Adaptation Program on Climate Resilient Infrastructures in Coastal Zone of Bangladesh

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Presently cyclonic storms cause destruction in the coastal zone of Bangladesh. The polder was designed originally to keep out the highest tides, without consideration of storm surges. This paper applies a cyclonic model to individual polders to design a new system taking into account future storm surge heights, wave run-up and land subsidence. The maximum surge height was obtained from 106 pre-selected locations in the model domain, for each location of the 38 cyclone simulations. The 38 values were analyzed to obtain the 25, 50 and 100 years return period. Improvements are proposed to make the physical and operational conditions of the polders satisfactory.

Introduction

The coastal zone in southern Bangladesh adjoining the Bay of Bengal is characterized by a delicately balanced natural morphology of an evolving flat Delta subject to very high tides and frequent cyclones coming in from the Bay of Bengal encountering very large sediment inflows from upstream. The strength of the tides and the flatness of the delta causes the tides to influence river processes a long way upstream in the southern estuaries. This entire area is called the coastal zone. The coastal zone, in its natural state, used to be subject to inundation by high tides, salinity intrusion, cyclonic storms and associated tidal surges etc. Since the 1960s, the construction of polders along the entire coastal belt provided protection to the people and their agriculture land from tidal inundation and saline water intrusion. A polder is a designated area that is enclosed on all sides by embankments and offering protection against tidal floods, salinity intrusion and sedimentation. The ability to drain the land during low tide that occurs twice a day has made it possible to build 139 polders wherein 1.2 million hectares of land are now under permanent agriculture within the coastal embankment system. The embankment system was designed originally to keep out the highest tides, without any consideration of possible storm surges. Recent cyclonic storm damages and the anticipation of worse future situations on account of climate change, has caused this strategy to be revised. Coastal Embankment Improvement Program will provide protection against anticipated long term impacts of sea level rise and increased cyclone intensity predicted in climate change projections.

Storm Surge and Wave Propagation Modelling

Tropical cyclone is a low-pressure system which develops in the tropics and is sufficiently intense to produce sustained gale force winds of at least 63 km/h. If the sustained wind reaches hurricane force of at least 118 km/h the system is defined as a severe tropical cyclone. Tropical cyclones can cause significant phenomena which can adversely impact on communities and the environment. The most common features are destructive winds, heavy rainfall and cyclone induced storm surge that can lead to flooding. The Bay of Bengal is one of the hotspots for the generation of tropical cyclones. About one-tenth of the global numbers of cyclones that form in different regions of the tropics occur in the Bay of Bengal (Gray, 1968; Ali, 1980). In this region cyclones occur in the pre- and post-monsoon seasons (i.e from March to May and October to November). Most of the cyclones hit the coasts of Bangladesh with a north-eastward approaching angle. Major tropical cyclonic disasters in 1970 and 1991 killed an estimated 500,000 and 140,000 people respectively. The severe cyclone which occurred in November 1970 was followed by one in May 1985, one in November 1988, one in April 1991 and one in May 1997. In the recent years cyclones Sidr in November 2007 and Aila in May 2009 struck the south western coastal zone proving yet again that the whole coastal zone is vulnerable to cyclones and storm surges.

Storm surge models comprise a Cyclone model and Hydrodynamic model. IWM has maintained the two-dimensional Bay of Bengal Model since 1995. The model was updated with the recent bathymetry of the estuary and rivers. Recently the storm surge model was further refined down to a 200m grid resolution incorporating the Sundarban area, updated with the recent bathymetric data and extended to the sea up to 16º latitude. The existing Bay of Bengal Model has been applied for storm surge modelling.

The storm surge model is the combination of Cyclone and Hydrodynamic models. For simulating the storm surge and associated flooding, the Bay of Bengal model, based on MIKE21 hydrodynamic modelling system, has been adopted. In the hydrodynamic model simulations, meteorological forces due to the cyclone has been estimated by applying wind and pressure fields derived from the analytical cyclone model. The MIKE 21 modelling system includes dynamic simulation of flooding and drying processes, which are very important for a realistic simulation of flooding in the coastal area and inundation. The model set-up comprises model grid, bathymetry, modelling parameters and calibration.

Hydrodynamic Model

The model is two way nested and includes four different resolution levels in different areas. The coastal region of Bangladesh and the Meghna estuary are resolved on a 200 m grid. Bathymetry of the model has been generated based on data collected from different sources. 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 ($m^{1/3}/s$). Velocity based Smagorinsky formulation has been used for eddy viscosity. The proportionality factor for each area has been considered 0.28.

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 the northern 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.

Cyclone Model

The description of a cyclone is based on a 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 metre 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, the Holland Single Vortex theory has been applied. The cyclone model needs the 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, $B = 2.0 - (P_c - 90)/160$

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

$$v_{10r} = .v_{g(r)}$$

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 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 formulations 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 factor is computed as:

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

For this paper 0.75 is used as geostrophic correction factor.

Storm Surge Modelling

During the period of 1960-2009, nineteen (19) severe cyclones hit the coast of Bangladesh. The most recent one is the Cyclone Aila of 2009. These cyclones have been considered in this study. The source of cyclone data is the Bangladesh Meteorological Department (BMD). The cyclones’ information includes cyclone period, position of cyclone, cyclone intensity, pressure drop (ΔP), maximum wind speed (Wm) and radius to maximum wind (R_m).

The calibrated and validated hydrodynamic/tidal model with input from the cyclone model i.e. wind and pressure fields are used to generate and calibrate the surge level using the wind friction factor as calibration parameter only. A linear wind friction factor is used (0.0016-0.0026).

Development of Wave Model

Understanding on wave dynamics in the coastal region of Bangladesh is fairly poor. Mathematical modelling exercises often do not include the wave impact to determine the coastal processes. Such simplicity may impose considerable errors while computing the design hydraulic loads on coastal protection works. Particularly the south-eastern coast is subject to noticeable wave attack during the monsoon. Also during cyclone, wave height is significant. Under the present study cyclonic wave fields across the coast for 19 severe cyclones as well as for normal monsoon condition were modelled. Spectral Wave module was applied in this study. MIKE 21 SW is a new generation spectral wind-wave model based on unstructured flexible mesh. The model simulates the growth, decay and transformation of wind generated waves and swells in the offshore and coastal areas. MIKE 21 SW includes the following physical phenomena:

- Wave growth by action of wind
- Non-linear wave-wave interaction
- Dissipation due to white capping
- Dissipation due to bottom friction
- Dissipation due to depth-induced wave breaking
- Refraction and shoaling due to depth variation
- Wave-current interaction
- Effect of time varying water depth.

Flexible mesh used for the Bay of Bengal model has been further updated for wave simulation. The model domain has been extended further. Finer resolution has been used in deep sea. Cyclonic wave generated from cyclonic wind and cyclonic wind originated far away from the Bangladesh coast. Considering generation locations of nineteen severe cyclone, the model domain for cyclonic wave simulation extended upto 4^o latitude. The wave modelling has made it possible to find the wave height and duration for the sea facing polders.

Storm Surges and their Probability of Occurrence

Under this study, time series storm surge levels in the peripheral rivers of coastal polders at different locations have been generated from simulation results. In the last 52 years there have been 19 major cyclones which have been sufficiently documented to allow them to be modelled using the Bay of Bengal Model. This cyclone made landfall at different tidal phases i.e. either low tide or high tidal phase. All these 19 cyclones were simulated based on the original tidal phase and then the opposite tidal condition i.e. if cyclone made landfall on low tide then both low tide and high tidal conditions of each cyclone were simulated. Total 38 cyclone tracks for the whole costal area have been considered based on the 19 observed cyclones. Simulations of 38 cyclones have been made to generate time series of storm surge level with and without climate change. Maximum surge levels for every cyclone have been extracted at the locations of interest. These surge level values are analyzed to determine the different return period for all the locations. Statistical analysis of surge level is carried out using Extreme Value Analysis (EVA) in MIKE Zero.

The wave heights generated by the cyclonic wind speeds are quite considerable along the sea-facing dykes and the dykes along the wide estuaries in the south. To know the wave characteristic during a cyclone, 19 wave simulations were carried out using the cyclonic wind and pressure field for the 19 naturally occurred cyclones. The domain of wave model for cyclonic wave up to 4 degree latitude to cover the whole area including these areas where cyclonic wind were first generated. This model doesn't include interior and Minor Rivers where wave height is not significant. The maximum significant wave height was obtained from 106 pre-selected locations in the model domain, for each cyclone of the 38 wave simulations. The 38 values obtained for each location were then analyzed to obtain the 10, 25, 50 and 100 years return period significant wave height. Statistical analysis of significant wave height is carried out using Extreme Value Analysis (EVA) in MIKE Zero. Same procedure applied to determine extreme value for wave as applied in determining for surge level but here the weibel distribution function was used.

Some peripheral rivers of the selected polders are far away from the coast and these are not included in the wave model. In order to know the wave condition during cyclone, significant wave heights and peak periods have been predicted from the cyclonic wind field. Cyclonic wind field for 19 severe cyclones have been generated using MIKE21 Cyclone module for the entire coastal region of Bangladesh. Maximum wind speed was obtained from the selected locations for each cyclone. The 19 wind speed values obtained for each location were then analyzed to obtain the 10, 25, 50 and 100 years return period wind speed. Here the trunked Gumbel distribution function was used. Wind speed for a 25 year return period at different locations was used to predict significant wave height and peak period. For predicting significant wave height and peak period, formula described in the coastal engineering has been applied. As the return period values were obtained by the curve fitting method, the standard deviation from the fitted curve was also recorded. There were, in fact, 106 points from which data was extracted. The maximum surge levels for all sampling locations have been tabulated for the four return periods for simulations carried out without and with climate change. The scenario with climate change (2050) assumed a sea level rise of 50cm and an increase of 10 per cent in the wind velocity in corresponding cyclone with an identical track. The extreme value analysis employs curve fitting. It is therefore necessary to remain aware of the goodness of fit and shown by the standard deviation in order to decide whether an additional margin should be left for safety.

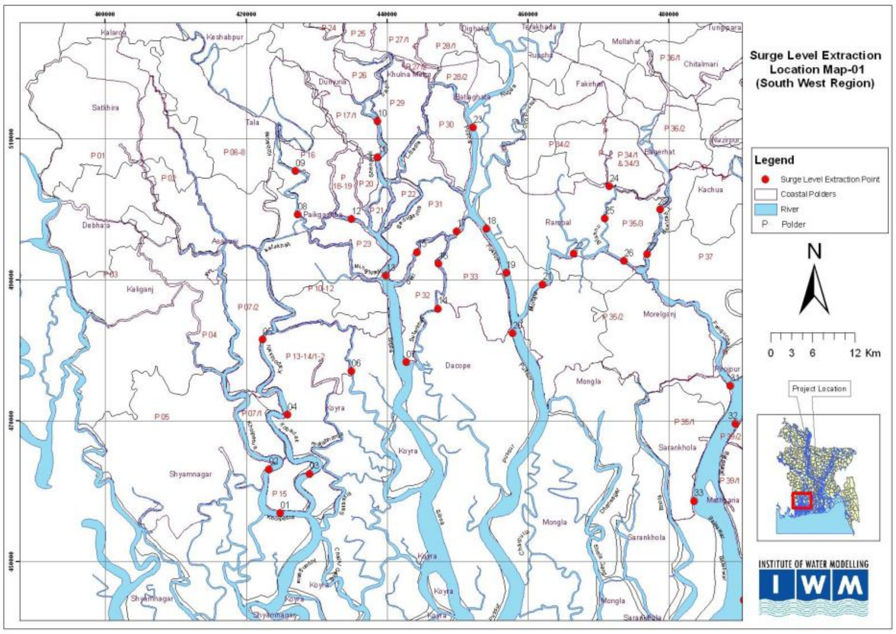

Figure- 1: Locations of storm surge level for different return period Storm surge height for different return period

Storm Induced Waves

The embankments have to resist more than the maximum surge height. It is necessary to allow sufficient freeboard to resist wave overtopping. The wave heights generated by the cyclonic wind speeds are quite considerable along the sea-facing dykes and the dykes along the wide estuaries in the south. To know the wave characteristic during cyclone, 19 wave simulations were carried out using the cyclonic wind and pressure field for 19 naturally occurred cyclone. The maximum significant wave height was obtained from the pre-selected locations (Figure-1) in the model domain, for each cyclone of the 19 wave simulations. The 19 values obtained for each location were then analyzed to obtain the 10, 25, 50 and 100 years return period significant wave height. The maximum significant wave height (H_{m0}) and the corresponding wave period T_p were extracted for each point of interest and the significant wave heights (H_{m0}) with return periods of 10, 25, 50 and 100 years were obtained using a GEV distribution for sea facing polders and polders facing the largest rivers near the sea based on the 19 maximum H_{m0} values at each point. The T_p values associated with each wave height was obtained by using the relation $T_p = A * (H_{m0})$, where A for each polder was obtained from the 19 data points at that station.

The freeboard necessary to limit wave overtopping volumes to acceptable levels was computed using the methodology given in the Eurotop Manual (2007). Figure 2 shows the parameters used in the overtopping computation. The height H_1 refers to the storm surge level and it should be noted that the additional freeboard H_2 required is more than the maximum level of the wave crests. H_2 may be reduced by reducing the river facing slope of the embankment and/or increasing the surface roughness.

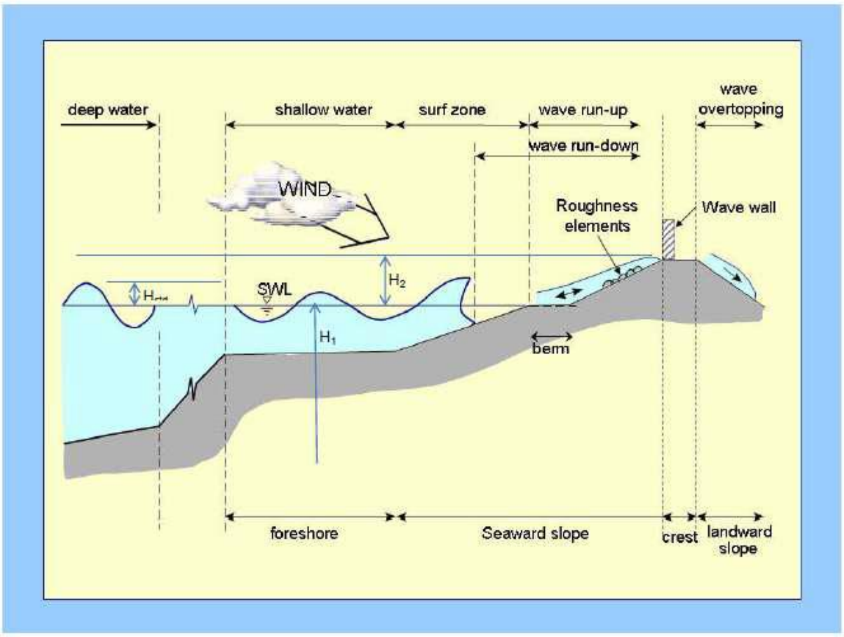

Figure 2: Layout for Wave Overtopping Calculation

Monsoon floods can raise water levels very high in some upstream areas. This occurs outside the two annual cyclone seasons. Particularly in these upstream areas, it is possible that the maximum water levels occur during the monsoon floods. The 25 years return period water levels in the river system were determined from a long simulation of the South West Region Model with climate change. The model was run for the period 1986 to 2009 after applying a sea level rise of 50 cm to the downstream tidal boundary and the increased monsoon precipitation predicted by IPCC in the NAM rainfall runoff model over the entire region. The external inflows (e.g. Gorai) were also increased in line with the climate change predictions in the Ganges Basin. A freeboard computation was carried out using the Eurotop methodology for surface waves generated using the 25 year return period wind speed obtained from the Khulna wind record. The embankment crest levels were checked against the 25 years return period monsoon flood levels and the required free board.

Land Subsidence

The lower deltaic area of Bangladesh is located on two active troughs, Faridpur Trough and Hatiya Trough. In this area, three types of subsidence are recognized (Hoque and Alam 1997):

- Tectonic subsidence
- Compaction of peat layers; and
- Human induced subsidence.

Tectonic subsidence

Tectonic subsidence has relevance in understanding the impact of climate change and variability. The subsidence of the Bengal Basin is largely the result of tectonic forces, and can be attributed to two major factors. One is related to the isostatic adjustment of the crust (sediment load and the rise of the Himalayas), while the other is related to dewatering and compaction (or consolidation) of the sediments of the Bengal Fan. Tectonic subsidence usually occurs over an extensive area, and unlike the subsidence due to groundwater withdrawal, is relatively uniform and proceeds at a slow rate. Areas subjected to tectonic subsidence are generally bounded by active faults or hinge zones-as is the case in the Bengal Basin.

Compaction of peat layers

Parts of lower deltaic plain are underlain by several layers of peat; in some places, even down to a depth of 35m. The compaction of these peat layers and swamp mud often results in local subsidence in the coastal area. A large tract of agricultural land and land under vegetation in coastal areas is subjected to this type of subsidence (Hoque & Alam 1997). Moreover, subsidence may also occur locally due to abstraction of groundwater for mining as the abstraction decreases groundwater pressure

Human induced subsidence

Another type of subsidence in local dimension is human-induced. Human-induced subsidence is caused principally by groundwater withdrawal, drainage of organic soils, and underground mining. Human-induced subsidence impacts when human activities affect the river systems, catchment areas and deltas. Over time, natural subsidence of deltaic sediments is compensated by delivery of new sediments. Since the flood plain is embanked by constructing embankment, the distribution of sediment over the flood plain is disturbed. Embankments along river channels keep sediment out of the adjacent land. The construction of dams and reservoir in upstream areas for flood protection, power supply, and irrigation can stop or strongly decrease the downstream supply of sediment.

Direct measurement of subsidence is possible by the use of GPS technology. This is a part of the on-going investigation by Dhaka University Earth Observatory (DUEO) in collaboration with Lamont-Doherty Earth Observatory of Columbia University, New York. GPS stations have been installed in several places including in the project area. The actual displacements of the GPS stations with respect to the International Terrestrial Reference Frame (ITRF) are being monitored. While the measurements are on-going, preliminary estimates point to high rates of subsidence in the range 9.1mm to 13.9mm per year in Patuakhali and Khulna. Further investigations are planned, including the installation of a station at Hiron Point which could make it possible to disaggregate the sea level rise and subsidence components of the water level record.

As a temporary measure, it has been decided to assume a subsidence rate of 10 mm per year and to apply an upward correction of 30 cm (10 mm per year for 30 years) to the design crest levels. This is done together with a strong recommendation that a long-term programme of monitoring a more extensive network of GPS stations be initiated immediately so that the subsequent phases of CEIP could benefit from a more accurate set of subsidence (and sea level rise) data.

Determining Design Crest Levels for Embankments.

After considering the results of the storm surge analysis it was decided that the design return period should be 25 years. The selection of crest levels for new dykes are based on the modelling outcomes described in the preceding sections:

a) The 25 years return period storm surge level
b) Alternatives for freeboard depending on overtopping limit of 5l/m/s for several possible embankment slopes and roughness.
c) 25 year return period monsoon level
d) 25 year return period monsoon freeboard
e) Allowance for subsidence

Conclusions & Recommendations

The study has developed a viable methodology for designing polder improvements to protect the polders from storm surges and to improve drainage problems within polders. The proposed designs are tailored not only for the present conditions but also to cater to future climate change scenarios.

The present condition of the embankments make it likely that an overtopping event can lead to disastrous breaches in the embankment at existing weak points – a seen after Sidr and Aila.

The new design will ensure that the embankment would be protected against events of 25 years return period for climate change conditions that would exist in 2050. Additional safety factors have also been built in by allowing for the higher estimates of subsidence and sea level rise.

The actual level of protection soon after project completion (say 2015) would be more than a 50 year return period.

The embankment crest levels have been raised to provide sufficient freeboard to severely limit overtopping by waves during extreme events as well. The project has identified the need to monitor land subsidence at selected stations all over the coastal zone.

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