emerged	4	1+1	50	2.0		
19	Emerged	4	0.5+0.5	25	1.6		
20	Emerged	4	0.5+0.5	25	1.8		
21	Emerged	4	0.5+0.5	25	2.0		
22	Emerged	4	0.5+0.5	50	1.6		
23	Emerged	4	0.5+0.5	50	1.8		
24	Emerged	4	0.5+0.5	50	2.0		
25	Submerged	2	1+1	25	1.6		
26	Submerged	2	1+1	25	1.8		
27	Submerged	2	1+1	25	2.0		
28	Submerged	2	1+1	50	1.6		
29	Submerged	2	1+1	50	1.8		
30	Submerged	2	1+1	50	2.0		
31	Submerged	2	0.5+0.5	25	1.6		
32	Submerged	2	0.5+0.5	25	1.8		
33	Submerged	2	0.5+0.5	25	2.0		
34	Submerged	2	0.5+0.5	50	1.6		
35	Submerged	2	0.5+0.5	50	1.8		
36	Submerged	2	0.5+0.5	50	2.0		
37	Submerged	4	1+1	25	1.6		
38	Submerged	4	1+1	25	1.8		
39	Submerged	4	1+1	25	2.0		
40	Submerged	4	1+1	50	1.6		
41	Submerged	4	1+1	50	1.8		

42	Submerged	4	1+1	50	2.0		
43	Submerged	4	0.5+0.5	25	1.6		
44	Submerged	4	0.5+0.5	25	1.8		
45	Submerged	4	0.5+0.5	25	2.0		
46	Submerged	4	0.5+0.5	50	1.6		
47	Submerged	4	0.5+0.5	50	1.8		
48	Submerged	4	0.5+0.5	50	2.0		
49	Without bio-shield				1.6		
50	Without bio-shield				1.8		
51	Without bio-shield				2.0		

*F= Flexible material (Polyethylene) and R= Rigid material (Bamboo sticks)

3.3.8 Data collection

Data collection is the most essential part of any laboratory experiment. Test runs were carried out for three different wave periods with 16 different conditions for each of the wave periods and three runs for no bio-shield conditions. Still water depth was kept 50 cm for all runs. The wave period was changed by varying the frequency of the wave paddle. The frequency of the wave paddle was set before every run which was related to the desired wave height and wave period by the method which has been discussed in article 3.3.3. Nine measuring locations were set for investigating the water surface variations that is given in article 3.3.1. Water level variations were measured at nine different locations at 5 seconds interval for 60 seconds at each measuring location. The time series collected data of this laboratory experiment is given in Appendix B as graphs and the Figure 3.8 shows some photo views of data acquisition during the laboratory experiment.



Figure 3.8: Photographs show laboratory experimental data collection procedure

3.4 Numerical Modelling

A numerical modelling software named MIKE21 developed by DHI (Danish Hydraulic Institute) is used to develop the Bay of Bengal (BoB model developed by Institute of Water Modeling) model which was applied to the Kuakata beach of Bangladesh to investigate the effectiveness of coastal bio-shield on current speed and surge level reduction caused by SIDR.

3.4.1 Theory

MIKE 21 has a number of modules for different purpose and each module has different sets of equations. In this study hydrodynamic and cyclone module of MIKE 21 have been used.

Governing Equation in Hydrodynamic Module:

The governing equations used in MIKE21 in solving hydraulic problems in coastal areas are:

Conservation of Mass Equation:

$$\frac{\partial \varepsilon}{\partial t} + \frac{\partial p}{\partial x} + \frac{\partial q}{\partial y} = 0 \dots\dots(3.1)$$

Conservation of momentum equation:

The momentum equation in the x-direction is given by:

$$\frac{\partial p}{\partial t} + \frac{\partial p^2}{\partial x} + \frac{\partial pq}{\partial y} + gh \frac{\partial \varepsilon}{\partial x} + \frac{f}{2} \frac{\sqrt{p^2 + q^2}}{h^2} p - \frac{1}{\rho} \frac{\partial \tau_{xy} h}{\partial y} - \Omega q - \frac{\rho_a}{\rho} C_w W W_x + \frac{h}{\rho} \frac{\partial p_a}{\partial x} = 0 \dots(3.2)$$

The momentum equation in the y-direction is given by:

$$\frac{\partial q}{\partial t} + \frac{\partial q^2}{\partial y} + \frac{\partial pq}{\partial x} + gh \frac{\partial \varepsilon}{\partial y} + \frac{f}{2} \frac{\sqrt{p^2 + q^2}}{h^2} q - \frac{1}{\rho} \frac{\partial \tau_{yx} h}{\partial x} + \Omega p - \frac{\rho_a}{\rho} C_w W W_y + \frac{h}{\rho} \frac{\partial p_a}{\partial y} = 0 \dots (3.3)$$

Where,

p and q = flux in x and y directions respectively (m³/s/m).

t = time (s), x and y (m) are Cartesian Co ordinate (s).

h =water depth (m).

g =acceleration due to gravity (9.81 m²/s).

ε =Sea surface elevation (m).

ρ_w & ρ_a =Air and water density respectively (kg /m³).

C_w =wind friction factor = 0.0008 + 0.000065W in accordance with Wu (1982).

W =wind speed (m/s).

Ω =Carioles' parameter

P_a =Atmospheric pressure (kg/m/s²).

Governing Equation in Cyclone Module:

The Cyclone module of MIKE21 has been used to generate the pressure and wind distributions all over the Bay of Bengal. Cyclone Model is normally described by relatively few parameters relate to pressure field, which is imposed to the water surface and a wind field which is acting as a drag force on the water body through a

wind shear stress description. A reasonable description of maximum wind and especially the extent of the high winds in the cyclone are important to obtain the right level setups and set down.

The wind fields consist of a rotational and a translational component. At a distance R from the centre of the cyclone the rotational wind speed V_r is given as

$$V_r = V_m \left(\frac{R}{R_m}\right)^7 \exp\left(7\left(1 - \frac{R}{R_m}\right)\right) \quad \text{for } R < R_m \quad \dots\dots\dots (3.4)$$

$$V_r = V_m \exp\left(C\left(1 - \frac{R}{R_m}\right)\right) \quad \text{for } R > R_m \quad \dots\dots\dots (3.5)$$

Where R and R_m are in km and C is given as

$$C = 0.0025R_m + 0.05 \quad \dots\dots\dots (3.6)$$

C determines the shape of wind distribution for $R > R_m$.

And translational component V_t is given as

$$V_t = -0.5V_f(-\cos\theta) \quad \dots\dots\dots (3.7)$$

Where, θ is the angle between the radial arm and the line of maximum winds. The total wind speed is $V = V_r + V_t$

And finally, the pressure at particular location is given as

$$P = P_c + (P_n - P_c) \exp\left(\frac{-R}{R_m}\right) \quad \dots\dots\dots (3.8)$$

Where P is pressure at radius R , P_c is central pressure, P_n is neutral pressure.

The two-dimensional numerical model known as BoB model was applied to the Kuakata beach of Patuakhali district. In this numerical modeling four simulations are done successfully for various scenarios to study the behavior of coastal bio-shields for the reduction of storm surge and cyclone energy along the Kuakata beach considering future climate change effects. The numerical modeling run conditions are given in the Table 3.2.

Table 3.2: Numerical Modeling Run Conditions

Run No	Width of bio-shield, (m)	Distance from embankment, (m)	Climate change Effect	Cyclonic Wind Speed (km/h)
1	200	200	Sea level rise 74 cm for the year 2100	210 (SIDR)
2	200	200	No sea level rise	
3	No bio-shield and no sea level rise			
4	No bio-shield and considering 74 cm of SLR			

3.4.2 Study Area

Bangladesh is one of the most vulnerable countries to several natural disasters and every year natural calamities upset people's lives in some part of the country, especially in the southern coastal areas of Bangladesh. The major disasters concerned here are the occurrences of cyclones and storm surges. These extreme natural events are termed disasters when they adversely affect the whole environment, including human beings, their shelters, or the resources essential for their livelihoods. The geographical setting of Bangladesh makes the country vulnerable to natural disasters mainly cyclonic storm surges. People of coastal area of Bangladesh are the main victim of these cyclonic storm surges. Presently, the Kuakata beach of Patuakhali district shown in Figure 3.9 is very much vulnerable to these natural disasters and it is the most attractive place to the visitors as well. That's why this beach is selected for the study.



Figure 3.9: Location of Kuakata beach on the Bangladesh map

Kuakata: Kuakata is a scenic sea beach on the south of Bangladesh. It is situated 320 km from Dhaka and 70 km from the Patuakhali district headquarters, Kuakata is a part of the Latachapli union of Kalapara upazila. The beach at Kuakata is 18 km long and 3 km wide. This sandy beach slopes into the Bay of Bengal. The most important attraction of the beach is that one can see both sunrise and sunset from some of its locations. Other attractions at Kuakata include blue sky, huge expanse of water, the evergreen forest in surrounding areas, rows of coconut trees, boats of many different kinds and their colourful sails, and surfing waves. The Figure 3.10 shows existing bio-shield on Kuakata beach of Bangladesh. Kuakata is also a sanctuary for migratory winter birds. On the eastern end of the beach is Gongamati Reserved Forest, an evergreen mangrove forest and snippet of the original Kuakata. When the Rakhines settled in the area in 1784, Kuakata was part of the larger Sundarbans forest. As a mangrove forest, Gongamati, like the Sundarbans, offers some protection against tidal surges, however it too is being threatened by logging and deforestation.



Figure 3.10: photographs showing coastal bio-shield on the Kuakata beach

3.4.3 The Bay of Bengal Model

The Bay of Bengal Model (BoBM) has been used for the study. The model is available in IWM. Bay of Bengal Model (BoBM) is a two-dimensional one layer hydrodynamic model based on Mike 21 Modelling software. The model covers the northern part of the Bay of Bengal from latitude $17^{\circ}00'00''$ to the coast of Bangladesh. The model area has been shown in the Figure 3.11. A model set-up on such a large area is necessary to include hydrological information moving from deep sea towards the Bangladeshi coastline as well as to reduce the boundary effect on the area of interest. The model that has been used in this study was updated totally for CERP. Also many local models have been developed and updated with recent data for different scenarios for a specific location. The core of the modelling study is based on the existing two-dimensional Bay of Bengal Model (BoBM).

3.4.4 Size of the Model (Model Grid)

The base model covers the northern part of the Bay of Bengal from latitude $17^{\circ}00'00''$ to the coast of Bangladesh. A model setup on such a large area is necessary to include estuarine processes. The base model is a three way nested model and the resolutions are 5400 m, 1800 m and 600 m. The Meghna Estuary is resolved on a 600 m grid. Extent of models has been shown in the Figure 3.11 and information on the grid is given in Table-3.3 and Table 3.4.

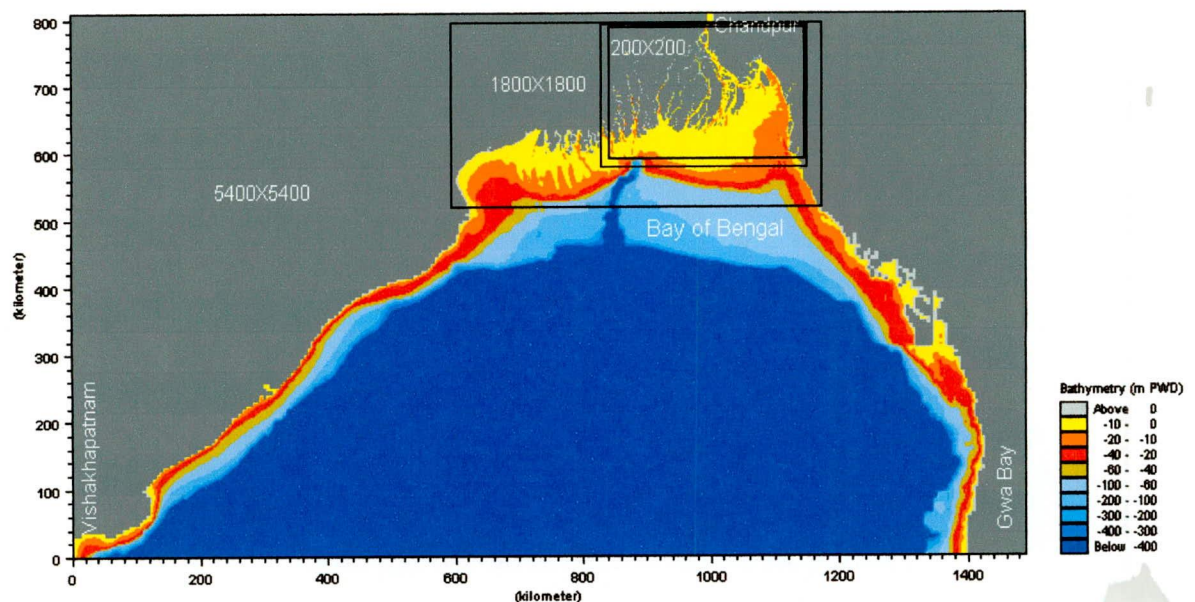


Figure 3.11: Nested bathymetry of Bay of Bengal Model (Source: IWM)

Table 3.3: Model grid specification

Model	Origin (degree)		Orientation (degree)	Grid spacing (m)	Grid Numbers
	Longitude	Latitude			
Coarse grid	81.2408	16.0044	-2.19	dx=5400 dy=5400	277X151
Intermediate grid	86.7473	20.8165	0.9147	dx=1800 dy=1800	322X154
Fine grid	88.8231	21.0273	-0.1238	dx=600 dy=600	603X411
200 m grid	88.9135	21.0582	0.0833	dx=200 dy=200	1782X1203

Table 3.4: Relative grid positions

Model	In 200 m grid	In fine grid	In intermediate grid	In coarse grid
Coarse grid				(0,0)
Intermediate grid			(0,0)	(111,96)
Fine grid		(0,0)	(120,16)	(151,101)
200 m grid	(0,0)	(15,5)	(125,3)	(153,102)

3.4.5 Bathymetry Generation

Bathymetry is the bottom topography of a river or a sea. As the model area is a huge one, it is not possible to survey all the area at a time. To make the bathymetry, bed level data has been collected from different sources of different time. Table 3.5 shows the source of bed level data utilized for generation of bathymetry of the model and the Figure 3.12 shows the model bathymetry of BoB model.

Table 3.5: Land-water data used for generating the bathymetry

Model component	Type of Data				
	Bathymetry	Source	Land	Source	Land-water boundary
Coarse grid	Admiralty maps	CSPS	-	-	Admiralty maps
Intermediate grid	Admiralty maps	CSPS	-	-	Admiralty maps
Fine grid	Admiralty maps	MES I	DEM (1952-64)	CSPS	LANDSAT 1996
	FAP 5B Survey (1997)	MES I	FINMAP (1990)	CSPS	LANDSAT 1998
	MES II survey (1998, 99)	MES II		IWM	
	BIWTA maps	MES II	KJDRP (1997)		

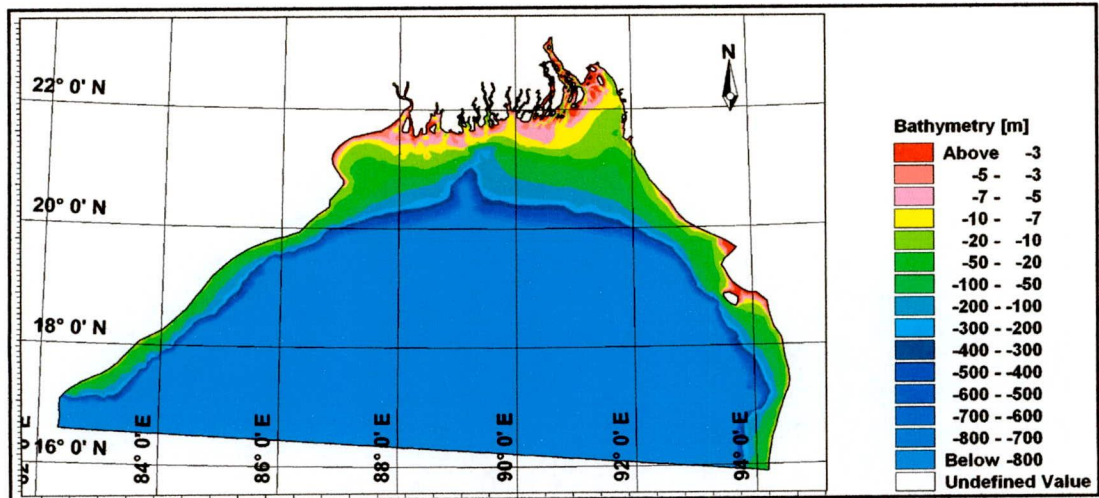


Figure 3.12: Bathymetry of Bay of Bengal Model (Source: IWM)

3.4.6 Eddy Viscosity

The eddy viscosity E has been specified in the model as a time-varying function of the local gradients in the velocity field. This formulation is based on the so-called Smagorinsky concept, which yields:

$$E = C_s^2 \Delta^2 \sqrt{\left(\frac{\partial U}{\partial x}\right)^2 + \frac{1}{2} \left(\frac{\partial U}{\partial y} + \frac{\partial U}{\partial x}\right) + \left(\frac{\partial V}{\partial y}\right)} \dots\dots\dots (3.9)$$

In the model only the value of C_s has to be specified and the recommended value is 0.2 to 1.0. In this research work 0.3 has been used because at this value the calibration and validation curve were best fitted.

3.4.7 Bed Resistance

In shallow areas bed friction is important and can effectively be used to adjust the amplitude of tides. Bed friction in the model is defined by the Manning number, M ($\text{m}^{1/3}/\text{s}$). The map of the Manning number distribution used for calibration is presented in Table 3.6.

Table 3.6: Manning number distribution

Areas with depths	Manning number ($\text{m}^{1/3}/\text{s}$)
Less than -20 m	32
-20 to -15 m	60
-15 to -10 m	65
-10 to -5 m	90
-5 to 0.46 m	100
Mangrove Forrest	15

Velocity based Smagorinsky formulation has been used for eddy viscosity. The proportionality factor for each area has been considered 0.28.

3.4.8 Boundary Generation

The model has two open boundaries; one is in the Lower Meghna river near Chandpur and another one is in the open sea located along the line extending from Vishakhapatnam of India to Gwa Bay of Myanmar. In the river boundary measured water level has been prescribed and in the sea boundary has been generated from Global Tide Model.

Another open boundary is located in the north in the Meghna River, which is narrow and shallow. The boundary is about 30 km north of the nearest water level station at Chandpur, which is required to be inside the fine grid model area. Observed water level at Chandpur has been used as north boundary of the model with elevation, tidal range and phase corrections. Several trials have been made to replicate water level at Chandpur. Finally 12% elevation correction, 40% tidal reduction and 50 minutes phase lag have been considered. Tidal constituents that were used to predict water level for these two stations have been shown in the Table 3.7.

Table 3.7: Tidal constituents for Vishakhapatnam and Gwa Bay

Tidal constituents	Vishakhapatnam		Gwa Bay	
	Phase (Degree)	Magnitude (m)	Phase (Degree)	Magnitude (m)
M ₂	239	0.48	266	0.69
S ₂	274	0.21	304	0.32
K ₁	336	0.11	330	0.14
O ₁	320	0.04	338	0.05
f ₄	-	-	180	0.193

(Reference: Admiralty Tide Table)

3.4.9 Boundary Condition

Nested rectangular models have been used in this research work for model simulation. In case of nested model boundary conditions were applied to coarse model only. The coarse model creates boundary for respective fine model gradually. This like 5400 m grid model creates boundary for 1800 m grid model, 1800 m

grid model creates boundary for 600 m grid model and so on. In the study boundary conditions have been applied at the south and north of coarse model (5400 m grid model). At the north boundary measured water level of Chandpur has been used for simulation. The variation of water level at Chandpur has been shown in the Figure 3.13 for November 2007.

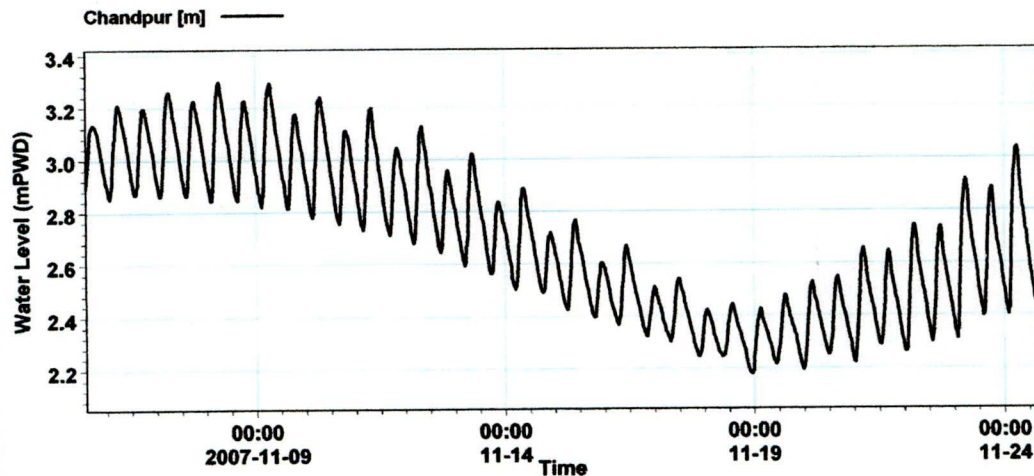


Figure 3.13: Water level at Chandpur

At the south boundary of coarse model time series water level has been used for simulation. This is generated from linear interpolation of water level of Vishakhapatnam and GWA Bay. Figure 3.14 shows the tidal fluctuation of Vishakhapatnam and GWA Bay.

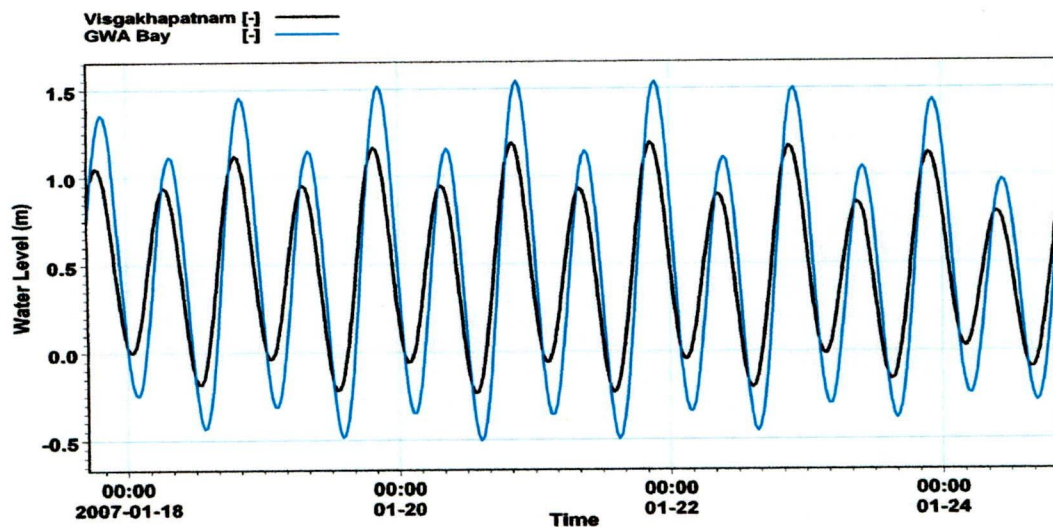


Figure 3.14: Tidal variation at Vishakhapatnam and GWA Bay

3.4.10 Cyclone Model

The description of a cyclone is based on few parameters related to the pressure field, which is imposed to the water surface and a wind field which is acting as a drag force on the water body through a wind shear stress description. The pressure field creates a local level setup close to the eye up to one meter only. Whereas the wind shear contributes more to the surge giving a level setup on the right side of the eye and a level set down on the left side.

To generate the wind field, Holland Single Vortex theory has been applied. The cyclone model needs following data/information for the description of wind field and pressure field:

- Radius of maximum winds, R_m ,
- Maximum wind speed, V_m and
- Cyclone track forward speed V_f and direction.
- Central pressure, P_c
- Neutral pressure, P_n
- Holland Parameter, $B = 2.0 \cdot (P_c - 90) / 160$

In order to obtain surface winds, a boundary layer wind speed correction has been applied to the gradient wind. The near-surface wind V_{10} , is usually obtained by the following relation (Harper et al., 2001):

$$V_{10r} = K_m \cdot V_{g(r)}$$

where V_g is the rotational wind gradient speed at a distance r from the centre of the cyclone. As mentioned by Harper et al, (2001) different values for the parameter K_m are available in the literature. These values can be entered in the Cyclone Wind Generation Tool using a constant type of geostrophic correction.

A speed-dependent formulation for K_m is also proposed by Harper et al. (2001) and seems widely used in Australia. This has been implemented in the Cyclone Wind Generation Tool as the "Harper et al." Geostrophic correction type where the K_m factor is computed as:

$$Km = \begin{cases} 0.81 & \text{for } Vg < 6 \text{ m/s} \\ 0.81 - 2.96 \cdot 10^{-3} (Vg - 6) & \text{for } 6 \leq Vg < 19.5 \\ 0.77 - 4.31 \cdot 10^{-3} Vg - 19.5) & \text{for } 19.5 \leq Vg < 45 \\ 0.66 & \text{for } Vg > 45 \text{ m/s} \end{cases}$$

For this study 0.75 is used as geostrophic correction factor. The pressure and wind field for cyclone SIDR is presented in Figure 3.15

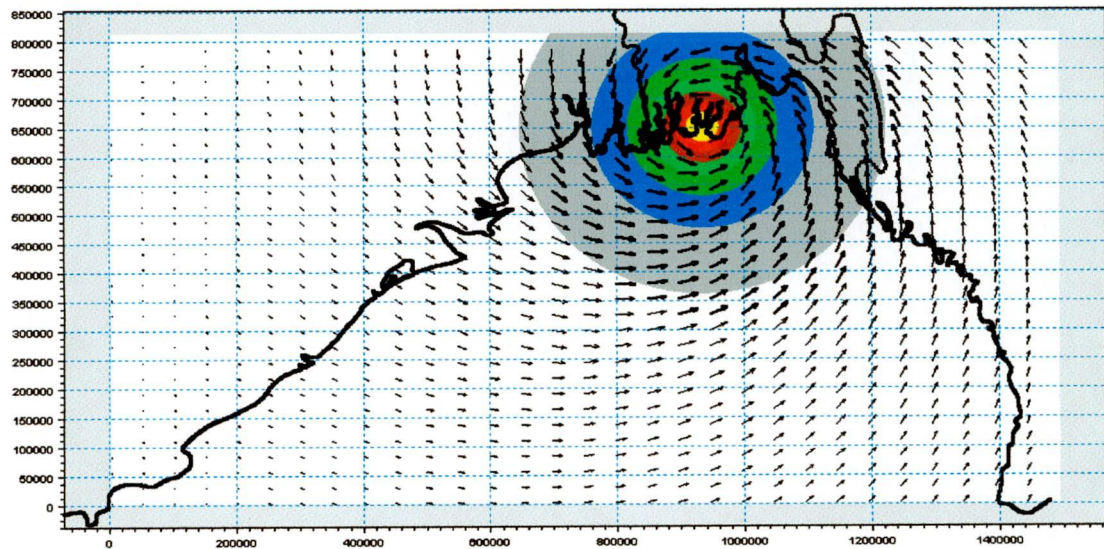


Figure 3.15: Pressure and wind field of SIDR

3.4.11 Calibration and Validation of Bay of Bengal Model

Water level data has been collected to produce boundary and to calibrate the model where discharge data has been collected to calibrate the model. A list of collected discharge and water level data has been presented in the Table 3.8.

Table 3.8: Description of collected water level and discharge data

Data Type	Stations/Locations	Duration
Water Level	Chandpur	2005
	Charchenga	February 2006
	Ramgati	November 2003
Discharge	North Hatiya	9 th February 2006
	West Shahbazpur	14 th December 2007
	East Shahbazpur	16 th December 2007

The existing BoBM model has been calibrated and validated against the measured water level and discharge data. The model has been calibrated against water level at Charchenga and discharge at North Hatiya during 2006. Calibration plots have been shown in the Figure 3.16, Figure 3.17.

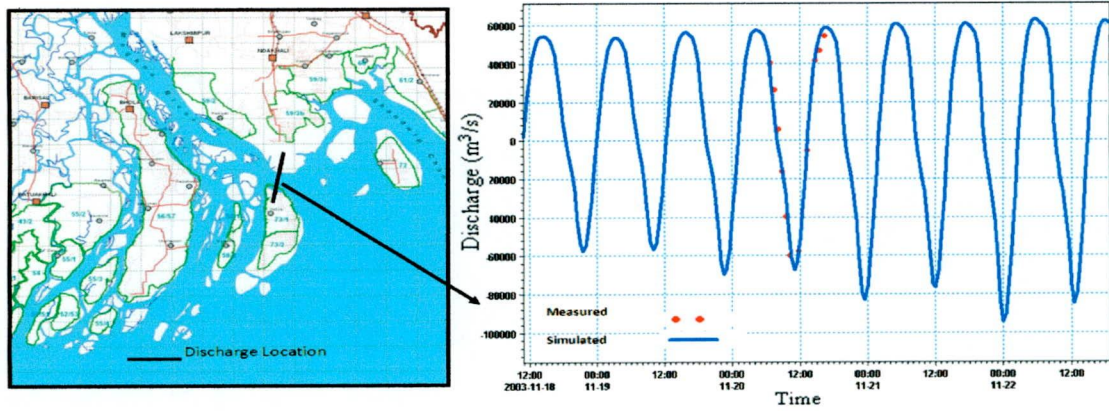


Figure 3.16: Calibration against discharge data at North Hatiya during 2006

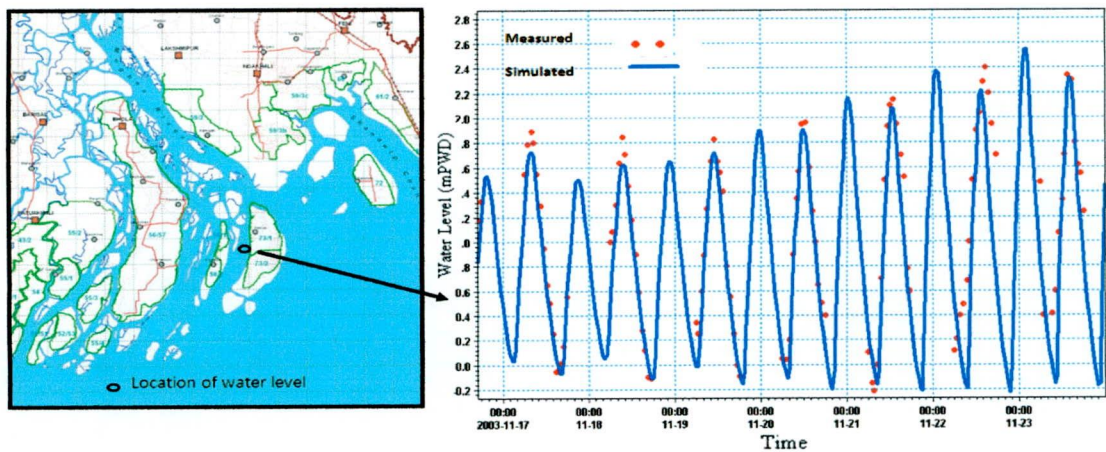


Figure 3.17: Calibration against water level data at Charchenga during 2006

The model has been validated against discharge at West Shahbazpur Channel and at East Shahbazpur Channel during December 2007. The validation plots have been shown in Figure 3.18 and Figure 3.19.

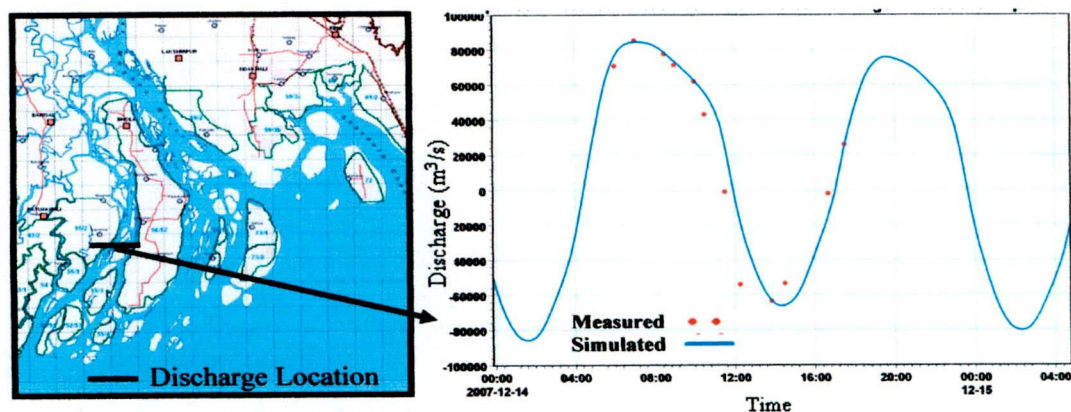


Figure 3.18: Validation against discharge data at West Shahbazpur Channel during December, 2007

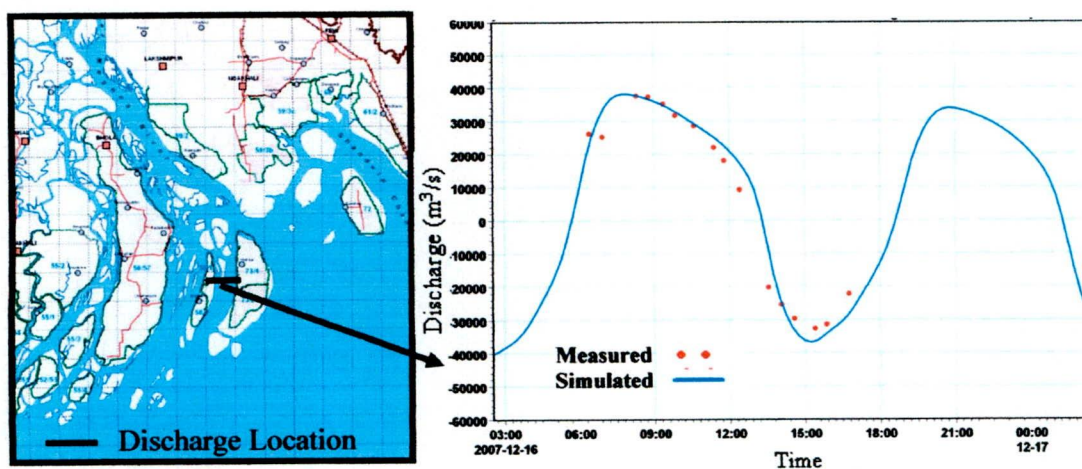


Figure 3.19: Validation against discharge data at East Shahbazpur Channel during December, 2007

3.4.12 Selection of Mangrove species

From previous experience it has been found that Mangrove forest reduces surge height and energy. Mangrove forest grows at the boundary of two environments and receives nutrients from terrestrial and marine sources. The mangrove community is often strikingly zoned parallel to the shoreline with a series of different species which dominated from open water to the landward margins (Snedaker, 1982). These zones are the response of individual mangrove species to the gradients of inundation frequency, water logging, nutrient availability and soil salt concentrations across the inter-tidal area (Hutchings and Saenger, 1987, Wolanski et al 1990). The Kuakata beach is exposed to the Bay of Bengal and most of the time hit by cyclonic surges. The beach is already enclosed by

polder-48. To investigate the impact on surge height for the forest parameters, mangrove forest of 200 m width has been laid along the Kuakata beach.

3.4.13 Equivalent Manning Number for Mangrove Tree

Mangrove tree creates resistance to the flow. The flow of water through the mangrove forest is obstructed by the matrix of roots/trunks of the mangrove trees' which creates resistance to flow and waves. This resistance can be represented by equivalent Manning's number. As there is no information available except *Rizophora*, root matrix specification of *Rizophora* species has been considered for this study. The roots within the height of 0.25 m and root matrix specification of *Rhizophora* species has been shown in Figure 3.20. This specification has been used for calculation of the equivalent Manning's number of mangrove tree. Above the height of 0.25 m, flow obstruction reduces with the increase of water level. The calculations of equivalent Manning's number for the mangrove tree considering root in the first step and trunk in the second step are given below.



Figure 3.20: Specification of a single *Rhizophora* root matrix with 19 mangrove trunks/roots

Step 1:

Bed shear stress (τ) is generally related to depth averaged flow velocity (V) on the basis of a factor ($f/2$):

$$\frac{\tau}{\rho} = \frac{f}{2} \cdot V^2 \dots\dots\dots (3.10)$$

where, ρ is the water density.

The friction factor is related to the Nikuradses roughness height (K_N) and Reynold's number (Re) by the Colebrook & White formula:

$$\sqrt{\frac{f}{2}} = 6.4 - 2.45 \ln \left(\frac{K_N}{h} + \frac{4.7}{Re \sqrt{f}} \right) \dots\dots\dots (3.11)$$

where, h is the water depth.

This is the most precise way of including the friction factor, but it can only be solved by iteration. In practical cases a Manning number determines the friction factor:

$$\frac{f}{2} = \frac{g}{M^2 h^{1/3}} \dots\dots\dots (3.12)$$

Combining the equations assuming a rough boundary layer we get

$$M = \sqrt{\frac{g}{h^{1/3}} (6.4 - 2.45 \ln(\frac{K_N}{h}))} \dots\dots\dots (3.13)$$

The Manning's number will nearly be constant if the water depth is far larger than the roughness height as is most often the case, but not our case when considering mangrove forests. The roots of mangrove forest can typically have a length scale of 0.25 m. Remembering how Nikuradses roughness height is defined, it has been assumed that a root height of 0.25m corresponds to a Nikuradses roughness height of (4 times 0.25 m) 1 m. A typical Nikuradses roughness height in nature is 0.25 m and a larger roughness height is expected for mangrove forest. It is now possible to calculate the Manning's number as a function of water depth as presented in Table 3.9.

Table 3.9: Manning's number as a function of water depth

Water depth (m)	Manning's number ($m^{1/3}/s$)
10	25.7
5	24.8
1	20.0
0.5	16.5
0.25	5.9

This is to be noticed that for water depth of 5 m and 10 m the Manning's number is nearly constant and for water depth of 1 m or less the variation is significant. It is assumed that a typical water depth is 0.5 m leading to a typical Manning's number of $16.5 m^{1/3}/s$.

Step 2:

The trunks also create resistance to the flow. The resistances induced by the trunks need to be incorporated in the bed resistance in the model:

$$A\tau_M = A\tau + nF \dots\dots\dots (3.14)$$

where, 'A' is horizontal area of the Mangrove forest, 'n' is number of trees in the area and 'F' the force from the trunk on the water body as can be calculated by:

$$F = c \frac{1}{2} \rho (Dh) V^2 \dots\dots\dots (3.15)$$

where c is a constant and D the diameter of the trunk.

Combining the equations leads to:

$$M_M = \left(\frac{1}{M^2} + \frac{n}{A} \cdot D \cdot c \cdot \frac{h^{4/3}}{2g} \right)^{1/2} \dots\dots\dots (3.16)$$

Inserting $M: 16.5 \text{ m}^{1/3}/\text{s}$, $\frac{n}{A} = \frac{19}{0.7 \times 0.7}$ (= 1 tree per 2.25 m^2 area), diameter = 0.04 m, $c = 1.0$ and $h = 0.5 \text{ m}$, we get the resulting Manning's number of $5.34 \text{ m}^{1/3}/\text{s}$. From the above findings, equivalent Manning's number becomes $5 \text{ m}^{1/3}/\text{s}$. This magnitude of equivalent Manning's number is very much similar to the magnitude found by Wolanski, et. al. (1992). He observed the Manning's friction coefficient, $n = 0.2 - 0.4$ (which corresponds to equivalent Manning's number of $5 - 2.5 \text{ m}^{1/3}/\text{s}$; from field observations and $n = 0.25$ from model studies (which corresponds to equivalent Manning's number of $4 \text{ m}^{1/3}/\text{s}$). The equivalent Manning's number has been considered $4 \text{ m}^{1/3}/\text{s}$ in this study based on the above considerations.

3.5 Summary

The data collection source of historical storm surges and existing bio-shields along the coastal belt of Bangladesh has been given in this chapter. The laboratory experiment that has been conducted in BUET described here. In this chapter the theory that determines the hydrodynamic condition and cyclonic storm condition has also been described. The study area where the Bay of Bengal model applied has been outlined. Calibration and validation of numerical modeling has been elucidated here and the calculation for equivalent Manning's number of mangrove bio-shield has also been determined. The methodology which has been adopted in this study is outlined in this chapter step by step.

CHAPTER FOUR

DATA ANALYSIS AND RESULTS

4.1 General

Different types of historical cyclone data, laboratory experimental data and numerical modeling data are analyzed in this chapter to investigate the effectiveness of coastal bio-shields for reduction of cyclonic and high frequency surge energy along coastal belt of Bangladesh considering future climate change effects. The results of these data analysis are also discussed in this chapter.

4.2 Historical Storm Surge and Cyclone Data Analysis

The frequency of storm surges and cyclones are analyzed here and wind speed and number of people died caused by cyclones and storm surges are also analyzed in this section to find out the future trend of these parameters in the coastal areas of Bangladesh.

4.2.1 Frequency of Storm Surges and Cyclones

The average annual frequency of tropical cyclones in the north Indian Ocean (Bay of Bengal and Arabian Sea) is about 5 (about 5-6 % of the Global annual average) and about 80 cyclones form around the globe in a year. The frequency is more in the Bay of Bengal than in the Arabian Sea, the ratio is being 4:1. The frequencies of Cyclonic systems over north Indian Ocean (Bay of Bengal and Arabian Sea) during 1891-2013 are given in the Figure 4.1.

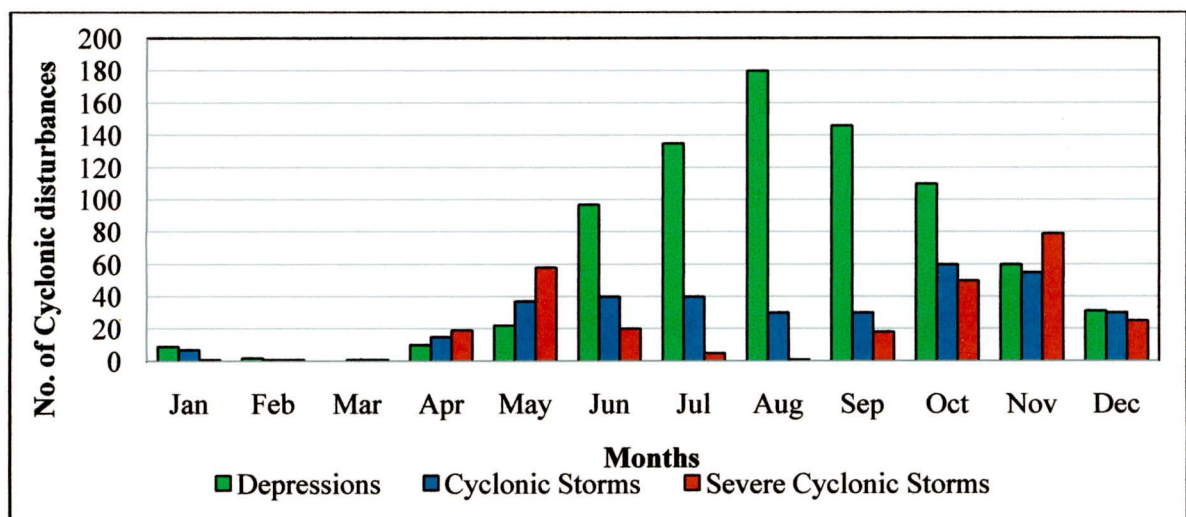


Figure 4.1: The frequencies of Cyclonic systems over north Indian Ocean during 1891-2013. (Source: IMD 2010)

The monthly frequency of tropical cyclones in the north Indian Ocean display a bi-modal characteristic with a primary peak in November and secondary peak in May. The months of May-June and October-November are known to produce cyclones of severe intensity. Tropical cyclones developing during the monsoon months (July to September) are generally not so intense. The Figure 4.2 shows the number of cyclonic storms that hit the coast of Bangladesh from 1881 to 2010 (Appendix A).

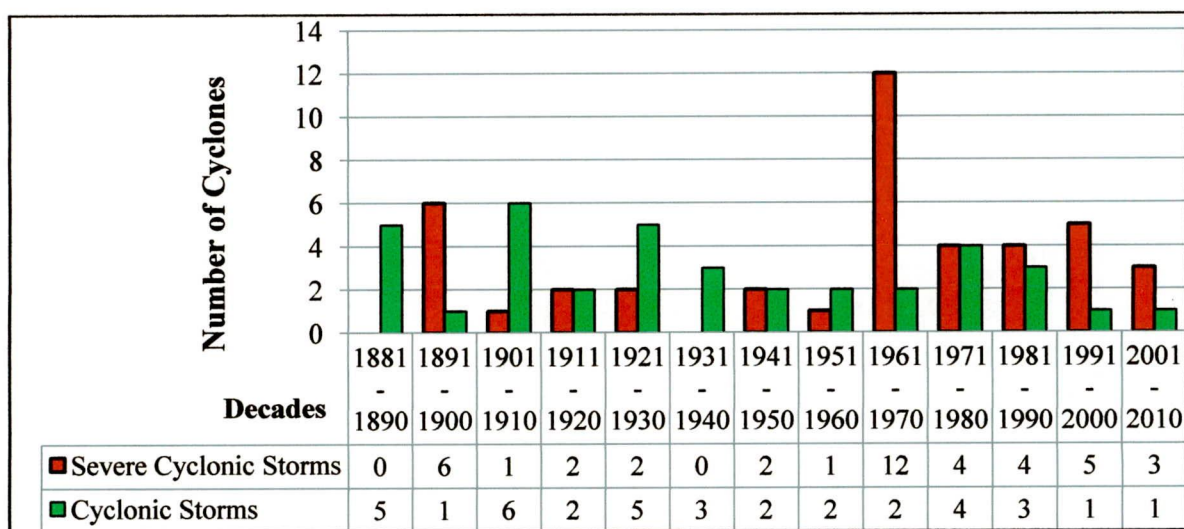


Figure 4.2: Number of cyclonic storms landed on Bangladesh coast in different decades.

The figure shows that the number of severe cyclones was 6 at the end of the 19th century and that number increased twice in the sixties of 20th century. From the figure it is also conspicuous that the number of devastating cyclones and surges remains almost constant in the subsequent decades of the last century.

4.2.2 Wind Speed of Cyclonic Storm Surges

In the 4th IPCC report it has been stated that intensity and frequency of cyclonic storm surge will be increased in the Bay of Bengal area in the near future. In this study wind speed data of 25 cyclones that hit the country from 1960 to 2007 has been collected (Appendix A). A trend line analysis has been done using the maximum wind speed of each cyclone and has been presented in the Figure 4.3. From the following figure it has been found that the wind speed or intensity of cyclone increases by 0.83 km/h each year due the the climate change and consequent effects.

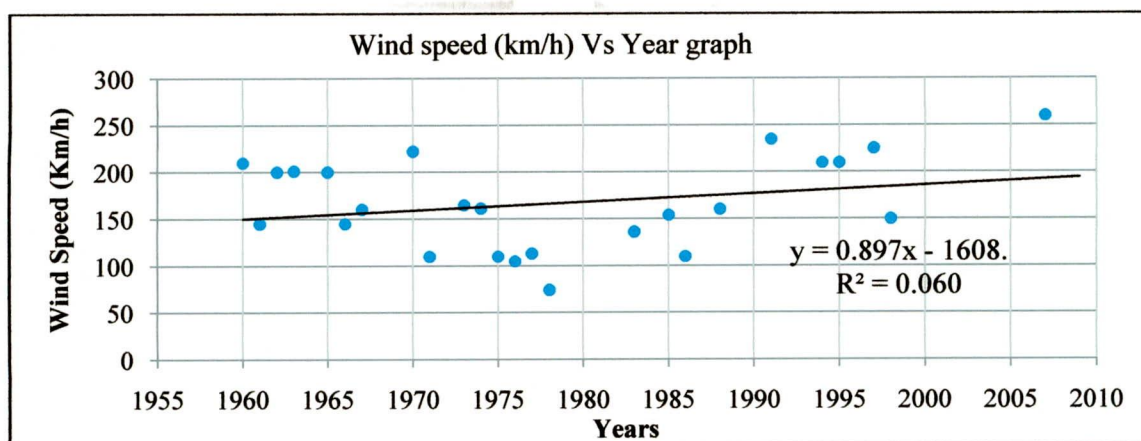


Figure 4.3: Increasing trend of maximum wind speed of cyclonic storms over the years

4.2.3 Number of People Died Caused by Cyclonic Storms

The Figure 4.4 shows a decreasing trend of human death toll caused by storm surges and cyclones that hit the country from 1960 to 2007. From this graph, it is also calculated that the decreasing rate of human death toll is 500 people per year. The graph shows such trend because of the growing successful institutional arrangement for disaster management in the recent years which includes development of early warning system, prevention and mitigation, preparedness, emergency response and post-disaster recovery (i.e. rehabilitation and reconstruction). There is now a growing awareness at Government levels that non-structural mitigation measures such as community disaster preparedness, training and public awareness, linked to micro-income generating projects need to be given a high priority (Bangladesh Country Report, 1999).

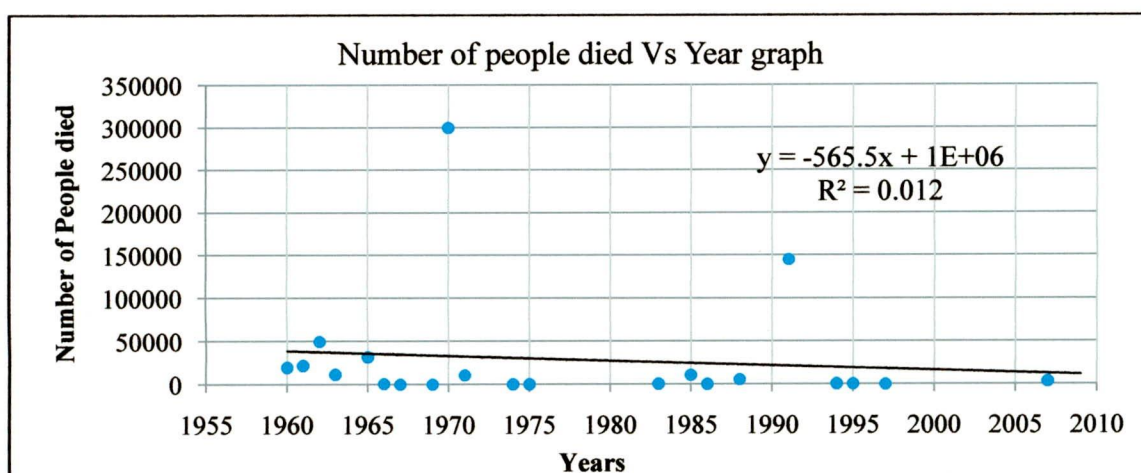


Figure 4.4: Decreasing trend of number of people died caused by storm surges and cyclones

4.3 Existing Coastal Bio-shields along the Bangladesh Coast

The coastal area of Bangladesh is very much vulnerable to natural disasters because of lack of sufficient bio-shield protections. One of the objectives of this study is to assess the existing bio-shields in the coastal areas of Bangladesh that has been planted or already is in position naturally. In this section, the existing bio-shields in the coastal areas of Bangladesh will be estimated and analyzed to find out the need for more bio-shields protection.

4.3.1 Afforestation Protection of Sea-facing Polders

In the past, foreshore afforestation schemes have proven cost effective in dissipating wave energy and reducing hydraulic load on embankments during storm surges. Currently, however, Bangladesh has insufficient foreshore forests. With an existing network of nearly 5,700 km long embankments in 139 polders (GOB, 2013), there are only 60 km or 6% of forest belts of the 957 km total length of embankment of 49 sea-facing polders, much of which is degraded (Dasgupta et al., 2010). The Figure 4.5 shows the amount of existing bio-shields protection of 49 sea facing polders.

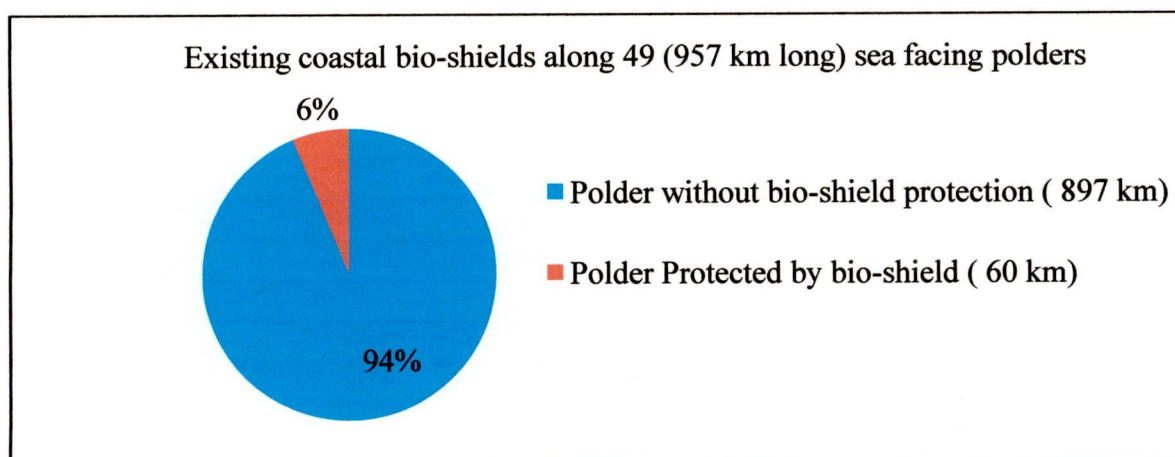


Figure 4.5: Existing bio-shields protection of 49 sea facing coastal polders of Bangladesh

The Department of Forests and Institute of Water Modeling recommend a minimum of 500 m width mangrove forest to protect sea-facing polders. They estimated the current length of coastal afforestation between the coastline and polders, using Google Earth and GIS methodology, to compute the gap between the recommended 500 m width mangroves and existing area-specific ones. The results indicate that 897 km length of existing sea polders would require mangrove forests for protection. For the recommended 500 m width protective forest belt, a foreshore area of 448.5 km^2 ($897 \text{ km} \times 0.5 \text{ km}$) would require

afforestation. At the current cost of US\$168,000 per km², the projected cost would total US\$75 million.

4.3.2 Existing Mangrove Protection

The largest single tract of natural mangrove forest is the Sundarban. It consists of a total of 6,01,700 hectare which is 4.07 % of total land mass of the country and 40 % of total forest land (DoF, 2013). Mangrove afforestation along the entire southern coastal frontier is an innovation of foresters. During 1960-61, Government undertook afforestation programme along the shore land of coastal districts. This initiative got momentum from 1980-81 with the aid of development partners and afforestation programs are extended over foreshore islands, embankments and along the open coasts. Since 1960-61 up to 1999-2000, 142,835 hectare of mangrove plantations have been raised under a number of coastal afforestation projects. The present net area of mangrove plantation is 132,000 hectare after losing some area due to natural calamities (DoF, 2013). The following Figure 4.6 shows the existing bio-shields map along the coast of Bangladesh.

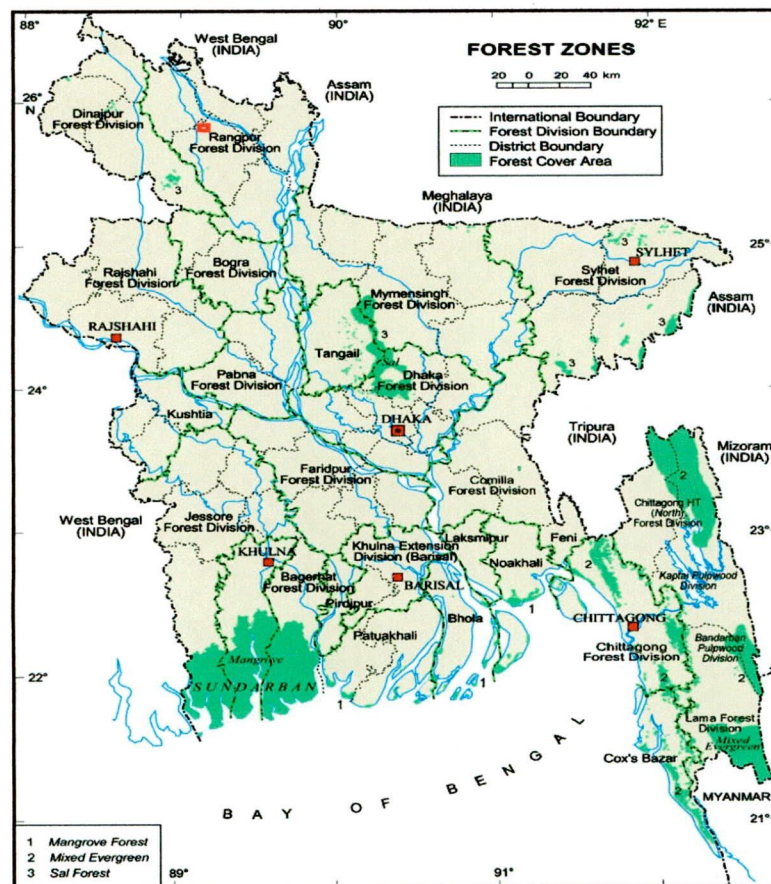


Figure 4.6: Existing bio-shields map along the coast of Bangladesh (Source: Banglapedia)

The 710 km long coastal belt of Bangladesh extending from Raimongal River to the west and Teknaf to the Southeast, some parts of which is already covered with natural and planted bio-shields. Mangrove is the dominating forest area in the coastal divisions. Core and buffer are the main forest in the hilly areas which acts as aegis during the severe natural disasters like cyclonic storms surges. Table 4.1 provides the existing areas under bio-shields protection.

Table 4.1: Existing coastal bio-shields along the coastal belt of Bangladesh

Name of Districts	Total Bio-shields Area (ha)
Cox's Bazar	94,061
Chittagong	170,003
Feni	8,171
Noakhali	155,722
Laksmipur	20,235
Bhola	145,692
Patuakhali	60,705
Pirojpur	2,428
Barguna	30,353
Bagerhat	270,150
Khulna	144,640
Satkhira	162,270

Source: Bangladesh Forest Department & Arannayk Foundation, 2013

The existing coastal bio-shields along the coastal belt of Bangladesh has been represented by bar and pie charts which are shown in the following Figure 4.7 and Figure 4.8. The coastal circle consisting of Bhola, Patuakhali, Barguna, Pirojpur, Noakhali, Feni and Laksmipur districts covers 423,306 ha of bio-shields protection and the Sundarban circle

consisting of Satkhira, Khulna and Bagerhat districts covers 577,060 ha of bio-shields protection. From the Figure 4.7 and Figure 4.8, it is found that Bagerhat district covers the most protection (21% of the total bio-shields) than other coastal districts and Pirojpur district covers the lowest bio-shields protection (almost 0%).

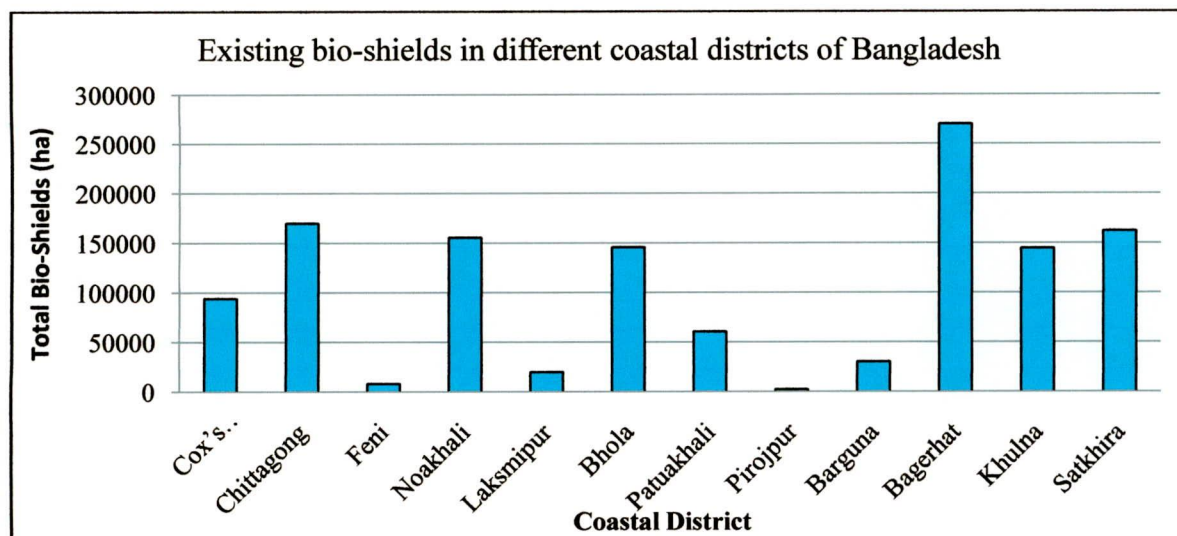


Figure 4.7: Existing bio-shields area of different coastal districts

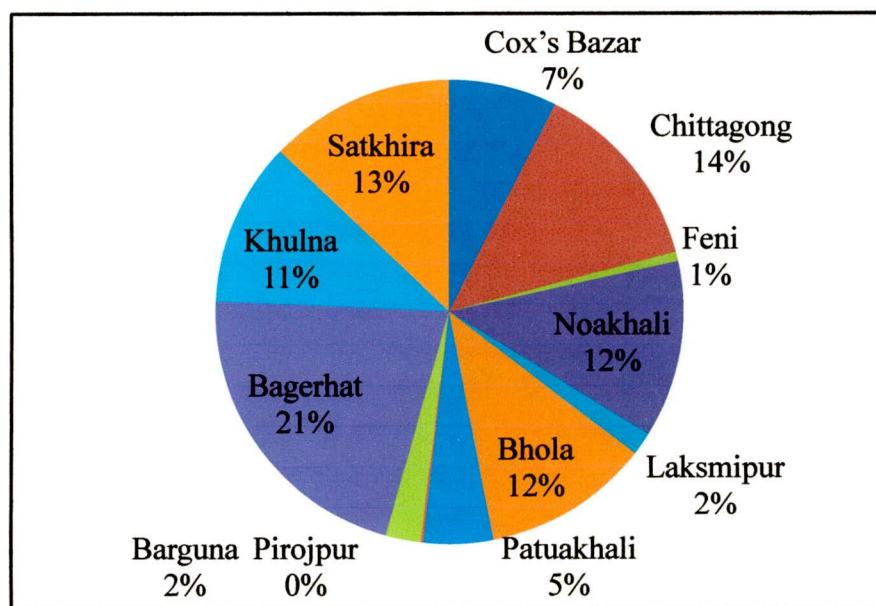


Figure 4.8: Percentage of existing bio-shields of different coastal districts of Bangladesh

Mangroves, locally known as Sundarban, play a vital role in the national economy of Bangladesh. Besides being a source of different renewable resources, they also serve as buffer zones against the cyclones and tidal surges. The Bangladesh coast supports about 587,400 ha of natural mangroves (Mahmood, 1986) and a further 100,000 ha of planted mangroves. The densest mangroves block, the Sundarbans (beautiful forest), is situated in

the southwest, mostly in Khulna District, where it covers 577,040 ha (FAO. 1984), one third of this area is tidal channels. It is not only the largest single forest resource in the country, but also the largest single compact mangrove resource in the world. The following Figure 4.9 shows a satellite image of Sundarban which is very compact and criss-crossed by many tidal channels.



Figure 4.9: Satellite image of Sundarban

Bangladesh's 687,000 ha of mangroves protect the coast from storm surges and cyclones and provide habitats and nurseries to numerous wildlife and fishery resources. It is estimated that the standing volume of the two main commercial species of the Sundarbans (Sundri -*Heritiera fomes* -and Gewa -*Excoecaria agallocha*) declined by 40-50 per cent between 1959 and 1983. This has been due to a local salinity increase as a consequence of the reduced river flows, following the completion of dams, barrages and embankments, as well as over-felling. Many areas within the Khulna, Barisal, Patuakhali and Chittagong Districts that once were covered by mangrove forests have since been given over to other land usage. Today, the Khulna and Chakaria Sundarbans are the only two compact mangrove tracts left intact. The Sundarban, world's richest mangrove forest not only acts as buffer zone during cyclones and storm surges but also it has panoramic beauty. The Figure 4.10 is showing some photographs of scenic beauty of Sundarban.



Figure 4.10: Photographs of Sundarban mangrove forest

4.4 Experimental Data Analysis

In this laboratory experiment, various combinations of bio-shields have been used to investigate the effectiveness of coastal bio-shields for the reduction of cyclonic and storm surge energies. Various combinations of comparison are made for three different wave periods. The combination for maximum reduction of wave height and the effective location of the bio-shield is also determined by analyzing the experimental data given in Appendix B as graphs. The comparisons of wave height reduction are tabulated separately for each of the measuring locations based on submergence conditions as well as wave periods.

The Table 4.2 shows a comparison of wave reduction for emerged conditions at measuring location G-1 which is located 6 m away from the embankment. For this case maximum wave height reduction occurs when bio-shield barrier of 2 m width (1 m Rigid + 1 m Flexible @ 50 mm c/c) is placed at 2 m distance from the embankment and the wave period is 2.0 sec. Here, the maximum wave height reduction is found as 3 cm or 18% of 17 cm of wave height for no bio-shield condition at the same measuring location.

For measuring location G-2 (Table 4.3) which is 5 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 @ 50 mm c/c) is placed at 4 m distance from the embankment and the wave period is 2.0 sec. Maximum reduction of wave height found for this location is 7 cm or 39% of the wave height of 18 cm which is for no bio-shield condition at the same measuring location. In this case the measuring location is situated just at middle of the bio-shield barrier.

For measuring location G-3 (Table 4.4) 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 and the wave period is 2.0 sec. Maximum reduction of wave height found for this location is 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.

Table 4.2: Wave height reduction for emerged conditions at location G-1 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
No bio-shield		13	14	17	Maximum reduction of wave height (17-14=3 cm) occurs when 2 m wide bio-shield at a distance of 2 m from embankment and T=2.0 sec
Bio-shield-2m at 2m @ 25 mm		17	19	19	
Bio-shield-2m at 2m @ 50 mm		17	14	14	
Bio-shield-1m at 2m @ 25 mm		17	20	22	
Bio-shield-1m at 2m @ 50 mm		13	20	21	
Bio-shield-2m at 4m @ 25 mm		15	16	16	
Bio-shield-2m at 4m @ 50 mm		16	19	20	
Bio-shield-1m at 4m @ 25 mm		14	16	17	
Bio-shield-1m at 4m @ 50 mm		17	17	18	
Maximum Reduction of Wave Height	cm	0	0	3	
	%	0	0	18	

Table 4.3: Wave height reduction for emerged conditions at location G-2 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
No bio-shield		15	17	18	Maximum reduction of wave height (18-11=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		15	17	21	
Bio-shield-2m at 2m @ 50 mm		16	17	19	
Bio-shield-1m at 2m @ 25 mm		14	16	18	
Bio-shield-1m at 2m @ 50 mm		13	17	22	
Bio-shield-2m at 4m @ 25 mm		13	11	14	
Bio-shield-2m at 4m @ 50 mm		12	14	11	
Bio-shield-1m at 4m @ 25 mm		14	15	14	
Bio-shield-1m at 4m @ 50 mm		14	14	16	
Maximum Reduction of Wave Height	cm	3	6	7	
	%	20	35	39	

Table 4.4: 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
No bio-shield		17	19	19	Maximum reduction of wave height (19-8=11 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		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	
Bio-shield-2m at 4m @ 50 mm		13	13	8	
Bio-shield-1m at 4m @ 25 mm		12	11	12	
Bio-shield-1m at 4m @ 50 mm		12	13	14	
Maximum Reduction of Wave Height	cm	8	9	11	
	%	47	52	58	

For measuring location G-4 (Table 4.5) 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 and the wave period is 2.0 sec. Maximum reduction of wave height found for this location is 15 cm or 71% 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 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.

Table 4.5: Wave height reduction for emerged conditions at location G-4 compared to no bio-shield condition

Emerg ed 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
No bio-shield		19	20	21	Maximum reduction of wave height (21-6=15 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	16	11	
Bio-shield-2m at 2m @ 50 mm		16	19	19	
Bio-shield-1m at 2m @ 25 mm		16	20	14	
Bio-shield-1m at 2m @ 50 mm		16	19	19	
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	
Maximum Reduction of Wave Height	cm	8	12	15	
	%	42	60	71	

For measuring location G-5 (presented in Table 4.6) 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 @ 50 mm c/c) is placed at 4 m distance from the embankment and the wave period is 1.6 sec. 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 1 m away from the bio-shield barrier towards the embankment.

For measuring location G-6 (Table 4.7) which is 2.5 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 @ 50 mm c/c) is placed at 4 m distance from the embankment and the wave period is 2.0 sec. Maximum reduction of wave height found for this location is 2 cm or 25% of the wave height of 8 cm which is for no bio-shield condition at the same measuring location. In this case the measuring location is situated 1.5 m away from the bio-shield barrier towards the embankment.

Table 4.6: Wave height reduction for emerged conditions at location G-5 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
No bio-shield		11	11	9	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	
Bio-shield-2m at 4m @ 50 mm		7	8	11	
Bio-shield-1m at 4m @ 25 mm		12	10	12	
Bio-shield-1m at 4m @ 50 mm		15	19	17	
Maximum Reduction of Wave Height	cm	4	3	1	
	%	36	27	11	

Table 4.7: Wave height reduction for emerged conditions at location G-6 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
No bio-shield		7	8	8	Maximum reduction of wave height (8-6=2 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		10	12	12	
Bio-shield-2m at 2m @ 50 mm		10	11	12	
Bio-shield-1m at 2m @ 25 mm		13	13	9	
Bio-shield-1m at 2m @ 50 mm		10	11	8	
Bio-shield-2m at 4m @ 25 mm		11	9	8	
Bio-shield-2m at 4m @ 50 mm		6	10	6	
Bio-shield-1m at 4m @ 25 mm		9	8	7	
Bio-shield-1m at 4m @ 50 mm		8	13	12	
Maximum Reduction of Wave Height	cm	1	0	2	
	%	14	0	25	

For measuring location G-7 (presented in Table 4.8) which is 2 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 and the wave period is 2.0 sec. Maximum reduction of wave height found for this location is 2 cm or 33% of the wave height of 6 cm for no bio-shield condition at the

same measuring location. In this case the measuring location is situated 2 m away from the bio-shield barrier towards the embankment.

Table 4.8: Wave height reduction for emerged conditions at location G-7 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
No bio-shield		4	4	6	Maximum reduction of wave height (6-4=2 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		7	7	7	
Bio-shield-2m at 2m @ 50 mm		4	5	4	
Bio-shield-1m at 2m @ 25 mm		8	5	5	
Bio-shield-1m at 2m @ 50 mm		7	9	10	
Bio-shield-2m at 4m @ 25 mm		6	6	6	
Bio-shield-2m at 4m @ 50 mm		5	4	4	
Bio-shield-1m at 4m @ 25 mm		4	5	5	
Bio-shield-1m at 4m @ 50 mm		5	6	5	
Maximum Reduction of Wave Height	cm	0	0	2	
	%	0	0	33	

Table 4.9: Wave height reduction for emerged conditions at location G-8 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
No bio-shield		6	6	6	Maximum reduction of wave height (6-3=3 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		12	10	8	
Bio-shield-2m at 2m @ 50 mm		5	6	6	
Bio-shield-1m at 2m @ 25 mm		5	6	5	
Bio-shield-1m at 2m @ 50 mm		6	10	7	
Bio-shield-2m at 4m @ 25 mm		5	4	4	
Bio-shield-2m at 4m @ 50 mm		5	5	3	
Bio-shield-1m at 4m @ 25 mm		4	4	10	
Bio-shield-1m at 4m @ 50 mm		5	4	8	
Maximum Reduction of Wave Height	cm	2	2	3	
	%	33	33	50	

For measuring location G-8 (Table 4.9) which is 1.5 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 and the wave period is 2.0 sec. Maximum reduction of wave height found for this location is 3 cm or

50% of the wave height of 6 cm for no bio-shield condition at the same measuring location. In this case the measuring location is situated 2.5 m away from the bio-shield barrier towards the embankment.

Again, the Table 4.10 shows a comparison of wave height reduction for submerged conditions at measuring location G-1 which is located basically in front of bio-shield barrier. In this case 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 and the wave period is 1.8 sec. The maximum wave height reduction found for this case is 2 cm or 14% of the wave height of 14 cm for no bio-shield condition at the same measuring location.

For measuring location G-2 (Table 4.11) which is 5 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 and the wave period is 1.8 sec. Maximum reduction of wave height found for this location is 3 cm or 18% of the wave height of 17 cm which is for no bio-shield condition at the same measuring location. In this case the measuring location is situated just at middle of the bio-shield barrier.

Table 4.10: Wave height reduction for submerged conditions at location G-1 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
No bio-shield		13	14	17	Maximum reduction of wave height (14-12=2 cm) occurs when 2 m wide bio-shield at a distance of 4 m from embankment and T=1.8 sec
Bio-shield-2m at 2m @ 25 mm		16	16	18	
Bio-shield-2m at 2m @ 50 mm		13	13	16	
Bio-shield-1m at 2m @ 25 mm		16	17	20	
Bio-shield-1m at 2m @ 50 mm		14	15	16	
Bio-shield-2m at 4m @ 25 mm		17	12	20	
Bio-shield-2m at 4m @ 50 mm		16	16	17	
Bio-shield-1m at 4m @ 25 mm		14	17	17	
Bio-shield-1m at 4m @ 50 mm		14	16	20	
Maximum Reduction of Wave Height	cm	0	2	1	
	%	0	14	6	

Table 4.11: Wave height reduction for submerged conditions at location G-2 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
No bio-shield		15	17	18	Maximum reduction of wave height (17-14=3 cm) occurs when 2 m wide bio-shield at a distance of 4 m from embankment and T=1.8 sec
Bio-shield-2m at 2m @ 25 mm		15	16	18	
Bio-shield-2m at 2m @ 50 mm		16	19	21	
Bio-shield-1m at 2m @ 25 mm		17	18	17	
Bio-shield-1m at 2m @ 50 mm		16	17	19	
Bio-shield-2m at 4m @ 25 mm		15	14	18	
Bio-shield-2m at 4m @ 50 mm		17	18	20	
Bio-shield-1m at 4m @ 25 mm		14	15	16	
Bio-shield-1m at 4m @ 50 mm		18	20	21	
Maximum Reduction of Wave Height	cm	1	3	2	
	%	7	18	11	

For measuring location G-3 (Table 4.12) 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 @ 25 mm c/c) is placed at 4 m distance from the embankment and the wave period is 2.0 sec. Maximum reduction of wave height found for this location is 7 cm or 36%. In this case the measuring location is situated just behind the bio-shield barrier.

Table 4.12: 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
No bio-shield		17	19	19	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	
Bio-shield-2m at 4m @ 25 mm		14	15	12	
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	
Maximum Reduction of Wave Height	cm	3	4	7	
	%	18	21	36	

Table 4.13: 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
No bio-shield		19	20	21	Maximum reduction of wave height (21-10=11 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	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	
Bio-shield-2m at 4m @ 25 mm		12	13	10	
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	
Maximum Reduction of Wave Height	cm	7	8	11	
	%	36	40	52	

For measuring location G-4 (Table 4.13) 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 and the wave period is 2.0 sec. 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 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.

For measuring location G-5 (Table 4.14) 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 and the wave period is 2.0 sec. 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.

For measuring location G-6 (Table 4.15) which is 2.5 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 and the wave

period is 2.0 sec. Maximum reduction of wave height found for this location is 3 cm or 30% of the wave height of 10 cm which is for no bio-shield condition at the same measuring location. In this case the measuring location is situated 1.5 m away from the bio-shield barrier towards the embankment.

Table 4.14: Wave height reduction for submerged 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
No bio-shield	11	11	9	Maximum reduction of wave height (9-5=4 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	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	
Bio-shield-2m at 4m @ 25 mm	14	14	5	
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	
Maximum Reduction of Wave Height	cm	1	3	4
	%	9	27	44

Table 4.15: Wave height reduction for submerged conditions at location G-6 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
No bio-shield	8	8	10	Maximum reduction of wave height (10-7=3 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	12	11	9	
Bio-shield-2m at 2m @ 50 mm	9	9	8	
Bio-shield-1m at 2m @ 25 mm	9	10	11	
Bio-shield-1m at 2m @ 50 mm	9	8	8	
Bio-shield-2m at 4m @ 25 mm	12	7	7	
Bio-shield-2m at 4m @ 50 mm	7	8	8	
Bio-shield-1m at 4m @ 25 mm	11	9	10	
Bio-shield-1m at 4m @ 50 mm	13	11	10	
Maximum Reduction of Wave Height	cm	1	1	3
	%	12	12	30

For measuring location G-7 (Table 4.16) which is 2 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 and the wave

period is 2.0 sec. Maximum reduction of wave height found for this location is 2 cm or 33% of the wave height of 6 cm for no bio-shield condition at the same measuring location. In this case the measuring location is situated 2 m away from the bio-shield barrier towards the embankment.

Table 4.16: Wave height reduction for submerged conditions at location G-7 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
No bio-shield		4	4	6	Maximum reduction of wave height (6-4=2 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		6	6	6	
Bio-shield-2m at 2m @ 50 mm		6	7	6	
Bio-shield-1m at 2m @ 25 mm		5	7	8	
Bio-shield-1m at 2m @ 50 mm		6	5	5	
Bio-shield-2m at 4m @ 25 mm		7	4	4	
Bio-shield-2m at 4m @ 50 mm		8	11	5	
Bio-shield-1m at 4m @ 25 mm		5	5	5	
Bio-shield-1m at 4m @ 50 mm		4	6	7	
Maximum Reduction of Wave Height	cm	0	0	2	
	%	0	0	33	

Table 4.17: Wave height reduction for submerged conditions at location G-8 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
No bio-shield		6	6	6	Maximum reduction of wave height (6-4=2 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		8	6	6	
Bio-shield-2m at 2m @ 50 mm		11	6	6	
Bio-shield-1m at 2m @ 25 mm		9	9	11	
Bio-shield-1m at 2m @ 50 mm		12	5	6	
Bio-shield-2m at 4m @ 25 mm		5	5	4	
Bio-shield-2m at 4m @ 50 mm		6	5	5	
Bio-shield-1m at 4m @ 25 mm		7	7	8	
Bio-shield-1m at 4m @ 50 mm		6	5	6	
Maximum Reduction of Wave Height	cm	1	1	2	
	%	17	17	33	

For measuring location G-8 (Table 4.17) which is 1.5 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 and the wave

period is 2.0 sec. Maximum reduction of wave height found for this location is 2 cm or 33% of the wave height of 6 cm for no bio-shield condition at the same measuring location. In this case the measuring location is situated 2.5 m away from the bio-shield barrier towards the embankment.

A set of comparisons of wave height reduction for different experimental emerged run conditions are shown in the following Figure 4.11, Figure 4.12 and Figure 4.13 for wave periods 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 (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 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 0.5 m away from the barrier towards 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. 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.

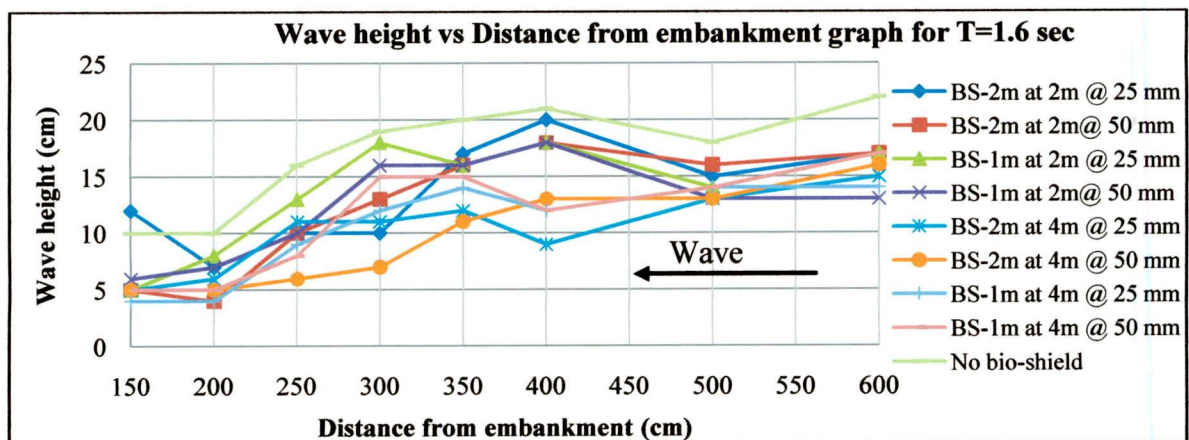


Figure 4.11: Variation of wave height with distance from embankment for different emerged bio-shield (BS) conditions and wave period, $T=1.6$ sec

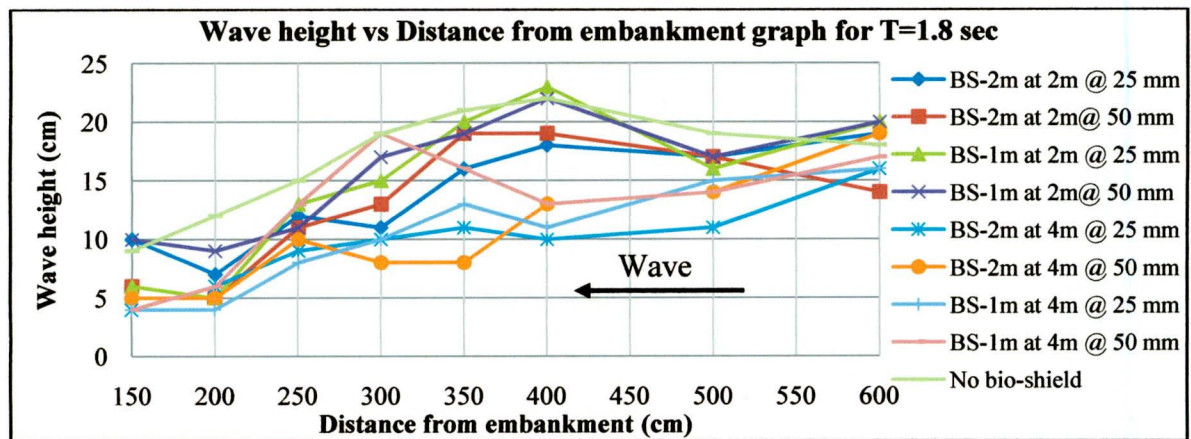


Figure 4.12: Variation of wave height with distance from embankment for different emerged bio-shield (BS) conditions and wave period, $T=1.8$ sec

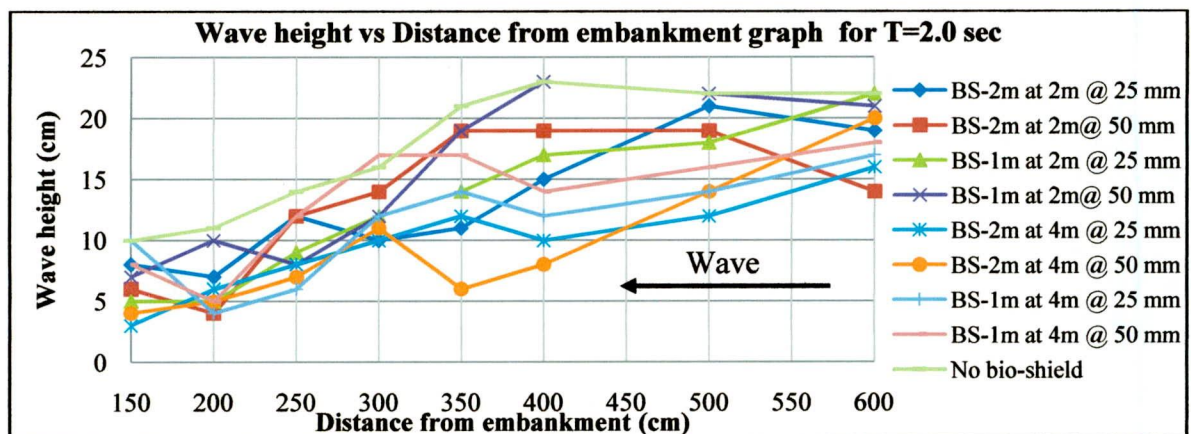


Figure 4.13: Variation of wave height with distance from embankment for different emerged bio-shield (BS) conditions and wave period, $T=2.0$ sec

Another set of comparisons of wave height reduction for different experimental submerged run conditions are shown in the Figure 4.14, Figure 4.15 and Figure 4.16 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 and 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. As stated earlier, the measuring location G-3 is situated just behind the bio-shield barrier and location G-4 is 0.5 m away from the barrier towards the embankment. 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 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. 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.

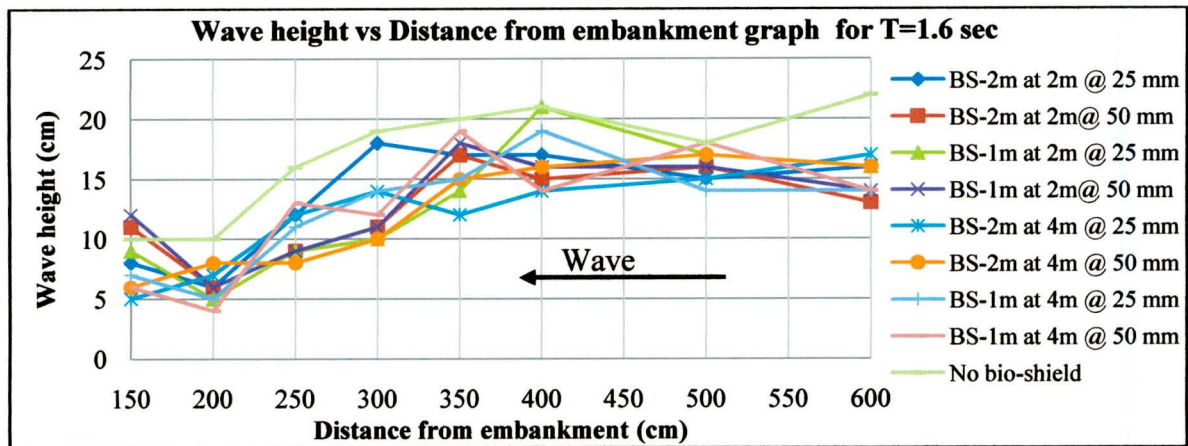


Figure 4.14: Variation of wave height with distance from embankment for different submerged bio-shield (BS) conditions and wave period, $T=1.6$ sec

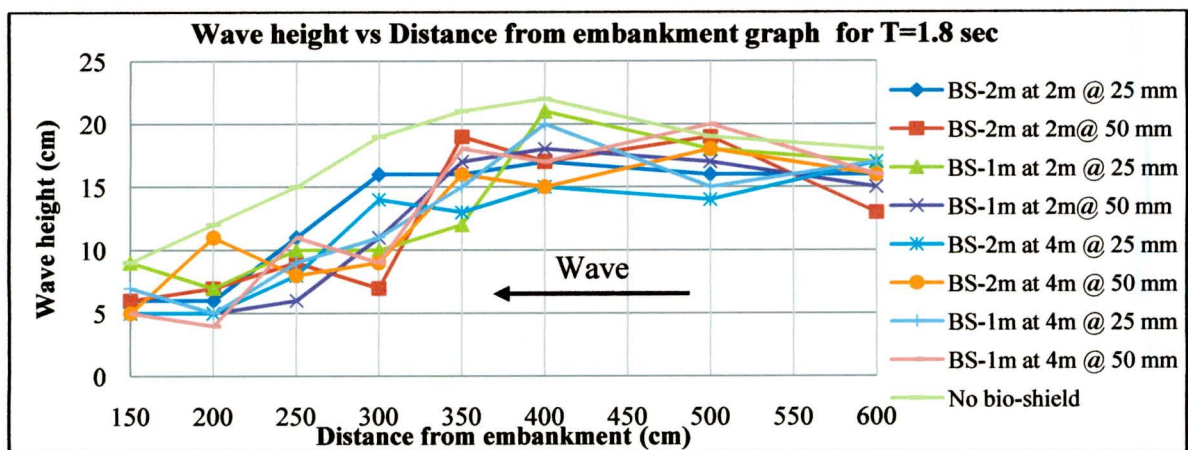


Figure 4.15: Variation of wave height with distance from embankment for different submerged bio-shield (BS) conditions and wave period, $T=1.8$ sec

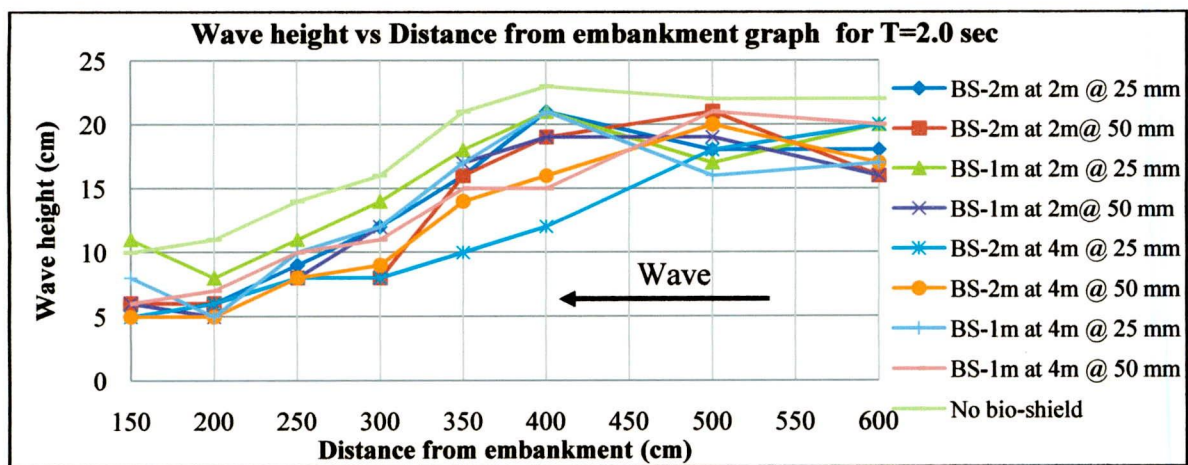


Figure 4.16: Variation of wave height with distance from embankment for different submerged bio-shield (BS) conditions and wave period, $T=2.0$ sec

4.5 Results and Discussion of Laboratory Experiment

The laboratory experiments were conducted on a 22 m long, 0.75 m wide and 0.75 m deep wave flume in the Hydraulic and River Engineering laboratory of Bangladesh University of Engineering and Technology to evaluate the effectiveness of coastal bio-shields for the reduction of high frequency surge waves. The experiments were multifarious including the rigid and flexible combination of bio-shields along with different densities, widths, submergence and distance from embankment for three different wave periods such as 1.6, 1.8 and 2.0 sec. In this section laboratory experimental data is analyzed in different ways to find out the most effective position of bio-shields for the reduction of the energy of high frequency surge waves. From the experimental data analysis, it is found that the maximum wave height reduction occurs for 2 m width of bio-shields when placed at 4 m away from the defined embankment at a measuring location which is 3.5 m away from the embankment for both emerged and submerged conditions of bio-shield. The maximum wave height reductions are 71 % and 52 % for emerged and submerged conditions of bio-shield respectively. The results of the laboratory experiment are shown in the Table 4.18, Table 4.19, Table 4.20, Table 4.21 and Table 4.22 for different experimental conditions.

Table 4.18: Wave height reductions by emerged and submerged bio-shield

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 (4 m away from embankment)	58 %	50	2
	2	4	G-4 (3.5 m away from embankment)	71 %	50	2
	2	4	G-5 (3 m away from embankment)	36 %	50	1.6
Submerged	2	4	G-3 (4 m away from embankment)	36 %	25	2
	2	4	G-4 (3.5 m away from embankment)	52 %	25	2
	2	4	G-5 (3 m away from embankment)	44 %	25	2

Table 4.19: Comparison of wave height reductions for different distances of bio-shield

Distance from Embankment (m)	Width of Bio-shield (R+F) (m)	Bio-shield Conditions	Measuring location	Maximum wave height reduction (%)	Spacing, mm c/c	Time periods (sec)
2	2	Emerged	G-3 (4 m away from embankment)	21	25	2.0
	2	Emerged	G-4 (3.5 m away from embankment)	47	25	2.0
	2	Submerged	G-5 (3 m away from embankment)	27	50	1.8
4	2	Emerged	G-3 (4 m away from embankment)	58	50	2.0
	2	Emerged	G-4 (3.5 m away from embankment)	71	50	2.0
	2	Submerged	G-5 (3 m away from embankment)	44	25	2.0

Table 4.20: Comparison of wave height reductions for different widths of bio-shield

Width of Bio-shield (R+F) (m)	Distance from Embankment (m)	Bio-shield Conditions	Measuring location	Maximum wave height reduction (%)	Spacing, mm c/c	Time periods (sec)
0.5+0.5	4	Emerged	G-3 (4 m away from embankment)	42	25	1.8
	2	Submerged	G-4 (3.5 m away from embankment)	40	25	1.8
	4	Submerged	G-5 (3 m away from embankment)	18	50	1.8
1+1	4	Emerged	G-3 (4 m away from embankment)	58	50	2.0
	4	Emerged	G-4 (3.5 m away from embankment)	71	50	2.0
	4	Submerged	G-5 (3 m away from embankment)	44	25	2.0

Table 4.21: Comparison of wave height reductions for different spacing of bio-shield

Spacing, mm c/c	Distance from Embankment (m)	Width of Bio-shield (R+F) (m)	Measuring location	Maximum wave height reduction (%)	Bio-shield Conditions	Time periods (sec)
25	4	2	G-3 (4 m away from embankment)	47	Emerged	2.0
	4	2	G-4 (3.5 m away from embankment)	52	Submerged	2.0
	4	2	G-5 (3 m away from embankment)	44	Submerged	2.0
50	4	2	G-3 (4 m away from embankment)	58	Emerged	2.0
	4	2	G-4 (3.5 m away from embankment)	71	Emerged	2.0
	4	2	G-5 (3 m away from embankment)	36	Emerged	1.6

From Table 4.19, it is seen that when bio-shields are placed at 2 m away from embankment, 47 % of wave height is reduced for 2 m width and 25 mm c/c spacing of bio-shield at a measuring location which is 3.5 away from the defined embankment. Again, if we compare wave height reductions for different widths of bio-shield, it is found from Table 4.20 that the maximum reduction of wave height is 42 % for 1 m (0.5 R+0.5F) width and 25 mm c/c spacing of bio-shield when placed at 4 m away from embankment for emerged bio-shield and 1.8 sec of wave periods at a measuring location which is 4 m away from the embankment. In the comparison of wave height reduction for different spacing of bio-shields (Table 4.21), the same reductions (71 % for emerged and 52 % for submerged bio-shield) are computed as found from the comparison of wave height reduction by emerged and submerged bio-shield (Table 4.18).

Finally, wave height reductions are calculated for three different wave periods such as 1.6, 1.8 and 2.0 sec as shown in the Table 4.22. For 1.6 sec of wave period, the maximum wave height reduction is found to be 47 % for 2 m width and 25 mm c/c spacing of bio-shield when placed at 4 m away from the defined embankment and at a measuring location which is also 4 m away from that embankment.

Table 4.22: Comparison of wave height reductions for different wave periods

Time periods (sec)	Distance from Embankment (m)	Width of Bio-shield (R+F) (m)	Measuring location	Spacing, mm c/c	Bio-shield Conditions	Maximum wave height reduction (%)
1.6	4	2	G-3 (4 m away from embankment)	25	Emerged	47
	4	2	G-4 (3.5 m away from embankment)	50	Emerged	42
	4	2	G-5 (3 m away from embankment)	50	Emerged	36
1.8	4	2	G-3 (4 m away from embankment)	25	Emerged	52
	4	2	G-4 (3.5 m away from embankment)	50	Emerged	60
	4 and 2	2	G-5 (3 m away from embankment)	50	Both	27
2.0	4	2	G-3 (4 m away from embankment)	50	Emerged	58
	4	2	G-4 (3.5 m away from embankment)	50	Emerged	71
	4	2	G-5 (3 m away from embankment)	25	Submerged	44

Again, for 1.8 sec and 2.0 of wave periods, the wave height reduction are 60 % and 71 % for emerged bio-shield of 2 m width and 50 mm c/c spacing placed at 4 m away from the defined embankment and at a measuring location which is 3.5 m from that embankment.

It is investigated from all the experimental data analysis that the maximum wave height reductions are 71% and 52% for emerged and submerged conditions of bio-shield respectively at a distance which is 3.5 m away from the embankment for wave periods of 2.0 sec and 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.

4.6 Numerical Modeling

A two-dimensional numerical model named Bay of Bengal model developed by Institute of Water Modeling (IWM) was used with the help of IWM to study the effect of coastal bio-shield in reducing the energy of storm surge SDR on the Kuakata beach of Bangladesh. In this numerical modeling four simulations were performed for four different conditions (i.e. no bio-shield and no SLR; no bio-shield and considering 74 cm of SLR; 200 m width of bio-shield at 200 m away from the polder-48 and no SLR; bio-shield of 200 m width at 200 m away from the polder-48 with 74 cm SLR). Surge levels and current speeds are measured at three specific locations on the kuakata beach (polder-48). The Figure 4.17 shows the measuring points on the map. The surge level and current speed are compared with the respective base conditions (i.e. no bio-shield and no SLR; no bio-shield and considering 74 cm of SLR) to find out the reduction of surge height and current speed diminished by the 200 m bio-shield barrier. The results of the numerical simulations are tabulated in the Table 4.23, Table 4.24 and Table 4.25.

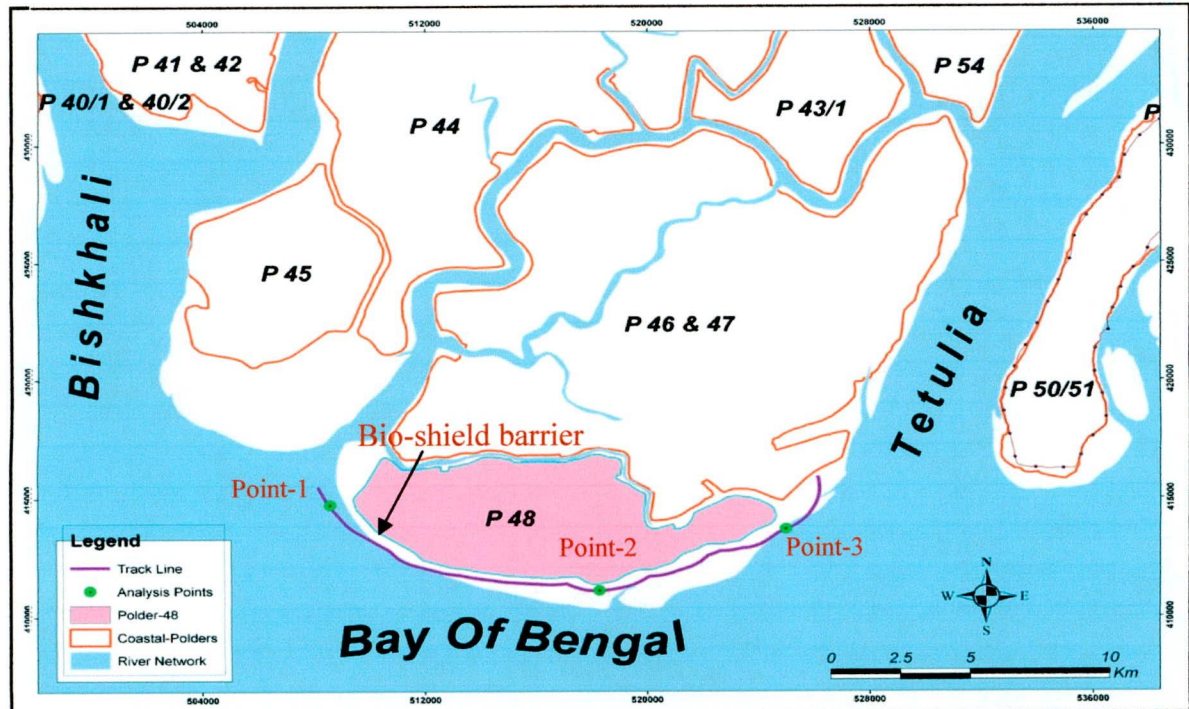


Figure 4.17: Three specific measuring points on the kuakata beach (Polder-48)

From the model results it is pretty obvious that the surge height and current speed or thrust of storm surge SDR reduces by 1 cm and 0.23 m/s or 70 % at point-1 for considering only

200 m width of bio-shield and no SLR. Again, when 74 cm of sea level rise (SLR) is considered the surge height and current speed also reduce by 2 cm and 0.24 m/s or 68 % by the 200 m bio-shield barrier. At point-2, the surge height again decreases by 1 cm and the current speed also reduces by 0.38 m/s or 63 % for considering only 200 m width of bio-shield and no SLR. Moreover, when 74 cm of sea level rise is considered the surge height decreases by 2 cm and current speed also reduces by 0.36 m/s or 58 %. Finally, at point-3 the surge height and current speed reduce by 2 cm and 0.48 m/s or 62 % respectively by 200 m width of bio-shield and no SLR. And again, the surge height and current speed reduce by 3 cm and 0.46 m/s or 59 % respectively for considering 74 cm of sea level rise.

In this numerical modeling, only 200 m width of bio-shield placed at 200 m away from polder-48 has been used to study the effect of coastal bio-shield in reducing the energy of storm surge SIDR. For this bio-shield condition, most of the measuring points are located on the land surface of Kuakata beach rather than located in the sea water. The effects of distance of bio-shields from the embankment or polder-48 would be more prominent if we consider the 300 m, 400 m, 500 m and 600 m distance of bio-shields from the polder. This is due to the limited facilities given to me by the CPE division of IWM. The roughness or bio-shield model set-up was time consuming job and the officials of CPE division were very much busy with their own works, that's why the model simulations have been limited to these four runs only.

Table 4.23: Comparison of surge level and current speed at measuring point-1

Item description	Surge level (mPWD)	Current Speed(m/s)	Change in surge height (cm)	Change in current Speed	
				m/s	%
No bio-shield and no SLR	1.99	0.33	-		
Bio-shield of 200 m width at 200 m distance from polder-48 and no SLR	1.98	0.10	- 1	-0.23	70
No bio-shield and considering 74 cm of SLR	2.70	0.35	-	-	-
Bio-shield of 200 m width at 200 m distance from polder-48 and considering 74 cm of SLR	2.68	0.11	- 2	-0.24	68

Table 4.24: Comparison of surge level and current speed at measuring point-2

Item description	Surge level (mPWD)	Current Speed(m/s)	Change in surge height (cm)	Change in current Speed	
				m/s	%
No bio-shield and no SLR	2.93	0.60	-		
Bio-shield of 200 m width at 200 m distance from polder-48 and no SLR	2.92	0.22	- 1	-0.38	63
No bio-shield and considering 74 cm of SLR	3.63	0.62	-	-	-
Bio-shield of 200 m width at 200 m distance from polder-48 and considering 74 cm of SLR	3.61	0.26	- 2	-0.36	58

Table 4.25: Comparison of surge level and current speed at measuring point-3

Item description	Surge level (mPWD)	Current Speed(m/s)	Change in surge height (cm)	Change in current Speed	
				m/s	%
No bio-shield and no SLR	4.74	0.77	-		
Bio-shield of 200 m width at 200 m distance from polder-48 and no SLR	4.72	0.29	- 2	-0.48	62
No bio-shield and considering 74 cm of SLR	5.45	0.78	-	-	-
Bio-shield of 200 m width at 200 m distance from polder-48 and considering 74 cm of SLR	5.42	0.32	- 3	- 0.46	59

4.7 Result Discussion of the Research Work

In this study, historical cyclone data has been analyzed to understand the future trend of cyclonic storm surges that hit the country almost every year causing massive devastation in properties and human lives as well. This study also includes estimation of existing bio-shield protection along the coastal belt of Bangladesh. Eventually, the main objectives of the study are to conduct a laboratory experiment and to use the result of a numerical model to study the effectiveness of coastal bio-shield in reducing the energy of high frequency

surges and cyclones. From the historical data analysis, it is plausible that the frequency and intensity of severe cyclonic storm surges will perpetually be increased in the future. This analysis has been done based on the available cyclone data including wind speed, surge height and the number of people died in the previous natural disasters. The historical analysis of wind speed (Figure 4.3) shows an increasing trend with 0.83 km/h each year increase of wind speed because of climate change effects which causes sea level rise along with the rise in global temperature. But the good news is that the number of population died in the previous natural disasters (Figure 4.4) shows a decreasing trend due to the presently growing institutional arrangement for disaster management.

In the past, foreshore afforestation schemes have proven cost effective in dissipating wave energy and reducing hydraulic load on embankments during storm surges. Currently, however, Bangladesh has insufficient foreshore forests. With an existing network of nearly 5,700 km long embankments in 139 polders (GOB, 2013), there are only 60 km of forest belts of the 957 km total length of embankment of 49 sea-facing polders, , much of which is already degraded (Dasgupta, et al. 2010). The Bangladesh Forest Department and Institute of Water Modeling recommend a minimum of 500 m width mangrove forest to protect sea-facing polders. Again, the coastal circle consisting of Bhola, Patuakhali, Barguna, Pirojpur, Noakhali, Feni and Laksmipur districts covers only 423,306 ha of bio-shields protection whereas the Sundarban circle consisting of Satkhira, Khulna and Bagerhat districts covers 577,060 ha of bio-shields protection.

The laboratory experiment on high frequency surges that has been carried out in the Hydraulics and River Engineering laboratory of BUET shows that the maximum wave height reduction occurs for 2 m width of bio-shield (1 m Rigid+ 1 m Flexible) when placed at 4 m distance from the defined embankment. The location of maximum wave height reduction is at 3.5 m away from the embankment and the reductions are 71 % and 52 % for emerged and submerged conditions of bio-shield respectively. From the analysis it is observed that the wave height reduction decreases with the decrease of distance from the embankment. So the optimum position for maximum surge height reduction is not just behind the bio-shield and not close to the embankment but a little bit away from bio-shield barrier towards the embankment.

In the laboratory experiment, a guiding scale ratio of 1:40 or Scale Factor (SF) of 40 was adopted. In order to scale down the prototype values and identify the experiment materials, it was assumed that the flow was due storm surges of high frequencies and considered also

the experimental ranges of various parameters including surge height, bio-shield spacing, bio-shield width and distances of bio-shield from the embankment. So the 2 m and 4 m distance of bio-shield in the experiment will represent 80 m and 160 m distance in the real field, respectively. Again, 25 mm c/c and 50 mm c/c spacing of bio-shield actually represent that the bio-shield spacing are 1 m c/c and 2 m c/c, respectively in the coastal areas. The 6 mm diameters of bamboo and polyethylene sticks in the laboratory experiment are representative of 24 cm diameter of trees which is the average diameter of mangrove trees in the coastal areas of Bangladesh. In the experimental study, 1 m (0.5 m Rigid + 0.5 m Flexible) and 2 m (1 m Rigid+ 1 m Flexible) width of bio-shield have been used which will represent 40 m and 80 m width of bio-shield belt in the real field.

It is also investigated from the experimental study that the reduction of wave height increases with the increase of wave periods (Table 4.22) and the waves with longer period will be 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 4.18). This is because of the wave-reflection and backwater effect caused by the dense bio-shield barrier. When the bio-shield spacing is 25 mm c/c, it can create enough hindrance on the way of incoming waves which cause wave-reflection and back water effect. But at 50 mm c/c spacing of bio-shield, the incoming waves pass through it without creating much obstacle and get reduced by the buffering function of bio-shield barrier. Again for submerged bio-shield, as the incoming waves pass over the bio-shield barrier, the bio-shield with 50 mm c/c spacing could not be able to create enough resistance to be got reduced most. But in this case 25 mm c/c spacing and 2 m width of bio-shield is enough to generate much resistance which can reduce the maximum wave height that is still less reduction than some cases for emerged bio-shield of 50 mm c/c spacing. That's why the maximum wave height reduction is at 50 mm c/c spacing for emerged bio-shield and for submerged bio-shield the maximum reduction is at 25 mm c/c spacing.

The results of numerical simulations that have been performed on the Kuakata beach (polder-48) of Bangladesh shows that a 200 m width of bio-shield barrier placed at 200 m distance from the polder-48 is capable of reducing up to 0.48 m/s or 62% of current speed

when SLR does not come into consideration and 0.46 m/s or 59 % for the consideration of 74 cm of SLR. It has also effects on surge height reduction, that is the bio-shield barrier can reduce the surge height up to 2 cm and 3 cm for without and with considering SLR respectively. The reduction in current speed and surge level would be more prominent if the width and location of bio-shields barrier would vary as two fold or three fold which is found in others studies (Hasan, 2009; Tanaka, 2008).

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 high frequency cyclonic storm surges for protecting the hinterland against various types of natural disasters. Sundri, Gewa and coconut trees are the specific species that are available in the coastal areas of Bangladesh can be used as bio-shield protection to save the coastal areas from natural disasters.

Laboratory experiment and numerical modeling data analysis have been included in the appendices and numerical model has also been documented in this report. A comprehensive literature review is conducted by this author, that identifies what had been done and what needed to be done related to this topic. The documented experimental procedure, numerical model results, data and references will be very useful for other researchers who are interested in this topic.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Coastal bio-shield has been widely recognized as a natural method to reduce the energy of storm surges and cyclones. Coastal forests and trees can, under certain conditions, act as bio-shields to protect lives and valuable assets against coastal hazards, including: tsunamis, cyclonic storms, wind and coastal erosion. However, there is limited knowledge and few models that address the effects of bio-shield on surge and waves. The main objective of this study was to conduct laboratory experiments and to use the results of a numerical model to quantify the reduction of high frequency surge and cyclone energy by coastal bio-shield along the Kuakata beach of Bangladesh. The study consisted of historical cyclonic storm surge data analysis, assessment of existing coastal bio-shields along the coastal belt of Bangladesh, a laboratory experiments and use of numerical model results. The study results are given below:

- (i). In the 4th IPCC report it has been stated that intensity and frequency of cyclonic storm surge will be increased in the Bay of Bengal area in the near future. In this study wind speed data of 25 cyclones that hit the country from 1960 to 2007 has been analyzed and found that the wind speed or intensity of cyclonic storm surges increases by 0.83 km/h each year due to the climate change and consequent effects. But the death toll caused by storm surges shows a decreasing trend and the decreasing rate is 500 people per year because of the present growing successful institutional arrangement for disaster management in the recent years which includes development of early warning system, prevention and mitigation, preparedness, emergency response and post-disaster recovery.

In the past, foreshore afforestation schemes have proven cost effective in dissipating wave energy and reducing hydraulic load on embankments during storm surges. Currently, however, Bangladesh has insufficient foreshore forests. With an existing network of nearly 5,700 km long embankments in 139

polders (GOB, 2013), there are only 60 km or 6% of forest belts of the 957 km total length of embankment of 49 sea-facing polders, much of which is already degraded (Dasgupta et al., 2010). The 710 km long coastal belt of Bangladesh extending from Raimongal River to the west and Teknaf to the Southeast is poorly covered with natural and planted bio-shields. The coastal circle consisting of Bhola, Patuakhali, Barguna, Pirojpur, Noakhali, Feni and Laksmipur districts covers only 423,306 ha of bio-shields protection whereas the Sundarban circle consisting of Satkhira, Khulna and Bagerhat districts covers 577,060 ha of bio-shields protection.

- (ii). To study the effectiveness of coastal bio-shield in reducing the energy of high frequency surges a laboratory experiment was conducted 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), Dhaka, Bangladesh. Bio-shields were represented by cylindrical bamboo sticks as rigid bio-shield and polyethylene (Polyethylene is 75 times more flexible than bamboo sticks) 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 spacing 25 mm c/c and 50 mm c/c of bio-shields, respectively. The length of bio-shield was fixed at 75 cm as the flume width was 75 cm but the width varies from 1 m to 2 m. There were two combinations of width of the bio-shield, i.e. (i) one meter flexible and one meter rigid and (ii) half meter flexible and half meter rigid. The experiments were conducted for two distances of bio-shield from the embankment such as 2 m and 4 m. The water level was always fixed at 50 cm for all the experimental run conditions. There were a total of 51 experimental runs covering 3 different wave periods of 1.6, 1.8 and 2.0 seconds. Water surface elevations were recorded with the wave staffs at 9 different locations (Figure 3.1 and Figure 3.2). 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.

From the laboratory experiment, it is investigated that the wave height is reduced most when bio-shield of 2 m width (1 m Rigid + 1 m Flexible) is placed at 4 m

distance from the embankment. It is also obvious from Table 4.5, Table 4.6, Appendix B, Appendix C and Appendix D that the maximum wave height reduction occurs at a measuring location G-4 which is 3.5 m away from the embankment for two spacing of bio-shields such as 25 mm c/c and 50 mm c/c. For emerged bio-shield conditions, the wave height reductions are 47%, 52% and 58% for wave periods of 1.6 sec, 1.8 sec and 2.0 sec respectively at a measuring location (G-3) which is situated just behind the bio-shield barrier (4 m from the embankment) and also the wave height reductions are 42%, 60% and 71% for wave periods of 1.6 sec, 1.8 sec and 2.0 sec respectively at (G-4) 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 conditions, same result is obtained 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 and it is also obvious from Table 4.13, Table 4.14, Appendix B, Appendix C and Appendix D that the maximum wave height reduction occurs at a measuring location (G-3) which is just behind the bio-shield barrier (4 m from the embankment) and at (G-4) 3.5 m away from the embankment. The wave height reductions are 18%, 21% and 36% for wave periods of 1.6 sec, 1.8 sec and 2.0 sec respectively at a measuring location (G-3) which is just behind the barrier (4 m from the embankment) and also the wave height reductions are 36%, 40% and 52% for wave periods of 1.6 sec, 1.8 sec and 2.0 sec respectively at (G-4) 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.

- (iii). A two-dimensional numerical model named Bay of Bengal model developed by Institute of Water Modeling (IWM) was used to simulate the effect of coastal bio-shield in reducing the energy of storm surge SIDR along the Kuakata beach of Bangladesh. In this numerical modeling four simulations were performed for four different conditions. Surge levels and current speeds are measured at three specific locations on the Kuakata beach (polder-48). From the result of the simulations it is

found that the surge level decreases by 1 cm and the current speed or thrust of cyclone SIDR reduces by 0.23 m/s or 70 % at point-1 for considering only 200 m width of bio-shield and no SLR. But, when 74 cm of sea level rise is considered for the year 2100 the surge height and current speed also reduce by 2 cm and 0.24 m/s or 68 % by the 200 m bio-shield barrier. At point-2, the surge height again decreases by 1 cm and the current speed also reduces by 0.38 m/s or 63 % for considering only 200 m width of bio-shield and no SLR. Moreover, when 74 cm of sea level rise is considered the surge height decreases by 2 cm and current speed also reduces by 0.36 m/s or 58 %. Finally, at point-3 the surge height and current speed reduce by 2 cm and 0.48 m/s or 62 % respectively by 200 m width of bio-shield and no SLR. And again, the surge height and current speed reduce by 3 cm and 0.46 m/s or 59 % respectively for considering 74 cm of sea level rise.

- (iv). 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 high frequency storm surges for protecting the hinterland. Sundri, Gewa and coconut trees are the specific species that are available in the coastal areas of Bangladesh can be used as bio-shield protection.

5.2 Recommendations

- (i). In this study, wind speed and population death toll data have been analyzed as a part of historical cyclonic storm surge data analysis but the surge heights has not been analyzed due to insufficient surge height data. In the future study surge height along with surge speed can be analyzed to understand the trend of these parameters.
- (ii). In the numerical modeling study, bathymetry of Bay of Bengal for 2007 has been used in this research work but inclusion of more recent bathymetry will aggrandize the reliability of the model results of the present research work.
- (iii). The study has been carried out considering the wind speed of the storm surge SIDR which occurred on the 15th of November, 2007. But according to the IPCC report and the historical cyclonic storm surge analysis the intensity and frequency of the cyclonic storm surges will be increased in the near future in the Bay of Bengal. So this study can be updated considering the future increased intensity of cyclonic surges.

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APPENDIX A

Chronology of Major Cyclones and Storm Surges in Bangladesh

Sl No.	Year, Month & date	Affected Area	Nature of the Phenomena	Approximate loss/damage
1	1582 (Date and month N/A)	Bakerganj (presently Barisal and Patuakhali)	Severe cyclonic storm	People killed = 200,000
2	1585 (Date and month N/A)	Bakerganj (now Barisal) near the mouth of the Meghna River estuary	Tropical storm	Damage data not available
3	1699 (Date and month N/A)	Sundarbans	Severe cyclonic Storm	People killed = 50,000.
4	1760 (Date and month N/A)	Sundarbans	Severe cyclonic storm	Damage data not available
5	1765 (Date and month N/A)	Chittagong coast	Severe cyclonic storm	Damage data not available
6	1767 (Date and month N/A)	Bakerganj (now Barisal) coast	Severe cyclonic storm S= 13.03 m	People killed: 30,000
7	1797, May-June	Chittagong	Severe cyclone	Every hut levelled to ground and 2 vessels sunk in the Chittagong port
8	1822, May	Barisal	Most severe cyclone	40,000 people killed and 100,00 cattle lost
9	1831, October	Barisal	Storm surge	Damage report not available
10	1872, October	Cox's Bazar	Cyclonic storm	270 people killed
11	1876, 27 Oct. to Nov. 1	Patuakhali, Noakhali and Chittagong coast	More severe storm surge of 12m height	400,000 lives were lost and enormous properties were destroyed
12	1895, October	Sundarbans	Cyclonic surge	Damage report not available
13	1897, October	Chittagong and Kutubdia island	Hurricane with surge	175,000 lives were lost
14	1898, May	Teknaf	Cyclonic storm surge	Damage report not available
15	1901, November	Western Sundarban	Cyclonic storm	Damage data not available

Sl No.	Year, Month & date	Affected Area	Nature of the Phenomena	Approximate loss/damage
16	1909, October	Chittagong	Cyclonic storm surge	Damage data not available
17	1909, December	Cox's Bazar	Cyclonic storm	Damage data not available
18	1911, April	Teknaf	Cyclonic storm	120,000 people killed
19	1917, May	Sundarbans	Cyclonic storm	70,000 people killed
20	1919, September	Barisal	Cyclonic storm	40,000 people killed
21	1922, April	Teknaf	Cyclonic storm	Damage data not available
22	1923, May	Teknaf	Cyclonic storm	Damage data not available
23	1926, May	Cox's Bazar	Cyclonic storm	606 people killed
24	1941, May 26	Eastern Meghna estuary	Cyclonic storm	7,000 people killed
25	1948, May 17-19	Between Noakhali & Chittagong	Cyclonic storm	Damage data not available
26	1950, Nov. 15-20	Patuakhali	Cyclonic storm	Damage data not available
27	1958, May 16-19	Eastern Meghna estuary	Cyclonic storm	Damage data not available
28	1958, October 21-24	Noakhali and West Meghna estuary	Cyclonic storm	12,000 people killed
29	1960, May 25-29	Sunderban Coast (landfall at Sundarbans)	Cyclonic storm, s= 3.2m and t=0.0m	106 people killed
30	1960, October 10-11	Meghna estuary (landfall at Noakhali)	Severe cyclonic storm, w=129 km/h, s=6.6m and t=1.5m.	6,000 to 11,446 people killed
31	1960, October 30-31	Chittagong coast (landfall at Chittagong)	Severe cyclonic storm, w=161 to 210 km/h, s=4.2m and t=1.8m.	70% buildings in Hatia blown-off and 8,149 lives lost
32	1961, May 6-9	Meghna estuary (landfall near Feni river) near Noakhali	Severe cyclonic storm, w=145 km/h, s=4.5m and t=1.2m at Galachipa.	11,468 people killed in Char Alexander and rail road damaged

w= Wind Speed, s= Surge height, t= Tidal height

Sl No.	Year, Month & date	Affected Area	Nature of the Phenomena	Approximate loss/damage
33	1961, May 27-30	Chittagong-Noakhali coast	Cyclonic storm, w=95 to 145 km/h and total water level was 7m at Chittagong.	10,466 people killed
34	1962, October 26-30	Feni-Chittagong coast	Cyclonic storm, w=200 km/h, s=5.8m and t=0.0m.	50,000 people killed
35	1963, May 28-29	Noakhali-Cox's Bazar Coast (landfall near Chittagong)	Severe cyclonic storm, w=201 km/h, s=5m and t=0.3m at Chittagong.	11,520 people killed
36	1963, June 5-8	Sundarbans	Cyclonic storm, s=3.1m and t=0.0m.	Damage data not available
37	1963, October 25-29	Teknaf	Cyclonic storm, w=105 km/h, s=2.2m and t=0.0m.	Damage data not available
38	1965, May 10-12	Barisal-Chittagong coast (landfall between Barisal and Noakhali)	Severe cyclonic storm, w=161 km/h, s=4.0m and t=1.2m.	19,270 people killed
39	1965, May 31 to June 1	Chittagong Coast (landfall near Chittagong)	Tide plus surge was 7.1m at Companyganj. At Chittagong 1.6m surge on tide.	12,000 people killed
40	1965, December 14-15	Cox's Bazar-Teknaf coast (landfall near Cox's Bazar)	Severe cyclonic storm, w=200 km/h, s=4.0m and t=0.2m.	40,000 salt beds in Cox's Bazar were inundated and 870 people were killed
41	1966, October 1	Chittagong and Sandwip (landfall near Chittagong)	Severe cyclonic storm, w=145 km/h, tide plus surge was 6-7m.	850 people killed
42	1966, December 12	Cox's Bazar	Cyclonic storm	Damage data not available

Sl No.	Year, Month & date	Affected Area	Nature of the Phenomena	Approximate loss/damage
43	1967, October 11	Sundarban-Noakhali coast (landfall at Noakhali)	Cyclonic storm, w=160 km/h, s=3.0m and t=0.0m.	Damage data not available
44	1967, October 23-24	Chittagong-Cox's Bazar coast (landfall in between)	Cyclonic storm, w=130 km/h, s=2m and t=0.0m.	128 people killed
45	1969, October 11	Khulna coast	Cyclonic storm	175 people killed
46	1970, May 5-7	Chittagong-Teknaf coast (landfall at Cox's Bazar)	Cyclonic storm, w=148 km/h, s=2.3m and t=0.2m.	18 people killed
47	1970, November 12-13	Khulna-Chittagong coast (landfall at Hatia)	Most severe cyclonic storm, w=222 km/h, s=5.5m and t=2.1m.	300,000 lives lost and innumerable animals were killed, widespread damage to crops and properties
48	1971, May 7-8	Meghna estuary	Cyclonic storm, w=80 km/h.	Damage data not available
49	1971, November 5-6	Chittagong coast (landfall near Chittagong)	Cyclonic storm, w=105 km/h, s=2.1m and t=0.0m.	Damage data not available
50	1971, November 28-30	Sundarbans coast	Cyclonic storm, w=110 km/h, s=1.0m and t=0.0m.	11,000 people killed
51	1973, November 16-18	Chittagong coast	Cyclonic storm, w=165 km/h, s=3.5m and t=1.0m.	Damage data not available
52	1973, December 6-9	Sundarban-Patuakhali coast (landfall at Sundarbans)	Severe cyclonic storm, w=122 km/h and s=4.5m.	183 people killed
53	1974, August 13-15	Khulna coast	Cyclonic storm, w=80 km/h, s=2.5m and t=1.7m.	Damage data not available
54	1974, November 24-28	Cox's Bazar-Chittagong-offshore Islands (landfall at Chittagong)	Severe cyclonic storm, w=161 km/h, s=3.1m and t=0.2m.	20 people killed

Sl No.	Year, Month & date	Affected Area	Nature of the Phenomena	Approximate loss/damage
55	1975, May 9-12	Sundarban-Bhola-Chittagong coast	Severe cyclonic storm, w=110 km/h.	5 people killed
56	1976, October 19-20	Meghna estuary	Cyclonic storm, w=105 km/h, tide plus surge at Companygonj was 3.5m.	Damage data not available
57	1977, May 9-12	Sundarban-Chittagong coast (landfall at Sundarbans)	Cyclonic storm, w=113 km/h, s=0.6m and t=0.7m.	Damage data not available
58	1978, September 30 to Oct. 3	Sundarban Khulna coast	Cyclonic storm, w=74 km/h.	Damage data not available
59	1983, October 15	Chittagong-Feni coast (landfall near Chittagong)	Cyclonic storm, w=122 km/h.	43 persons were killed, 1000 fishermen missing and 20% aman crops destroyed
60	1983, November 9	Chittagong-Teknaf coast (landfall between Chittagong and Cox's Bazar)	Severe cyclonic storm, w=136 km/h, s=2.5m.	300 fishermen with 50 boats missing; 2000 houses, 22 institutions destroyed
61	1985 May 24-25	Noakhali-Cox's Bazar coast (landfall at Sandwip)	Severe cyclonic storm, w=154 km/h, s=3.2m and t=1.8m.	11,069 people killed, 94,379 houses damaged, 64 km road and 390 km embankment damaged
62	1986, November 9	Barguna-Chittagong coast	Cyclonic storm, w=110 km/h.	14 lives lost and huge damage to crops and properties
63	1988, November 29	Sundarbans	Severe cyclonic storm, w=160 km/h, s=3.5m and t=1.5m.	5,708 people killed and 6,000 missing; 65,000 cattle were lost
64	1990, October 7-8	Barguna-Noakhali coast	Cyclonic storm, s=2m.	150 fishermen with 16 mechanised boats missing

w= Wind Speed, s= Surge height, t= Tidal height

Sl No.	Year, Month & date	Affected Area	Nature of the Phenomena	Approximate loss/damage
65	1991, April 29	Patuakhali-Cox's Bazar coast (landfall north of Chittagong)	Most severe cyclonic storm, w=235 km/h, s=5.8m and t=1.7m.	145,000 people killed, 70,000 cattle killed, crops were damaged
66	1994, 29 April-3 May	coastal islands near Cox's Bazar	Severe cyclonic storm, w=210 km/h	400 people, 8,000 cattle
67	1995, 21-25 November	Coastal islands near Cox's Bazar.	severe cyclonic storm, w=210 km/h	650 people, 17,000 cattle
68	1997, 16-19 May	coastal islands and chars near Chittagong, Cox's Bazar, Noakhali and Bhola districts	Most severe cyclonic storm, w=225 km/h, s=3.05m	126 people killed
69	1997, 25-27 September	coastal islands near Chittagong, Cox's Bazar, Noakhali and Bhola	Severe cyclonic storm, w=150 km/h, s=1.83-3.05m	Damage data not available
70	1998, 16-20 May	coastal islands near Chittagong, Cox's Bazar, and Noakhali	Severe cyclonic storm, w=150 km/h, s=1.83-2.44m	Damage data not available
71	1998, 19-22 November	coastal islands and sand shoals near Khulna, Barisal, and Patuakhali	Severe cyclonic storm, w=90 km/h, s=1.22-2.44m	Damage data not available
72	2007, November 15	Southern coastal region of Bangladesh	Severe Cyclonic Storm, w=260 km/h, s=5.0 m	3,447 people killed, People missing 1,180, Houses Damaged 1210685, Crop Damage 1705922 acre, Tree destroyed 3369366
73	2008, April 27-May 3	coastal islands and sand shoals near Khulna, Barisal, and Patuakhali	Severe Cyclonic Storm, w=165 km/h, s=	15 people killed
74	2009, May 23-26	Southern coastal region of Bangladesh	Cyclonic storm, w=110 km/h, s=3.0 m	330 people died
75	2013, May 10-17	Southern coastal region of Bangladesh	Cyclonic storm, w=95 km/h, s=1.0 m	107 people died and 6 missing

w= Wind Speed, s= Surge height, t= Tidal height

APPENDIX B

Variation of Water Level with Distance from Embankment for Different Experimental Conditions

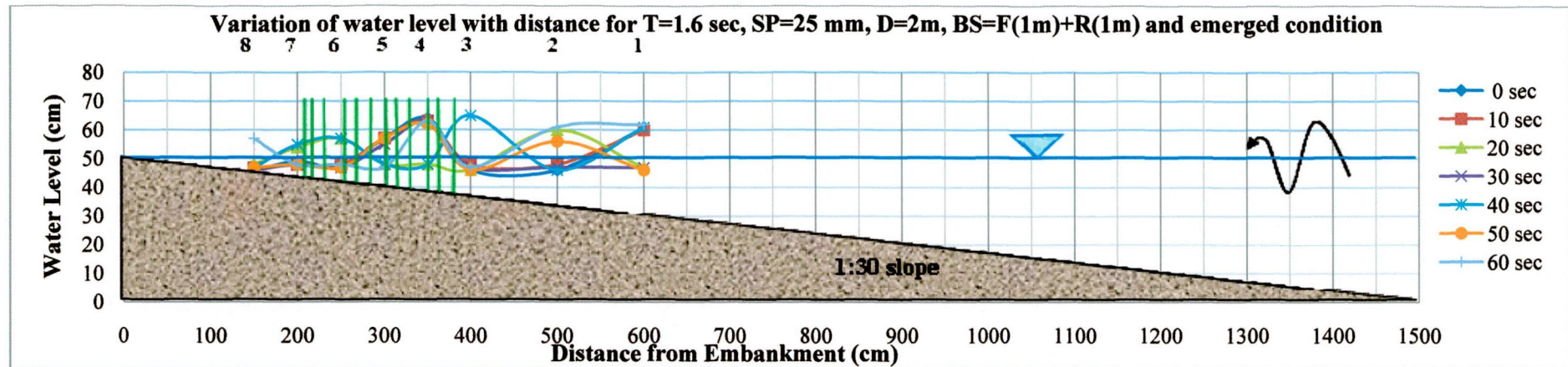


Figure 1: Variation of water level with distance for $T=1.6$ sec, bio-shield spacing-25 mm C/C, width of bio-shield-2m, distance from embankment-2m and emerged

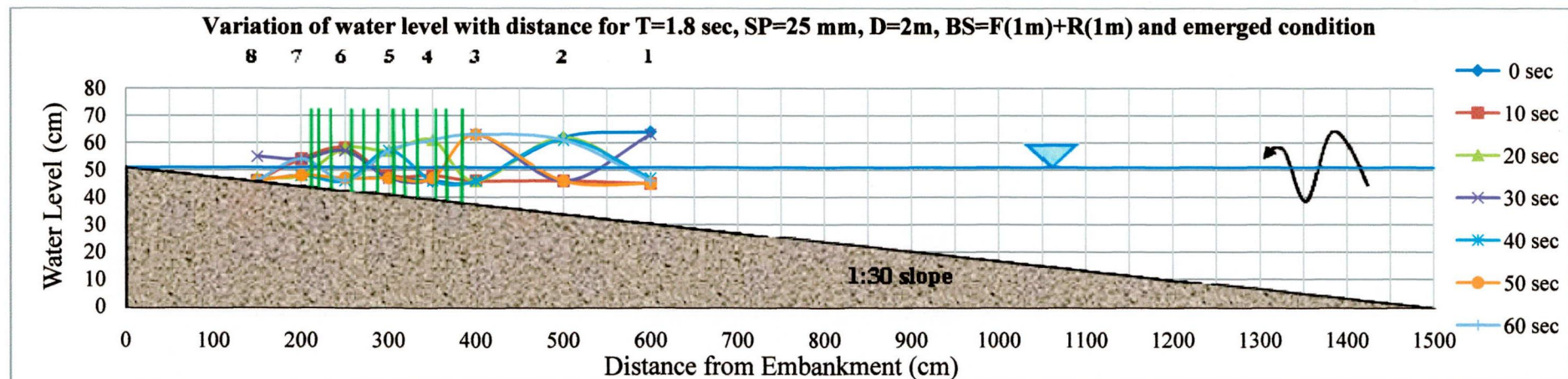


Figure 2: Variation of water level with distance for $T=1.8$ sec, bio-shield spacing-25 mm C/C, width of bio-shield-2m, distance from embankment-2m and emerged

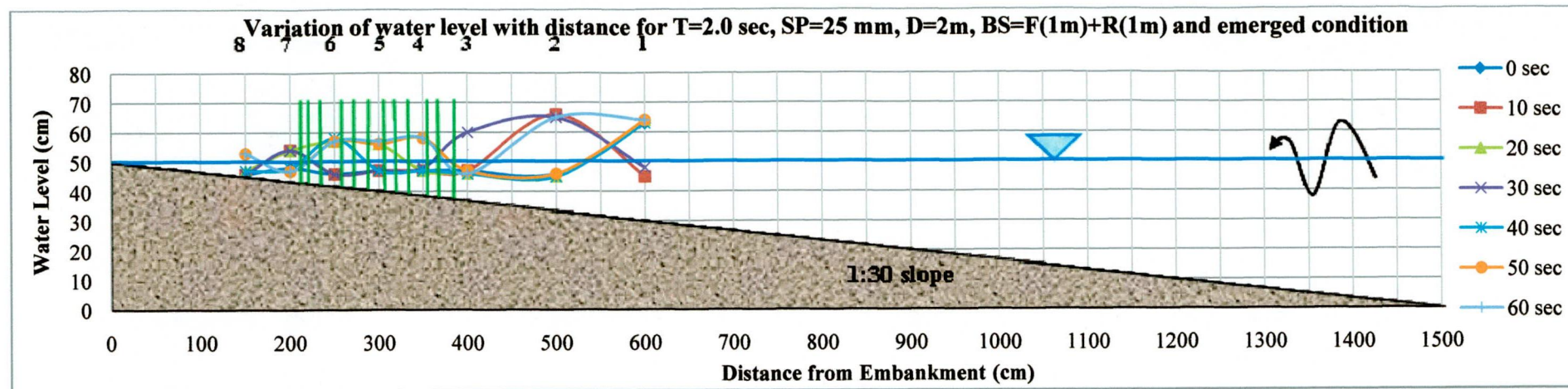


Figure 3: Variation of water level with distance for $T=2.0$ sec, bio-shield spacing-25 mm C/C, width of bio-shield-2m, distance from embankment-2m and emerged

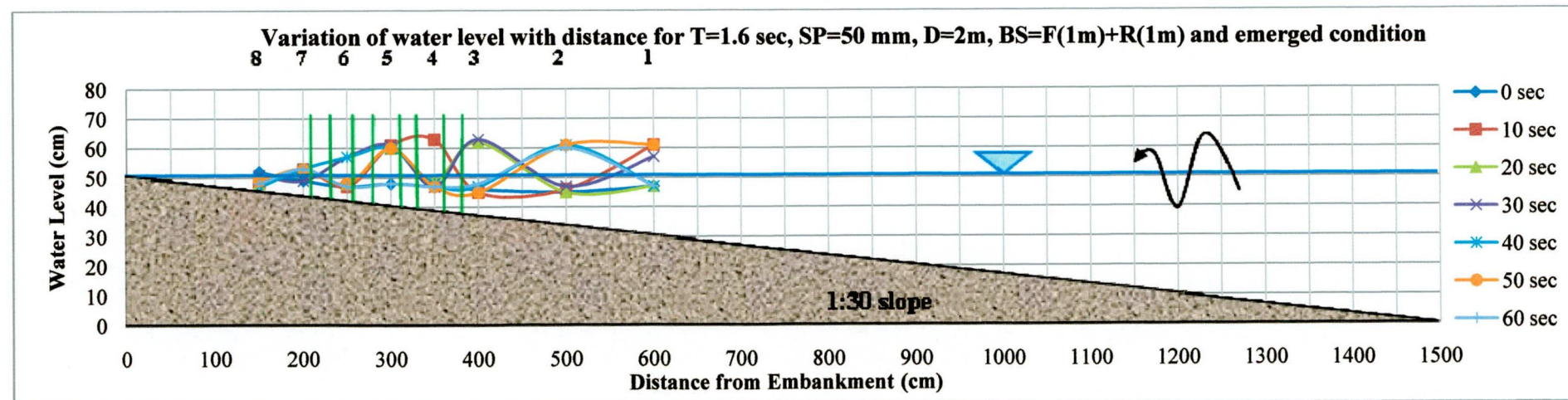


Figure 4: Variation of water level with distance for $T=1.6$ sec, bio-shield spacing-50 mm C/C, width of bio-shield-2m, distance from embankment-2m and emerged

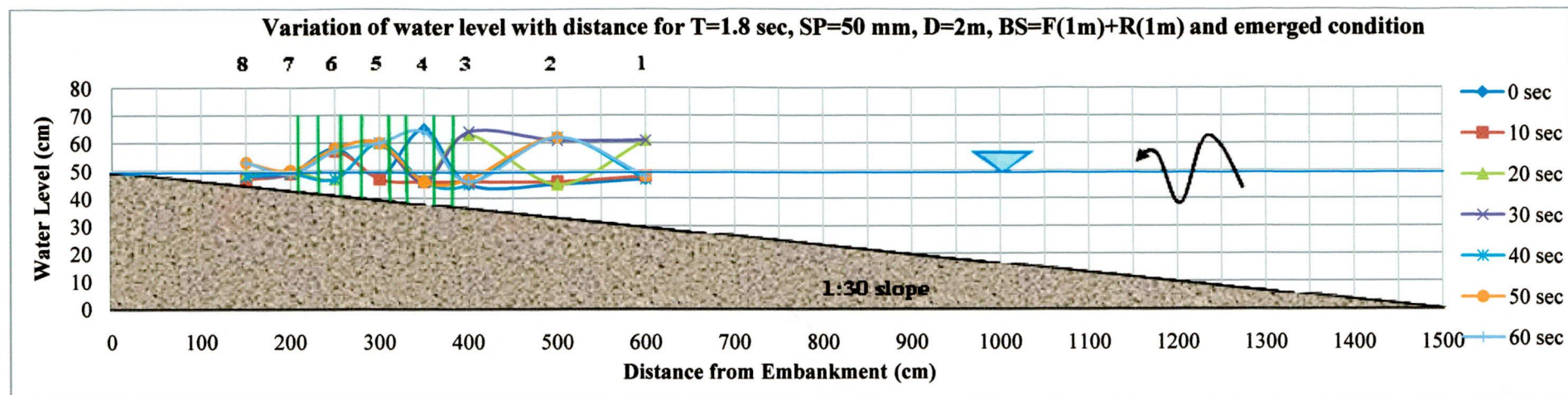


Figure 5: Variation of water level with distance for $T=1.8$ sec, bio-shield spacing-50 mm C/C, width of bio-shield-2m, distance from embankment-2m and emerged

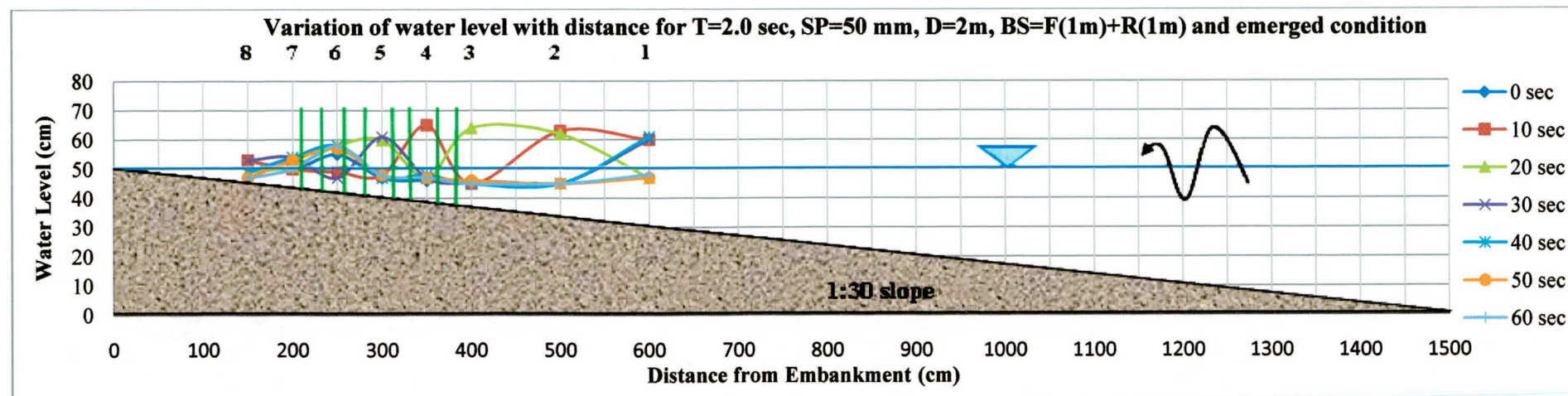


Figure 6: Variation of water level with distance for $T=2.0$ sec, bio-shield spacing-50 mm C/C, width of bio-shield-2m, distance from embankment-2m and emerged

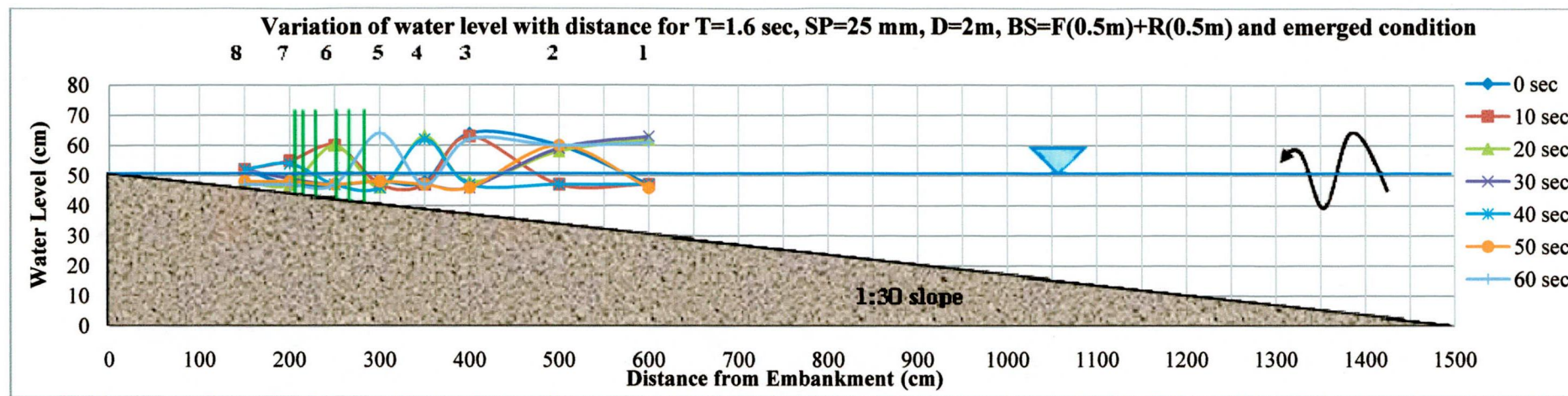


Figure 7: Variation of water level with distance for $T=1.6$ sec, bio-shield spacing-25 mm C/C, width of bio-shield-1m, distance from embankment-2m and emerged

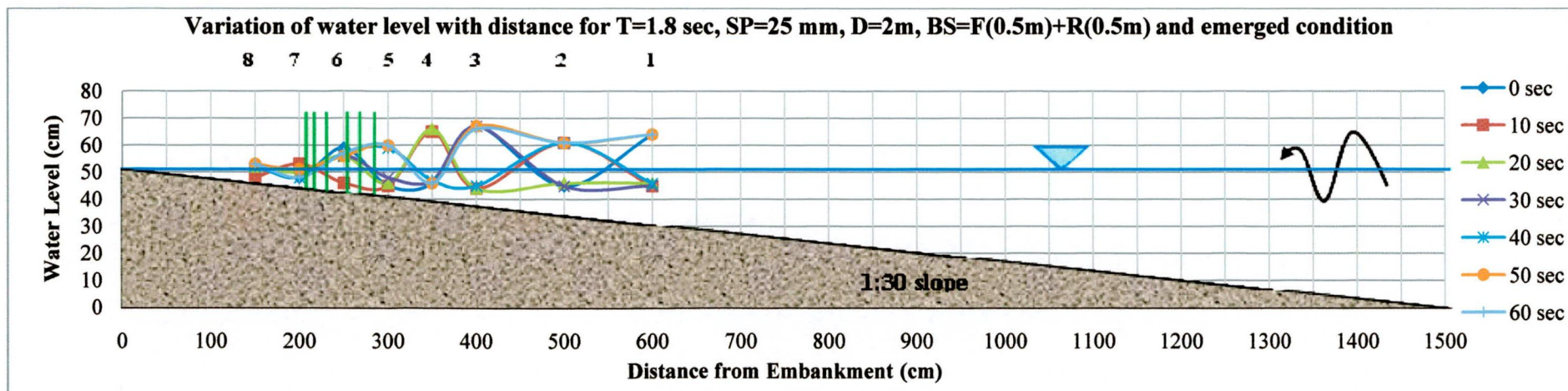


Figure 8: Variation of water level with distance for $T=1.8$ sec, bio-shield spacing-25 mm C/C, width of bio-shield-1m, distance from embankment-2m and emerged

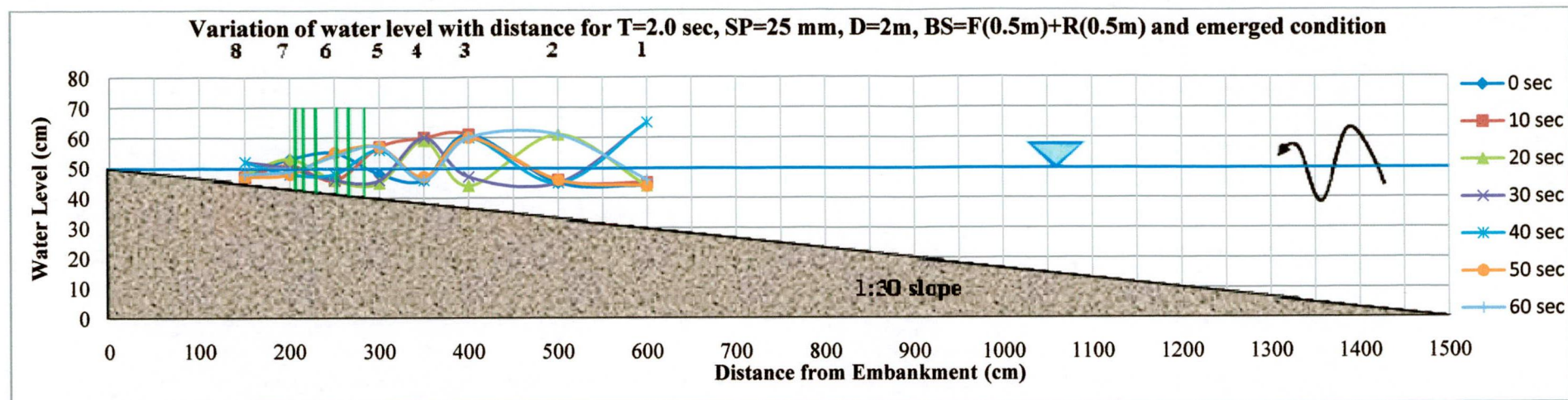


Figure 9: Variation of water level with distance for $T=2.0$ sec, bio-shield spacing-25 mm C/C, width of bio-shield-1m, distance from embankment-2m and emerged

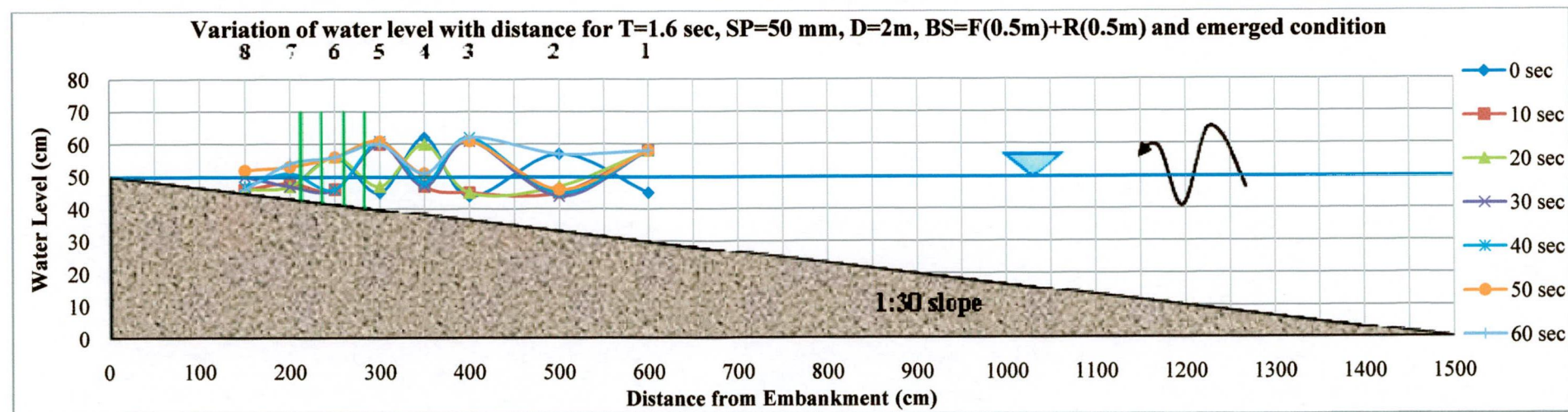


Figure 10: Variation of water level with distance for $T=1.6$ sec, bio-shield spacing-50 mm C/C, width of bio-shield-1m, distance from embankment-2m and emerged

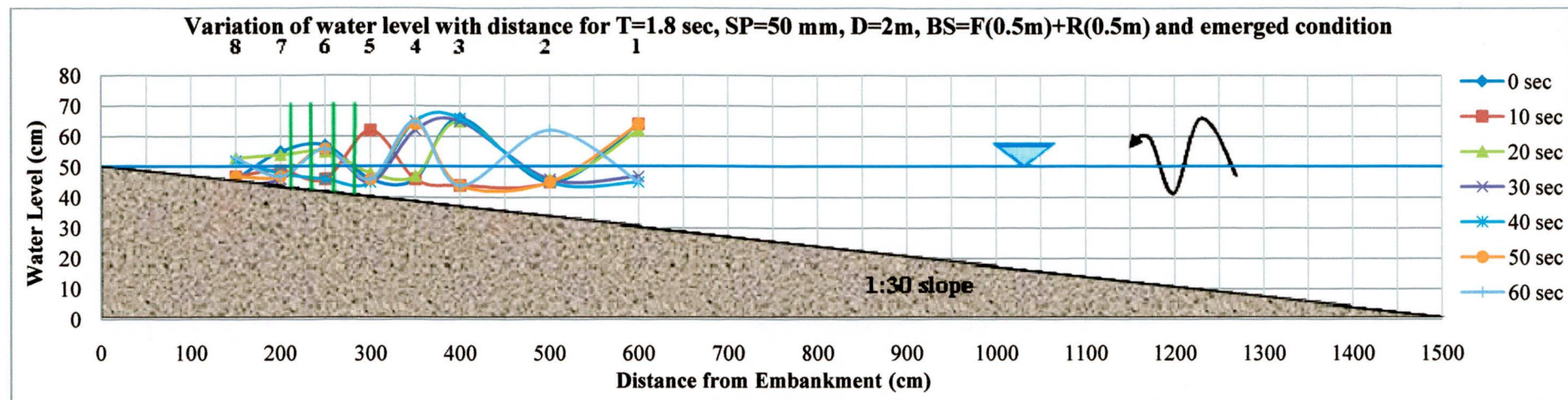


Figure 11: Variation of water level with distance for $T=1.8$ sec, bio-shield spacing-50 mm C/C, width of bio-shield-1m, distance from embankment-2m and emerged

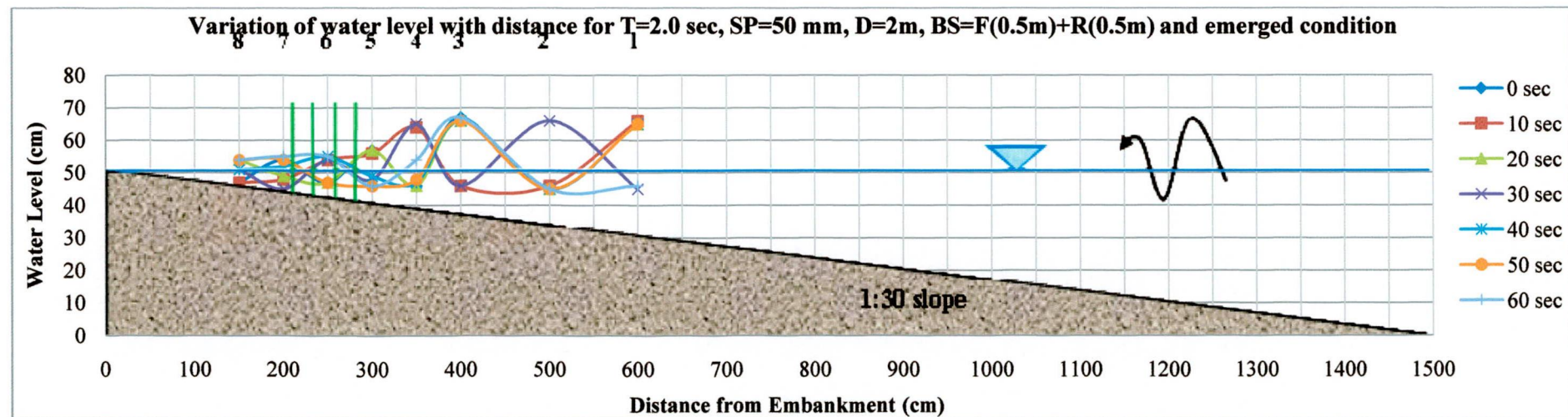


Figure 12: Variation of water level with distance for $T=2.0$ sec, bio-shield spacing-50 mm C/C, width of bio-shield-1m, distance from embankment-2m and emerged

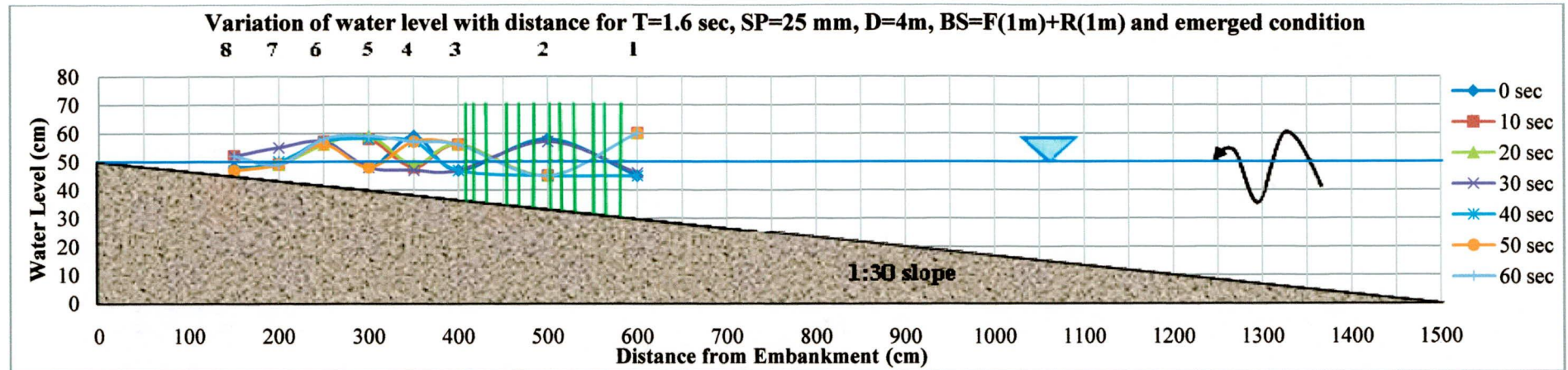


Figure 13: Variation of water level with distance for $T=1.6$ sec, bio-shield spacing-25 mm C/C, width of bio-shield-2m, distance from embankment-4m and emerged

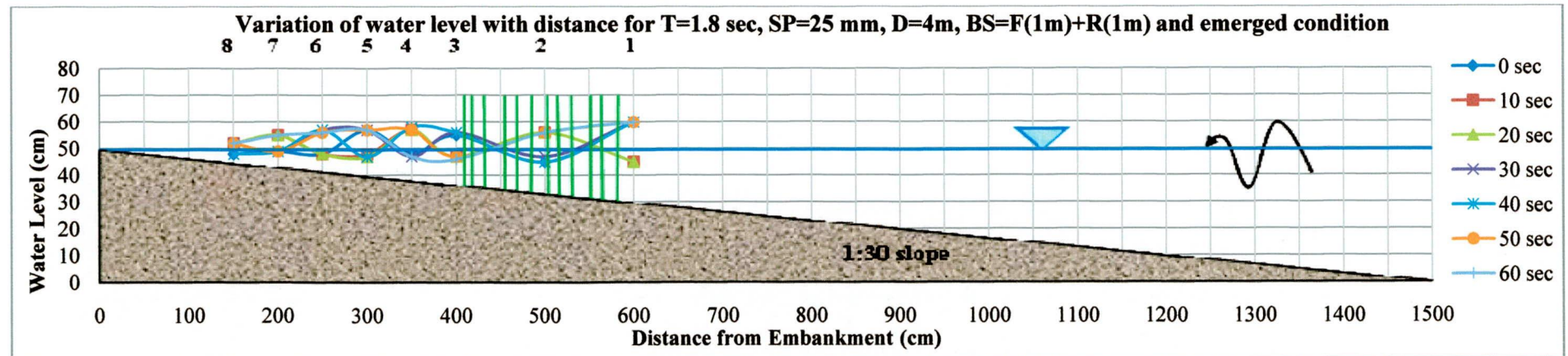


Figure 14: Variation of water level with distance for $T=1.8$ sec, bio-shield spacing-25 mm C/C, width of bio-shield-2m, distance from embankment-4m and emerged

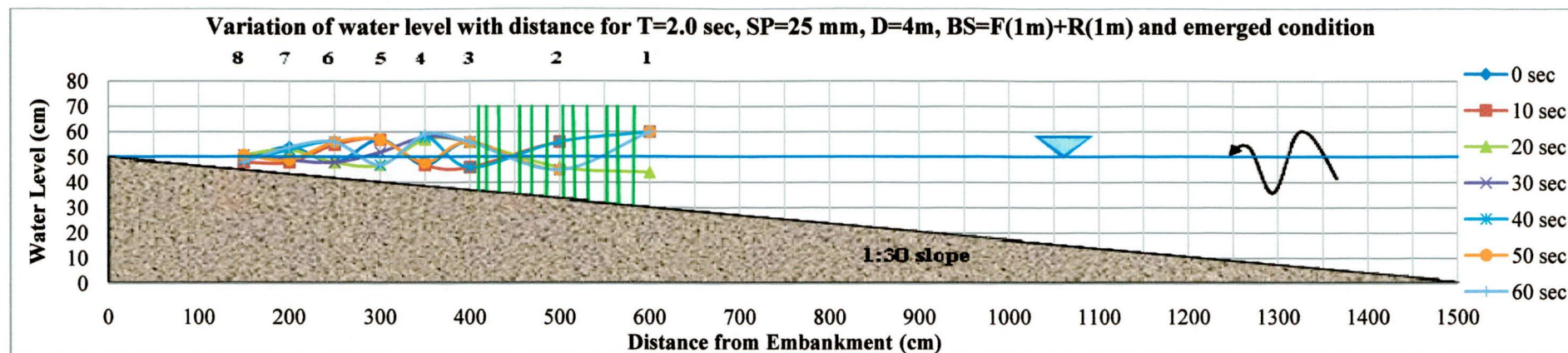


Figure 15: Variation of water level with distance for $T=2.0$ sec, bio-shield spacing-25 mm C/C, width of bio-shield-2m, distance from embankment-4m and emerged

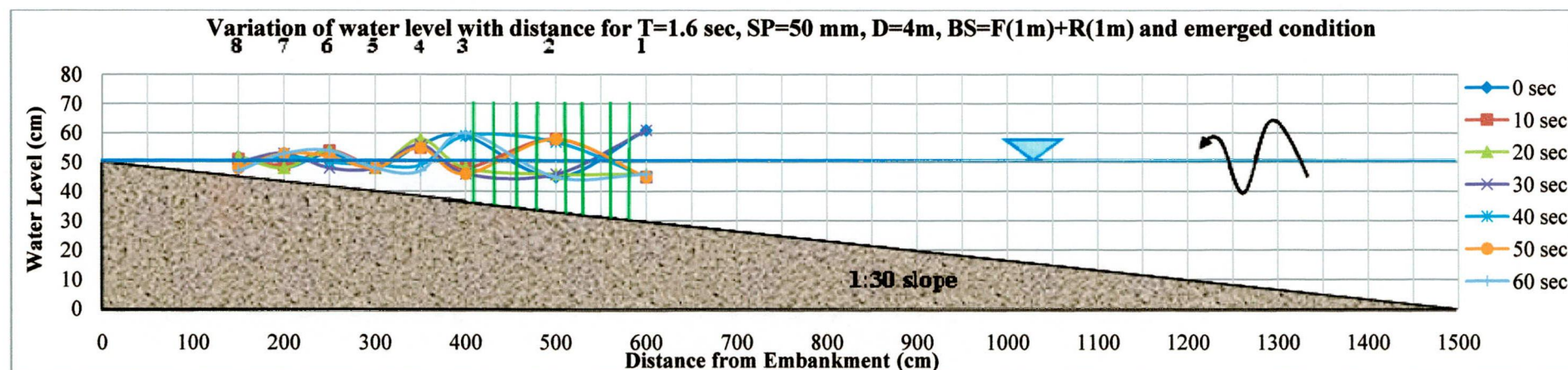


Figure 16: Variation of water level with distance for $T=1.6$ sec, bio-shield spacing-50 mm C/C, width of bio-shield-2m, distance from embankment-4m and emerged

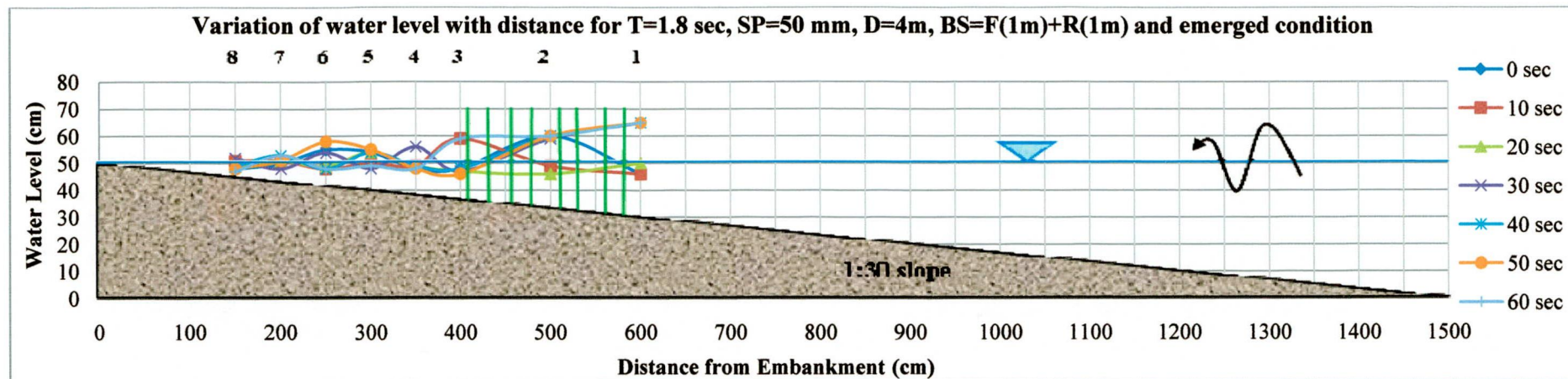


Figure 17: Variation of water level with distance for $T=1.8$ sec, bio-shield spacing-50 mm C/C, width of bio-shield-2m, distance from embankment-4m and emerged

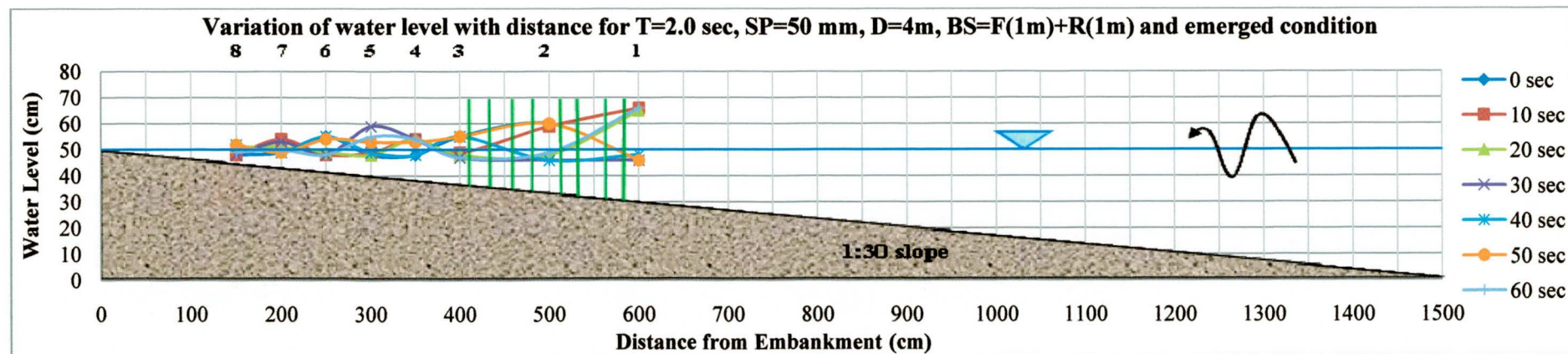


Figure 18: Variation of water level with distance for $T=2.0$ sec, bio-shield spacing-50 mm C/C, width of bio-shield-2m, distance from embankment-4m and emerged

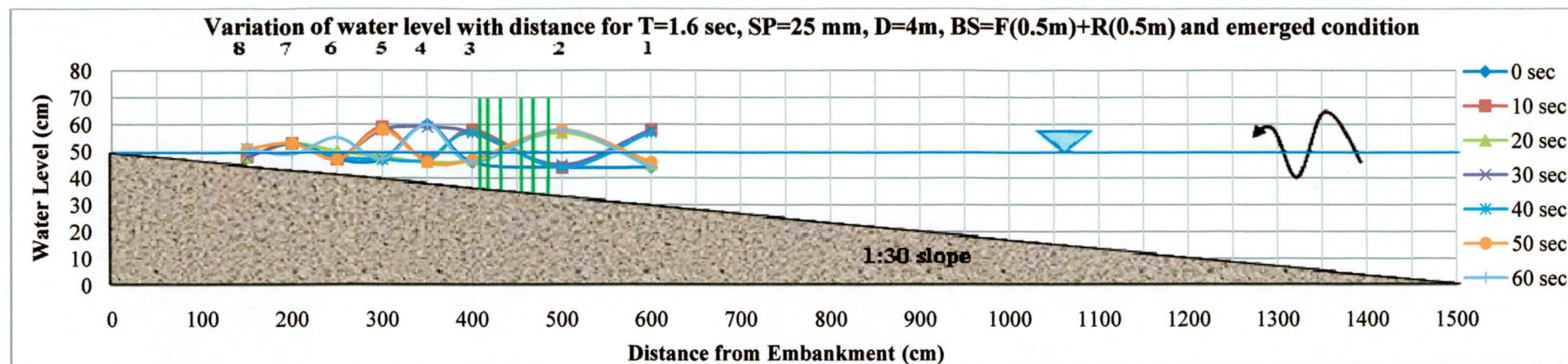


Figure 19: Variation of water level with distance for $T=1.6$ sec, bio-shield spacing-25 mm C/C, width of bio-shield-1m, distance from embankment-4m and emerged

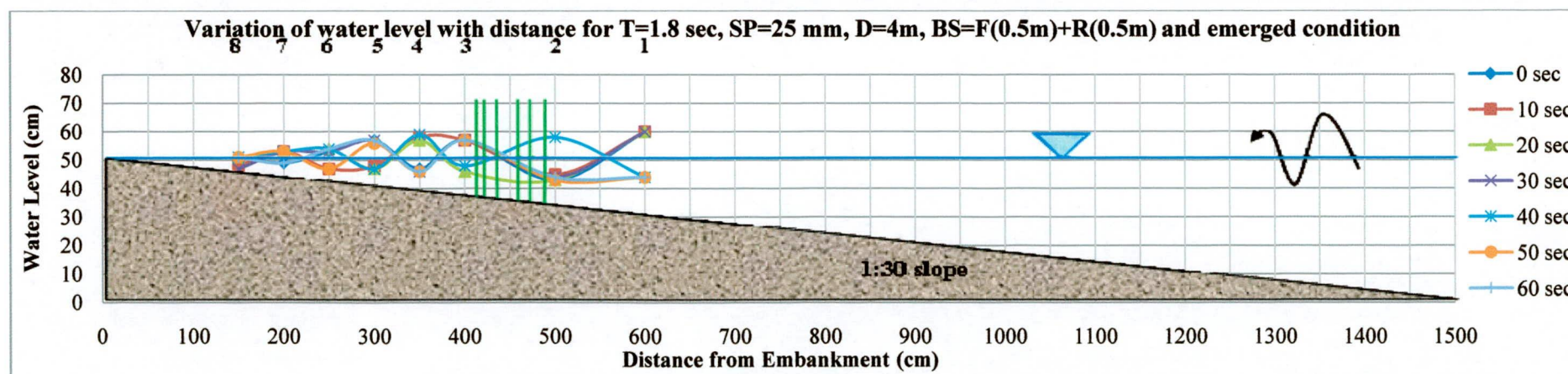


Figure 20: Variation of water level with distance for $T=1.8$ sec, bio-shield spacing-25 mm C/C, width of bio-shield-1m, distance from embankment-4m and emerged

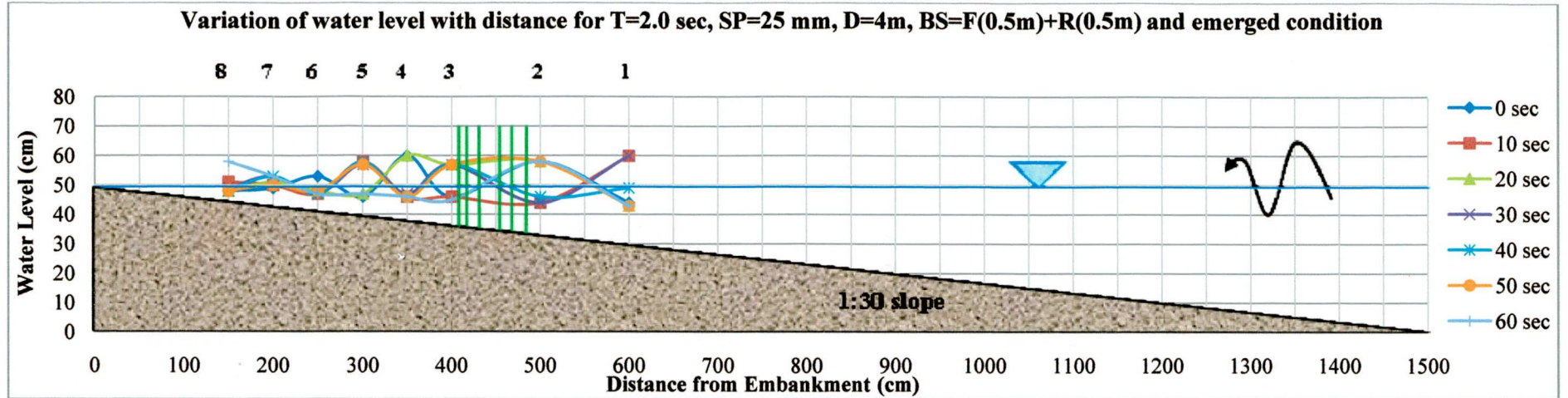


Figure 21: Variation of water level with distance for $T=2.0$ sec, bio-shield spacing-25 mm C/C, width of bio-shield-1m, distance from embankment-4m and emerged

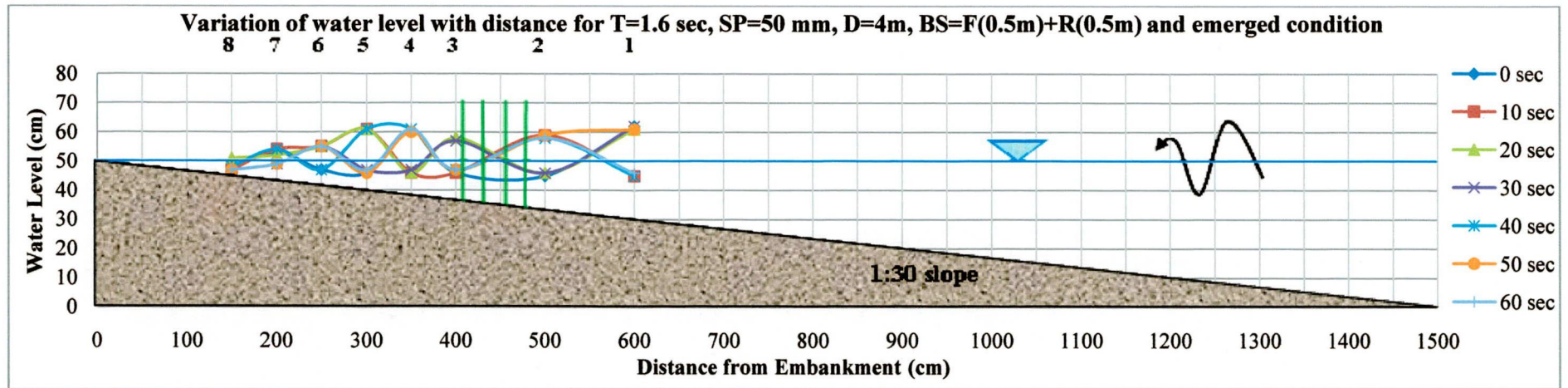


Figure 22: Variation of water level with distance for $T=1.6$ sec, bio-shield spacing-50 mm C/C, width of bio-shield-1m, distance from embankment-4m and emerged

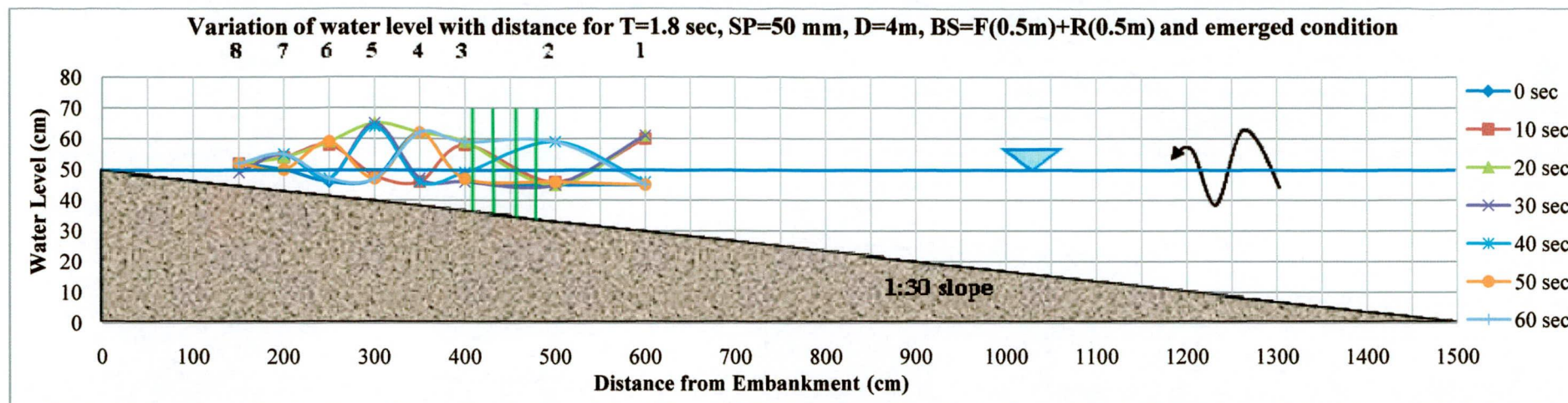


Figure 23: Variation of water level with distance for $T=1.8$ sec, bio-shield spacing-50 mm C/C, width of bio-shield-1m, distance from embankment-4m and emerged

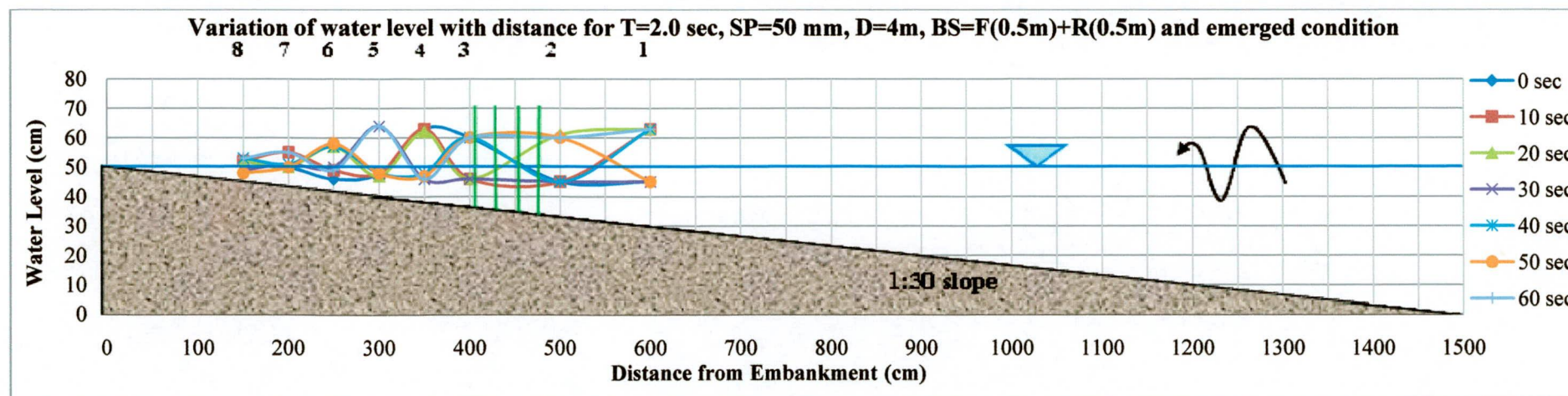


Figure 24: Variation of water level with distance for $T=2.0$ sec, bio-shield spacing-50 mm C/C, width of bio-shield-1m, distance from embankment-4m and emerged

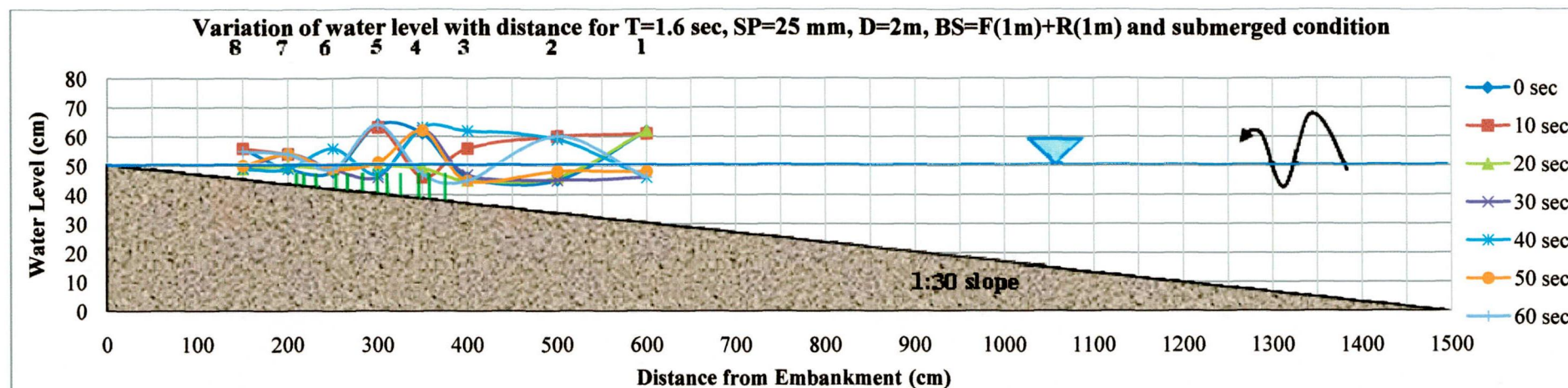


Figure 25: Variation of water level with distance for $T=1.6$ sec, bio-shield spacing-25 mm C/C, width of bio-shield-2m, distance from embankment-2m and submerged

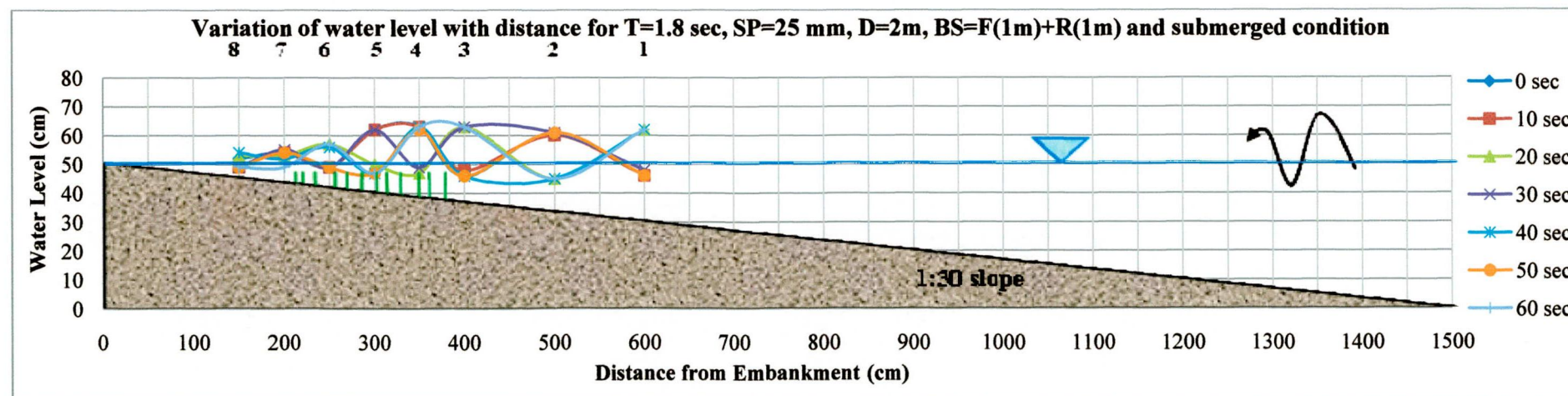
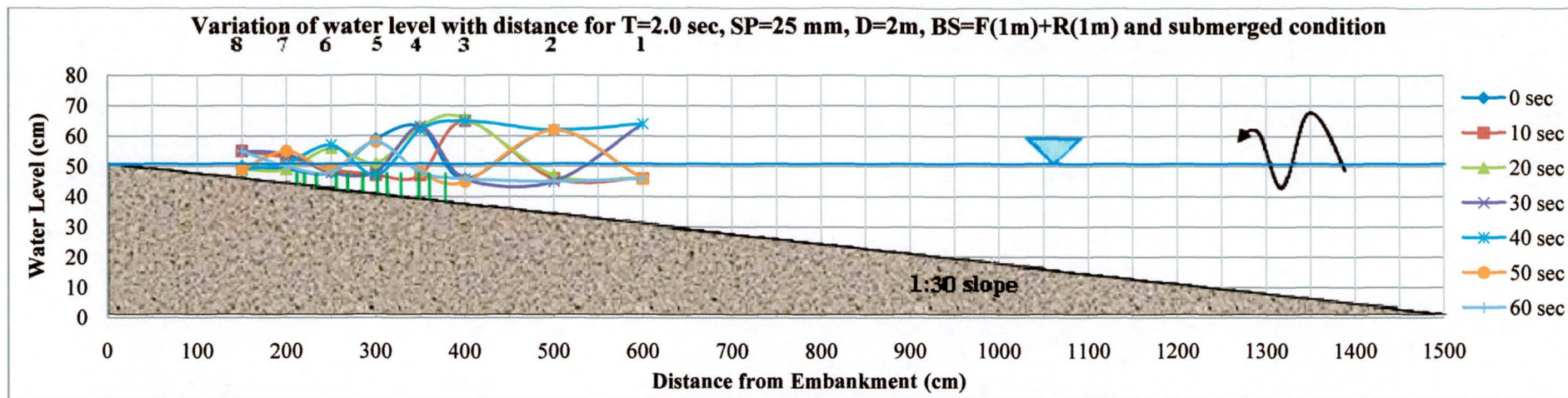


Figure 26: Variation of water level with distance for $T=1.8$ sec, bio-shield spacing-25 mm C/C, width of bio-shield-2m, distance from embankment-2m and submerged



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Figure 27: Variation of water level with distance for $T=2.0$ sec, bio-shield spacing-25 mm C/C, width of bio-shield-2m, distance from embankment-2m and submerged

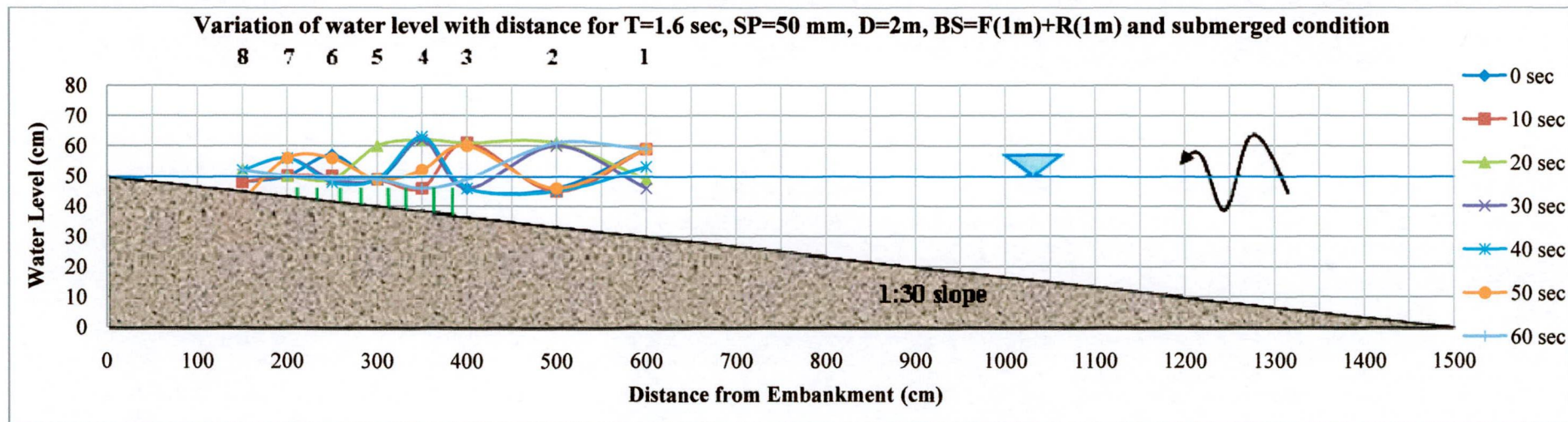


Figure 28: Variation of water level with distance for $T=1.6$ sec, bio-shield spacing-50 mm C/C, width of bio-shield-2m, distance from embankment-2m and submerged

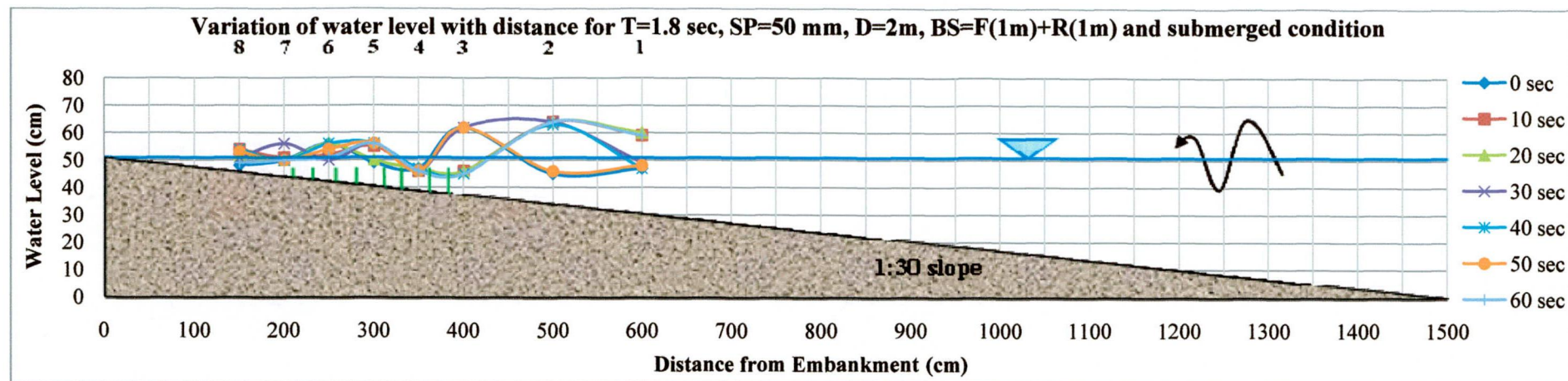


Figure 29: Variation of water level with distance for $T=1.8$ sec, bio-shield spacing-50 mm C/C, width of bio-shield-2m, distance from embankment-2m and submerged

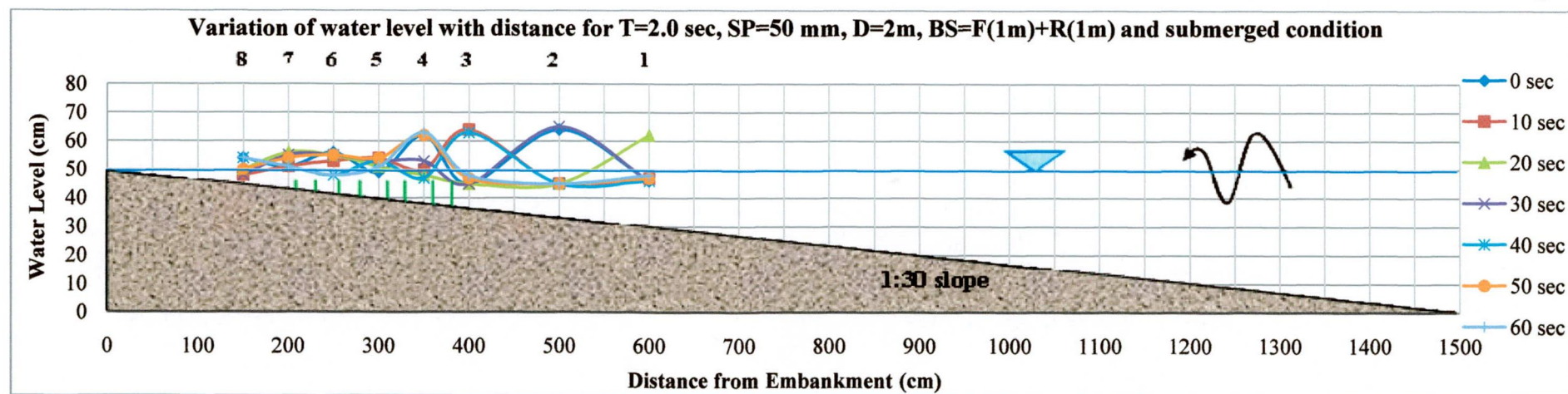


Figure 30: Variation of water level with distance for $T=2.0$ sec, bio-shield spacing-50 mm C/C, width of bio-shield-2m, distance from embankment-2m and submerged

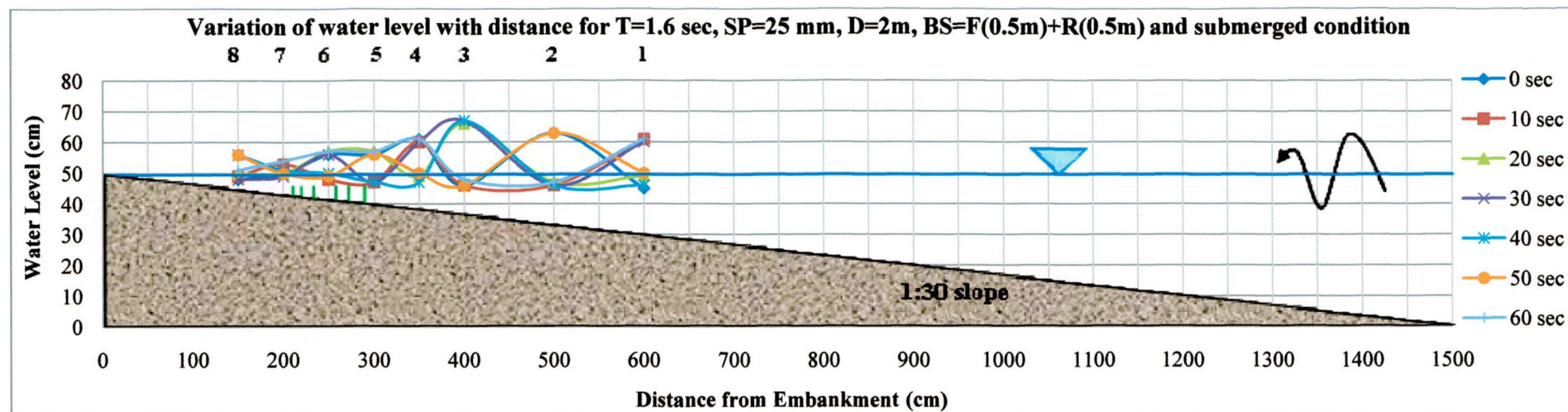


Figure 31: Variation of water level with distance for $T=1.6$ sec, bio-shield spacing-25 mm C/C, width of bio-shield-1m, distance from embankment-2m and submerged

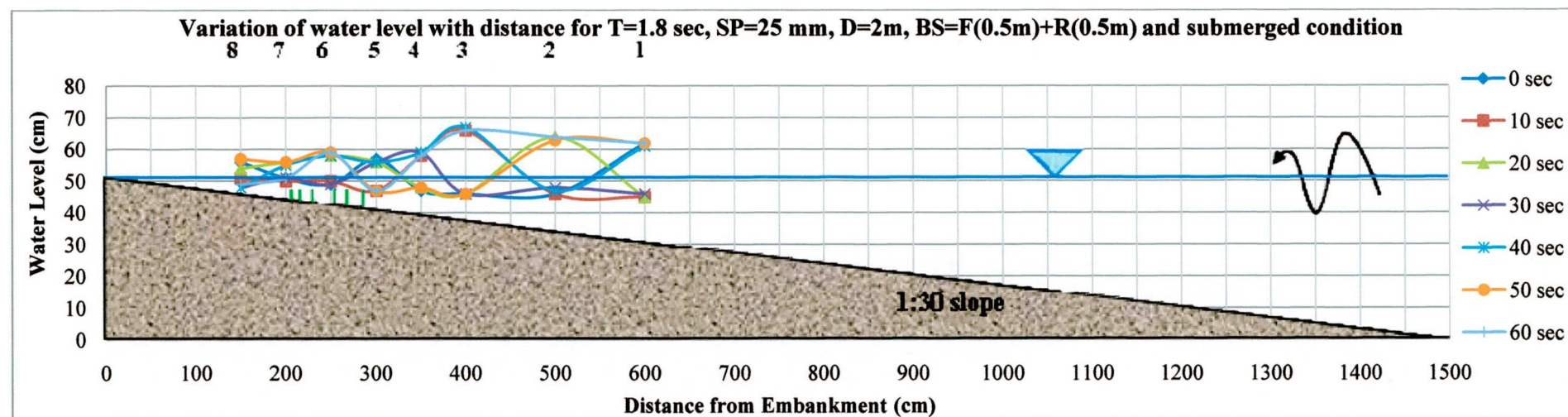


Figure 32: Variation of water level with distance for $T=1.8$ sec, bio-shield spacing-25 mm C/C, width of bio-shield-1m, distance from embankment-2m and submerged

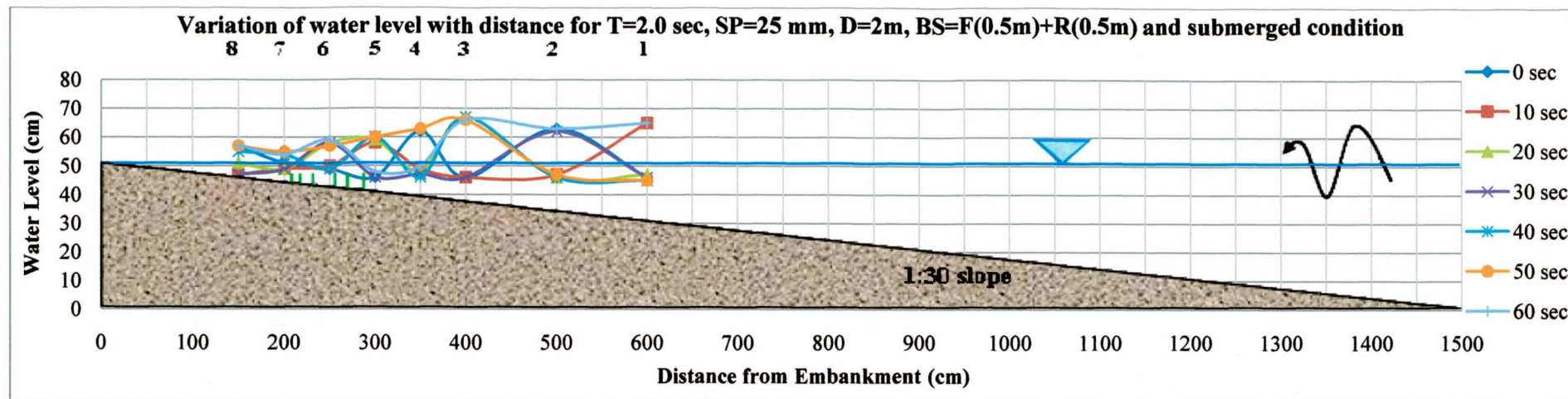


Figure 33: Variation of water level with distance for $T=2.0$ sec, bio-shield spacing-25 mm C/C, width of bio-shield-1m, distance from embankment-2m and submerged

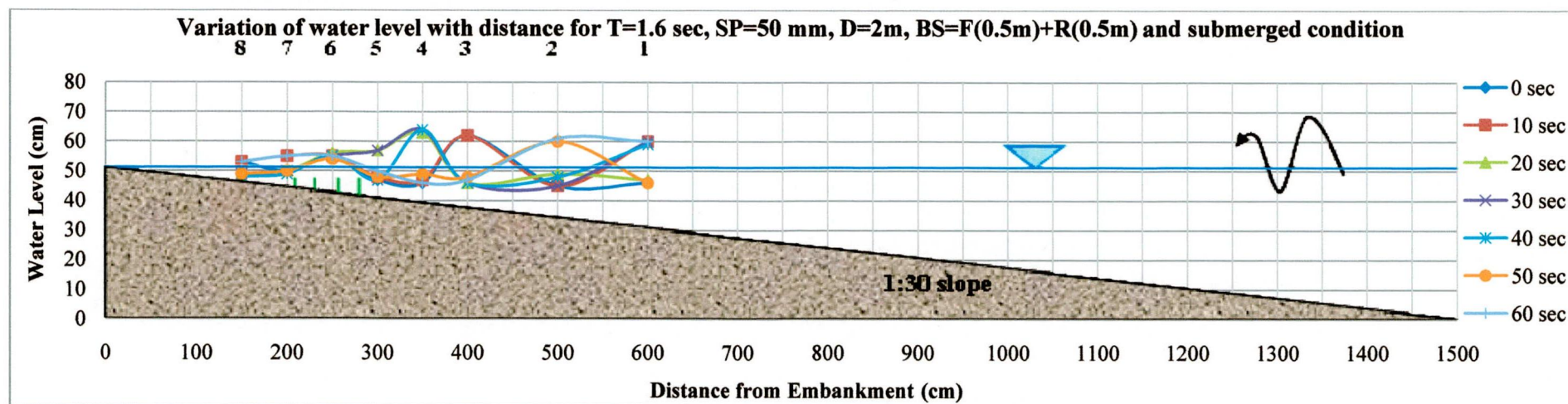


Figure 34: Variation of water level with distance for $T=1.6$ sec, bio-shield spacing-50 mm C/C, width of bio-shield-1m, distance from embankment-2m and submerged

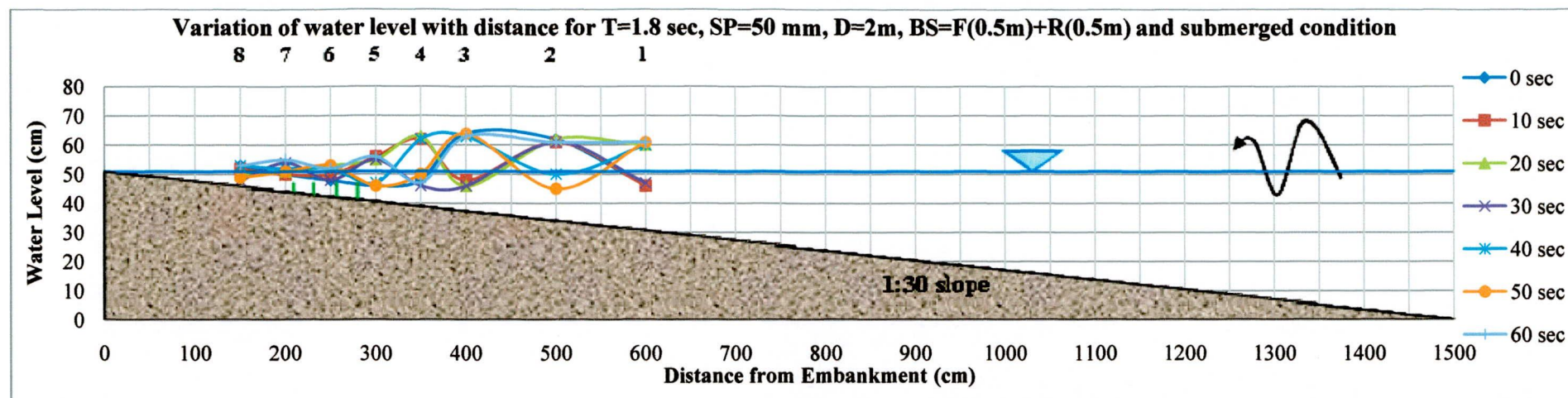


Figure 35: Variation of water level with distance for $T=1.8$ sec, bio-shield spacing-50 mm C/C, width of bio-shield-1m, distance from embankment-2m and submerged

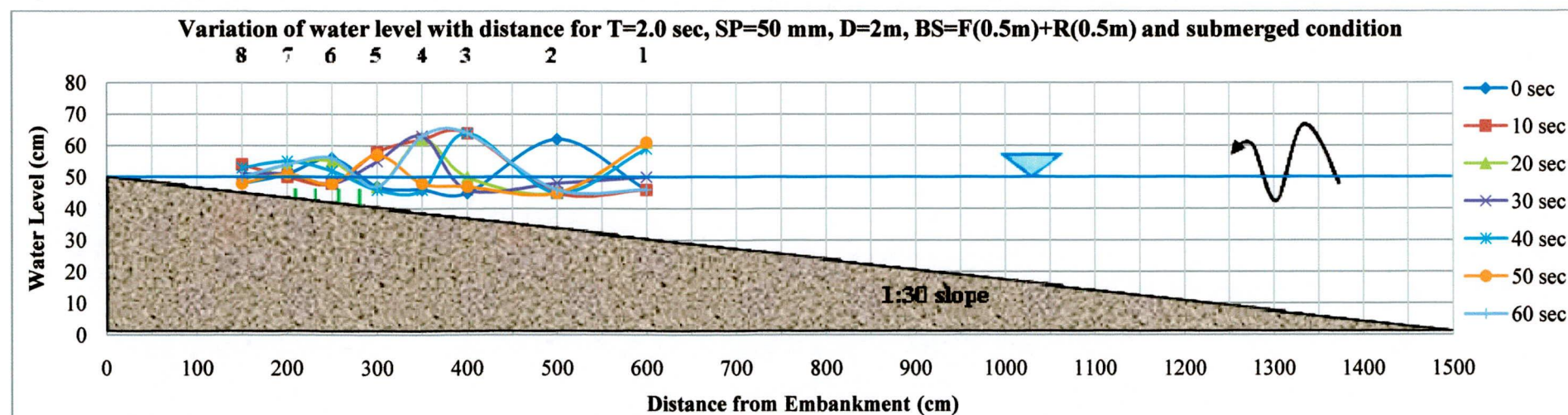


Figure 36: Variation of water level with distance for $T=2.0$ sec, bio-shield spacing-50 mm C/C, width of bio-shield-1m, distance from embankment-2m and submerged

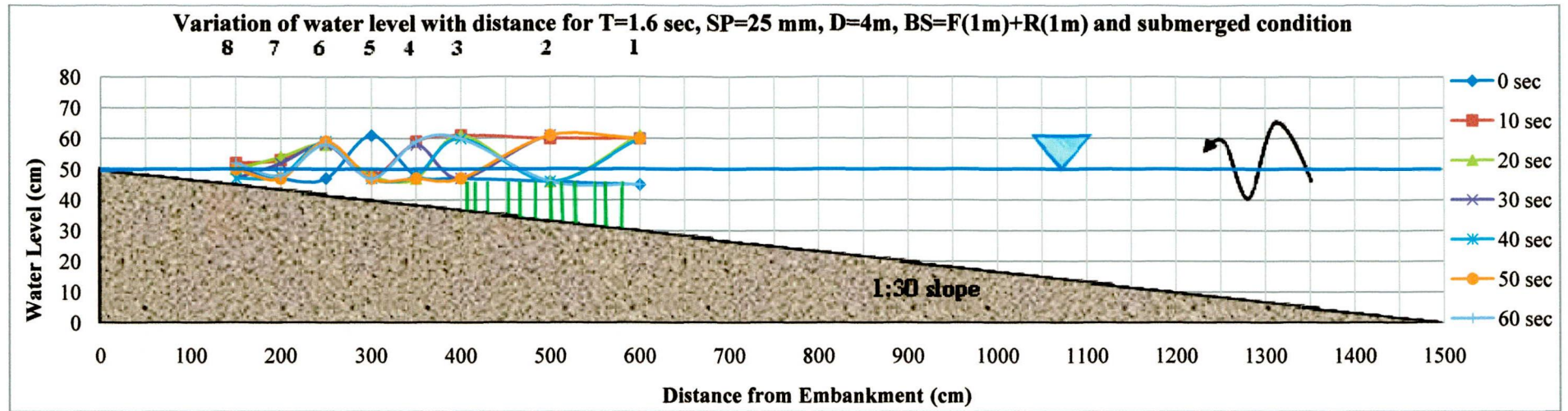


Figure 37: Variation of water level with distance for $T=1.6$ sec, bio-shield spacing-25 mm C/C, width of bio-shield-2m, distance from embankment-4m and submerged

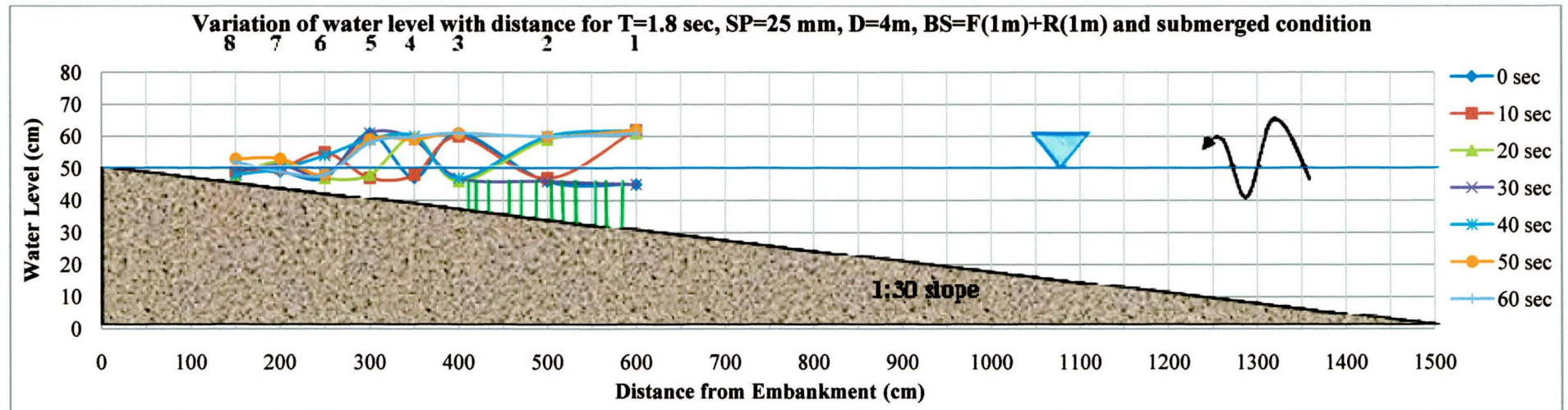


Figure 38: Variation of water level with distance for $T=1.8$ sec, bio-shield spacing-25 mm C/C, width of bio-shield-2m, distance from embankment-4m and submerged

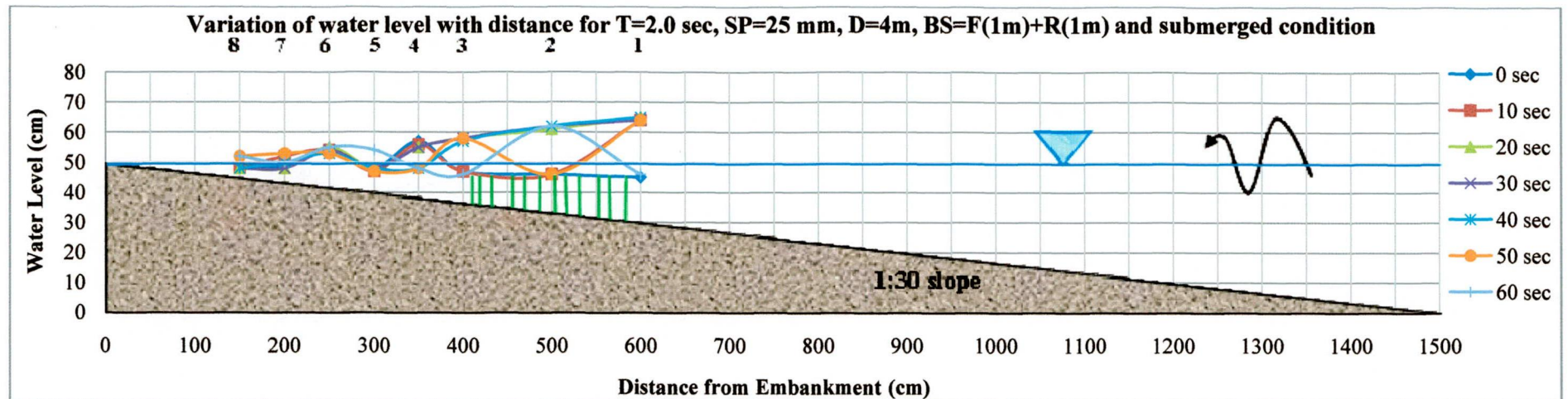


Figure 39: Variation of water level with distance for $T=2.0$ sec, bio-shield spacing-25 mm C/C, width of bio-shield-2m, distance from embankment-4m and submerged

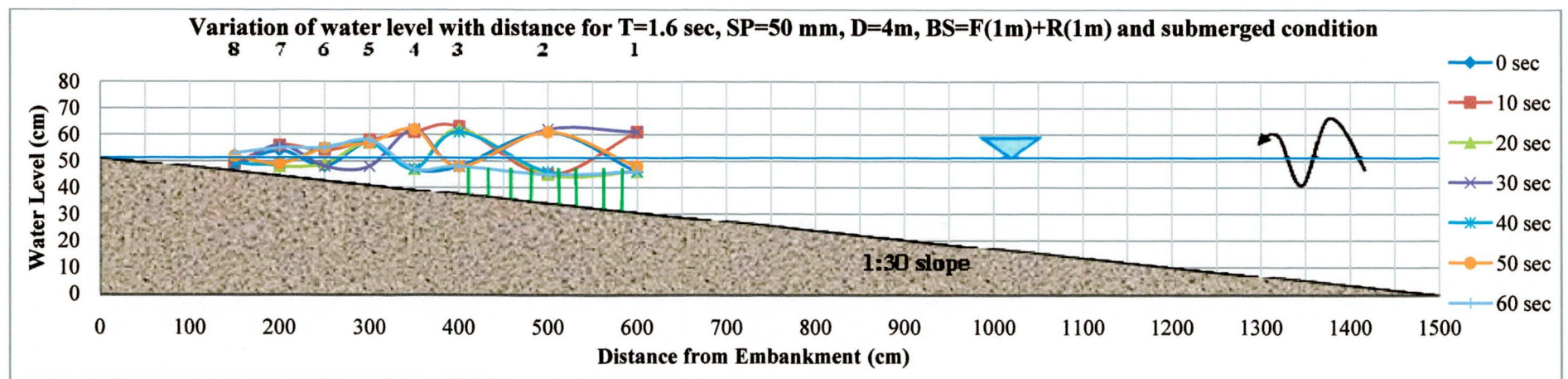


Figure 40: Variation of water level with distance for $T=1.6$ sec, bio-shield spacing-50 mm C/C, width of bio-shield-2m, distance from embankment-4m and submerged

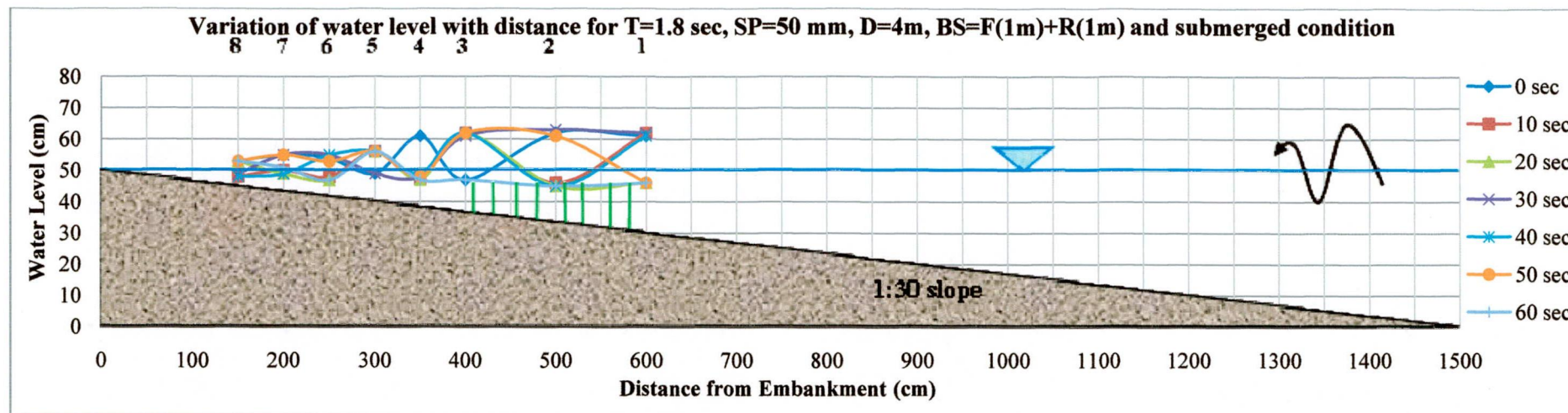


Figure 41: Variation of water level with distance for $T=1.8$ sec, bio-shield spacing-50 mm C/C, width of bio-shield-2m, distance from embankment-4m and submerged

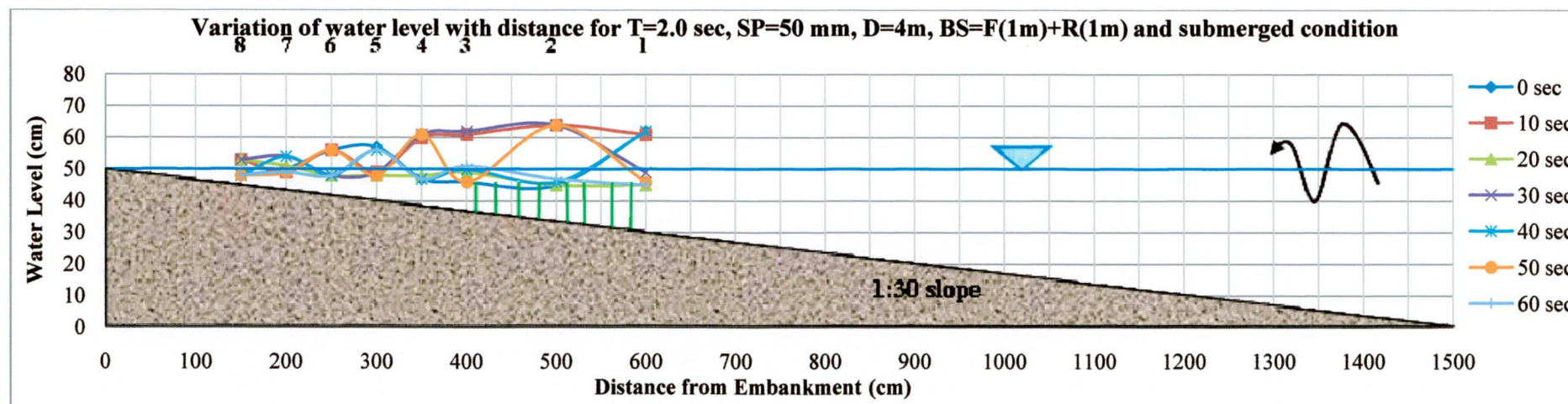


Figure 42: Variation of water level with distance for $T=2.0$ sec, bio-shield spacing-50 mm C/C, width of bio-shield-2m, distance from embankment-4m and submerged

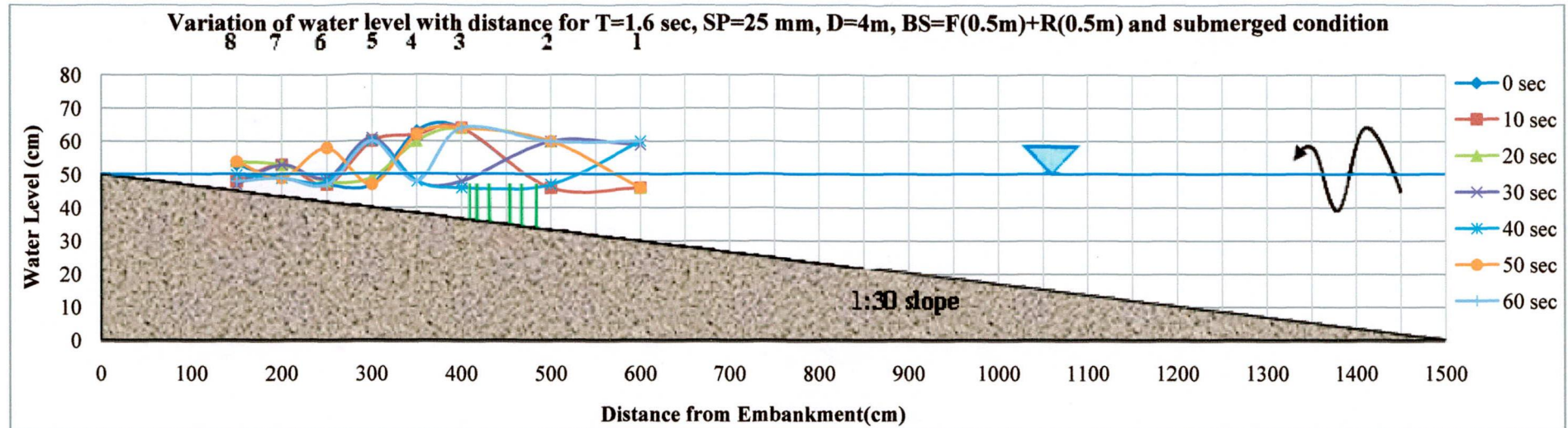


Figure 43: Variation of water level with distance for $T=1.6$ sec, bio-shield spacing-25 mm C/C, width of bio-shield-1m, distance from embankment-4m and submerged

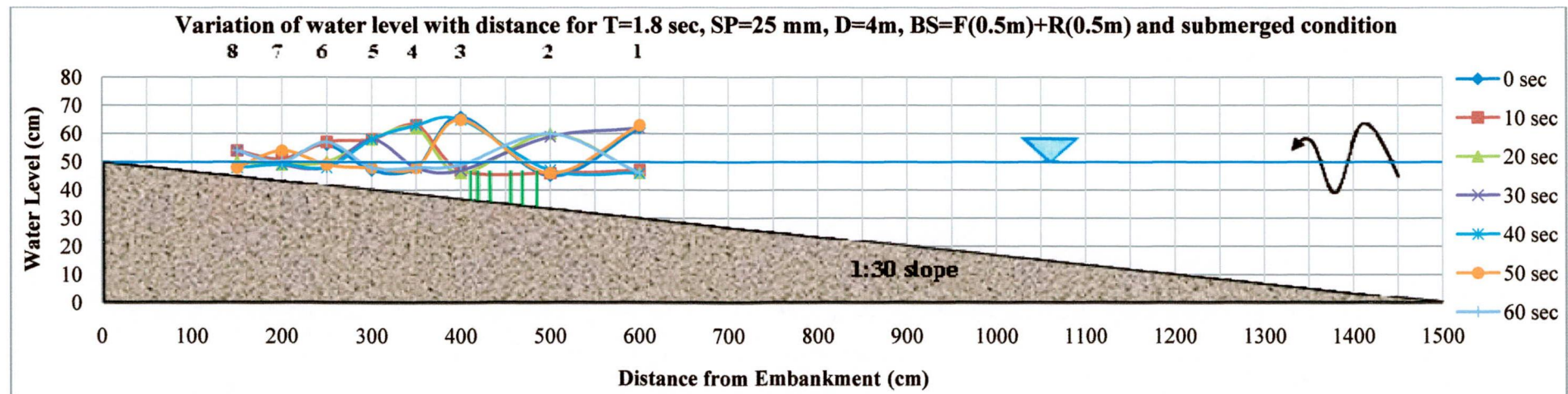


Figure 44: Variation of water level with distance for $T=1.8$ sec, bio-shield spacing-25 mm C/C, width of bio-shield-1m, distance from embankment-4m and submerged

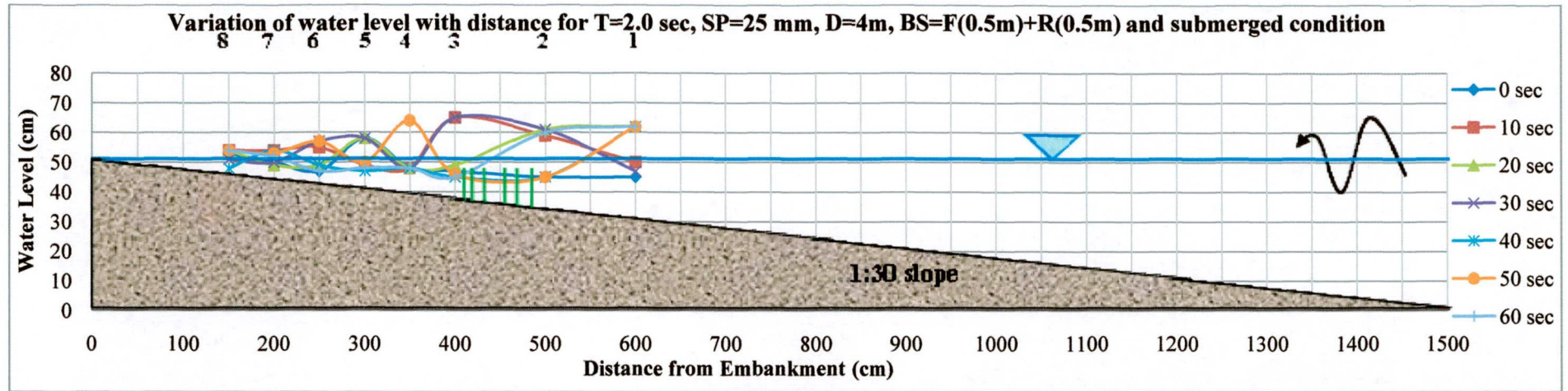


Figure 45: Variation of water level with distance for $T=2.0$ sec, bio-shield spacing-25 mm C/C, width of bio-shield-1m, distance from embankment-4m and submerged

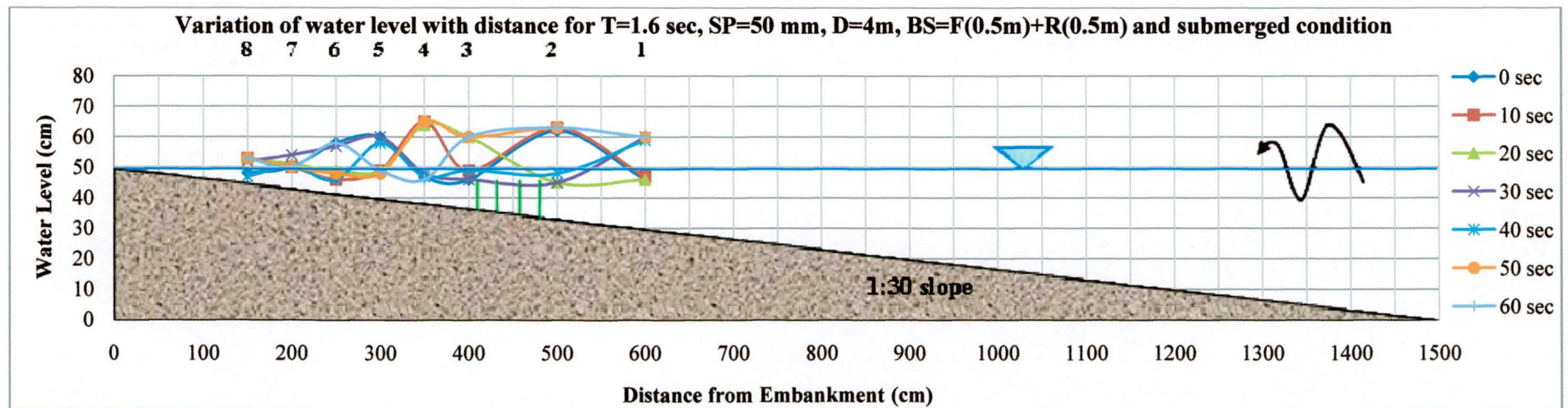


Figure 46: Variation of water level with distance for $T=1.6$ sec, bio-shield spacing-50 mm C/C, width of bio-shield-1m, distance from embankment-4m and submerged

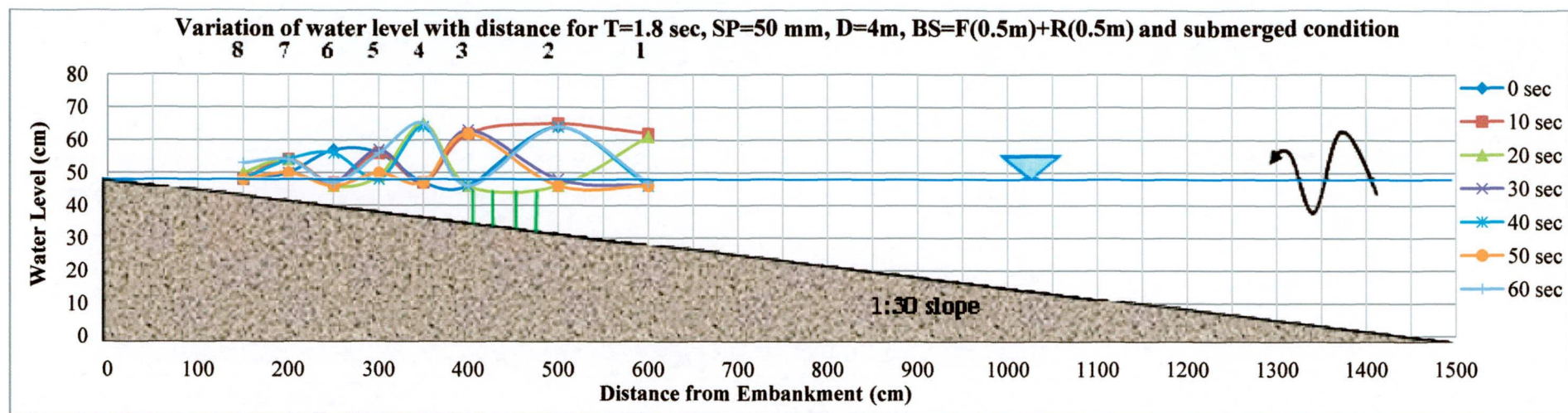


Figure 47: Variation of water level with distance for $T=1.8$ sec, bio-shield spacing-50 mm C/C, width of bio-shield-1m, distance from embankment-4m and submerged

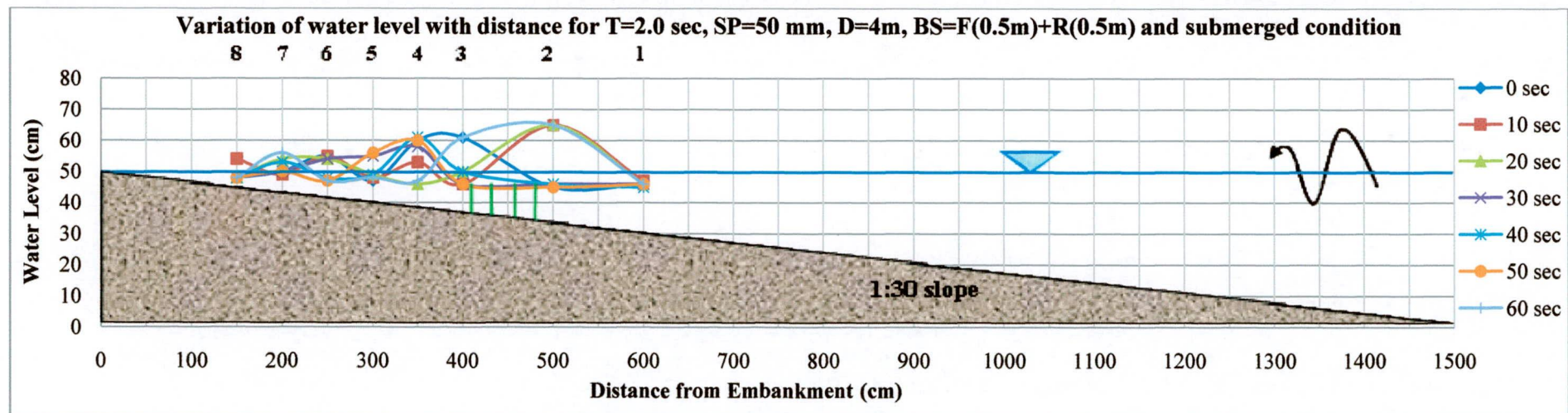


Figure 48: Variation of water level with distance for $T=2.0$ sec, bio-shield spacing-50 mm C/C, width of bio-shield-1m, distance from embankment-4m and submerged

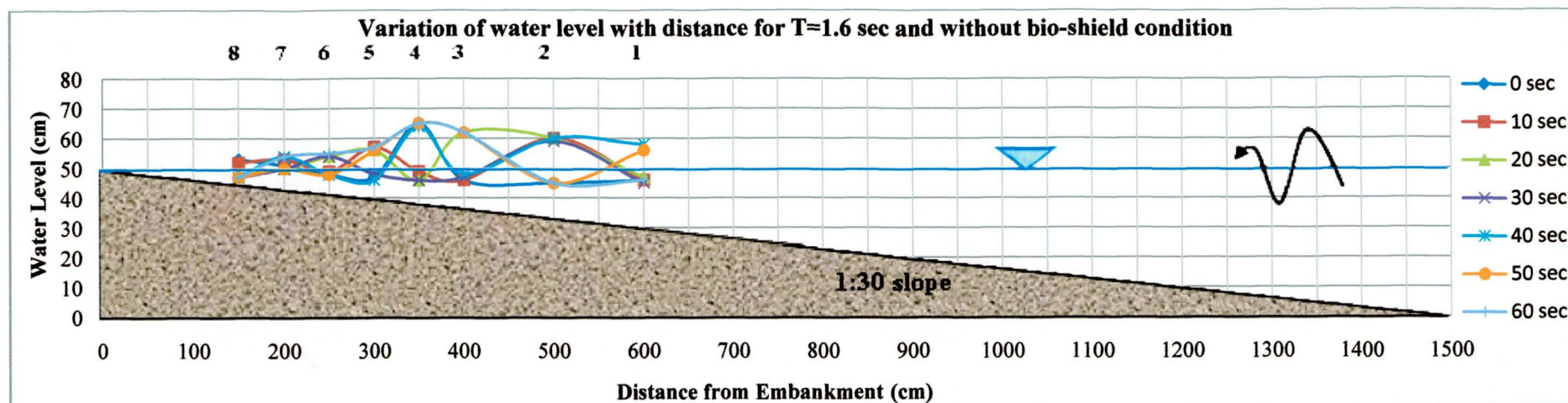


Figure 49: Variation of water level with distance for $T=1.6$ sec and without bio-shield

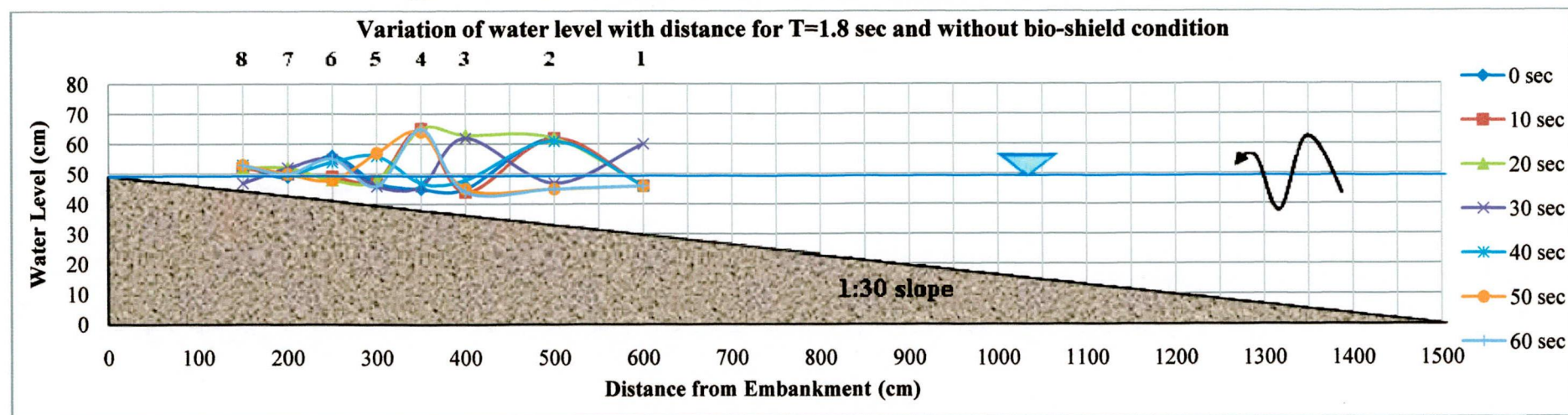


Figure 50: Variation of water level with distance for $T=1.8$ sec and without bio-shield

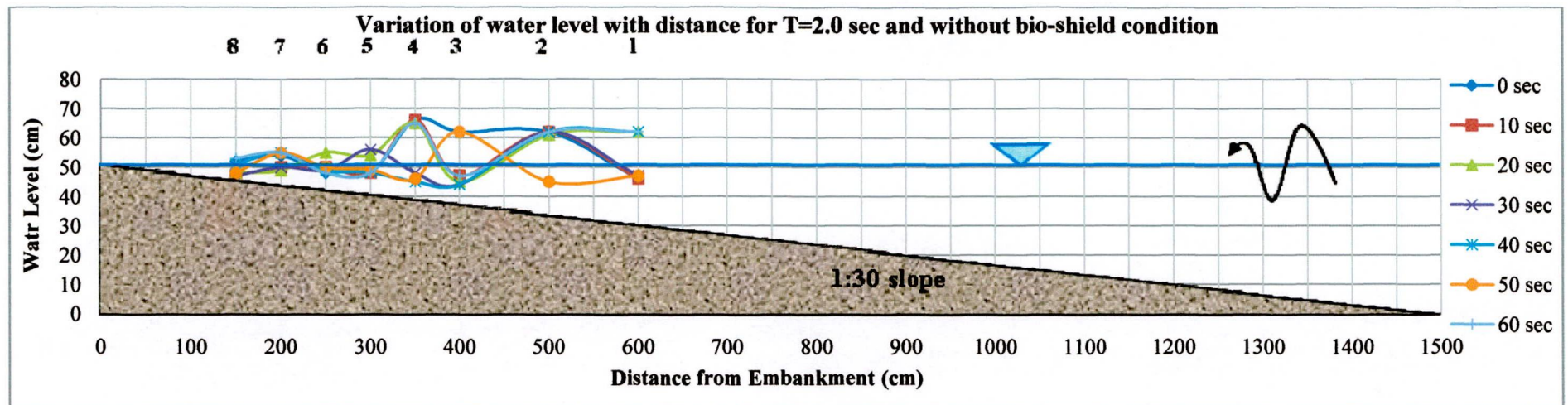
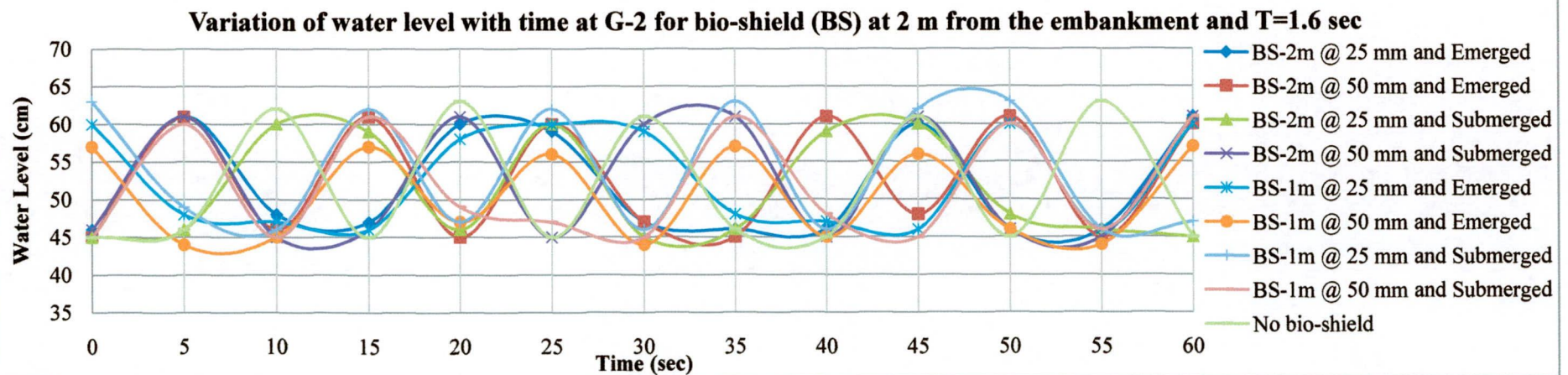
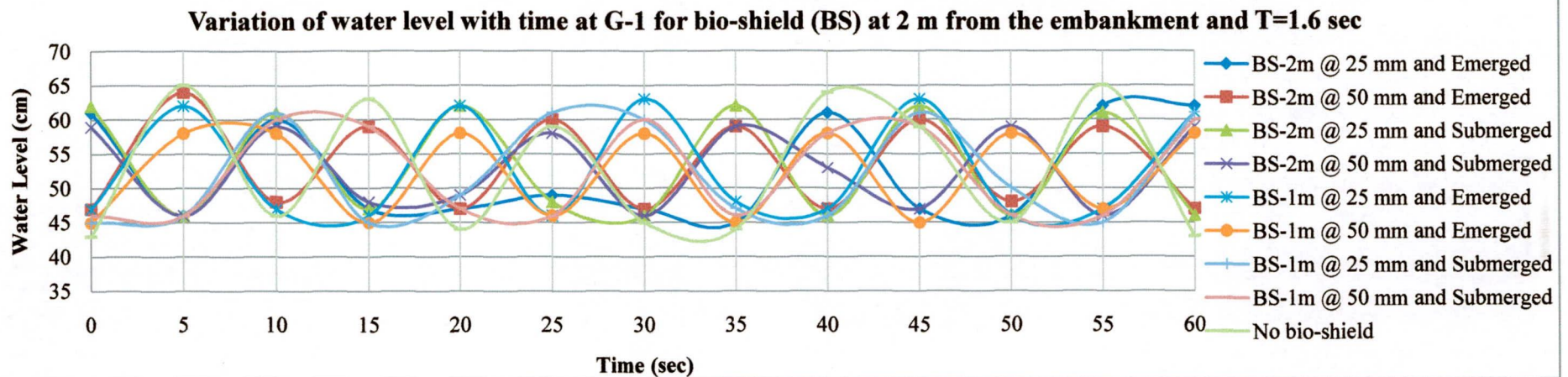
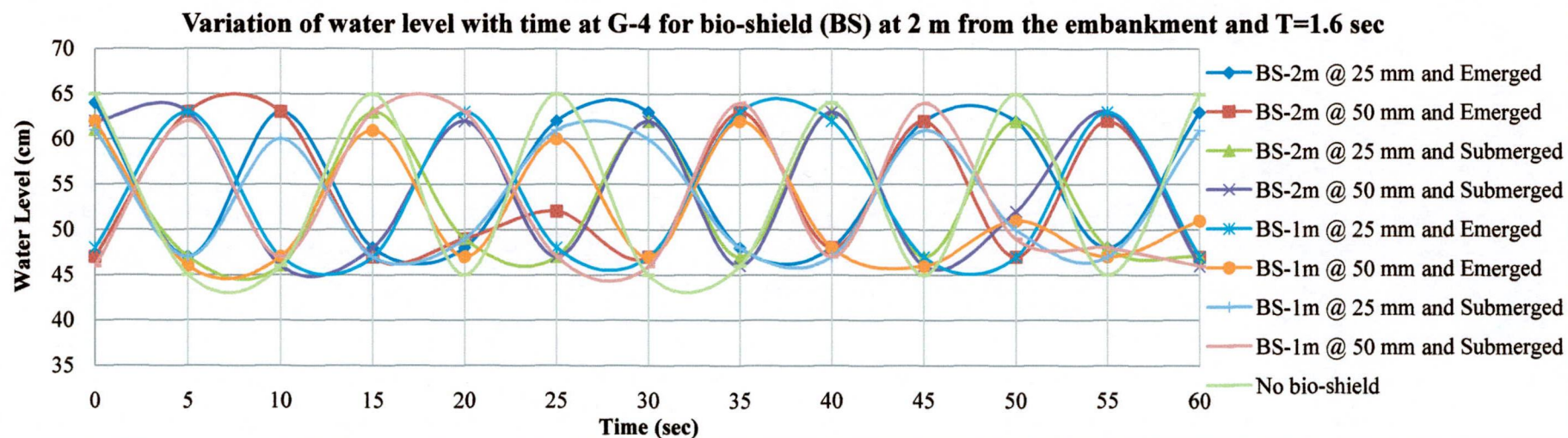


Figure 51: Variation of water level with distance for $T=2.0$ sec and without bio-shield

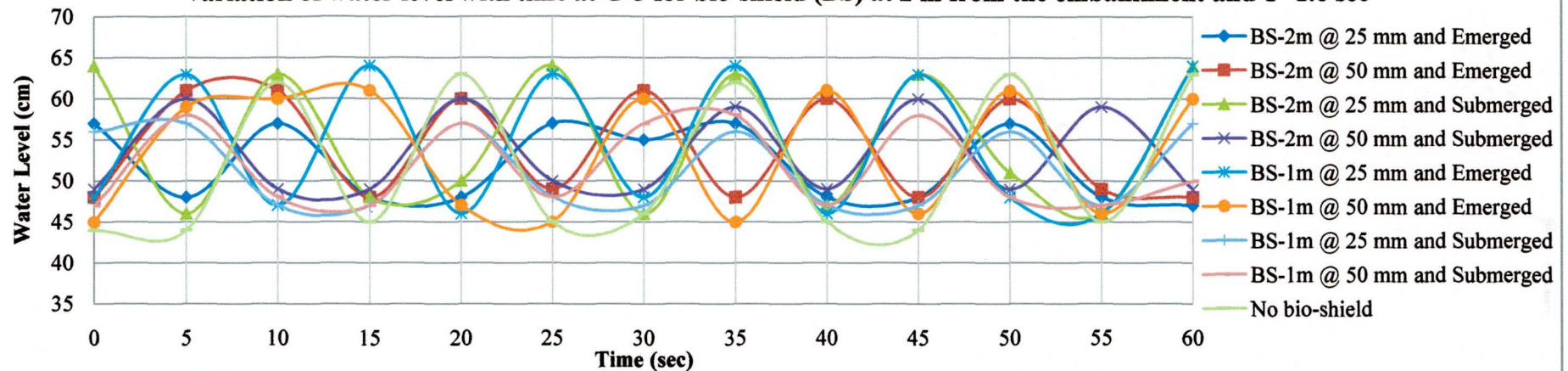
APPENDIX C

Comparison of Water Level for Various Experimental Run Conditions

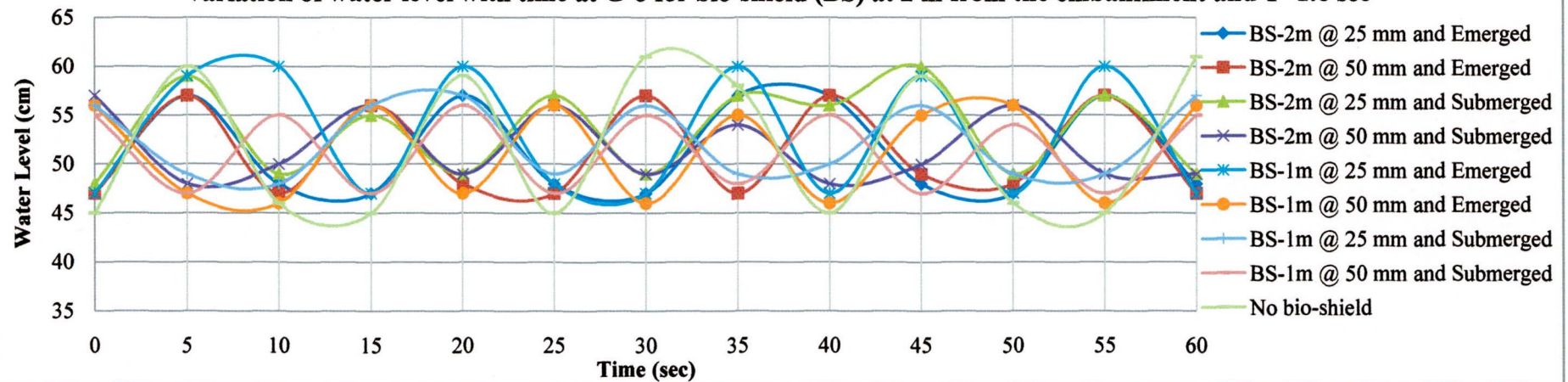




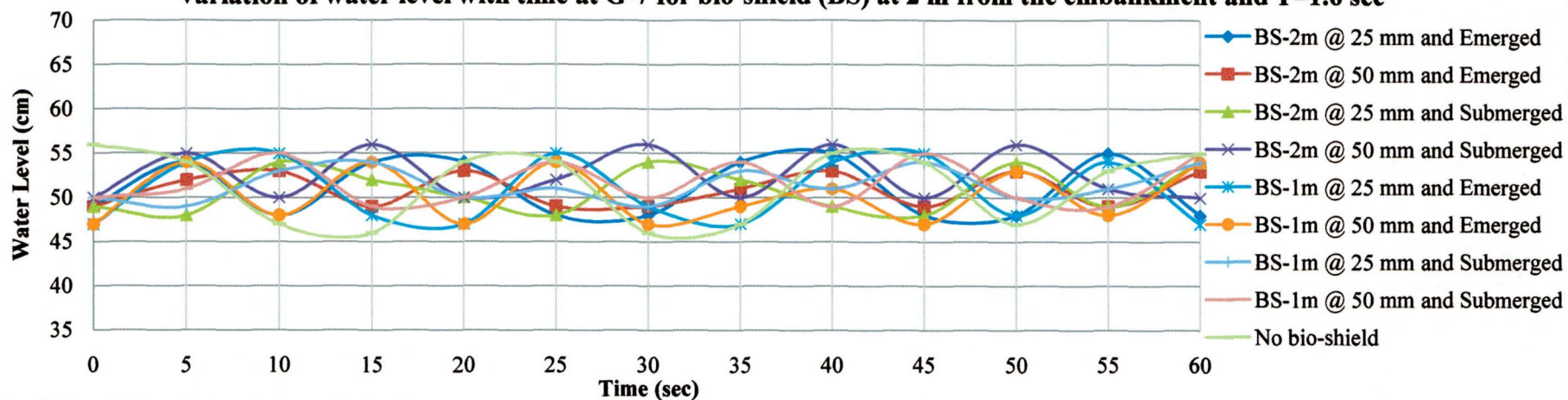
Variation of water level with time at G-5 for bio-shield (BS) at 2 m from the embankment and $T=1.6$ sec



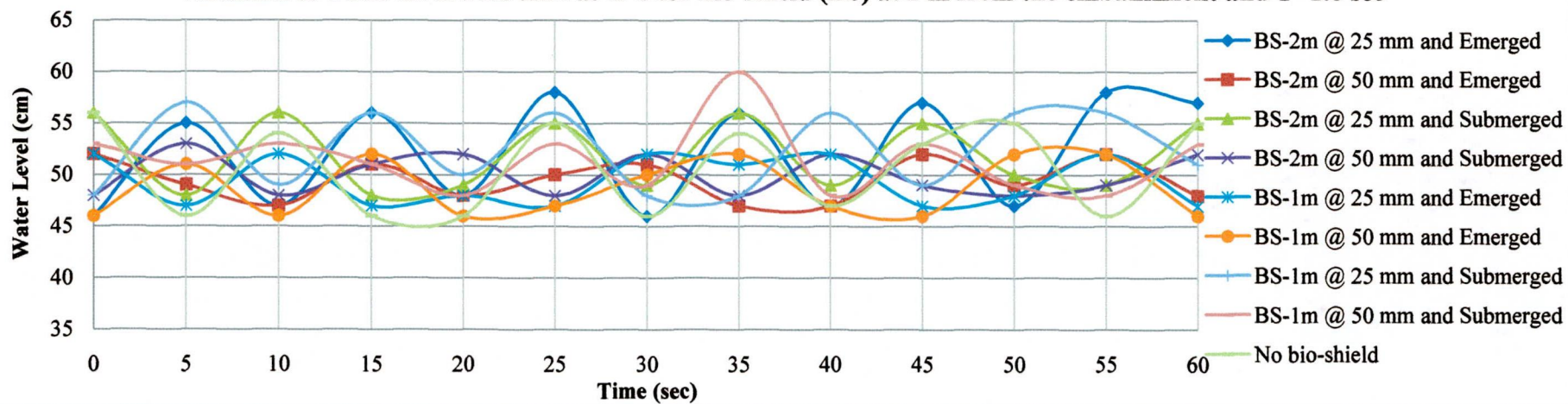
Variation of water level with time at G-6 for bio-shield (BS) at 2 m from the embankment and $T=1.6$ sec



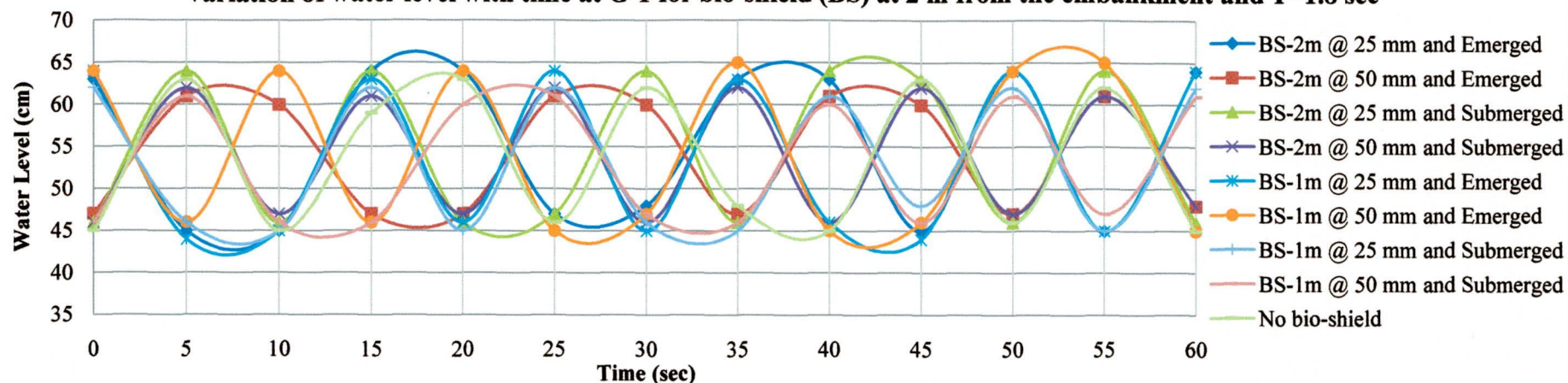
Variation of water level with time at G-7 for bio-shield (BS) at 2 m from the embankment and $T=1.6$ sec



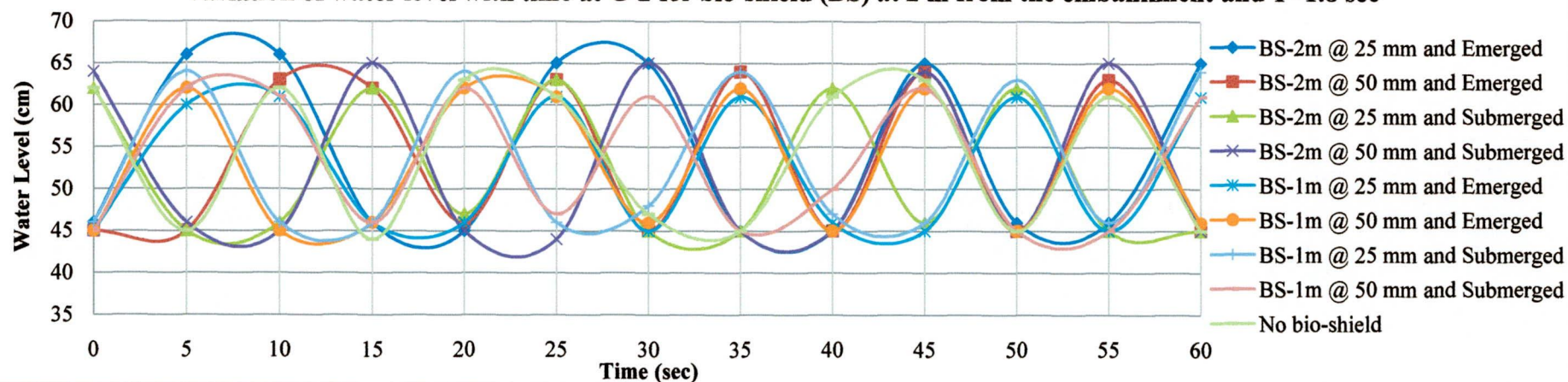
Variation of water level with time at G-8 for bio-shield (BS) at 2 m from the embankment and $T=1.6$ sec

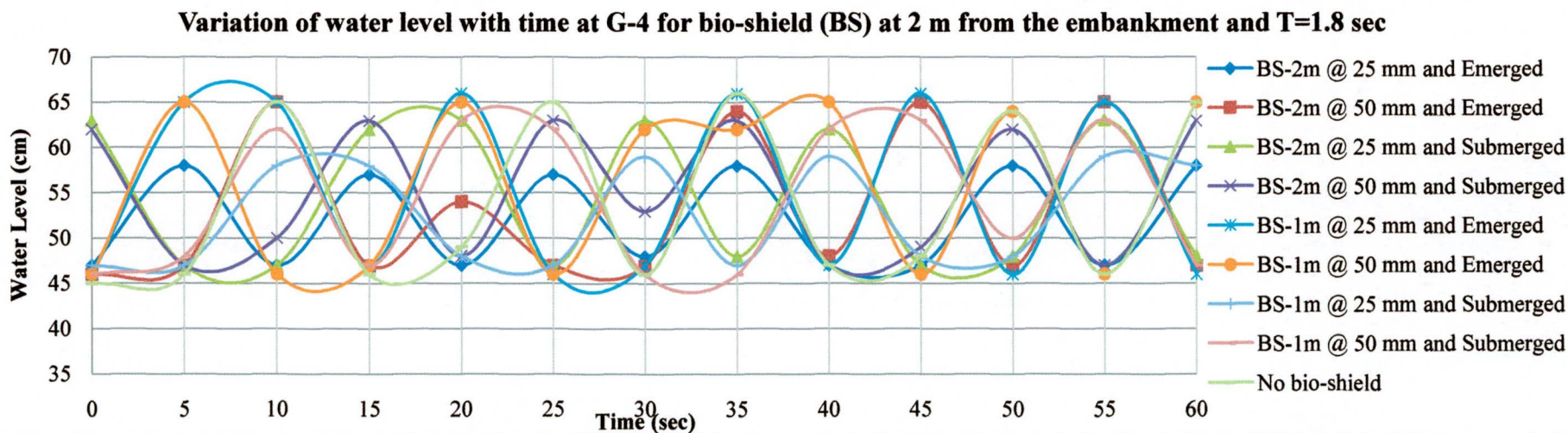


Variation of water level with time at G-1 for bio-shield (BS) at 2 m from the embankment and $T=1.8$ sec

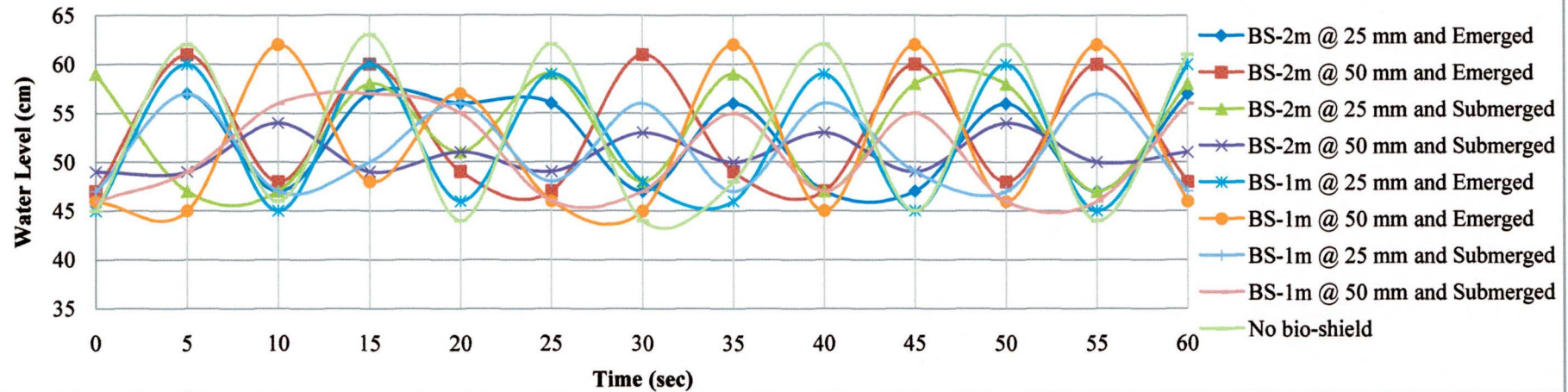


Variation of water level with time at G-2 for bio-shield (BS) at 2 m from the embankment and $T=1.8$ sec

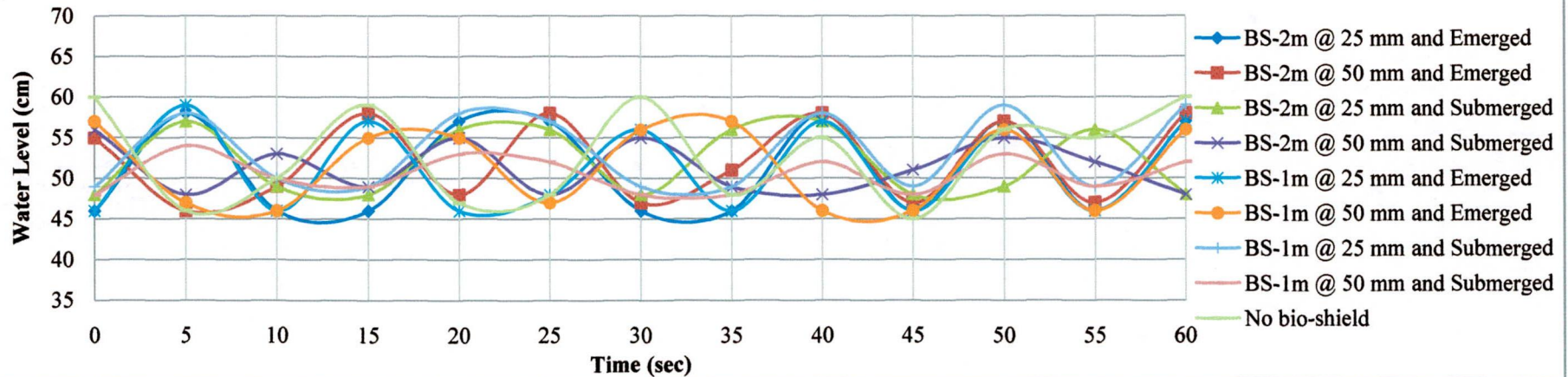




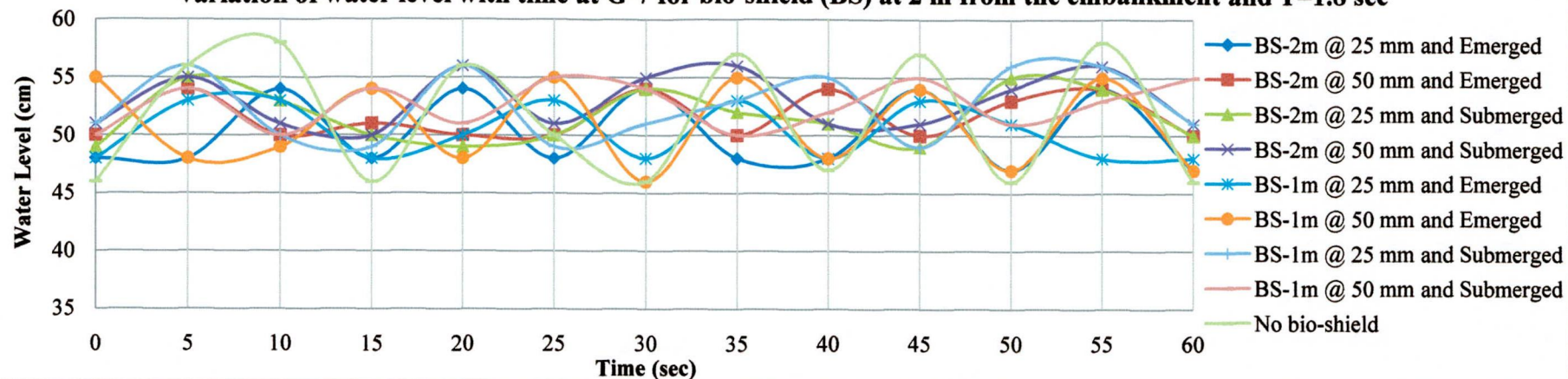
Variation of water level with time at G-5 for bio-shield (BS) at 2 m from the embankment and $T=1.8$ sec



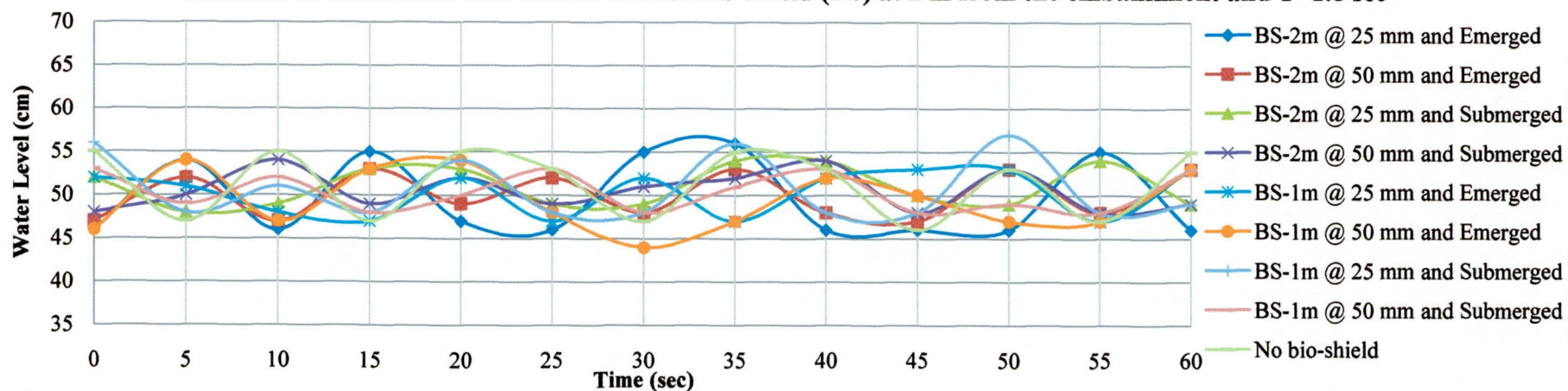
Variation of water level with time at G-6 for bio-shield (BS) at 2 m from the embankment and $T=1.8$ sec



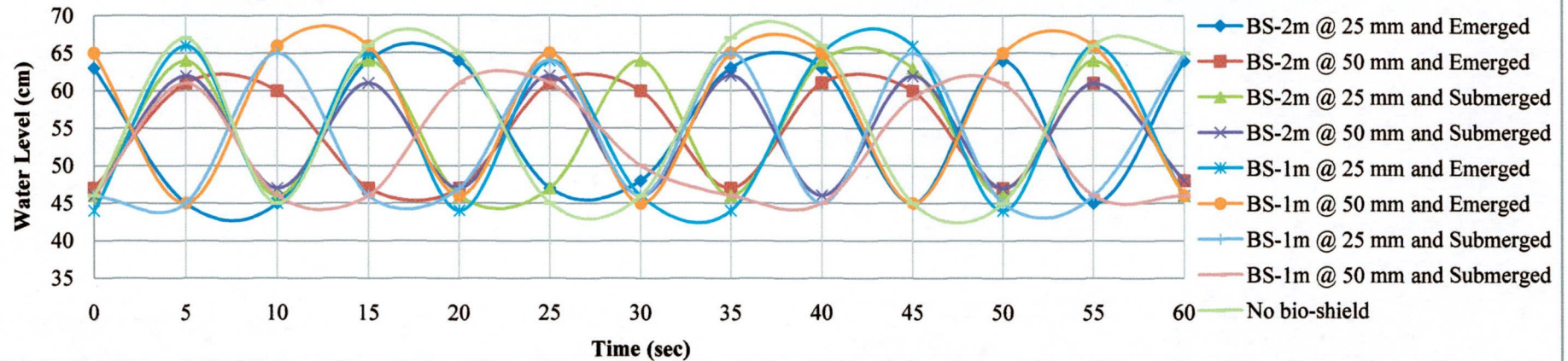
Variation of water level with time at G-7 for bio-shield (BS) at 2 m from the embankment and $T=1.8$ sec



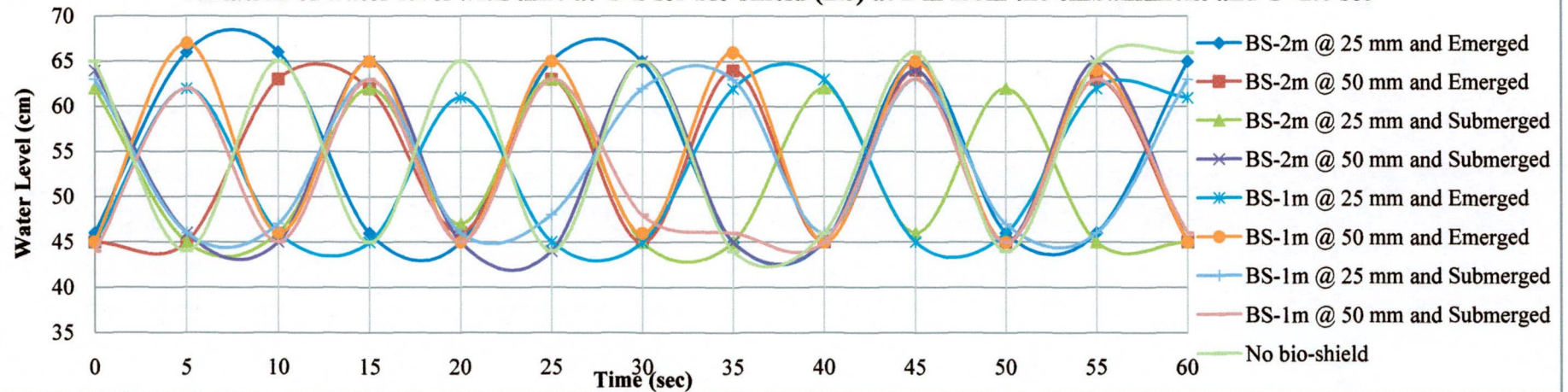
Variation of water level with time at G-8 for bio-shield (BS) at 2 m from the embankment and $T=1.8$ sec



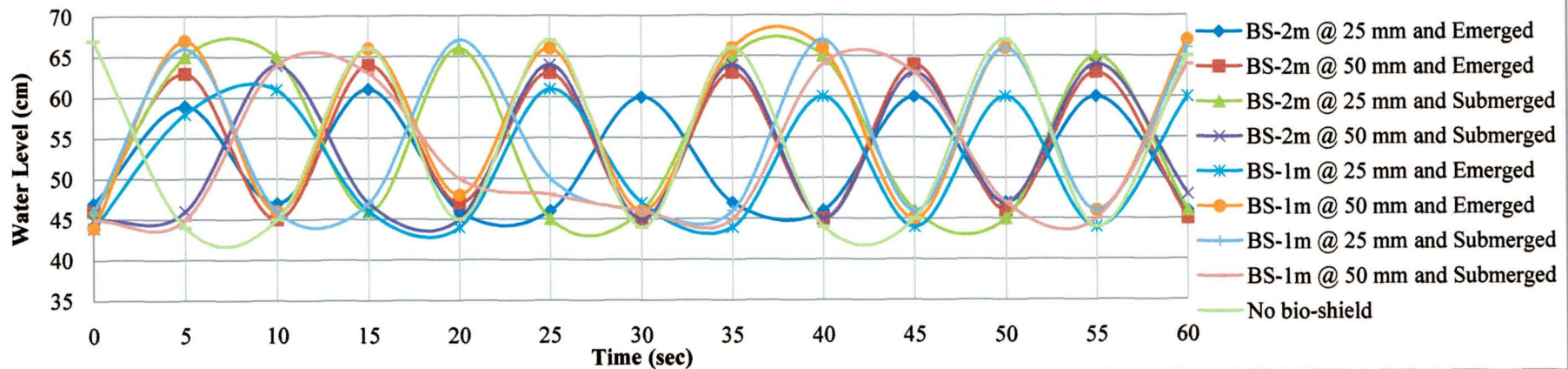
Variation of water level with time at G-1 for bio-shield (BS) at 2 m from the embankment and $T=2.0$ sec



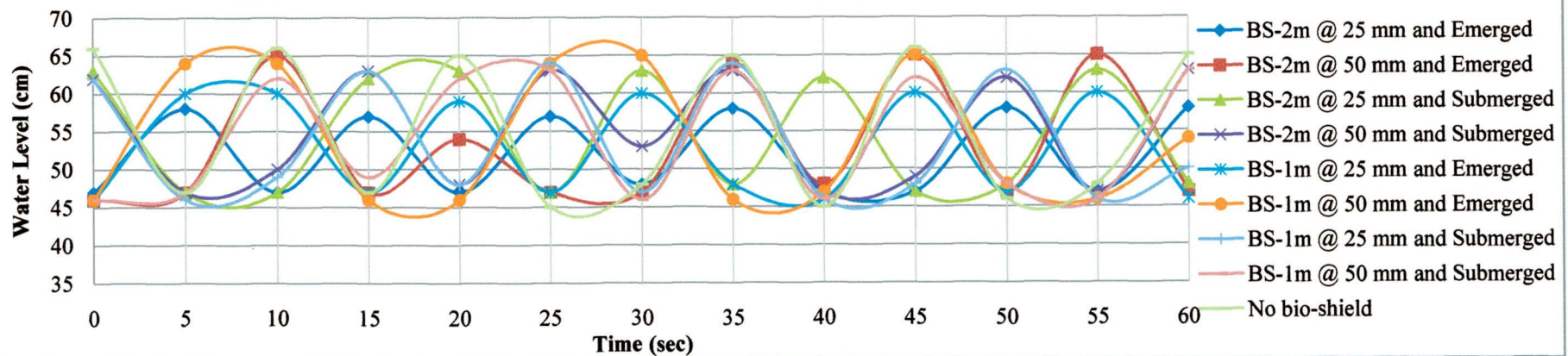
Variation of water level with time at G-2 for bio-shield (BS) at 2 m from the embankment and $T=2.0$ sec



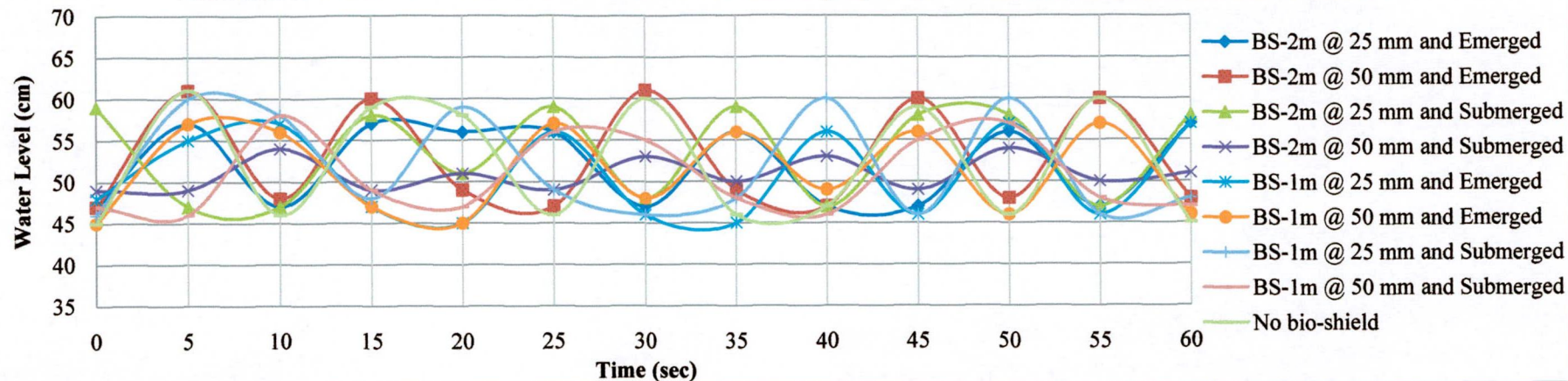
Variation of water level with time at G-3 for bio-shield (BS) at 2 m from the embankment and $T=2.0$ sec



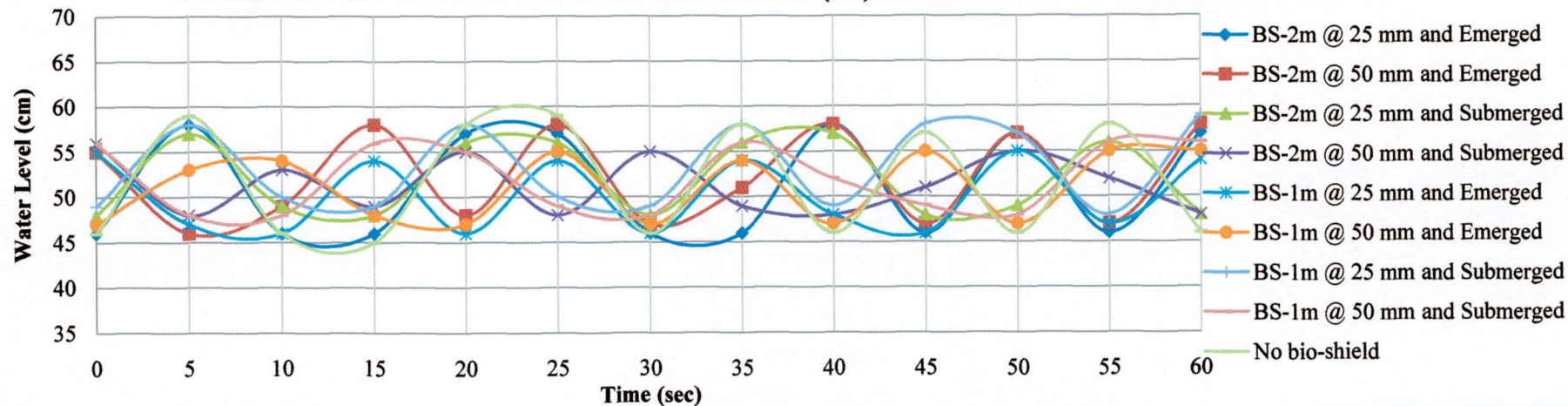
Variation of water level with time at G-4 for bio-shield (BS) at 2 m from the embankment and $T=2.0$ sec



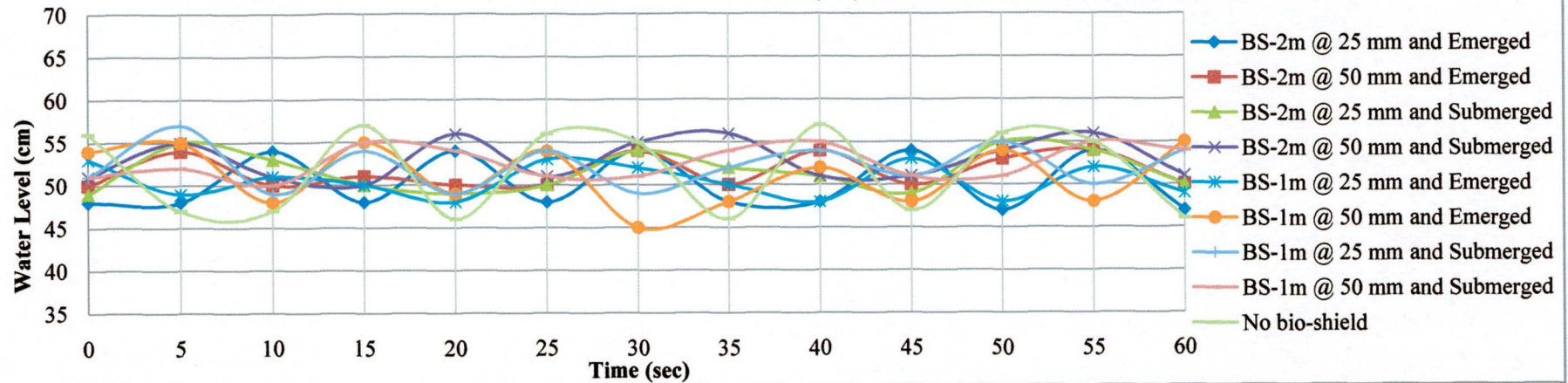
Variation of water level with time at G-5 for bio-shield (BS) at 2 m from the embankment and $T=2.0$ sec



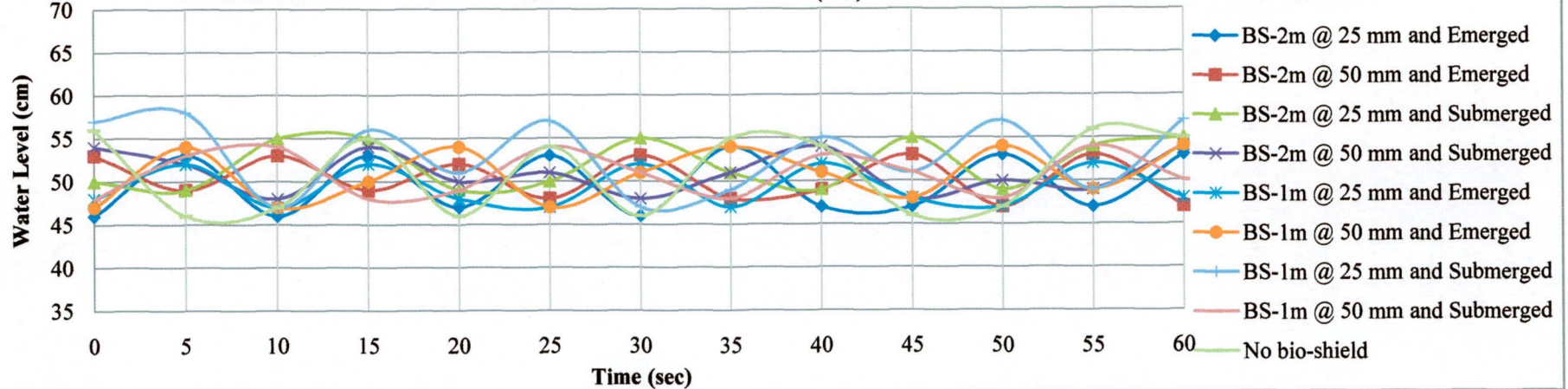
Variation of water level with time at G-6 for bio-shield (BS) at 2 m from the embankment and $T=2.0$ sec



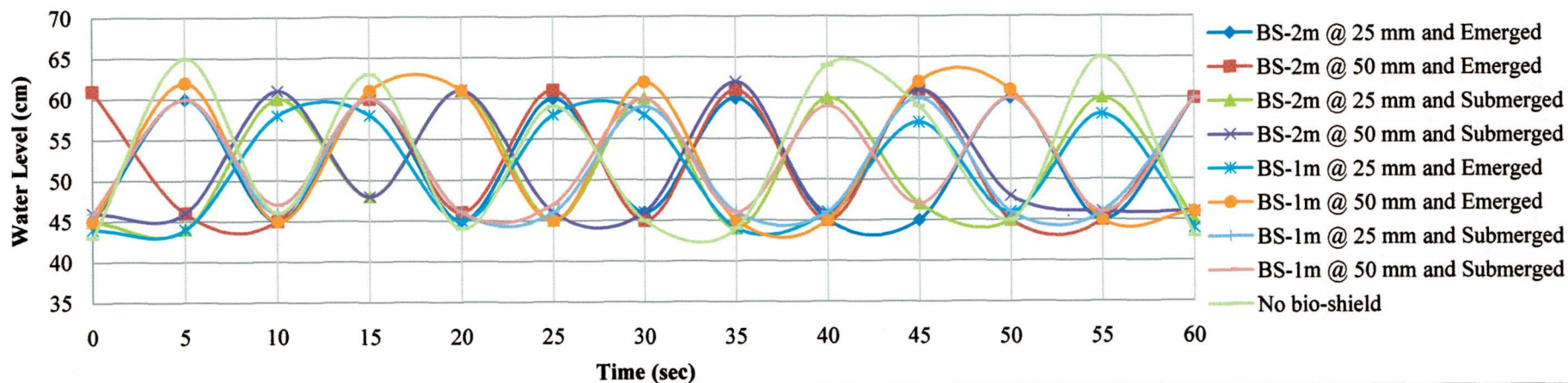
Variation of water level with time at G-7 for bio-shield (BS) at 2 m from the embankment and $T=2.0$ sec



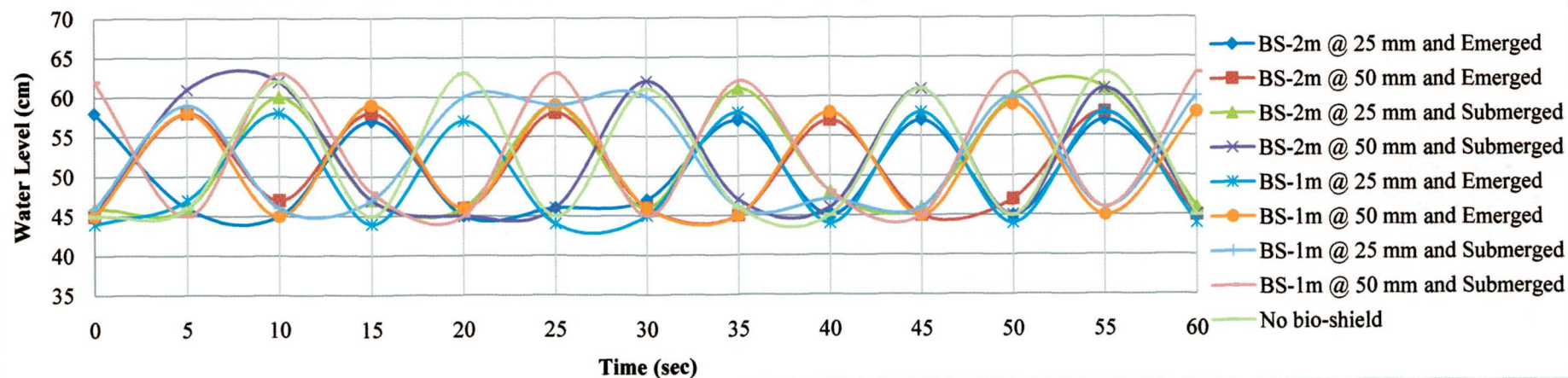
Variation of water level with time at G-8 for bio-shield (BS) at 2 m from the embankment and $T=2.0$ sec



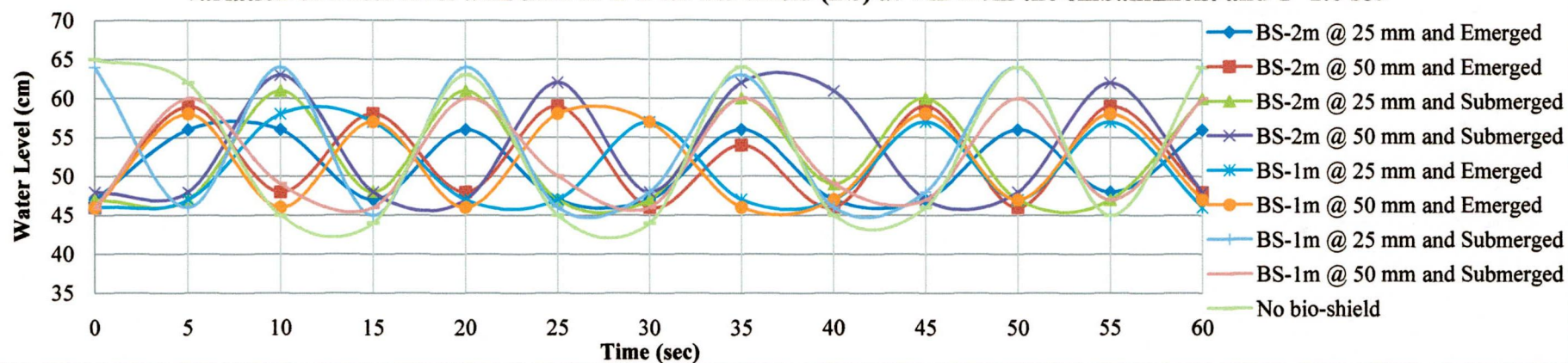
Variation of water level with time at G-1 for bio-shield (BS) at 4 m from the embankment and $T=1.6$ sec



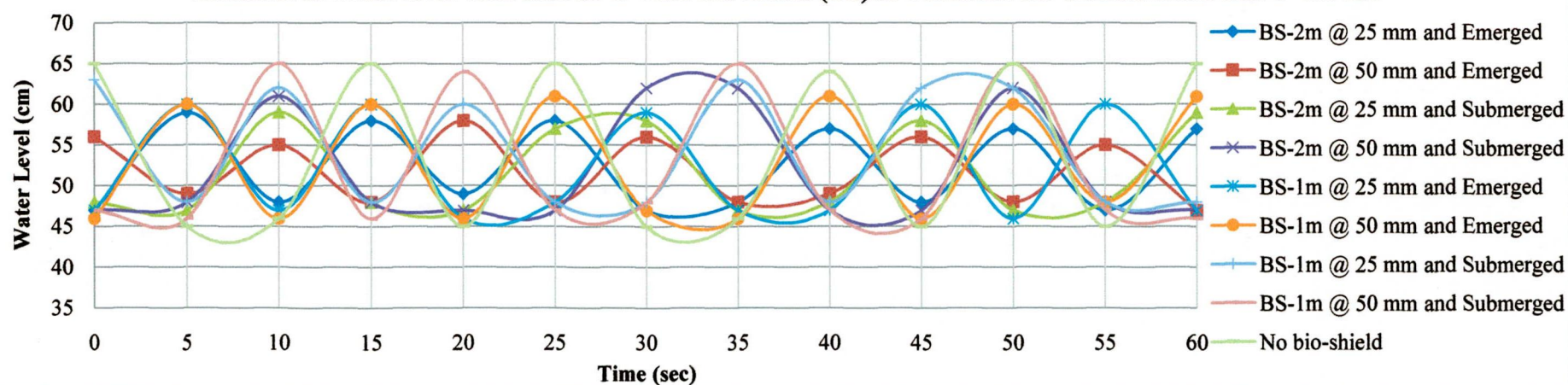
Variation of water level with time at G-2 for bio-shield (BS) at 4 m from the embankment and $T=1.6$ sec



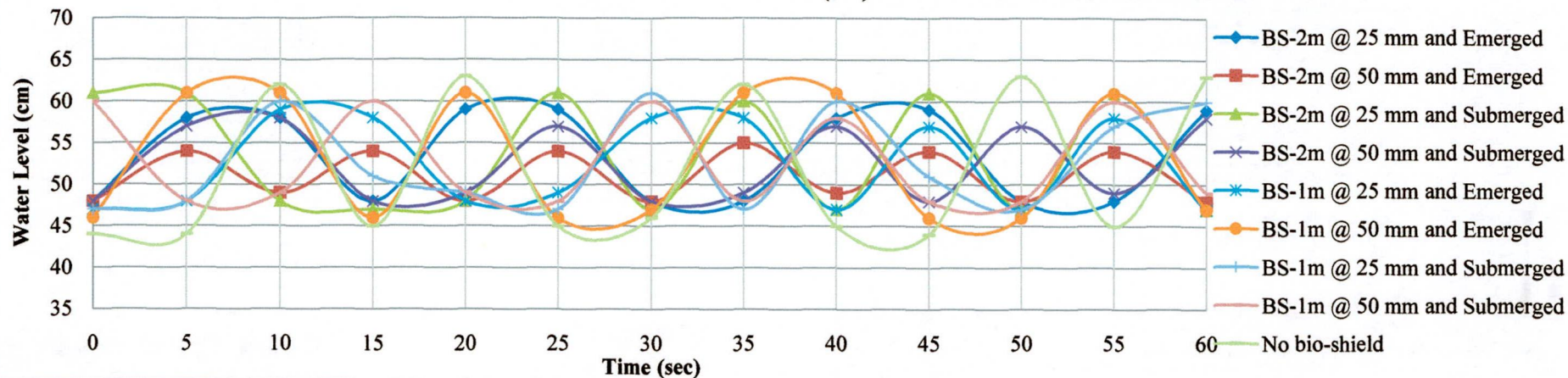
Variation of water level with time at G-3 for bio-shield (BS) at 4 m from the embankment and $T=1.6$ sec



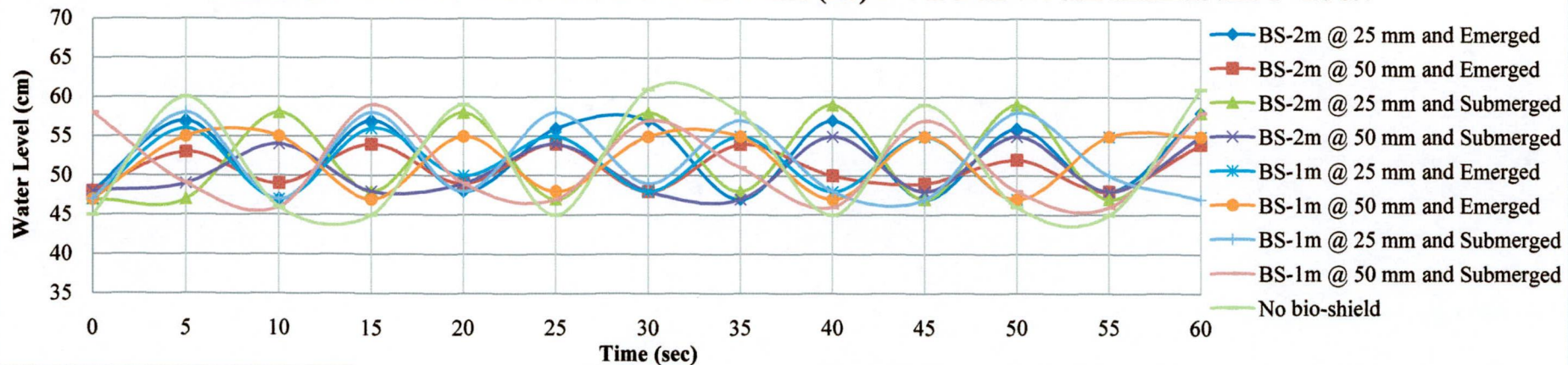
Variation of water level with time at G-4 for bio-shield (BS) at 4 m from the embankment and $T=1.6$ sec



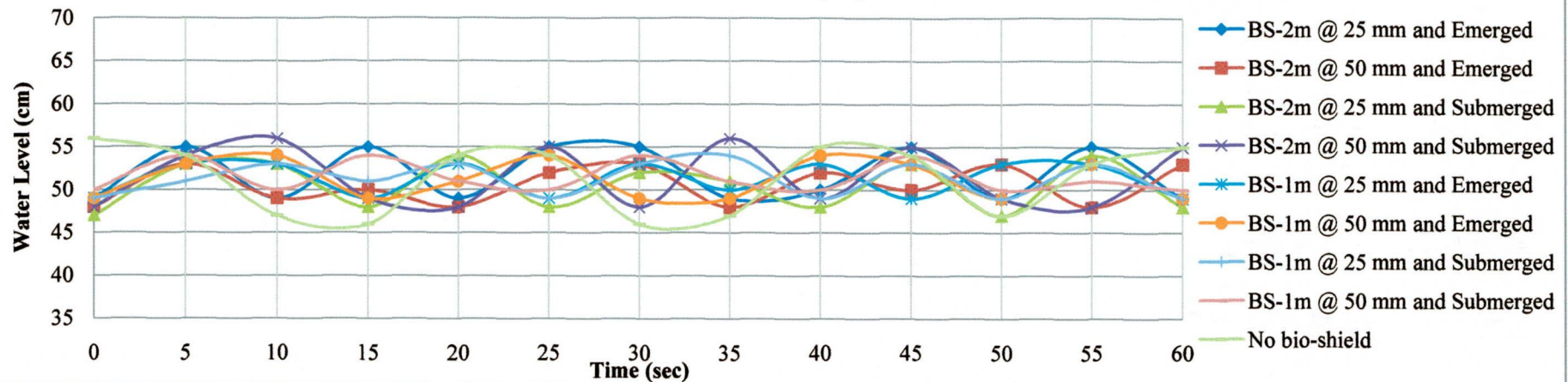
Variation of water level with time at G-5 for bio-shield (BS) at 4 m from the embankment and $T=1.6$ sec



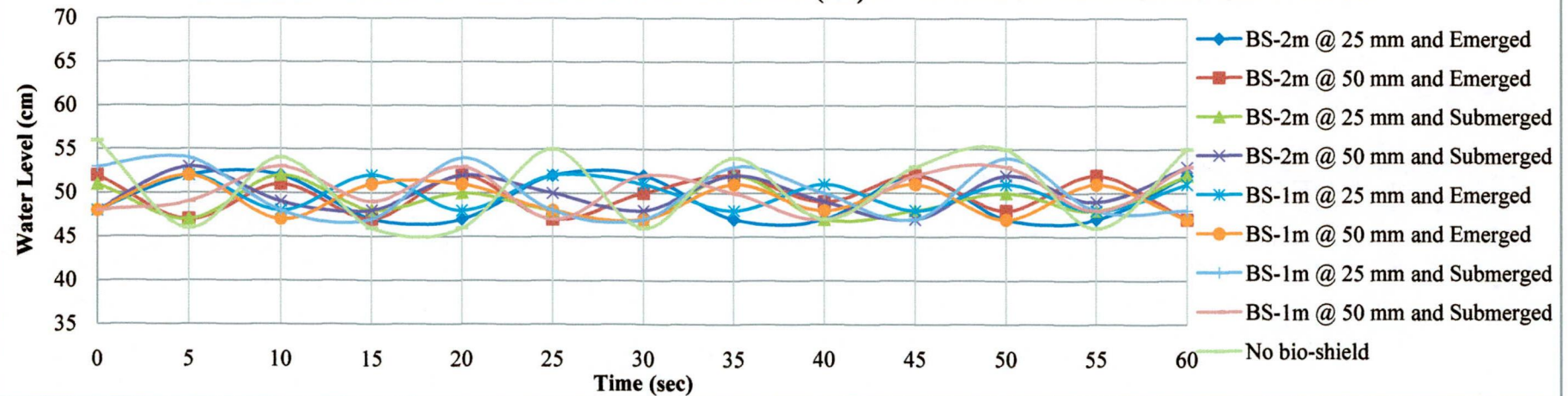
Variation of water level with time at G-6 for bio-shield (BS) at 4 m from the embankment and $T=1.6$ sec



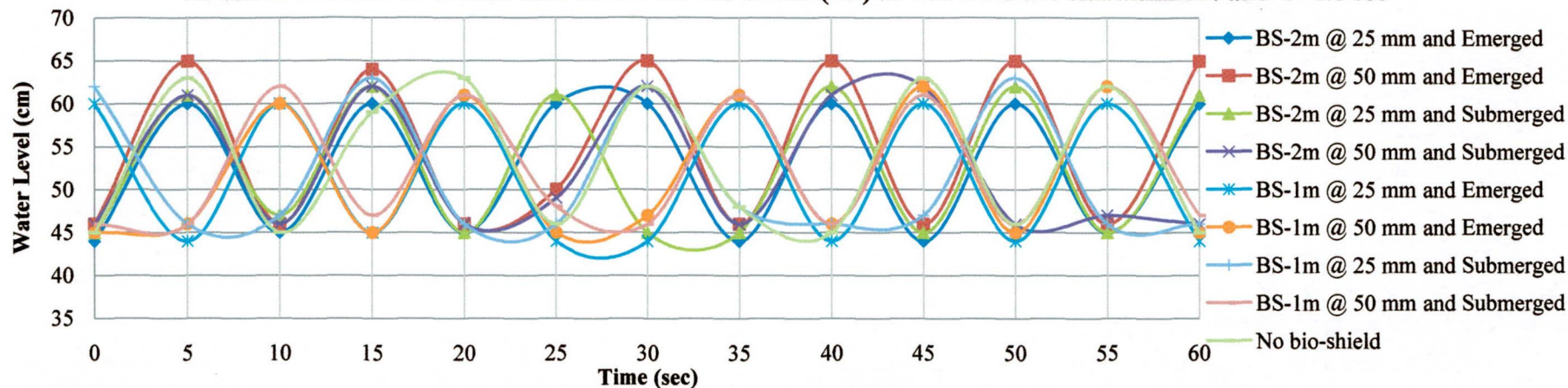
Variation of water level with time at G-7 for bio-shield (BS) at 4 m from the embankment and $T=1.6$ sec



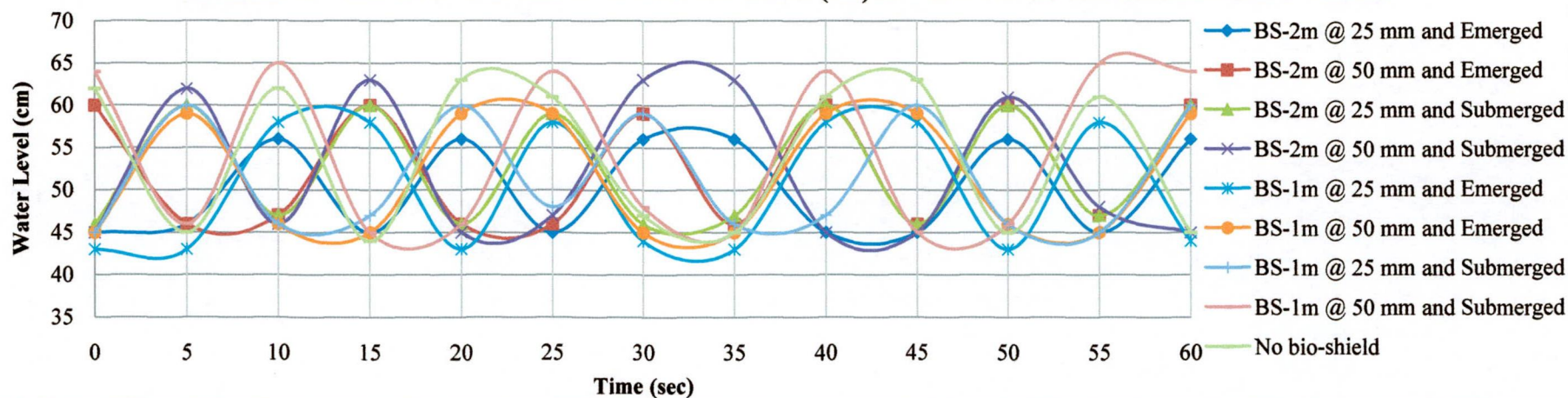
Variation of water level with time at G-8 for bio-shield (BS) at 4 m from the embankment and $T=1.6$ sec



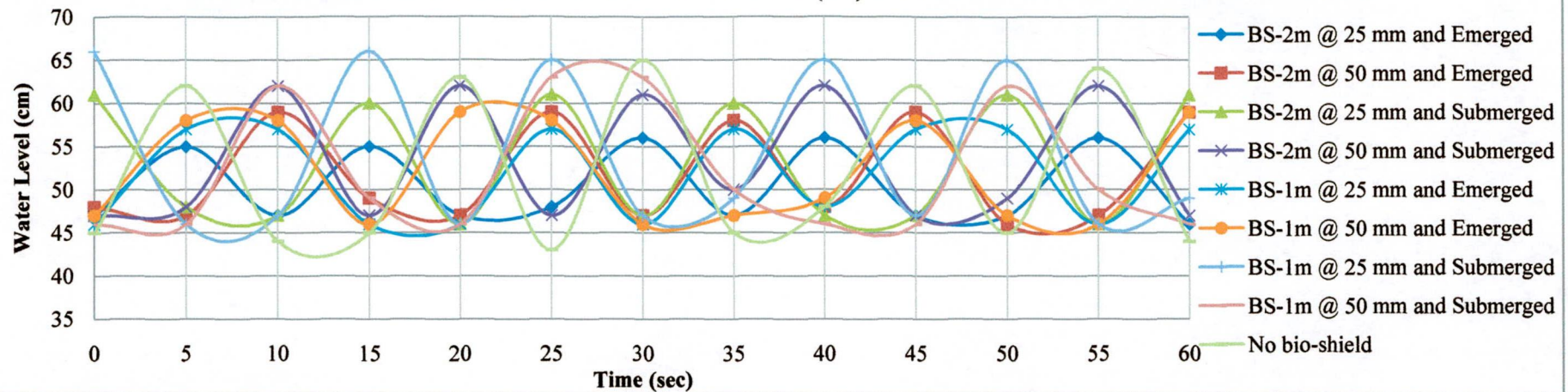
Variation of water level with time at G-1 for bio-shield (BS) at 4 m from the embankment and $T=1.8$ sec



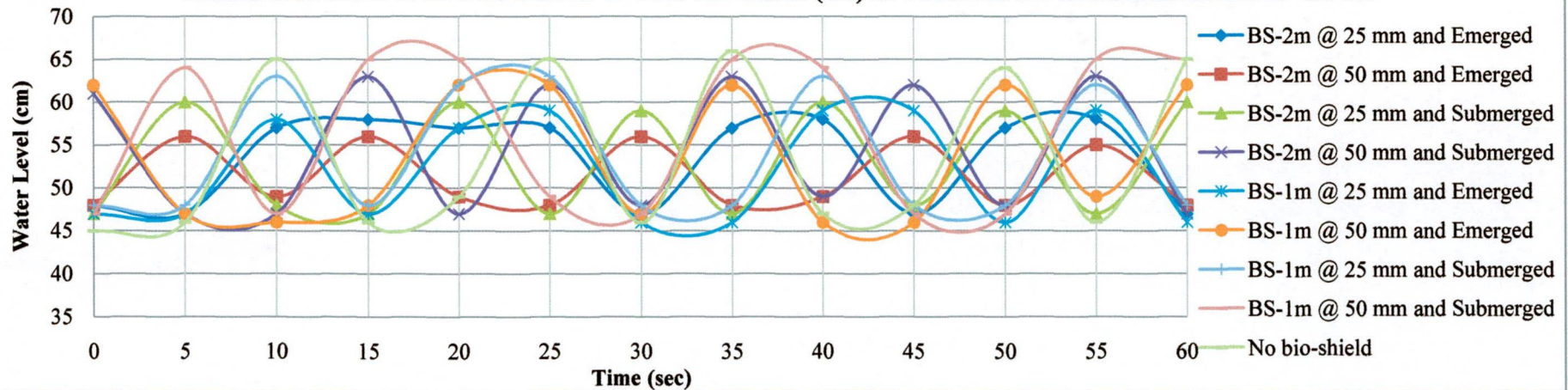
Variation of water level with time at G-2 for bio-shield (BS) at 4 m from the embankment and $T=1.8$ sec



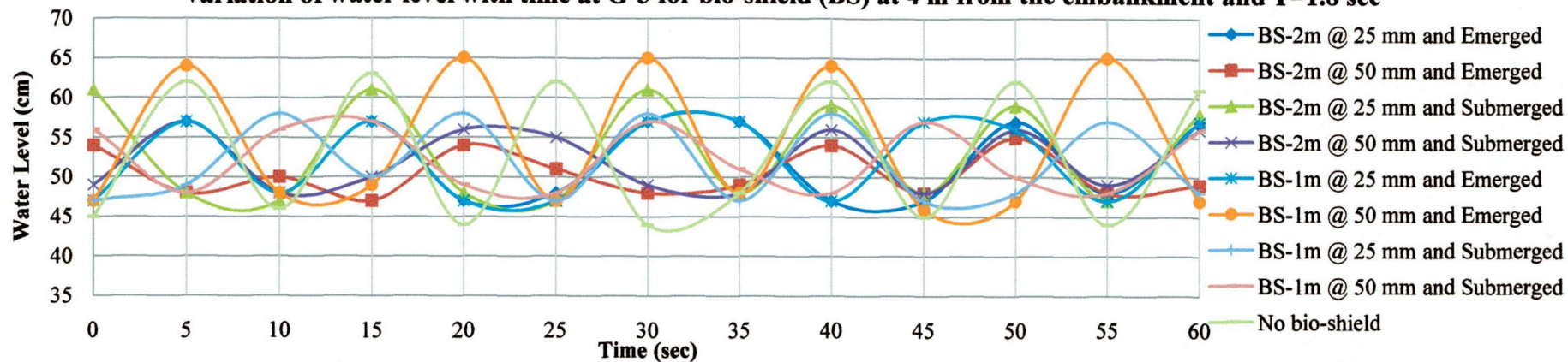
Variation of water level with time at G-3 for bio-shield (BS) at 4 m from the embankment and $T=1.8$ sec



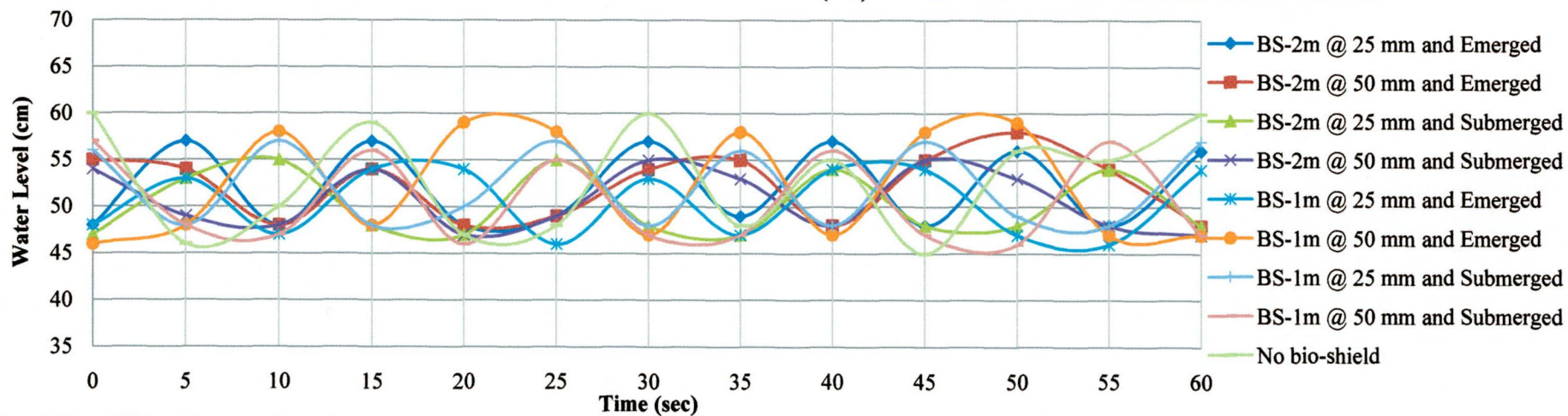
Variation of water level with time at G-4 for bio-shield (BS) at 4 m from the embankment and $T=1.8$ sec



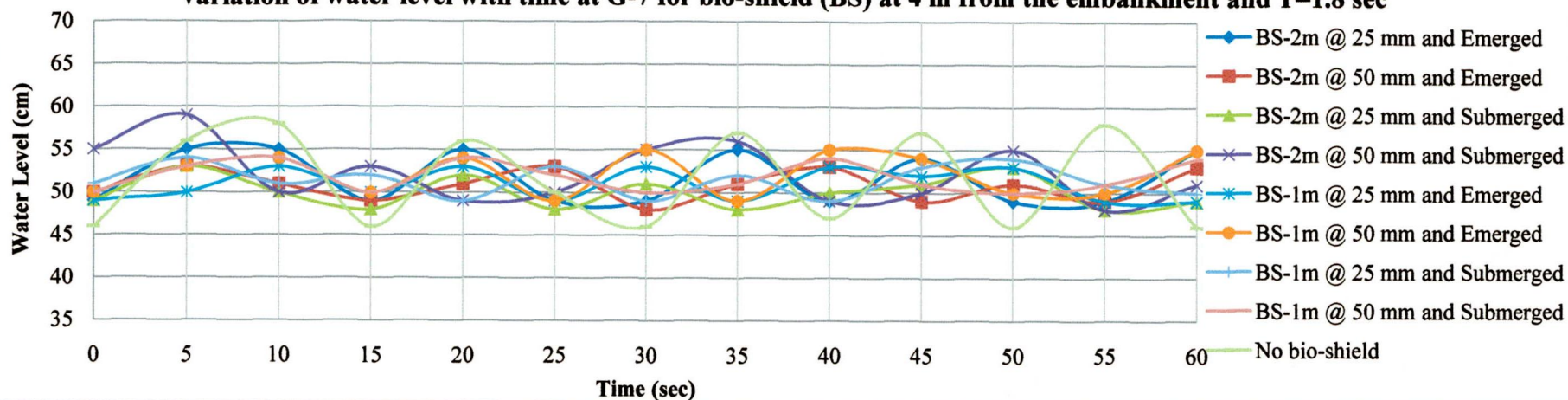
Variation of water level with time at G-5 for bio-shield (BS) at 4 m from the embankment and $T=1.8$ sec



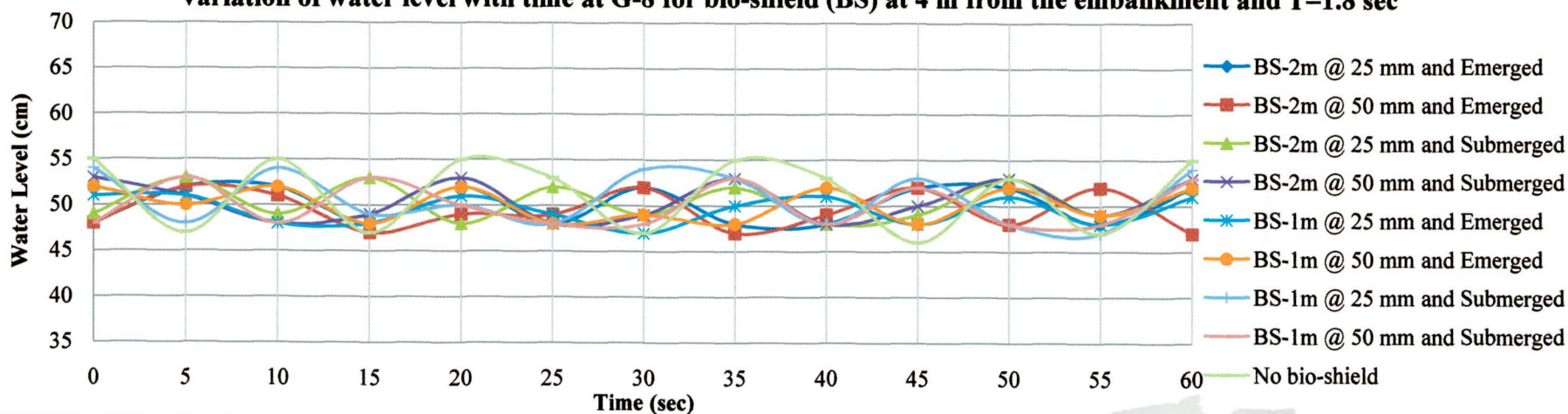
Variation of water level with time at G-6 for bio-shield (BS) at 4 m from the embankment and $T=1.8$ sec



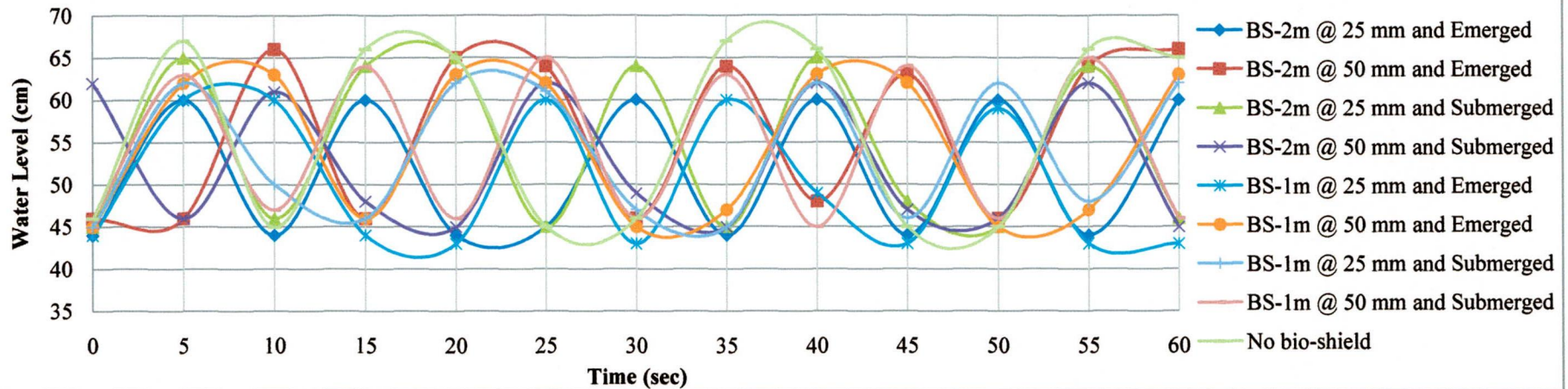
Variation of water level with time at G-7 for bio-shield (BS) at 4 m from the embankment and $T=1.8$ sec



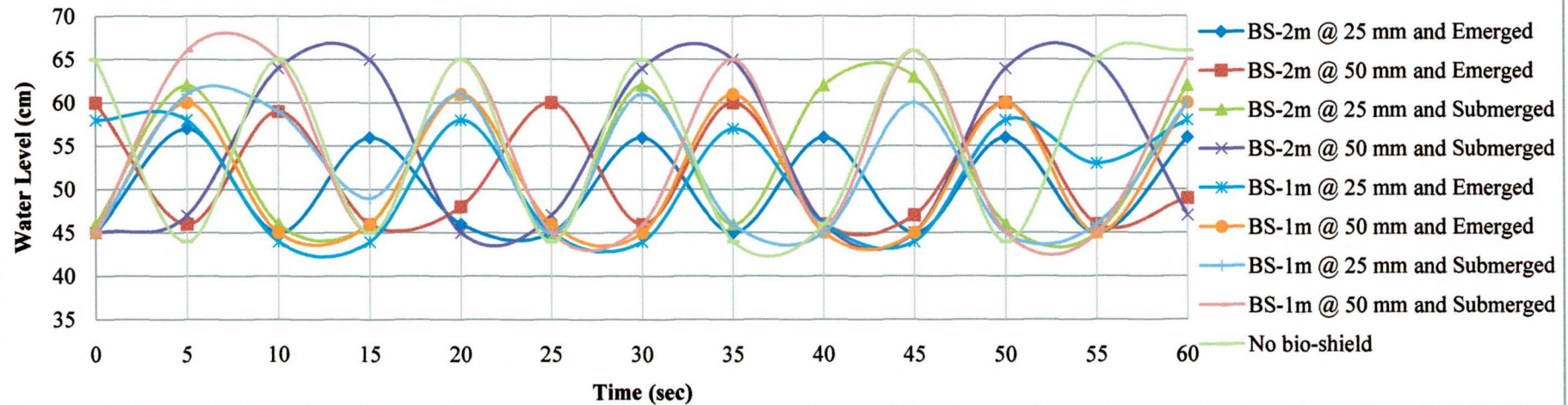
Variation of water level with time at G-8 for bio-shield (BS) at 4 m from the embankment and $T=1.8$ sec



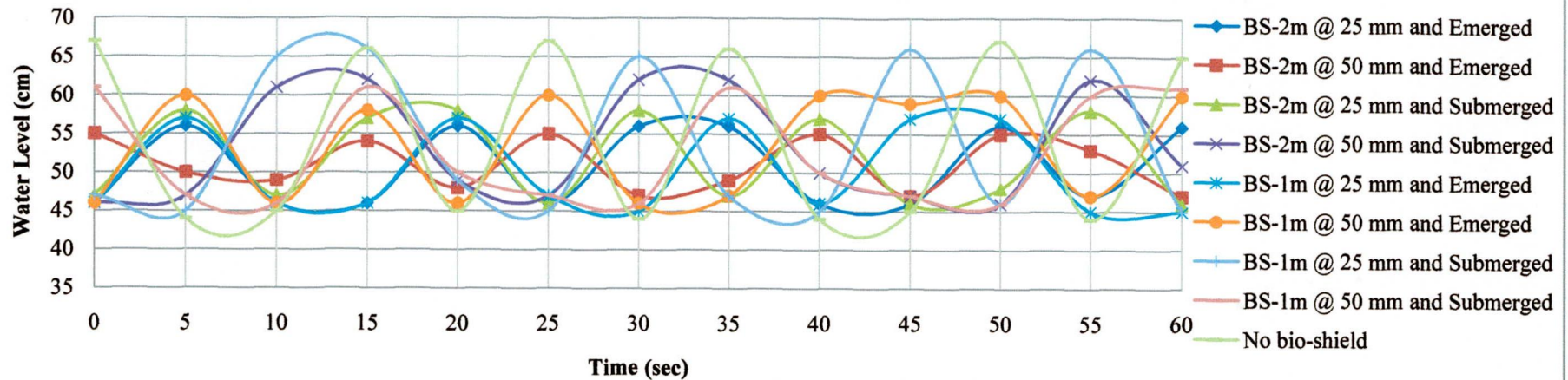
Variation of water level with time at G-1 for bio-shield (BS) at 4 m from the embankment and $T=2.0$ sec



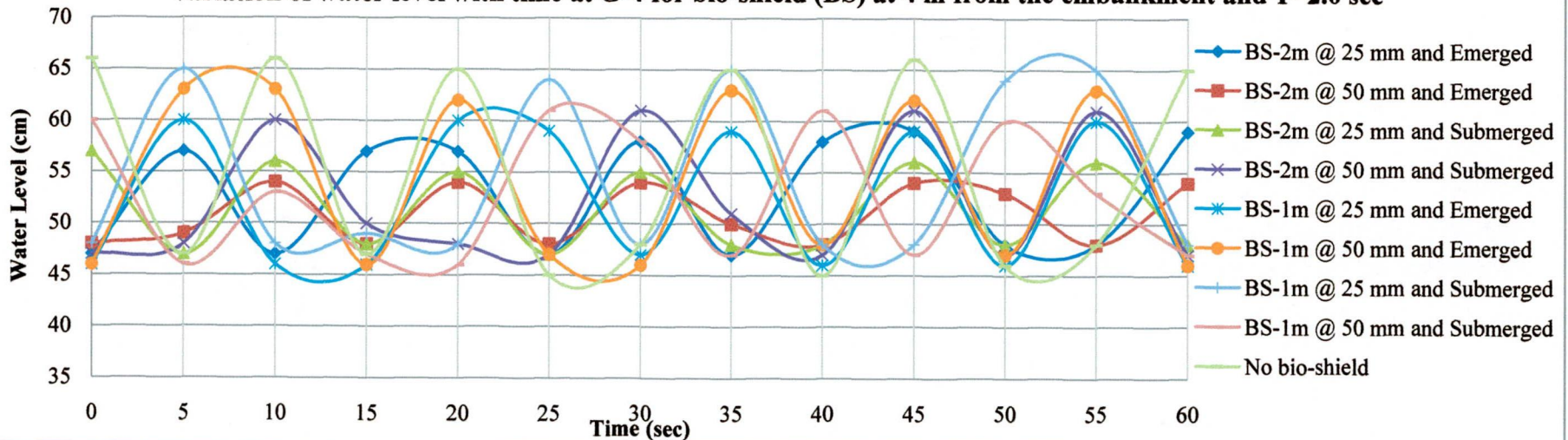
Variation of water level with time at G-2 for bio-shield (BS) at 4 m from the embankment and $T=2.0$ sec



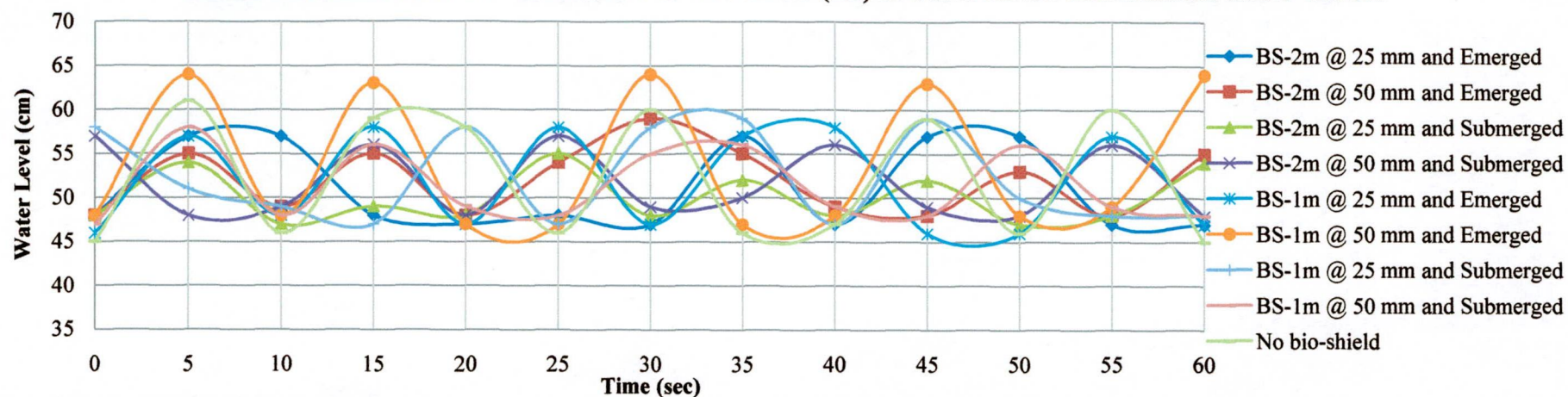
Variation of water level with time at G-3 for bio-shield (BS) at 4 m from the embankment and $T=2.0$ sec



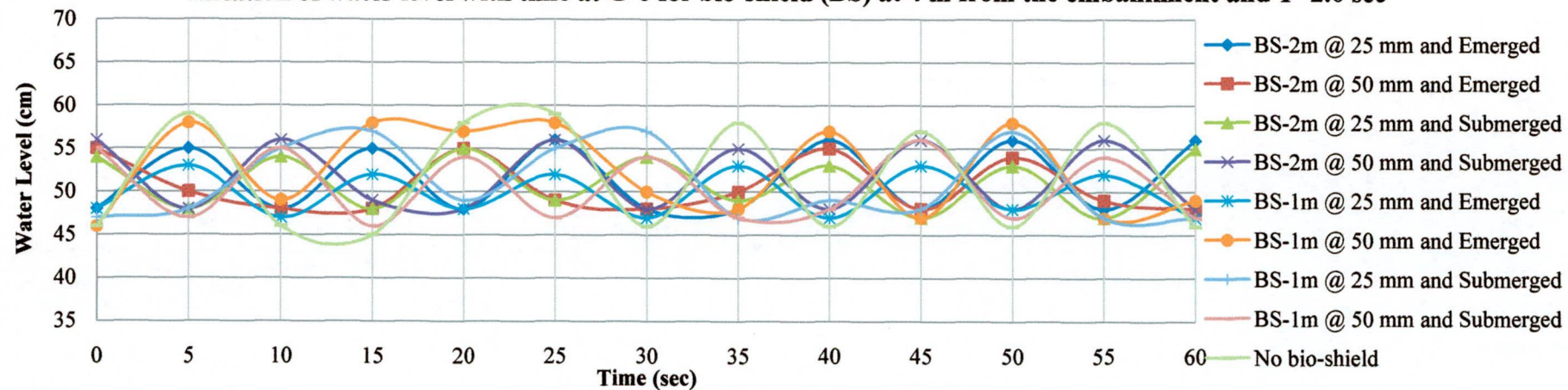
Variation of water level with time at G-4 for bio-shield (BS) at 4 m from the embankment and $T=2.0$ sec



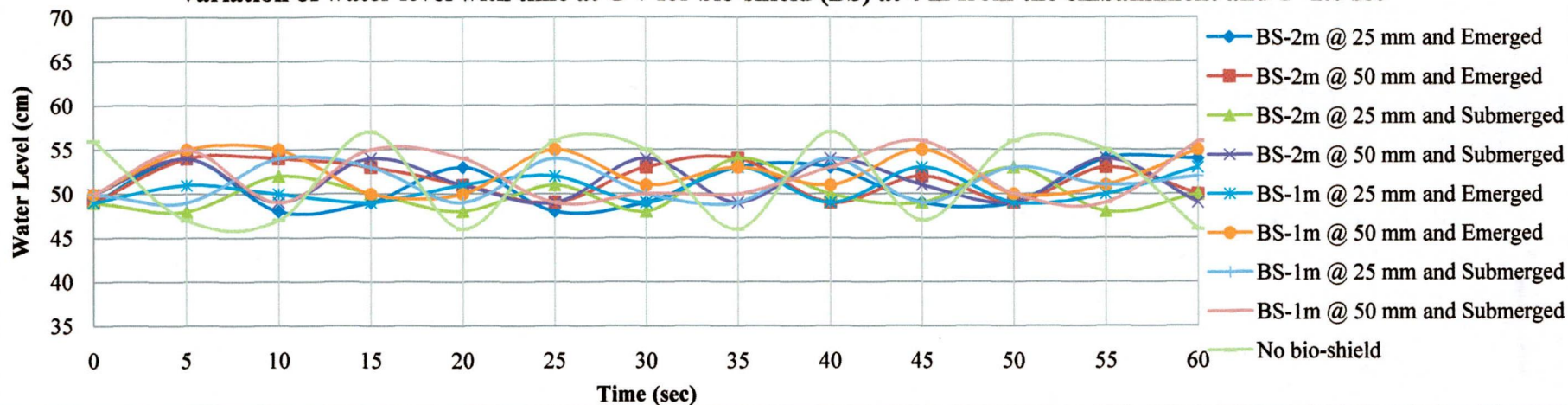
Variation of water level with time at G-5 for bio-shield (BS) at 4 m from the embankment and $T=2.0$ sec



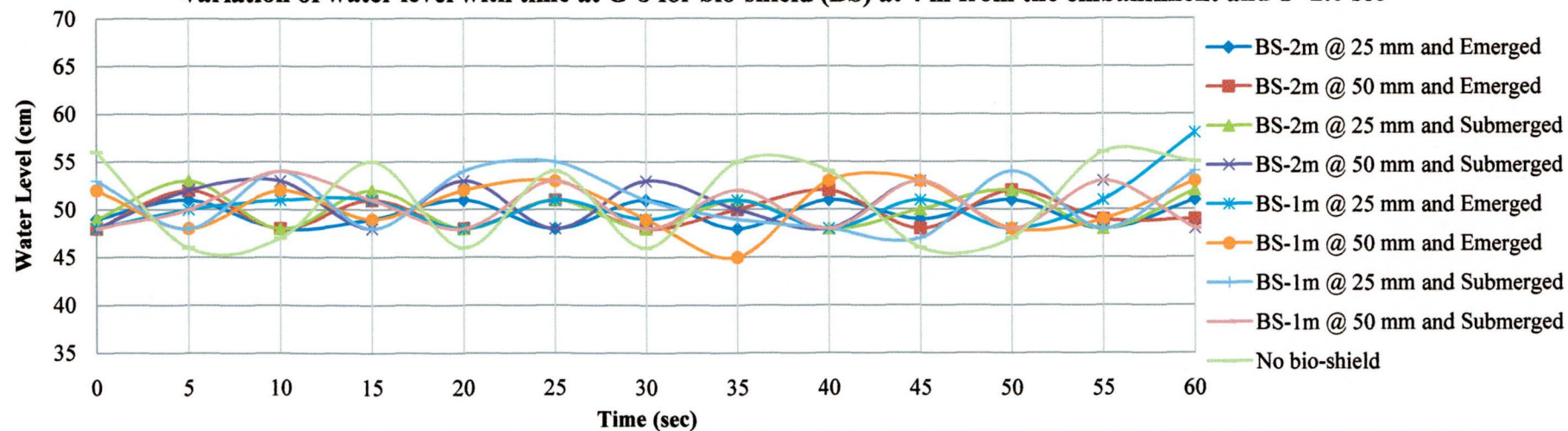
Variation of water level with time at G-6 for bio-shield (BS) at 4 m from the embankment and $T=2.0$ sec



Variation of water level with time at G-7 for bio-shield (BS) at 4 m from the embankment and $T=2.0$ sec



Variation of water level with time at G-8 for bio-shield (BS) at 4 m from the embankment and $T=2.0$ sec



APPENDIX D

Comparison of Wave Height Reduction with Distance from Embankment for Various Experimental Run Conditions

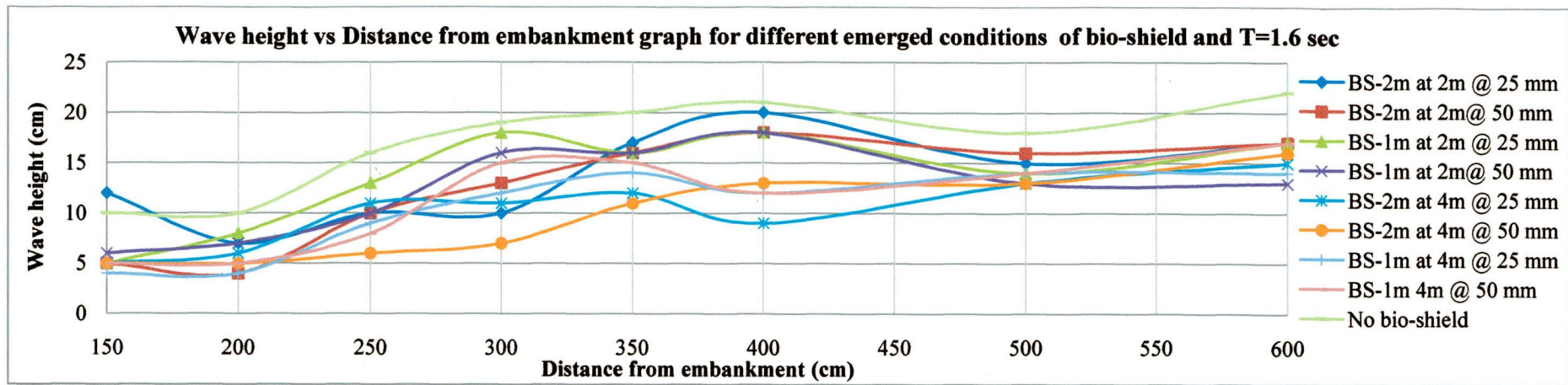


Figure 1: Variation of wave height with distance from embankment for different emerged conditions of bio-shield and wave period, $T=1.6$ sec

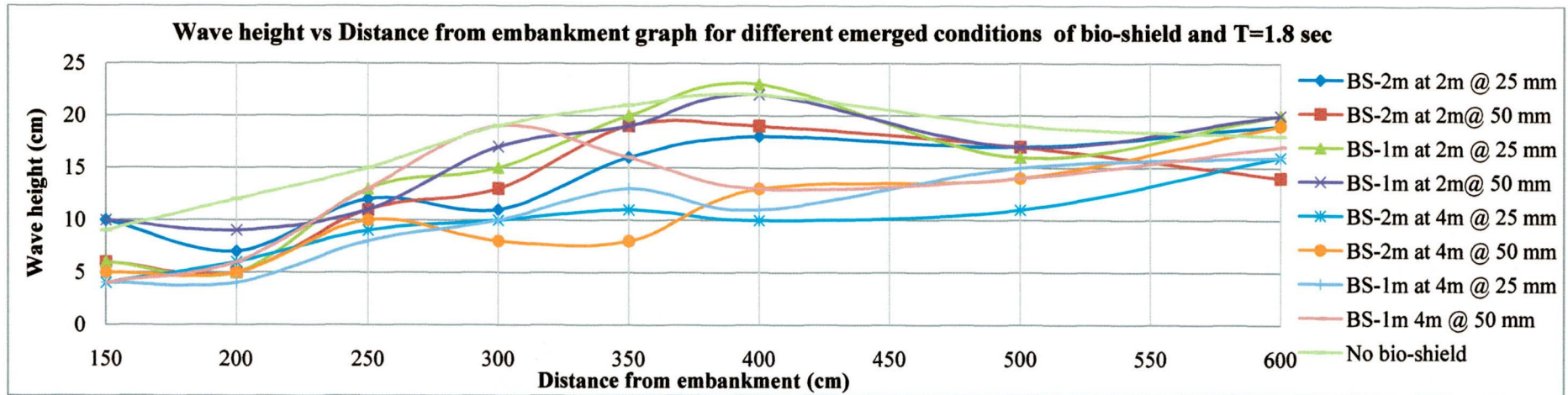


Figure 2: Variation of wave height with distance from embankment for different emerged conditions of bio-shield and wave period, $T=1.8$ sec

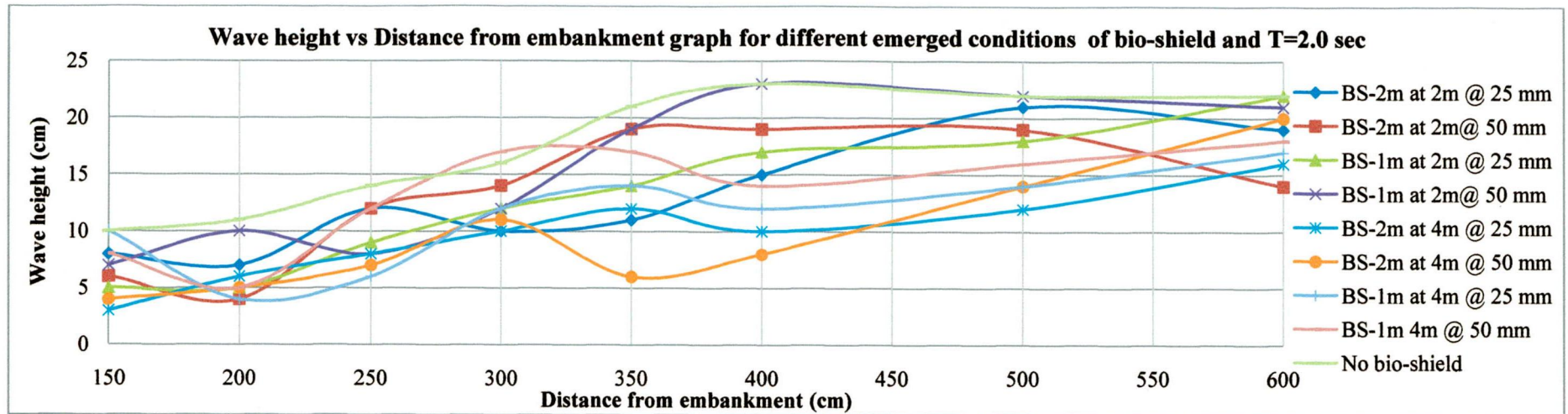


Figure 3: Variation of wave height with distance from embankment for different emerged conditions of bio-shield and wave period, $T=2.0$ sec

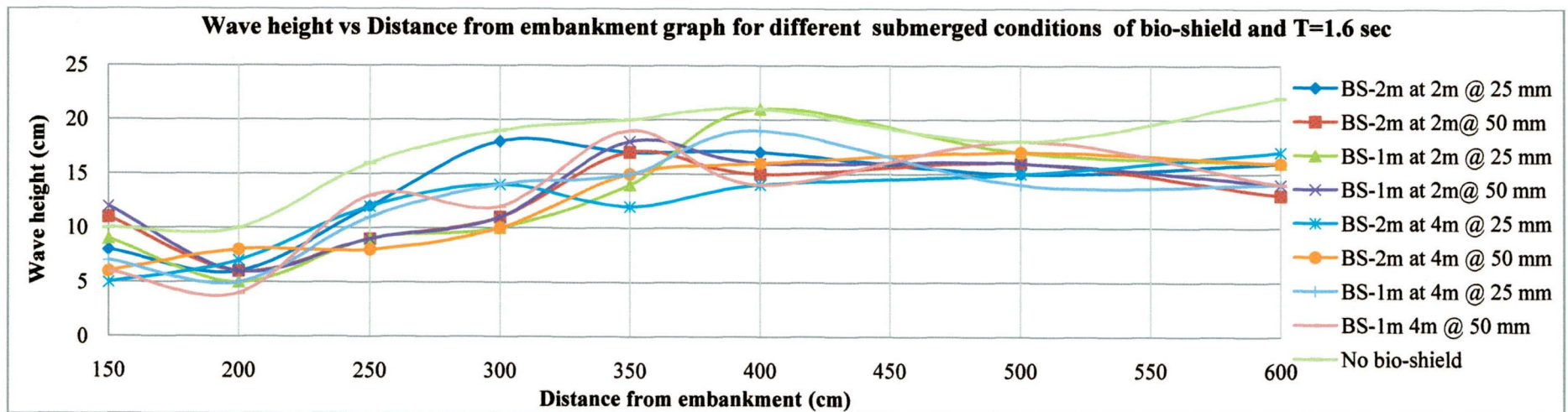


Figure 4: Variation of wave height with distance from embankment for different submerged conditions of bio-shield and wave period, $T=1.6$ sec

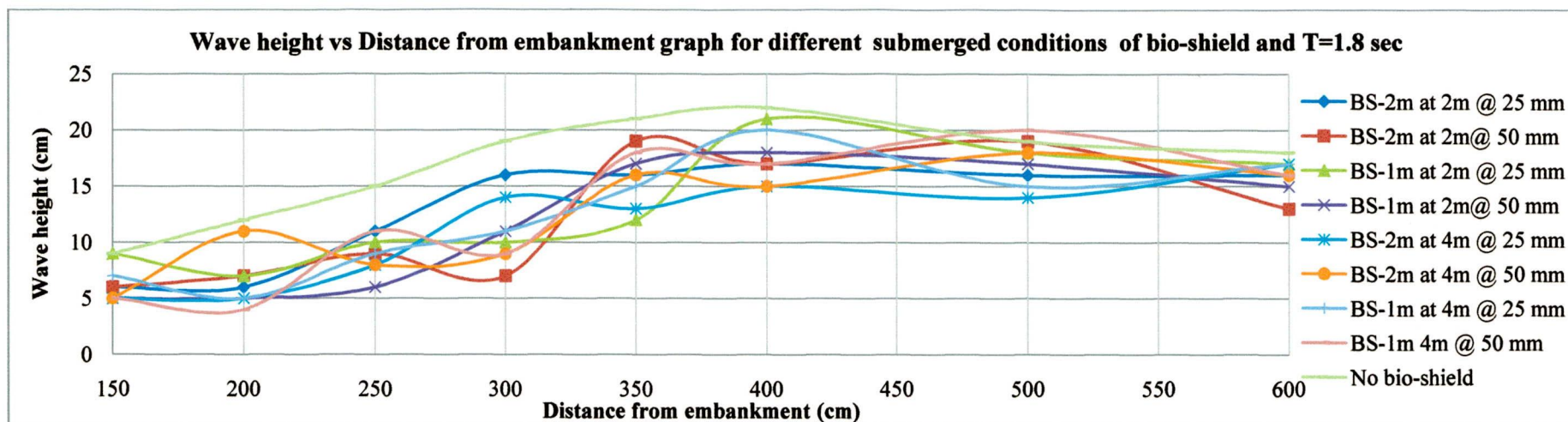


Figure 5: Variation of wave height with distance from embankment for different submerged conditions of bio-shield and wave period, $T=1.8$ sec

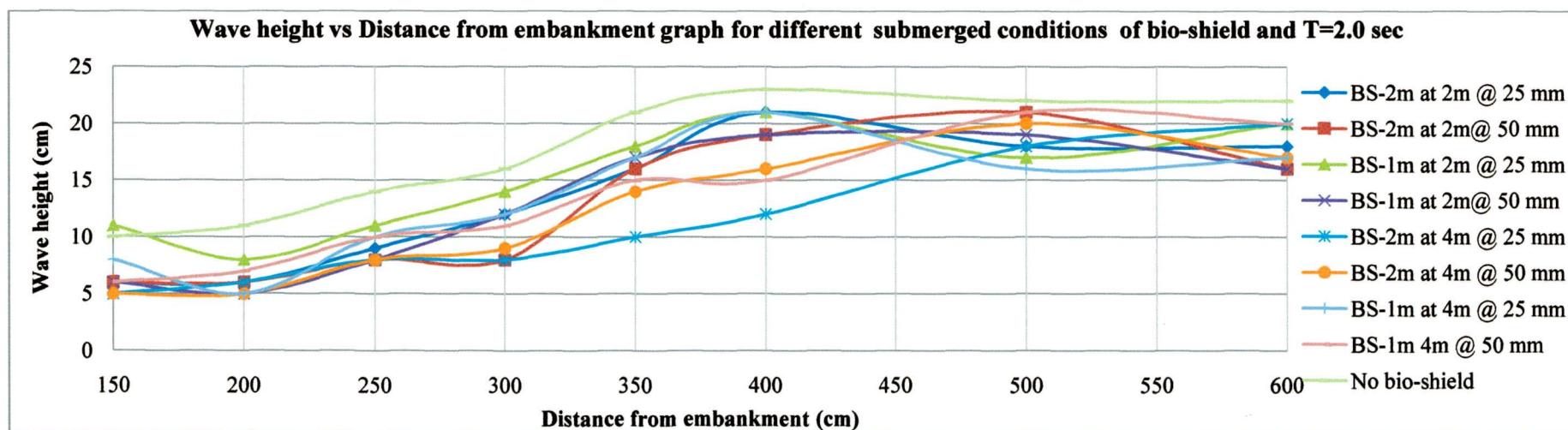


Figure 6: Variation of wave height with distance from embankment for different submerged conditions of bio-shield and wave period, $T=2.0$ sec

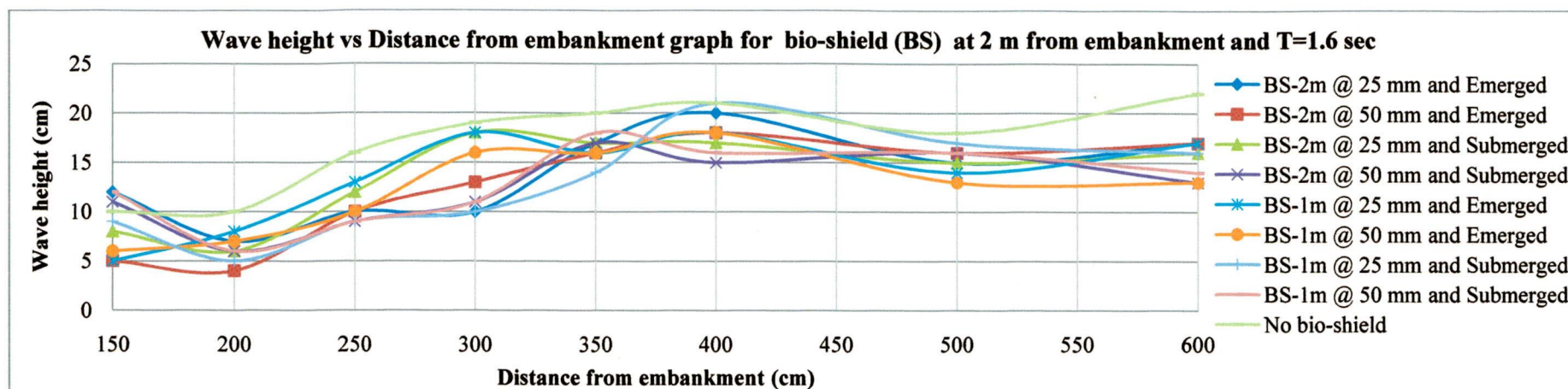


Figure 7: Variation of wave height with distance from embankment for different emerged and submerged conditions of bio-shield when placed at 2 m from embankment and wave period, $T=1.6$ sec

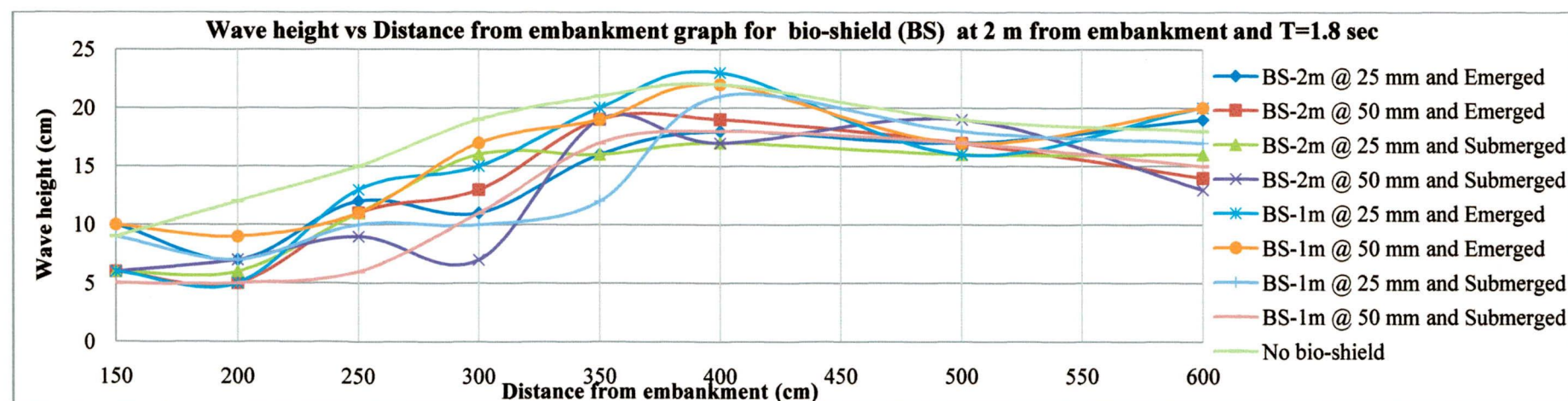


Figure 8: Variation of wave height with distance from embankment for different emerged and submerged conditions of bio-shield when placed at 2 m from embankment and wave period, $T=1.8$ sec

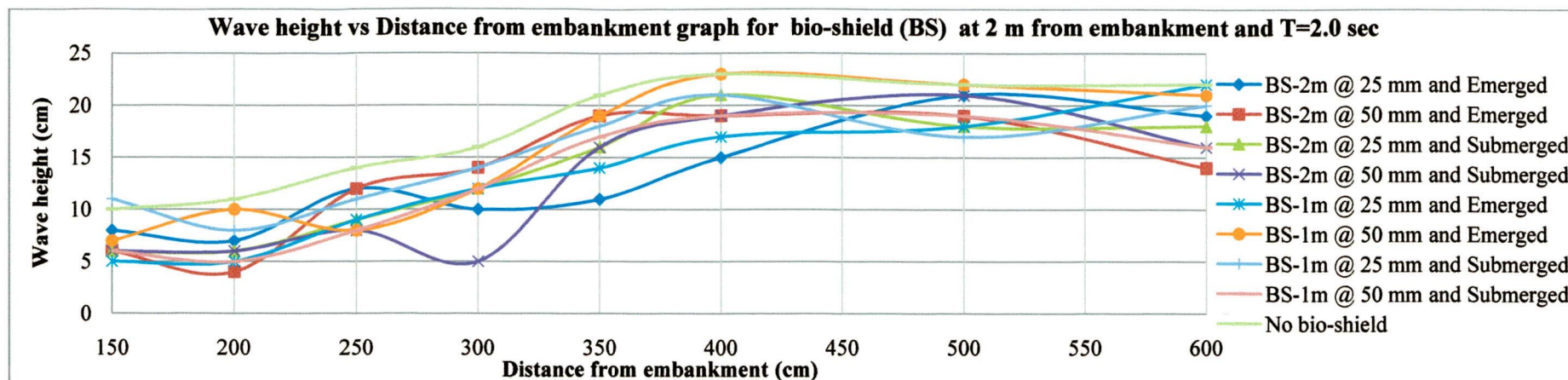


Figure 9: Variation of wave height with distance from embankment for different emerged and submerged conditions of bio-shield when placed at 2 m from embankment and wave period, $T=2.0$ sec

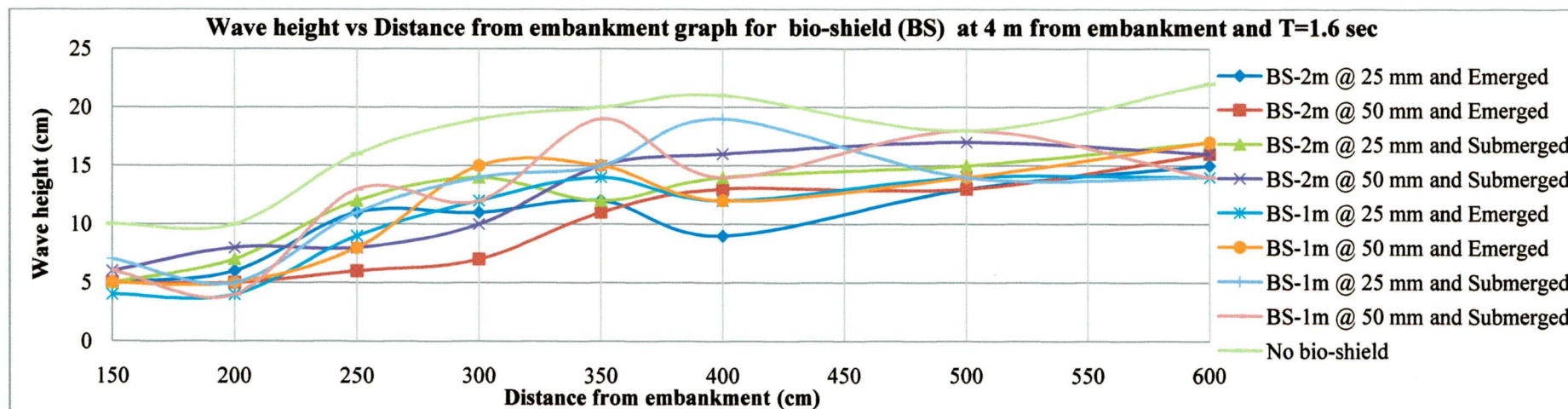


Figure 10: Variation of wave height with distance from embankment for different emerged and submerged conditions of bio-shield when placed at 4 m from embankment and wave period, $T=1.6$ sec

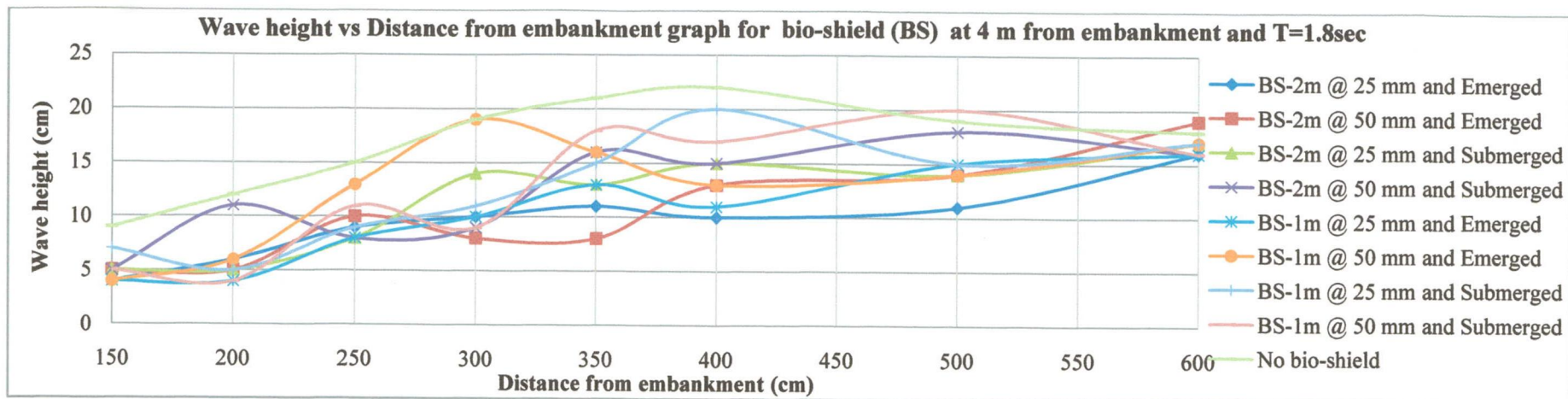


Figure 11: Variation of wave height with distance from embankment for different emerged and submerged conditions of bio-shield when placed at 4 m from embankment and wave period, $T=1.8\text{ sec}$

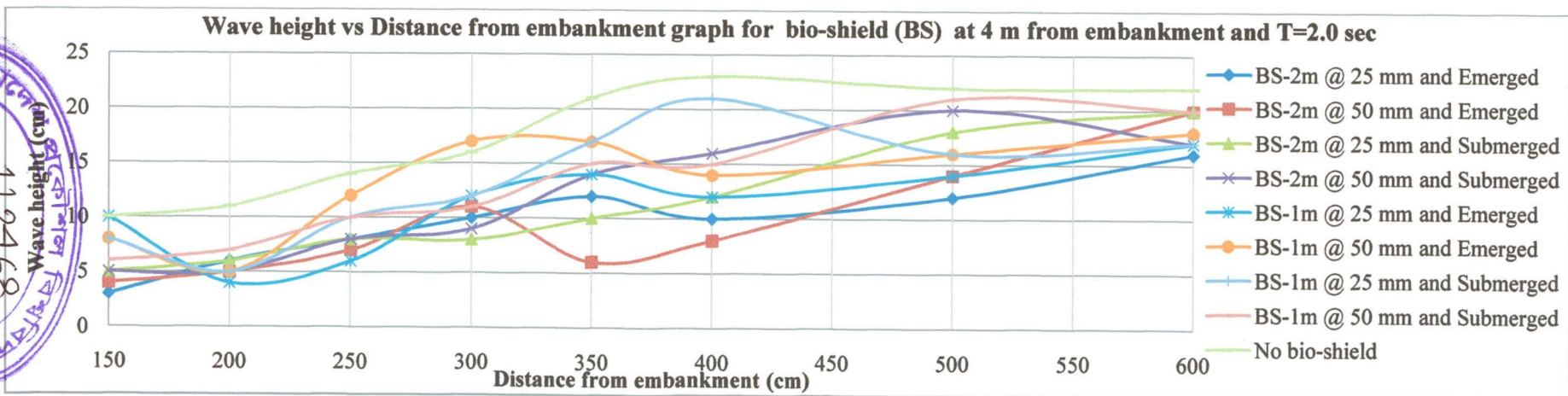


Figure 12: Variation of wave height with distance from embankment for different emerged and submerged conditions of bio-shield when placed at 4 m from embankment and wave period, $T=2.0\text{ sec}$

