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CREST LEVEL FIXATION CONSIDERING CLIMATE CHANGE IMPACT USING STATE-OF-THE-ART MATHEMATICAL MODELING: MATARBARI ISLAND

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Abstract. The Bay of Bengal is one of the hotspots for the formation of tropical cyclones, which usually occur in the pre-and post-monsoon seasons. The majority of the cyclones strike Bangladesh's coast (710 km) from a north-easterly direction. Out of 139 coastal polders constructed by Bangladesh Water Development Board, 49 polders are sea faced which are most vulnerable to cyclone-induced storm surges. Matarbari Island (polder-70) is also a sea-faced polder where huge infrastructure development works (i.e., coal power plant, economic zone, deep seaport, renewable energy) are undergoing likely to be one of the most important economic hubs of Bangladesh. The western side of the study area (Matarbari Island) is seaside, and the Eastern side is surrounded by Kuhuela River. The sea-facing embankment length is 12 km whereas the perimeter of the polder is 35 km. The average crest level of the existing polder is 4-5.5 mPWD (sea facing) and 3.2-6 mPWD (riverside) which is not sufficient to protect polder land from storm surges. So, it is of utmost importance to elevate the crest level to save the highly economically valuable area from such natural calamity. This research work focuses on estimating the design crest level using state-of-the-art mathematical modeling. The storm surge model, a combination of hydrodynamic and cyclone models, has been simulated by MIKE 21 FM and the wave model has been simulated by MIKE 21 SW which are reliable, powerful, and commercial modeling tools. From storm surge model gives the surge level whereas wave climate (i.e., sig. wave height, peak wave period, and mean wave direction) is found from the wave model result. Freeboard is calculated from the wave climate with the assistance of the EuroTop manual. Design crest level is fixed based on surge level, freeboard, and land subsidence considering climate change impact by frequency analysis done by MIKE EVA. From the simulated model result analysis, it is found that the required design crest level (1 in 100 years) of the embankment on the seaside ranges from +10.25 to 10.5 mPWD whereas at the eastern side (Kuhelia riverside) it is +6.25 to +7 mPWD. Necessary slope and shore protection works are required to protect the embankment from erosion. Design parameters can be achieved from the model results. Significant wave height, peak wave period, and velocity range from 0.73-3.92 m, 2.87-6.65 s, etc., and 0.6-3.9 m/sec. It is recommended that the existing crest level must be raised to design crest level with proper protection measures to save the village area and industrial zone on Matarbari Island.
Keywords: Storm Surge model, Wave model, Design crest level, Climate change, ctorm curge inundation

1 INTRODUCTION

Matarbari island union, known as polder-70, is under Maheshkhali Upazilla. Matarbari is completely isolated in the most north-western area, having 30.1 sq.km and 57,814 population (Census, 2011). Matarbari island being a sea facing island is prone to flood, erosion, high tide, cyclone, and storm surge.Several of the government's multipurpose development projects, centered on the MIDI (Maheshkhali-Matarbari Integrated Infrastructure Development Initiative), have already been implemented. Among the ongoing projects is the Maheshkhali Economic Zone-3 of the Singapore-Bangladesh Economic Zone Authority (BEZA). The implementation of the 700 MW Coal Power Plant (PPP), the 1200 MW Matarbari Coal Power Plant (PPP), and the 7.03 km express road by the Roads and Highways Department is crucial. Significant obstacles to the implementation and sustainability of these government programs will be floods and cyclones. As a result, the importance of improved connectivity and natural disaster response in the area is increasing daily. By selecting an appropriate design crest level using mathematical modeling, this study seeks to safeguard current and future development projects in the study region against flood, erosion, high tide, cyclones, and storm surge.

In the realm of coastal engineering and climate resilience, the accurate establishment of embankment crest levels has assumed a paramount role, particularly in light of the intensifying impacts of climate change (Alam et al 1999, Anwar et al 2022, DHI et al 2022 and IPCC 2007). Matarbari Island, located in a coastal region vulnerable to rising sea levels and extreme climatic events, serves as a compelling illustration of the urgent necessity to cultivate advanced methodologies for determining crest levels that effectively factor in these dynamic environmental shifts. As global climate dynamics continue to evolve, traditional approaches to embankment design and crest level assessment are increasingly inadequate to ensure sustained stability and flood protection (IPCC 2021, Jisan et al 2018). This paper centers on the innovative fusion of sophisticated mathematical modeling techniques to comprehend and integrate the intricate complexities of climate change repercussions when estimating embankment crest levels for Matarbari Island.

Consistently underscored by the Intergovernmental Panel on Climate Change (IPCC), the acceleration of climate change is characterized by escalating sea levels, augmented storm intensities, and revised precipitation patterns (IPCC 2007, IPCC 2021). These transformations pose unparalleled challenges to coastal regions, necessitating a departure from conventional design paradigms. In response to these imperatives, this study capitalizes on the latent potential of advanced mathematical models to furnish a holistic framework for the projection of crest levels. By harmonizing predictive climate datasets, hydrodynamic simulations, and geotechnical considerations, the proposed methodology aspires to furnish a comprehensive grasp of the intricate interplay between embankment design and the evolving tapestry of climatic conditions (Sarwar et al 2016, Sing O.P 2002, SMRC 1998 and Vidal, J. 2013) Through the utilization of cutting-edge mathematical modeling, this study seeks to contribute to a paradigm shift in embankment design, one characterized by adaptability, resilience, and efficacy in confronting climate-induced threats.

2 METHODS

2.1 Study area

Matarbari is a union in MaheshkhaliUpazila of Cox's Bazar District. The union consists of an island surrounded by a Polder 70 coastal embankment. The island is located at 21.734933°N and 91.897565°E and is flanked on its north by the Matamuhuri river, on its east and south by the Kohelia river, and on its west by the Bay of Bengal.

The downstream of Maheshkhali river is directly connected to sea (Bay of Bengal), 22 km (areal distance) away from the southern embankment of Polder-70. Moreover, Maheshkhali Channel has a number of distributaries along its course which have no impact on the aforementioned polders. The land area of Matarbari island is 43.5 square kilometers whereas the perimeter of the island is 35 km along which 12 km is sea facing which is about 34.2 % of the total perimeter. The embankment constructed in 1960s has an average crest level of 4-5.5 m PWD (sea facing) and 3.2-6 m PWD (riverside) which is no longer a befitting protection against rising sea level and land subsidence. Major professions include salt production, shrimp and crab farming, Bay of Bengal fishing, agriculture, and day labor.

Two prominent models used in this study are storm surge model and wave model, both have been used to determine the design crest level. Storm surge model was required to compute the design surge level and wave model was used to get significant wave height for free board calculation.

2.2 Storm surge model

Various types of data were collected like water level data, water flow, cross-section/ bathymetry, sediment data, wind data from different sources like CPA (Chittagong Port Authority), BWDB (Bangladesh Water Development Board), IWM (Institute of Water Modelling), BMD (Bangladesh Meteorological Authority).

Storm surge model is a combination of 2D hydrodynamic model and cyclone model. A two-dimensional hydrodynamic model was developed to explore hydrological characteristics of Matarbari Island such as existing crest level, water level inside thepolder (i.e., in Khal) and in the peripheral river. IWM has long maintained a 2D hydrodynamic model (BoBM) of the Bay of Bengal. In this study, the bathymetry ofthe model has been updated with the collected bathymetry data. Triangular fine resolution mesh (about 300

m) is provided in the seaside of the polder. Local model derived from Bay of Bengal model is illustrated in the Figure 2.

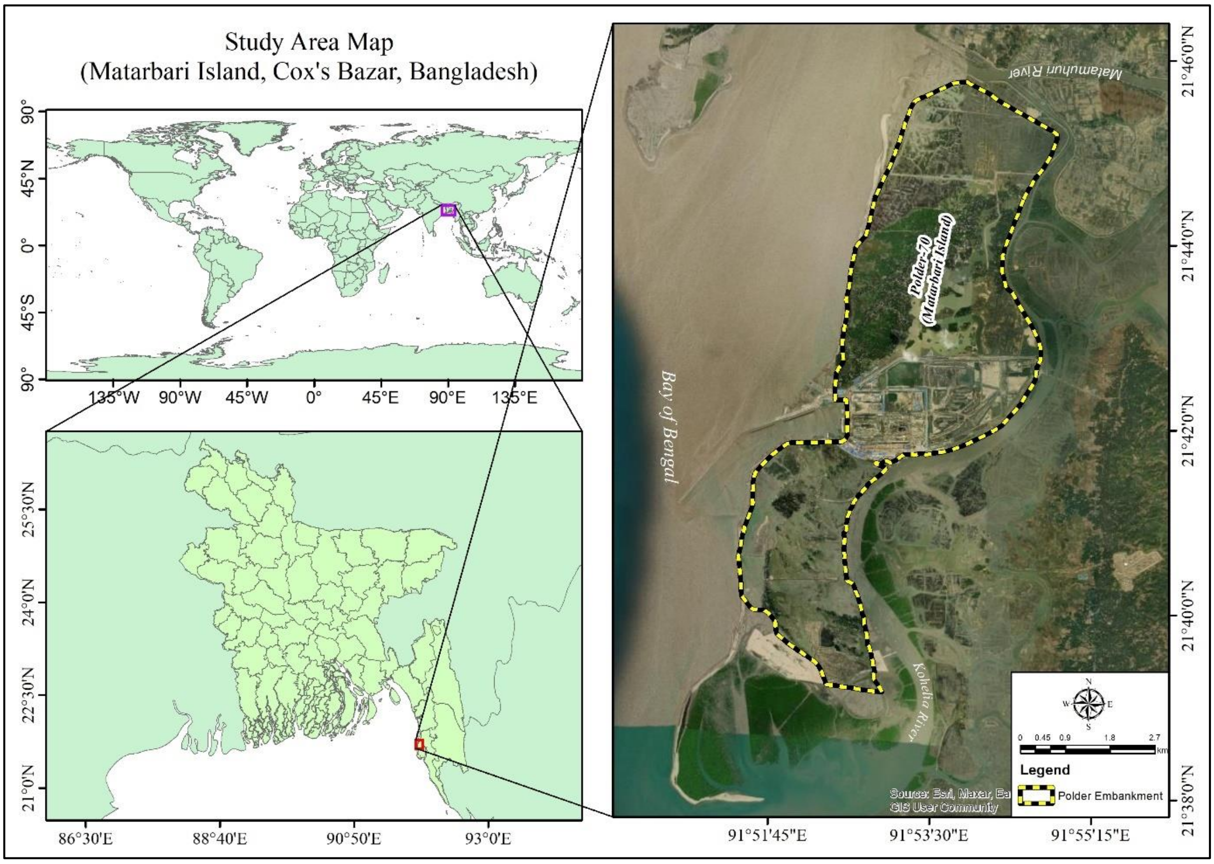

Figure 1. Study area

There are 19(nineteen) severe cyclones that hit the coastal area from 1960 to 2009. Thesecyclones made landfall at different tidal phases i.e., at low tide, at high tidal phase or in between low and high tide phase. All these 19 cyclones were simulated at original tidal phase and then opposite tidal conditions, i.e., if a cyclone made landfall on low tide, then both low tide and high tidal conditions of each cyclone were simulated. A total of 54 cyclone tracks (simulations) for the whole costal area will be considered based on 19 observed cyclones. To generate time series storm surge level, 54 cyclones have been considered under baseline condition and climate change scenario. Maximum surge levels for every cyclone have been extracted at 8 extraction points surrounding the polder. These surge level values were analyzed to determine the different return period for all the locations. Statistical analysis of surge level was carried out using Extreme Value Analysis (EVA) in MIKE Zero. Frequency analysis has been carried out to find the storm surge level for different return periods along the embankment to investigate the performance of existing coastal embankment. The present crest level of the embankments of coastal polder is based on extreme tide level with some added free board. Storm surge usually exceeds this embankment level.

Storm surge level at the proposed locations have been extracted for each cyclone and used for determining the design surge levels for different design periods. Different statistical methods like Log Normal, Log Pearson Type III, Weibull and Exponential are considered during computation of the design surge levels for different return periods. Exponential distribution result is selected for storm surge level. Climate changes effect like increase in sea level rise and changes in the wind speed is used for developing the future climate change conditions. The developed climate changes effects are added with all cyclonic storm surge models for preparing the future storm surge level at the interested locations. In this study, the bathymetry of the model has been updated with the collected bathymetry data under this project. Triangular fine resolution mesh (about 300 m) is provided in the sea side of both polders. Flexible mesh of the 2D model domain is used.The 2D hydrodynamic model is calibrated with recently measured water level data in Dhurong, Ujantia and SapmararDeil for the year 2022. The model is further validated with the measured water level in the domain for the year 2017 and 2016. Calibration and Validation location is shown in the Figure 3. The calibration plot is shown in the Figure 4.

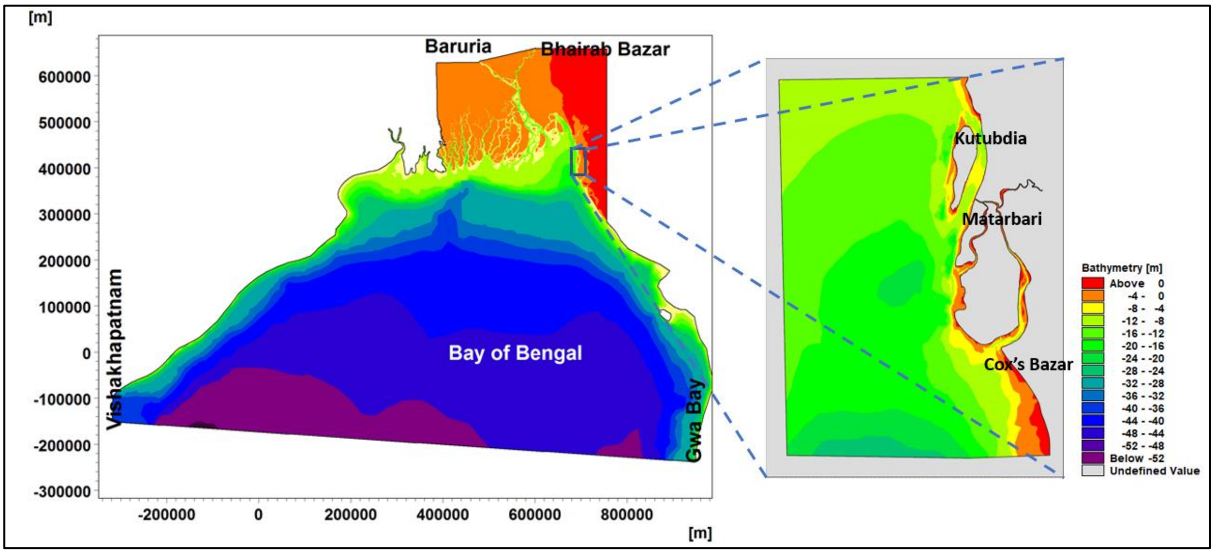

Figure 2. Extent of Bay of Bengal model (left) and dedicated HD model (right)

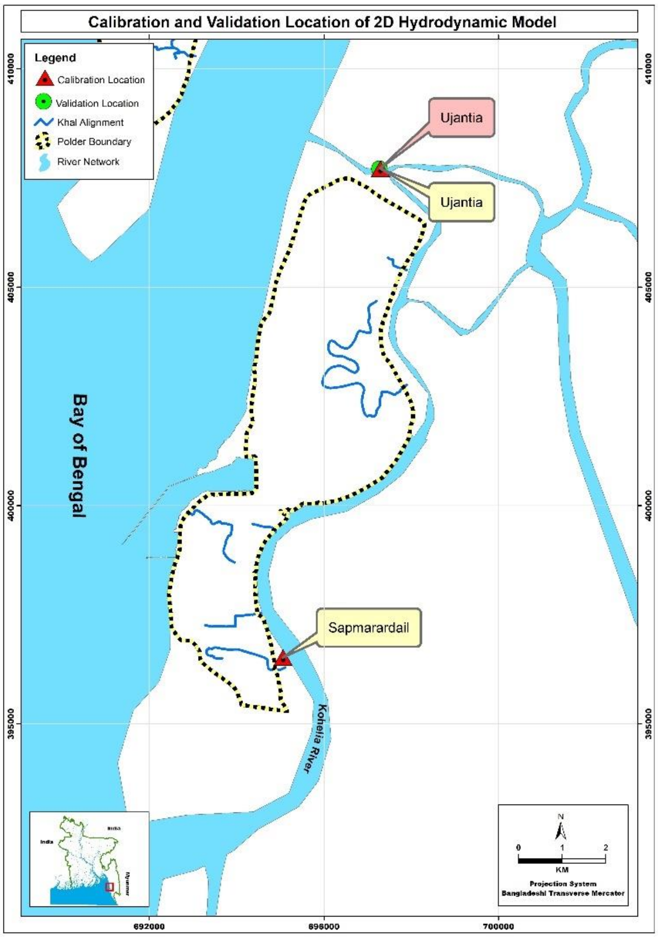

Figure 3. Calibration and validation location for 2D hydrodynamic model

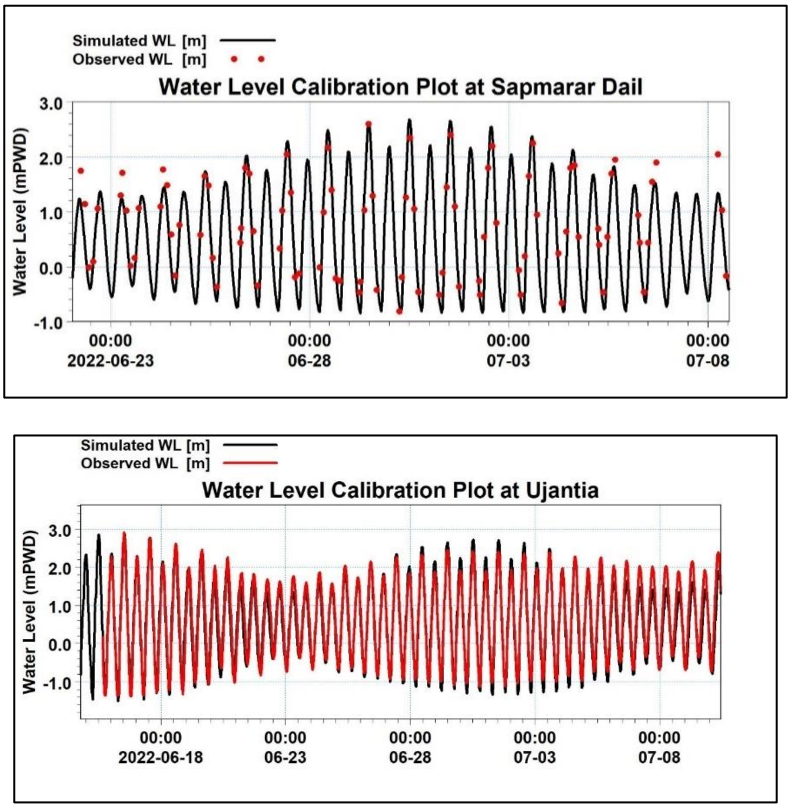

Figure 4. Calibration plot of 2D hydrodynamic model

And the validation plot of 2D hydrodynamic model is shown in the Figure 5. It is evident that simulated and observed water level matched well to serve the purpose.

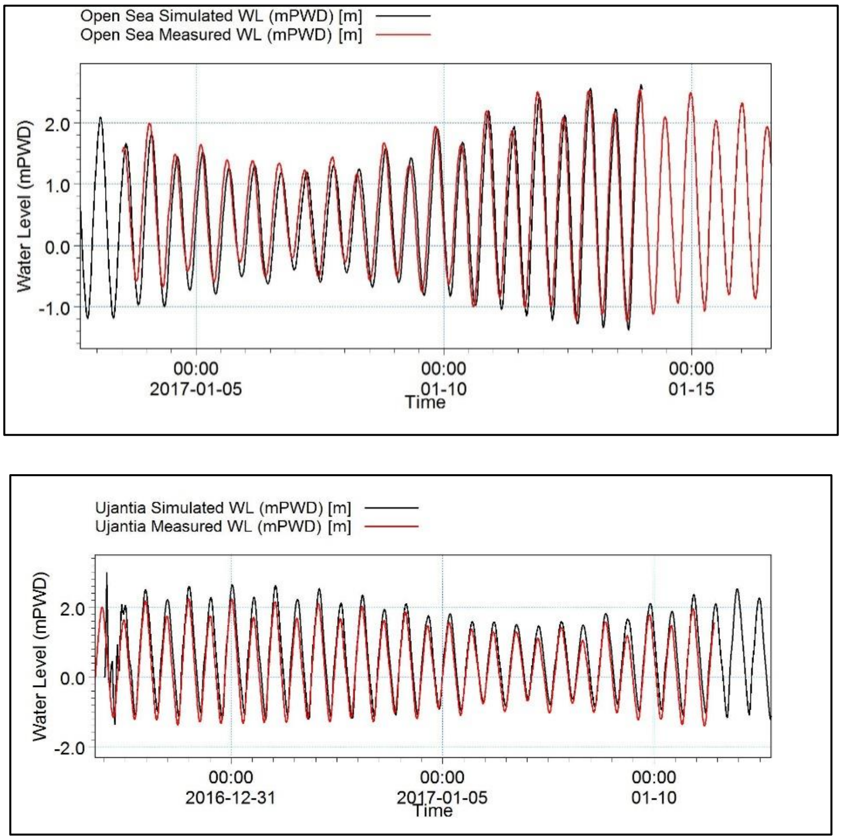

Figure 5. Validation plot of 2D hydrodynamic model

2.3 Cyclone model

The cyclone is characterized by 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 produces 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.

Holland Single Vortex theory has been applied for generating the wind field. The cyclone model requires following data/information for the description of wind field and pressure field: Maximum wind speed, $V_{m,}$ Cyclones track forward speed V_f and direction, Maximum wind speed, $V_{m,}$ Cyclones track forward speed V_f and direction, Central pressure, $P_{c,}$ Central pressure, $P_{c,}$ Central pressure, $P_{c,}$ Neutral pressure, $P_{n,}$ Holland and Parameter, B= 2.0-(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 is usually obtained by the following relation (Harper et al., 2001):

$V_{10\,r}$= Km. $_{(r)}$

where Vg is the rotational wind gradient speed at a distance r from the center of the cyclone. As mentioned by Harper et al, (2001) different values for the parameter K_m are available in the literature.

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:

$$K_m = \begin{cases} 0.81 & for V_g < 6\ m/s \\ 0.81 - 2.96\ 10{-}3\ (Vg - 6) & for\ 6 \le V_g < 19.5 \\ 0.77 - 4.31\ 10{-}3\ V_g - 19.5) & for\ 19.5 \le V_g < 45 \\ 0.66 & for V_g > 45\ m/s \end{cases}$$

For this study 0.75 is used as geotropic correction factor. The pressure and wind field for cyclone SIDR is presented in Figure 6.

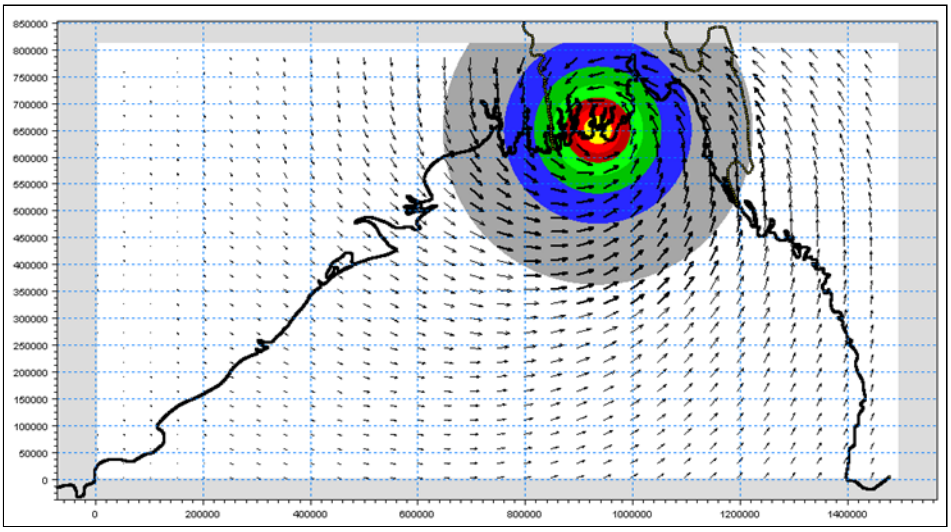

Figure 6. Example of pressure and wind field (SIDR, 2007)

2.4 Simulation of storm surge model

Due to its physical position, the coast of Bangladesh is highly susceptible to cyclonic storm surge. In the past fifty years, Bangladesh's coastline has been struck by nineteen strong cyclones. Incorporating the storm surge impact into the design of any coastal project is therefore vital. In this investigation, the existing Bay of Bengal Storm Surge Model will be utilized to incorporate the impact of storm surges. Combining the Cyclone and Hydrodynamic models produces the storm surge model. The Bay of Bengal model based on the MIKE21FM hydrodynamic modeling system will be utilized to simulate storm surges and related flooding. In the simulations of the hydrodynamic model, the cyclone's meteorological forcing will be provided by applying wind and pressure fields generated from the analytical cyclone model. The MIKE 21FM modeling system incorporates simulations of dynamic flooding and drying processes, which are crucial for a realistic simulation of coastal flooding and inundation.

The bathymetry of the storm surge model at and around Matarbari be updated using new data gathered by the IWM survey team. A dedicated storm surge domain is used which is illustrated in the Figure 2. In storm surge model land part is incorporated as surge overflows the land also. North, South, and West boundaries are the main boundaries, derived from BoB storm surge model, used in dedicated storm surge model as shown in the Figure 2. There is another boundary in Matamuhuri that has no significance compared to the other 3 boundaries as model domain is completely dominated by tide. So, a constant discharge (say, 100 m^3/s) is used. Figure 2 illustrates the domain of the storm surge model for the Bay of Bengal from where North, South, and West boundaries are generated. Model domain of dedicated storm surge model is illustrated by Figure 2. (right).

2.5 Development of cyclonic wave model

In the coastal region of Bangladesh, knowledge of wave dynamics is somewhat limited. Typically, mathematical modeling exercises omit wave effect when determining coastal dynamics. Such simplicity may result in significant inaccuracies when calculating the hydraulic design loads for coastal protection measures. Under the current study, coastal wave fields during severe cyclonic conditions are modeled. The Spectral Wave module has been used for the investigation. MIKE 21 SW is a spectral wind-wave model of the next generation based on an unstructured flexible mesh. The model simulates the growth, decline, and transformation of offshore and coastal wind-generated waves and swells. Same domain used for the wave model of the Study Area (Figure 1.).

North, South, and West boundaries are generated from the calibrated and validated BoB wave model. Closed boundary is given in the Matamuhuri river as there is no effect of wave in this point. Dedicated wave models is also verified with the measured wave data within the domain, offshore to Cox's bazar. During simulation of the wave model for each cyclone, the storm surge state and wind and pressure field of that cyclone will be input parameters. The proposed cyclonic wave model will offer wave spectra (significant wave height, peak period, etc.) during the duration of the cyclone. Using the generated wave height and peak duration, the wave runup is computed from where eventually free board is estimated. Parameter used at the boundary data for the local wave model is given in the Table 1.

Table 1. Parameters of Boundary Data used for Wave Model Simulation

Sl. No.	Boundary Data Parameter
1	Significant Wave Height
2	Peak Wave Period
3	Mean Wave Direction
4	Directional Standard Deviation

2.5.1 Wind forcing

Both Bay of Bengal and local wave model is forced by the cyclonic wind field generated by the Cyclone wind generation toolbox of MIKE model. The wind field during all sever cyclonic events (19 nos.) during 1960 to 2021 which made landfall to the Bay of Bengal coast is generated using this toolbox at actual condition as well as at climate change condition. For simulation of cyclonic wave using the dedicated model, the existing result of Bay of Bengal wave model is used for each cyclonic event to generate the boundary conditions of the dedicated model.

3 RESULTS AND DISCUSSION

For Matarbari Island crest level ranges between 2.962 m PWD to 6.788 m PWD, where at seaside it ranges 4.092 m PWD to 6.788 m PWD and along Kuhelia river crest level ranges 2.962 mPWD to 6.022 mPWD which is not sufficient to protect against storm surges that are currently occurring. The existing crest level profile of the embankment is shown in the Figure 7. Embankment Long Profile of Matarbari Island (Polder-70)

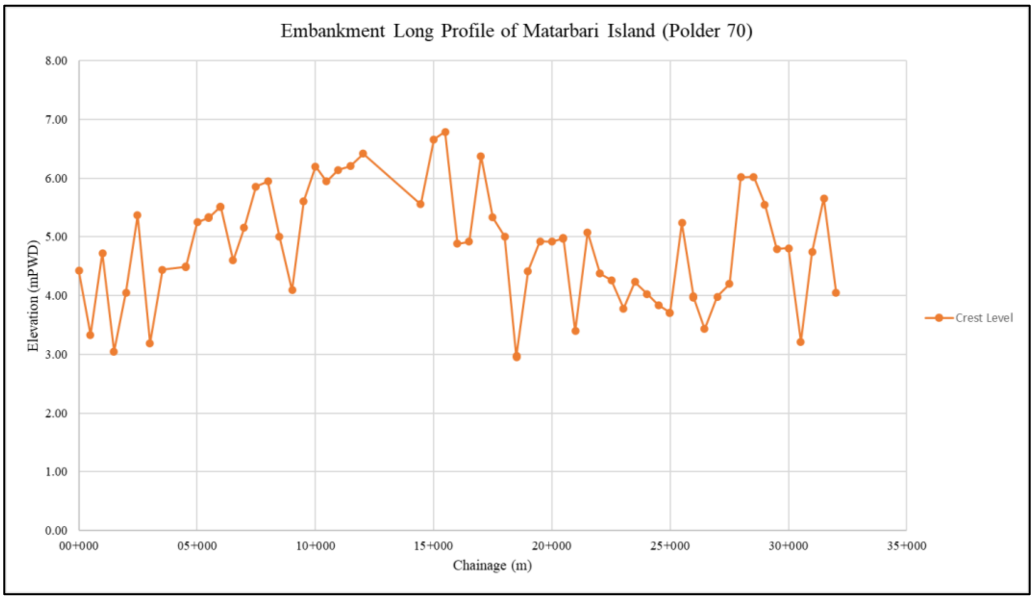

Figure 7. Embankment Long Profile of Matarbari Island (Polder-70)

3.1 Computation of design surge level

Frequency analysis has been carried out to find the storm surge level for different return periods along the embankment to investigate the performance of existing coastal embankment. The present crest level of the embankments of coastal polder is based on extreme tide level with some added free board. Storm surge usually exceeds this embankment level. Under the present study, time series storm surge levels in the peripheral rivers of coastal Matarbari polder at different locations have been extracted from simulation results. 8 extraction points are selected to serve this purpose around the polder at almost regular interval (i.e., say 5 km) which is illustrated. Point M-6 is located near Sitepara, vulnerable to erosion, area of Matarbari.

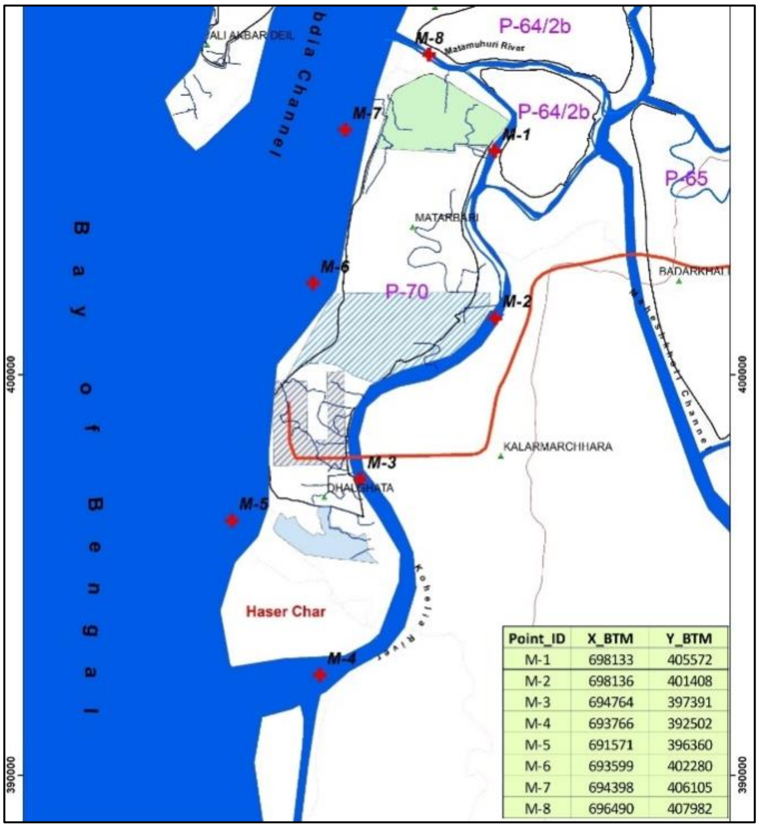

Figure 8. Storm Surge and Wave Extraction Location around Mataribari Island

Table 2. Maximum Storm Surge Level at Point M-6 for Different Cyclone Event

Maximum Storm Surge Level at Point M-6				
SL	Cyclone No.	Cyclone Event	Surge Level	
			Base Condition	Climate Change (2050)
1	1	1960 (Original)	4.40697	4.64134
2		1960_LT	4.87003	5.44618
3		1960_HT	3.3663	3.93056
4	2	1961 (Original)	3.02876	3.42229
5		1961_LT	2.19824	2.47963
6		1961_HT	2.57126	2.97889
7	3	1963 (Original)	2.69929	3.23582
8		1963_LT	2.69929	3.17264
9		1963_HT	2.99974	3.48167
10	4	1965_May	2.31397	2.51461
11		1965_May_LT	2.63936	2.99391
12		1965_May_HT	2.08033	2.32286
13	5	1965_Dec (Org and HT)	2.67372	2.85294
14		1965_Dec_LT	2.11431	2.59106
15	6	1966 (Original)	2.27397	2.47602
16		1966_LT	2.87126	3.06778
17		1966_HT	2.26964	3.35493
18	7	1970 (Original)	3.42976	3.60117
19		1970_LT	3.418	3.75223
20		1970_HT	3.17432	3.51725
21	8	1974 (Original)	2.17365	2.61073
22		1974_LT	3.09653	3.2956
23		1974_HT	2.38767	2.71144
24	9	1983 (Original)	2.92288	3.33199
25		1983_LT	3.05943	3.49074
26		1983_HT	2.30064	2.5027
27	10	1985 (Original)	2.12318	2.32551
28		1985_LT	2.14096	2.44571
29		1985_HT	3.00498	3.41894
30	11	1986 (Original)	2.02373	2.22938
31		1986_LT	2.03273	2.23819
32		1986_HT	2.04519	2.43452
33	12	1988 (Original)	2.41544	2.71205
34		1988_LT	3.29563	3.67082
35		1988_HT	2.08376	2.29377
36	13	1991 (Original)	4.86947	5.05769
37		1991_LT	4.3092	4.3092
38		1991_HT	5.30745	5.30745
39	14	1995 (Original)	2.90075	3.29499
40		1995_LT	2.4756	2.67833
41		1995_HT	2.51211	2.74782
42	15	1997_May (Org and	2.49134	2.69167

Maximum Storm Surge Level at Point M-6				
SL	Cyclone No.	Cyclone Event	Surge Level	
			Base Condition	Climate Change (2050)
		HT)		
43		1997_May_LT	3.23662	3.72752
44	16	1997_Sep	3.43234	3.64629
45		1997_Sep_LT	2.96237	3.51023
46		1997_Sep_HT	3.03146	3.54801
47	17	1998 (Original and LT)	3.16387	3.59982
48		1998_HT	2.2547	2.5916
49	18	2007 (Original)	2.24595	2.62084
50		2007_LT	2.51749	2.97048
51		2007_HT	2.01537	2.2928
52	19	2009 (Original)	2.46533	2.6689
53		2009_LT	2.47786	2.6807
54		2009_HT	2.58075	2.81424

There are 19 (nineteen) severe cyclones that hit the coastal area from 1960 to 2009. These cyclones made landfall at different tidal phases i.e., at low tide, at high tidal phase or in between low and high tide phase. All these 19 cyclones were simulated at original tidal phase and then opposite tidal conditions, i.e., if a cyclone made landfall on low tide, then both low tide and high tidal conditions of each cyclone were simulated. A total of 54 cyclone tracks (simulations) for the whole costal area will be considered based on 19 observed cyclones. To generate time series storm surge level, 54 cyclones have been considered under baseline condition and climate change scenario. Maximum surge levels for every cyclone have been extracted at the locations of interest shown in the Figure 8 and these surge level values will be analyzed to determine the different return period for all the locations. Statistical analysis of surge level will be carried out using Extreme Value Analysis (EVA) in MIKE Zero. Frequency analysis for point M-6 graphs for base and climate change condition are shown in the Figure 9 and Figure 10 respectively.

Storm surge level at the proposed locations have been extracted for each cyclone and used for determining the design surge levels for different design periods. Different statistical methods like Log Normal, Log Pearson Type III, Weibull and Exponential are considered during computation of the design surge levels for different return periods. Exponential distribution result is selected for storm surge level.

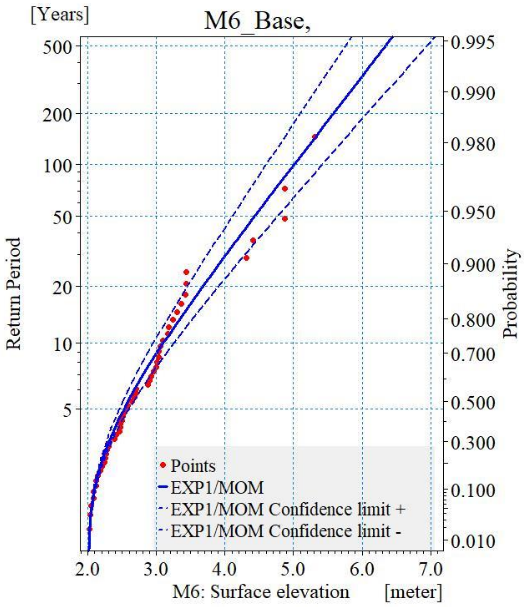

Figure 9. Frequency Distribution Curve of Maximum Storm Surge Level of Point M6 (Base Condition)

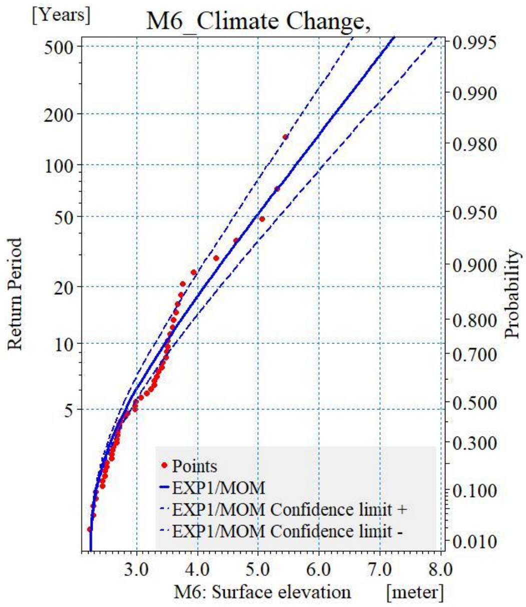

Figure 10. Frequency Distribution Curve of Maximum Storm Surge Level of Point M6 (Climate Change Condition)

Climate changes effect like increase in sea level rise and changes in the wind speed are used for developing the future climate change conditions. The developed climate changes effects are added with all cyclonic storm surge models for preparing the future storm surge level at the interested locations. The frequency distribution matrix for point M-6 (near Sitepara) is presented in the following

Table 3. Frequency Distribution Matrix for Stom Surge Level Point M-6 (Near Site Para)

Return Period	Base Condition				Climate Change (2050)			
	WEI2	LN2	LP3	EXP1	WEI2	LN2	LP3	EXP1
10	3.112	3.061	3.085	3.101	3.434	3.434	3.468	3.468
20	3.632	3.899	3.574	3.675	4.241	4.241	3.946	4.115
50	4.296	5.467	4.261	4.435	5.645	5.645	4.58	4.971
100	4.787	7.081	4.826	5.009	7.01	7.01	5.077	5.618
CHISQ	4.17	12.472	1.906	4.925	19.642	19.642	11.717	17.755
KS	0.081	0.13	0.07	0.085	0.126	0.126	0.095	0.112

Similar procedure followed for determining the design surge levels for different return periods at the other locations which is presented in the Figure 8.

Table 4. Surge Level at Selected Locations Around the Polder 70 (Matarbari)

Location No.	BTM X	BTM Y	Surge Level (mPWD) in Different Return Period							
			Base				Climate Change (2050)			
			10	20	50	100	10	20	50	100
M-1	698133	405572	3.15	3.71	4.45	5.01	3.43	4.04	4.85	5.46
M-2	698136	401408	3.20	3.80	4.60	5.20	3.52	4.24	5.19	5.90
M-3	694764	397391	3.13	3.72	4.50	5.09	3.48	4.15	5.04	5.71
M-4	693766	392502	3.02	3.58	4.31	4.87	3.38	3.99	4.79	5.39
M-5	691571	396360	2.97	3.50	4.20	4.72	3.34	3.93	4.71	5.30
M-6	693599	402280	3.10	3.68	4.44	5.01	3.47	4.12	4.97	5.62
M-7	694398	406105	3.15	3.73	4.51	5.09	3.52	4.18	5.06	5.73
M-8	696490	407982	3.27	3.89	4.72	5.34	3.63	4.40	5.42	6.19

3.2 Computation of design wave height

The simulated significant wave height and peak period are extracted from the specific cyclonic wave model result for the specific location (Figure 8). Later, these data are used for preparing the design significant wave height for each location. Different statistical methods like Log Normal, Log Pearson Type III, Exponential, and Weibull distribution methods are considered for computing the design wave height. PDS is method is adopted for frequency analysis by MIKE EVA.

The design significant wave height is used for calculating wave runup for different wave overtopping conditions. For point M-6 maximum significant wave height for different cyclones (total 19 at original phase) and associated peak wave period are listed in the Table 5.

Table 5. Maximum Significant Wave Height During Each Cyclone and Associated Peak Wave Period for Point M-6

Cyclone No.	**Cyclone event**	**Base Condition**		**Climate Change (2050) Condition**	
		Sig. Wave Height	**Peak Wave Period**	**Sig. Wave Height**	**Peak Wave Period**
1	1960 (Orginal)	3.51	9.35	3.62	9.26
2	1961 (Original)	1.01	5.92	1.46	7.71

Cyclone No.	Cyclone event	Base Condition		Climate Change (2050) Condition	
		Sig. Wave Height	Peak Wave Period	Sig. Wave Height	Peak Wave Period
3	1963 (Orginal)	2.59	8.79	2.75	8.66
4	1965_May	1.84	6.81	1.64	6.25
5	1965_Dec (Org and HT)	2.39	7.80	2.35	8.30
6	1966 (Orginal)	2.23	7.70	2.37	7.95
7	1970 (Orginal)	2.12	8.37	2.32	8.05
8	1974 (Orginal)	2.11	7.20	2.24	7.30
9	1983 (Orginal)	1.85	6.00	2.04	6.23
10	1985 (Orginal)	1.76	6.04	1.93	9.02
11	1986 (Orginal)	1.94	6.60	1.97	5.96
12	1988 (Orginal)	1.28	9.45	1.90	5.77
13	1991 (Orginal)	3.62	8.75	3.89	9.23
14	1995 (Orginal)	0.66	15.92	0.71	16.94
15	1997_May (Org and HT)	2.30	6.85	2.54	8.59
16	1997_Sep	2.81	8.72	2.18	7.25
17	1998 (Orginal and LT)	1.77	6.90	1.87	8.40
18	2007 (Orginal)	1.60	16.59	1.78	16.83
19	2009 (Orginal)	0.80	9.41	0.79	9.51

Frequency analysis is done by MIKE EVA. Design significant wave height and corresponding peak wave period are found out for different period. Frequency analysis plot and distribution matrix for point M-6 (near Sitepara) are presented by the Figure 11and Figure 12 respectively.

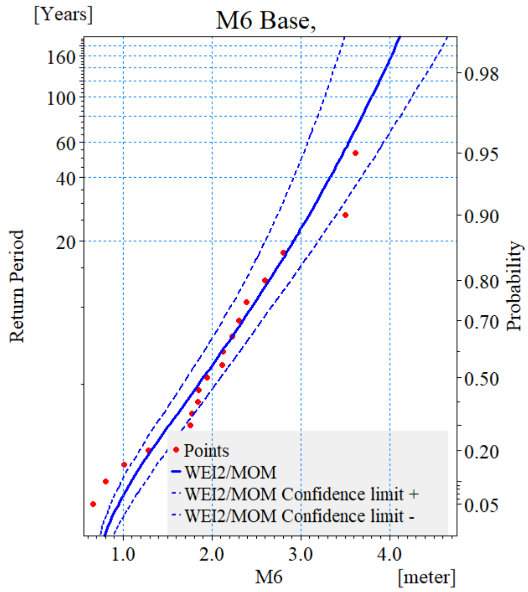

Figure 11. .Frequency Distribution Curve of Maximum Significant Wave Height of Point M6 (Base Condition)

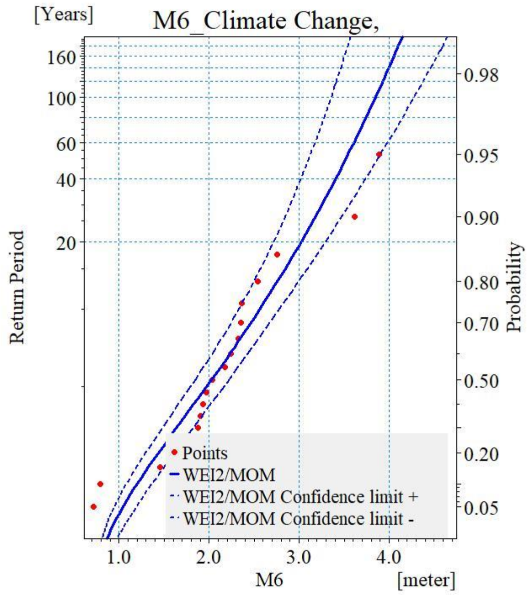

Figure 12. .Frequency Distribution Curve of Maximum Significant Wave Height of Point M6 (Climate Change Condition)

Table 6. Frequency Distribution Matrix for Significant Wave Height of Point M-6 (Near Site Para)

Return Period	**Base Condition**				**Climate Change (2050)**			
	WEI2	**LN2**	**LP3**	**EXP1**	**WEI2**	**LN2**	**LP3**	**EXP1**
10	2.45	2.54	2.52	2.47	2.57	2.79	2.65	2.60
20	2.92	3.66	2.96	3.41	3.02	4.22	3.02	3.59
50	3.45	5.51	3.40	4.65	3.52	6.71	3.37	4.89
100	3.80	7.25	3.66	5.59	3.85	9.15	3.55	5.88
CHISQ	2.00	1.37	1.68	2.95	5.16	10.84	5.16	5.16
KS	0.17	0.27	0.14	0.29	0.16	0.30	0.18	0.33

Similar processes are applicable for other points of interest except M-1, M-2, M-3, M-4 and M-8. Significant wave heights for both base and climate change condition are found out and shown in the **Error! Reference source not found.**

Table 7. Significant Wave Height at Selected Locations Around the Polder 70 (Matarbari)

Location No.	BTM X	BTM Y	Significant Wave Height (m) in Different Return Period							
			Base				Climate Change (2050)			
			10	20	50	100	10	20	50	100
M-1	698133	405572	0.47	0.62	0.82	0.90	0.51	0.67	0.90	0.90
M-2	698136	401408	0.49	0.65	0.86	1.02	0.53	0.70	0.93	1.12
M-3	694764	397391	0.97	1.27	1.69	2.01	1.04	1.38	1.83	2.19
M-4	693766	392502	0.71	0.93	1.24	1.48	0.77	1.01	1.35	1.61
M-5	691571	396360	2.71	3.12	3.56	3.85	2.82	3.21	3.64	3.92
M-6	693599	402280	2.45	2.92	3.45	3.80	2.57	3.02	3.52	3.85
M-7	694398	406105	2.43	2.93	3.50	3.88	2.52	3.00	3.55	3.91
M-8	696490	407982	0.32	0.42	0.56	0.67	0.35	0.46	0.61	0.73

Point M-1, M-2, M-3, M-4, and M-8 are located on the peripheral river, away from the coast. In this case different technique is adopted to find design significant wave height and peak wave period. (Ref.: Coastal Engineering Manual, Part II, Chap 2, pp 2-48, 1 August 2008). In order to know the wave condition during cyclone, significant wave height and peak period have been predicted from the cyclonic wind field. Cyclonic wind field for 19 severe cyclones have been generated using Mike 21 Cyclone module for the entire coastal region of Bangladesh. Maximum wind speed was obtained from the selected locations (M-1, M-2, M-3, M-4 and M-8) for each cyclone. The 19 wind speed values obtained for each location were then analyzed to obtain the 10, 20, 50 and 100 years return period wind speed. A sample of frequency distribution plot for point M-3 is shown by the Figure 13 and Figure 14.

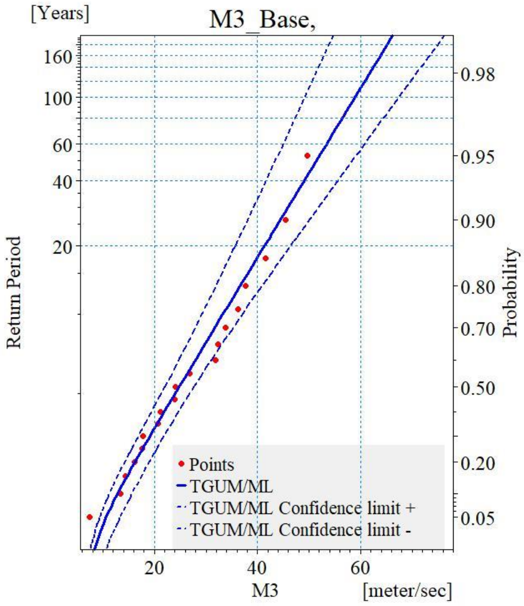

Figure 13. Frequency Distribution Curve of Maximum Wind Speed of Point M3 (Base Condition)

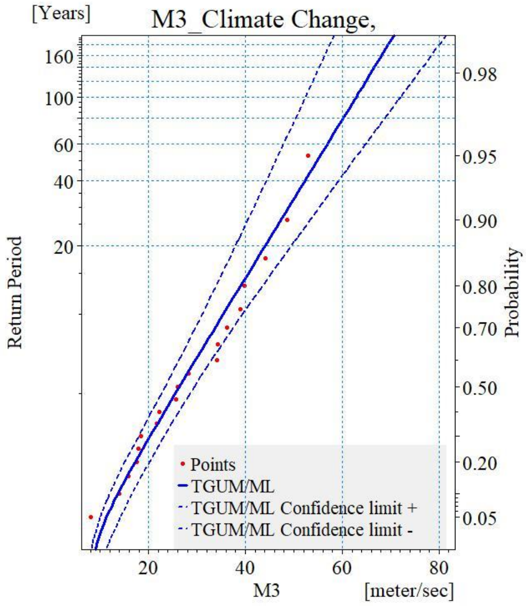

Figure 14. Frequency Distribution Curve of Maximum Wind Speed of Point M3 (Climate Change Condition)

Cyclonic wind speed for different return period for base and climate change condition near the Matarbari Island embankment (along Kuhelia river) is presented in the **Error! Reference source not found.**.

Table 8. Frequency Distribution Matrix for Wind Speed at Point M-3

Return Period	Base Condition				Climate Change (2050)			
	WEI2	LN2	LP3	TGUM/ML	WEI2	LN2	LP3	TGUM/ML
10	33.452	32.622	33.974	33.331	35.584	34.728	36.074	35.458
20	40.362	42.912	41.044	41.413	43.044	45.955	43.754	44.1
50	48.045	57.927	48.735	51.472	51.373	62.491	52.251	54.86
100	53.168	70.594	53.718	58.892	56.945	76.548	57.849	62.796
CHISQ	1.368	0.737	0.737	0.737	1.368	0.737	1.368	0.737
KS	0.118	0.144	0.106	0.125	0.124	0.147	0.113	0.13

Using this wind speed for selected locations (M-1, M-2, M-3, M-4 and M-8), fetch length and corresponding depth, significant wave height and peak wave period are determined by the help of Coastal Engineering Manual guidelines. Significant wave height and peak wave period for these coast-away points are listed in the Table 9. Wind Speed and Peak Wave Period for Various Return Period at Coast Away Location

Table 9. Wind Speed and Peak Wave Period for Various Return Period at Coast Away Location

Location No	Location Union Name	BTM X	BTM Y	Fetch Length X (km)	Depth h (m)	Different Return Period (Years)	Base Condition			Climate Change Condition (2050)		
							Wind Speed (m/s)	Wave Height Hm0 (m0)	Peak Wave Period Tp (Sec)	Wind Speed (m/s)	Wave Height Hm0 (m0)	Peak Wave Period Tp (Sec)
M1	Magnama	698133	405572	0.5	1.5	10	33.48	0.47	1.52	35.629	0.51	1.56
						20	41.63	0.62	1.67	44.341	0.67	1.71
						50	51.779	0.82	1.83	55.182	0.90	1.88
						100	59.25	0.9	1.94	63.177	0.90	2.00

Location No	Location Union Name	BTM X	BTM Y	Fetch Length X (km)	Depth h (m)	Different Return Period (Years)	Base Condition			Climate Change Condition (2050)		
							Wind Speed (m/s)	Wave Height Hm0 (m0)	Peak Wave Period Tp (Sec)	Wind Speed (m/s)	Wave Height Hm0 (m0)	Peak Wave Period Tp (Sec)
M2	Matarbari	698136	401408	0.55	1.92	10	33.33	0.49	1.57	35.458	0.53	1.61
						20	41.41	0.65	1.72	44.1	0.7	1.76
						50	51.47	0.86	1.89	54.86	0.93	1.94
						100	58.88	1.02	2	62.796	1.12	2.06
M3	Dhalghata	694650	397391	2.13	3.9	10	33.33	0.97	2.46	35.458	1.04	2.52
						20	41.41	1.27	2.7	44.1	1.38	2.77
						50	51.47	1.69	2.96	54.86	1.83	3.05
						100	58.89	2.01	3.14	62.796	2.19	3.23
M4	Dhalghata	693766	393600	1.17	4.7	10	33.13	0.71	2.01	35.247	0.77	2.06
						20	41.13	0.93	2.2	43.832	1.01	2.26
						50	51.08	1.24	2.42	54.529	1.35	2.49
						100	58.43	1.48	2.56	62.421	1.61	2.64
M8	Magnama	696400	407900	0.23	4.82	10	33.48	0.32	1.17	35.629	0.35	1.2
						20	41.65	0.42	1.29	44.341	0.46	1.32
						50	51.81	0.56	1.41	55.182	0.61	1.45
						100	59.31	0.67	1.5	63.177	0.73	1.54

4.3 Wave run-up and freeboard for embankment crest level

Wave generated during nineteen severe cyclones is significant and causes considerable wave run-up and overtopping during cyclone which are important for designing embankment crest level and slope. The wave run-up height is defined as the vertical difference between the highest point of wave run-up and the still water level (SWL). Due to the stochastic nature of the incoming waves, each wave will give a different run-up level. Most of the coastal dike heights have been designed to a wave run-up height Ru2%. This is the wave run-up height which is exceeded by 2% of the number of incoming waves at the toe of the structure. The idea behind this was that if only 2% of the waves reach the crest of a dike or embankment during design conditions, the crest and inner slope do not need specific protection measures other than clay with grass. It is for this reason that much research in the past has been focused on the 2%-wave run-up height.

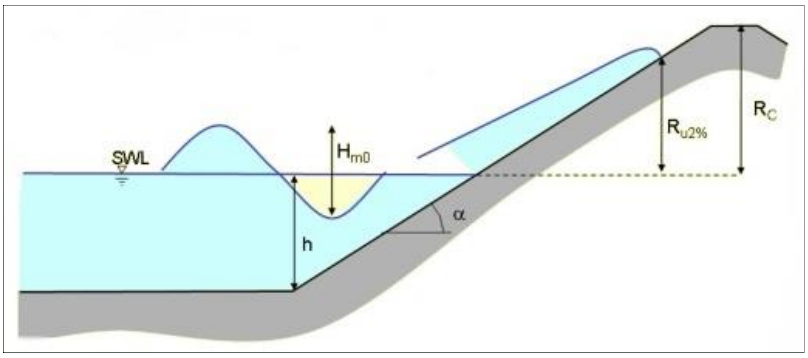

Figure 15. Definition of the wave run-up height $R_{u2\%}$ on a smooth impermeable Slope (Source: Eurotop Manual, 2007)

Here, $R_{u2\%}$= Wave run-up height exceeded by 2% of the incoming waves, R_C is Freeboard, H_{m0} is significant wave height, h is Water depth at the toe of the structure, αis seaward slope steepness and SWL is still water level.

For designing embankment crest level, wave run-up caused by 10-yr, 20-yr, 50-yr and 100-yr return period significant wave height, was predicted. Wave run-up was computed using the methodology given in the Eurotop Manual (2007). Free board embankment formation level was determined allowing 5 l/s/m overtopping by the iteration process is presented in Table 10. Here the freeboard calculation has been made for the slope roughness factor 1.0.

Table 10. Free Board Computation for Potential Locations

Location	Free Board (m) for different Return Period							
	Base Condition				Climate Change Condition (2050)			
	10 yr	20 yr	50 yr	100 yr	10 yr	20 yr	50 yr	100 yr
M1	0.15	0.22	0.31	0.36	0.17	0.24	0.34	0.37
M2	0.17	0.24	0.33	0.41	0.18	0.26	0.36	0.45
M3	0.51	0.69	0.95	1.16	0.55	0.76	1.04	1.27
M4	0.31	0.43	0.60	0.73	0.34	0.47	0.66	0.80
M5	2.77	3.30	3.90	4.30	2.91	3.44	4.01	4.39
M6	2.44	3.05	3.78	4.23	2.59	3.18	3.85	4.30
M7	2.42	3.06	3.81	4.34	2.53	3.16	3.88	4.38
M8	0.08	0.11	0.16	0.20	0.09	0.13	0.18	0.23

3.3 Computation of embankment crest level

The design crest level and side slope for embankment will be established based on maximum storm surge level, freeboard allowing 5 l/s/m overtopping, potential climate change impact and land subsidence. Polder 70 and polder 71 are close to the sea and along the wide rivers where storm surge level is significant. Considering these, these 2 polders will be designed based on maximum storm surge level and wave run-up for cyclonic wave. Based on the results of the storm surge and the project life, the design return period should be fixed.

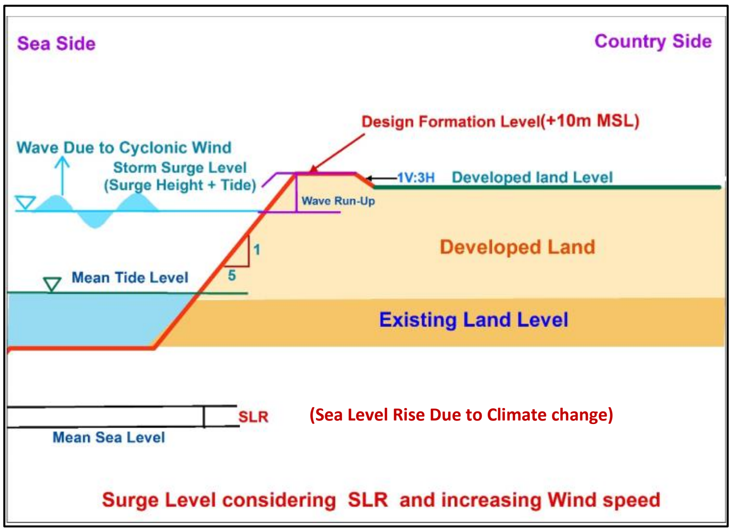

Figure 16. A typical computation for fixing embankment crest level (source: IWM)

The designer has several options in selecting slope and surface roughness. Here sea/channel side slope is considered as 1:5 and roughness 1 considering concrete block would be used for protection work. Designer also has a choice of being more cautious by adding the standard deviation to the surge height. In this context, it should be noted that there are other safety factors built into this methodology. In earlier years the design would have a higher degree of protection. A typical computation for fixing embankment crest level is illustrated by Figure 16. Here to find design crest level at the point of interest freeboard, land subsidence and standard deviation are added with the storm surge level. Table 11 represents the design crest level at climate change condition at 50-yr return period and 100-yr return period. Design crest level comparison at base and climate change condition is shown in the

Table 11. Computation of Embankment Crest Level at Potential Locations

Location	Modelled Storm Surge Level (mPWD) A	Standard Deviation B	Free Board (m) C	Allowance for Subsidence (m) D	Design Crest Level (mPWD) A+B+C+D
50 Year Return Period (Climate Change)					
M-1	4.848	0.353	0.34	0.06	5.60
M-2	5.185	0.414	0.36	0.06	6.02
M-3	5.038	0.389	1.04	0.06	6.53
M-4	4.788	0.35	0.66	0.06	5.86
M-5	4.707	0.341	4.01	0.06	9.12
M-6	4.971	0.374	3.85	0.06	9.26
M-7	5.064	0.386	3.88	0.06	9.39
M-8	5.423	0.446	0.18	0.06	6.11
100 Year Return Period (Climate Change)					
Location	Modelled Storm Surge Level (mPWD) A	Standard Deviation B	Free Board (m) C	Allowance for Subsidence (m) D	Design Crest Level (mPWD) A+B+C+D
M-1	5.458	0.44	0.37	0.06	6.32
M-2	5.901	0.51	0.45	0.06	6.92
M-3	5.71	0.48	1.27	0.06	7.52
M-4	5.393	0.43	0.80	0.06	6.69
M-5	5.296	0.42	4.39	0.06	10.17
M-6	5.618	0.46	4.3	0.06	10.44
M-7	5.732	0.48	4.38	0.06	10.65
M-8	6.194	0.551	0.23	0.06	7.04

Table 12. Design Crest level at the Potential Locations

Lofcation	**50-yr Return Period**		**100-yr Return Period**	
	Base	**CC**	**Base**	**CC**
M-1	5.15	5.60	5.83	6.32
M-2	5.34	6.02	6.10	6.92
M-3	5.85	6.53	6.73	7.52
M-4	5.29	5.86	6.06	6.69
M-5	8.46	9.12	9.46	10.17
M-6	8.61	9.26	9.71	10.44
M-7	8.71	9.39	9.90	10.65
M-8	5.30	6.11	6.05	7.04

Table 13. Computation of design surge level at the location of interest

Storm Surge Model	**Simulation Options**	**Extraction of Cyclonic Storm Surge Levels**	**Statistical Analysis**	**Consideration**
Development of Cyclonic Storm Surge Models cyclones that hit	without Climate Change Condition (Base condition)	Extraction surge levels for cyclones at one location without climate change	Computation of Design Surge Level without climate change	Recommended Design Surge Level with climate change

study area		condition	condition	
	Climate Change Condition	Extraction surge levels for cyclones at one location with climate change condition	Computation of Design Surge Level with climate change condition	

Like storm surge level, wave height near polder embankment can be found out for two options, i.e., base and climate change conditions. The following Table 14. Computation of design wave height near polder embankment will guide the overall procedure for calculating the design significant wave height at the location of interest with and without climate change condition.

Table 14. Computation of design wave height near polder embankment

Cyclonic Wave Model	Simulation Options	Extraction of Significant Wave Heights	Statistical Analysis	Consideration
Development Cyclonic Wave Models	without Climate Change Condition (Base condition)	Extraction Significant Wave Heights for cyclones at one location without climate change condition	Computation of Design Significant Wave Height without climate change condition	Recommended Design Significant Wave Height with climate change condition
	Climate Change Condition	Extraction of Significant Wave Heights for cyclones at one location with climate change condition	Computation of Design Significant Wave Height with climate change condition	

From frequency analysis for different return periods (i.e., 10, 20, 50, 100 year) crest level of the embankment is determined. In the coordination meeting with BWDB higher officials, it has been decided that crest level must be designed based on 100-year return period considering climate change scenario. But the implementation of embankment construction needs to follow an adaptive approach. IWM will provide an implementation plan.

4 CONCLUSIONS

The objective of this study was to conduct a comprehensive and unified investigation to create a strategy for enhancing the coastal embankment, improving drainage, protecting against erosion, preventing saline water intrusion, and reclaiming land (Dhalghata) at Matarbari island in Cox's Bazar. This island is susceptible to several natural disasters like tropical cyclones, storm surges, coastal erosion, and rising sea levels.

The erosion of embankments is a significant problem for Matarbari islands, leading to decreased effectiveness of the polder's ability to protect against tidal floods and storm surges. In Matarbari, 23.597 km of existing embankment is entirely earthen, with 4.22 km, including geo-bag protection, being severely affected by wave action during cyclones and regular high tides. Coastal erosion is also a challenge for integrated management and development of these islands. Satellite images indicate erosion rates Matarbari from 1.99-10.31 m/yr.

It is recommended to implement embankment re-sectioning and slope protection works for the suggested reach of the embankment. Design embankment crest level is suggested for 100-yr return period considering cyclonic storm surge and wave under climate change condition for Matarbari. The design crest level is 10mPWD at seaside and 6.5 mPWD at river side.CC block is suggested for protection of embankment slope with a side slope 5H:1V in the seaside.

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