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Review Article

Numerical Modelling of Storm Surge from the 1991 Cyclone in the Bay of Bengal (Bangladesh) by Royal HaskoningDHV

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Abstract

Cyclone modelling results are used to derive robust design conditions for coastal and marine structures and facilities. Cyclone modelling results are also used for emergency planning and decision-making to estimate potential loss of life, damage to properties and marine facilities and to develop rescue and mitigation measures and plan clean-up operations. Royal HaskoningDHV (hereafter RHDHV) has set up regional tidal hydrodynamic and wave generation/transformation models covering the Bay of Bengal and its surrounding areas to address the above issues. A long list of major cyclones was initially identified in the Bay of Bengal affecting the Bangladeshi coastline since 1945. The 1991 Cyclone (22-30 April 1991) was found to be the second strongest cyclone affecting the coastal areas of Bangladesh since 1945 (after the Bhola Cyclone on 7-13 November 1970). As less information is available on the 1991 Cyclone, this paper has concentrated on this event to illustrate the use of numerical modelling technique to simulate storm surge generated by cyclones. The MIKE21 Flow Model developed by DHI was used in the study. Sample results of storm surge from the modelling study are presented in this paper for illustration purposes. Structural design considerations and cyclone risk reduction measures are also discussed. The model could be used to simulate any cyclone generated anywhere within the Bay of Bengal and its surrounding areas. The methodology described in this paper for modelling cyclone surge in the Bay of Bengal could also be applied to simulate cyclones at other sites around the world.

Keywords: Numerical modelling; Natural hazards; Cyclones; Storm surge; Port development; Bay of Bengal; 1991 Cyclone.

Introduction

Cyclones (also known as hurricanes or typhoons) need favourable conditions to form such as a) warm sea surface temperature b) large convective instability c) low level positive vorticity d) weak vertical wind shear of horizontal wind and e) Coriolis force. Cyclones require ocean temperatures of at least 26.5°C for their formation and growth through a relatively deep layer (~50m). Cyclones are associated with steep pressure gradients and consequently generate strong winds and storm surges. The destruction from a cyclone depends on its intensity, size and location. Cyclones generate high winds, waves, water levels (surge) and are associated with intense rainfall.

Cyclones cause significant loss of life and damage to properties, ecosystems and marine structures and facilities. Heavy and prolonged rains associated with cyclones cause floods of low-lying areas and lead to mudslides and landslides causing loss of life and property. The generation of large waves and high-water levels result in damage to coastal and offshore structures.

During the last two centuries, cyclones have been responsible for the deaths of about 1.9 million people worldwide [1]. It is estimated that 10,000 people per year perish due to cyclones [1]. Bangladesh is especially vulnerable to cyclones with around 718,000 deaths in the past 50 years [2]. The deadliest cyclone in Bangladesh was the 1970 Bhola Cyclone, with a death toll of up to 500,000 [3]. At least 138,000 people were killed and as many as 10 million people became homeless during the 1991 Cyclone in Bangladesh [4].

Despite their devastating effects, cyclones are essential to the Earth's atmosphere as they bring rain to dry areas and transfer heat and energy between the equator and the cooler regions nearer the poles.

The objective of the paper is to provide improved and comprehensive model results (both positive and negative surges) to researchers and practitioners over a wider region. These results are useful for deriving robust design conditions for coastal and marine structures and facilities. The results are also valuable in estimating potential loss of life, damage to properties and marine facilities, to develop rescue and mitigation measures and to plan clean-up operations. Structural design considerations and cyclone risk reduction measures are also provided.

Royal HaskoningDHV has identified 14 major cyclones in the Bay of Bengal since 1970. The 1991 Cyclone (22-30 April 1991) was found to be the second strongest cyclone affecting the coastal areas of Bangladesh since 1970 (after the Bhola Cyclone on 7-13 November 1970). Numerical modelling of surge from this 1991 cyclone is reported in this paper.

The latest version of the MIKE21 software (2019 version) was used which enabled the application of the latest technical advancement [5]. Generally, a spectral wave model is run first to derive radiation stress to input into a tidal model. In the present study, the wave and tidal modelling were carried out simultaneously in a coupled mode where the tidal model obtained the necessary radiation stress directly from the wave model and thereby improved the accuracy of the model prediction. The use of powerful computers allowed the adoption of fine model mesh/grid to improve accuracy in simulation results. Besides the model results at selected key locations, two-dimensional plots of model results are provided in the paper to allow researchers and practitioners to extract model results anywhere within the wider region. Cyclones can result in negative surges (reduction in water depth) which can affect the operation of coastal facilities and ports. Therefore, maximum negative surges are provided along with a two-dimensional plot showing values over a wider region.

The Bay of Bengal is a potentially energetic region for the development of cyclonic storms accounting for about 7% of the global annual total number of tropical storms [6]. Historical cyclone tracks in the Bay of Bengal by monthly occurrence during 1877-2010 were obtained by RHDHV for a project in the east coast of India from the Indian Meteorological Department [7] as presented in Table 1.

A total of 14 major cyclones have affected the Bay of Bengal since 1970 as shown in Table 2.

Data in Table 2 for Cyclone 1 was obtained from [3] whereas data for Cyclone 10 was obtained from IMD [7] where 3-minutes mean wind speed of 102 knots was converted to 1-minute mean of 112 knots using the methodology from [8]. Data in Table 2 for the remaining cyclones were obtained from the Joint Typhoon Warning Center (JTWC), USA [9].

The monsoon season in the Bay of Bengal is from June to September. Cyclones of the pre-monsoon and post-monsoon seasons are the most destructive due to greater instability in the atmosphere and the weak vertical winds. They generally form over the Andaman Sea or south-east of the Bay of Bengal. They initially move to west or north-west and then to north and finally to north-east across Bangladesh.

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
7	2	2	23	75	104	142	177	158	156	109	38

Table 1: Monthly occurrence of historical cyclones in the Bay of Bengal during 1877-2010 [7].

No.	Year	Codes &Names	Time & Date		Maximum 1-minute mean sustained wind speeds (knots)	Minimum central pressure (hPa)	Radius of maximum wind speeds (nm)
			Start	End			
1	1970	Bhola Cyclone	07/11/1970 18:00	13/11/1970 00:00	130	960	N/A
2	1972	TC 14B	15/11/1972 06:00	23/11/1972 00:00	90	N/A	N/A
3	1975	TC 02B	01/05/1975 00:00	11/05/1975 12:00	95	N/A	N/A
4	1977	TC 05B	09/11/1977 00:00	23/11/1977 00:00	110	N/A	N/A
5	1977	TC 06B	14/11/1977 00:00	20/11/1977 12:00	110	N/A	N/A
6	1982	TC 01B	30/04/1982 06:00	05/05/1982 12:00	120	NIA	N/A
7	1988	TC 04B	21/11/1988 18:00	30/11/1988 00:00	110	N/A	N/A
8	1990	TC 02B	03/05/1990 12:00	11/05/1990 06:00	125	N/A	N/A
9	1991	TC 02B (BoB 01)	22/04/1991 18:00	30/04/1991 18:00	140	N/A	N/A
10	1992	BoB-8	16/11/1992 06:00	21/11/1992 18:00	112	952	N/A
11	1994	TC 02B	26/04/1994 18:00	03/05/1994 12:00	125	N/A	N/A
12	1999	TC 05B	25/10/1999 00:00	03/11/1999 06:00	140	N/A	N/A
13	2013	TC 02B (Phailin)	07/10/2013 12:00	13/10/2013 12:00	140	918	10
14	2014	TC 03B (Hudhud)	06/10/2014 06:00	13/10/2014 12:00	115	937	10, 15

Table 2: Major Cyclones in the Bay of Bengal since 1970.

The 1991 Cyclone was classified as Super Cyclonic Storm (BOB 01) by IMD [7] and as Category 5 Cyclone (02B) by JTWC [9]. The cyclone formed in the morning at 09:00 BST (Bangladesh Standard Time) of 25 April 1991 as a depression at 10.0°N and 89.0°E. It intensified into a deep depression the same evening and then very quickly turned into a cyclonic storm at midnight of 25 April with a maximum sustained wind of 65-87 km/h and a central pressure of 996 hPa. It retained this intensity until 15:00 BST of 27 April when it was found to have developed into a severe cyclonic storm with maximum wind speeds of 90-115 km/h and central pressure of 990 hPa. At midnight of 27 April it turned into a very severe cyclonic storm with wind speeds more than 130 km/h. The cyclone started moving in a north-easterly direction on 28 April and finally crossed the coast north of Chittagong Port in the early morning (04:00 BST) of 30 April as a super cyclonic storm. The maximum wind speed observed at Sandwip Island was 235 km/h and the central pressure was 920 hPa with pressure drop of 80 hPa. The actual wind speed is likely to have been much higher as the wind measuring device was blown away after this speed was recorded. This low pressure, in conjunction with the full moon, raised the water level significantly with the cyclone making landfall during the high tide. Much of the above information was obtained from [10] and [11].

The 1991 Cyclone killed an estimated 138,000 people and approximately 13.4 million people affected. Around one million homes were destroyed leaving about 10 million people homeless. The coastline was devastated due to the high velocity wind and the storm surge. A concrete levee near the mouth of the Karnaphuli River in Patenga was washed away by the cyclone. A 100-ton crane from the Port of Chittagong was uprooted and smashed on the Karnaphuli River Bridge breaking it into two parts. The Bangladesh Navy and Bangladesh Air Force bases were heavily affected with heavy damage to ships and aircraft. Huge numbers of boats and smaller ships ran aground. Land erosion resulted in farmers losing land and crops which were washed away. The salt industry and shrimp farms were left devastated. The estimated damage from the cyclone was around $1.5 billion (1991) in Bangladesh. Continuous rainfall and gusty winds affected Tripura and Mizoram states of north-east India causing some loss of life, destroying many houses and disrupting telecommunication systems. The above information was obtained from [4].

1991 Cyclone Data

Track and other data

The track (route) of the 1991 Cyclone was obtained from [4] as shown in Figure 1. The cyclone data was obtained from the JTWC [9] and are presented in Table 3.

Wind and pressure fields generation

The MIKE21 Cyclone Wind Generation Tool of DHI [12] was used to generate the cyclonic wind and pressure fields. The tool allows users to compute wind and pressure fields from cyclone data. Several cyclone parametric models are included in the tool including Young and Sobey model (1981), Holland – single vortex model (1981), Holland – double vortex model (1980) and Rankine vortex model [12]. All six input parameters required by the Young and Sobey model (i.e. time, track, radius of maximum wind speed, maximum wind speed, central pressure and neutral pressure) were available for the study and this model was, therefore, used to generate the cyclonic wind and pressure fields. The other models require some additional parameters (such as Holland parameter B and Rankine parameter X) that need to be calculated using empirical relationships which add further uncertainty to the generated wind and pressure fields and were, therefore, not used for the study. The wind and pressure fields were used to drive the cyclone wave and surge models described later.

Surge Modelling for the 1991 Cyclone

The model

RHDHV has set up a two-dimensional Regional Tidal Hydrodynamic Model for the Bay of Bengal and its surroundings using the MIKE21 Flow Model FM software of DHI [5]. The model is based on the numerical solution of the two-dimensional shallow water incompressible Reynolds averaged Navier-Stokes equations invoking the assumptions of Boussinesq and of hydrostatic pressure. Thus, the model consists of continuity, momentum, temperature, salinity and density equations.

The regional model covers the coastlines of six countries – India, Sri Lanka, Bangladesh, Myanmar, Malaysia and Indonesia (see Figure 2). An unstructured flexible (triangular) mesh (with variable cell sizes) was used in the study which allowed use of fine mesh at shallow areas where changes in physical processes occur quickly and over shorter distances. It also allowed to use fine mesh size at areas of importance (such as areas of cyclone landfall). The model bathymetry (as shown in Figure 2) was obtained from the C-Map Global Database [13]. This regional tidal model was used to derive cyclone surge in the study.

The MIKE21 Flow Model FM was coupled with the MIKE21 Spectral Wave (SW) model where the tidal model

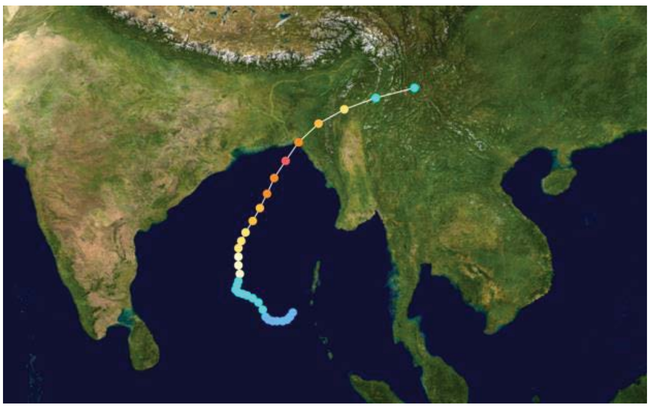

Figure 1: Track and intensity of the 1991 Cyclone in Bangladesh [4].

Date	Time (UTC)	Duration (hours)	Longitude (°E)	Latitude (°N)	Radius of maximum winds (km)	Maximum 1-hourly wind speeds (m/s)	Central pressure (hPa)	Constant neutral pressure (hPa)
22-04-1991	1800	0	91.2	10.0	63.0	8.29	1041.9	1013
23-04-1991	0	6	91.0	9.7	63.0	8.29	1041.9	1013
"	600	12	90.8	9.5	63.0	8.29	1041.9	1013
"	1200	18	90.5	9.4	61.1	10.36	1036.7	1013
"	1800	24	90.1	9.4	61.1	10.36	1036.7	1013
24-04-1991	0	30	89.8	9.4	61.1	10.36	1036.7	1013
"	600	36	89.5	9.5	59.3	12.44	1031.6	1013
"	1200	42	89.3	9.7	59.3	12.44	1031.6	1013
"	1800	48	89.1	10.2	57.4	14.51	1026.4	1013
25-04-1991	0	54	88.8	10.7	57.4	14.51	1026.4	1013
"	600	60	88.4	11.0	55.6	16.58	1021.2	1013
"	1200	66	88.0	11.2	55.6	16.58	1021.2	1013
"	1800	72	87.7	11.3	53.7	18.65	1016.0	1013
26-04-1991	0	78	87.4	11.4	51.9	20.73	1010.8	1013
"	600	84	87.2	11.6	51.9	20.73	1010.8	1013
"	1200	90	87.3	11.9	50.0	22.80	1005.6	1013
"	1800	96	87.4	12.2	48.2	24.87	1000.4	1013
27-04-1991	0	102	87.5	12.7	46.3	26.94	995.2	1013
"	600	108	87.4	13.3	42.6	31.09	984.8	1013
"	1200	114	87.4	13.9	40.7	33.16	979.7	1013
"	1800	120	87.4	14.5	38.9	35.23	974.5	1013
28-04-1991	0	126	87.6	15.0	37.0	37.31	969.3	1013
"	600	132	87.9	15.6	35.2	39.38	964.1	1013
"	1200	138	88.4	16.4	33.3	41.45	958.9	1013
"	1800	144	88.9	17.3	29.6	45.60	948.5	1013
29-04-1991	0	150	89.4	18.3	25.9	49.74	938.1	1013
"	600	156	89.9	19.4	22.2	53.89	927.7	1013
"	1200	162	90.7	20.6	18.5	58.03	917.4	1013
"	1800	168	91.6	21.9	20.4	55.96	922.6	1013
30-04-1991	0	174	93.0	23.2	29.6	45.60	948.5	1013
"	600	180	94.8	24.2	38.9	35.23	974.5	1013
"	1200	186	97.0	25.0	48.2	24.87	1000.4	1013
"	1800	192	99.7	25.7	55.6	16.58	1021.2	1013

Table 3: Track and Data of the 1991 Cyclone [9].

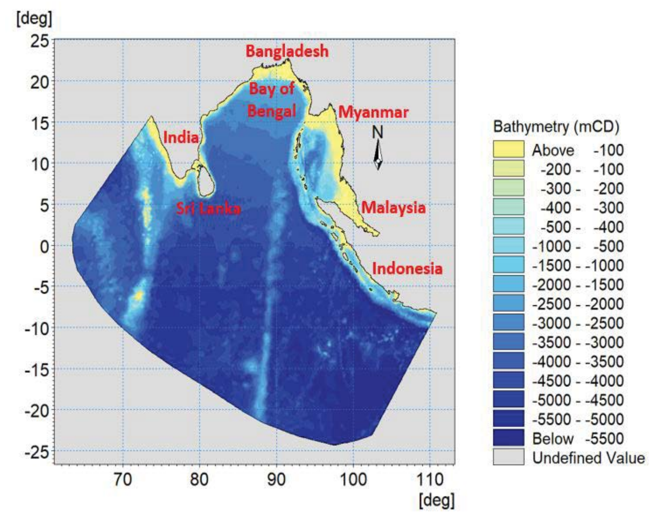

Figure 2: Model extent and bathymetry.

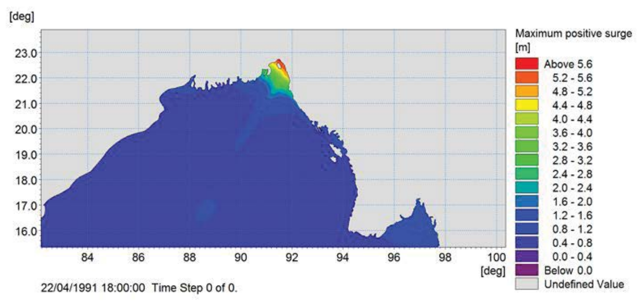

Figure 3: Maximum positive surge during the entire duration of the 1991 Cyclone.

obtained the necessary radiation stress directly from the wave model and thereby improved the accuracy of the model prediction. The use of powerful computers allowed the adoption of fine model mesh/grid to improve accuracy in simulation results.

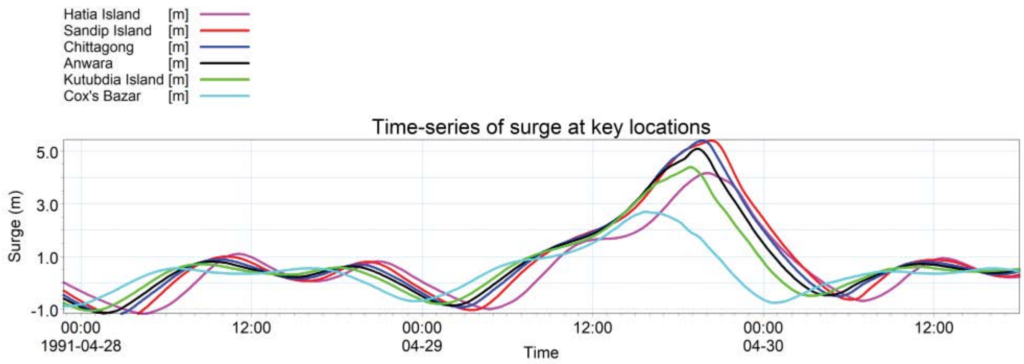

Figure 4: Time-series of surge at selected locations along the coastline of Bangladesh.

Sources	Locations					
	Hatia Island	Sandwip Island	Chittagong	Anwara	Kutubdia Island	Cox's Bazar
BUET [14]	4.5	>5.0	>5.0	>5.0	>5.0	4.5
George Mason University [15]	3.8	4.3	5.2	5.2	-	2.9
Salek [16] as in [15]	-	-	5.0	-	-	3.9
Dube [17] as in [15]	-	-	4.8	-	-	2.6
Flather [18]	4.5	5.1	6.0	6.0	4.9	5.1
This study	4.2	5.4	5.3	5.1	4.4	2.7

Table 4: Maximum positive surge (m) comparison.

The hydrodynamic solver is assumed to be dynamic and hence the in-stationary formulation was used. The higher order numerical scheme was used to improve accuracy in model prediction. Flooding and Drying were included in the model for treatment of the moving boundaries (flooding and drying fronts). Barotropic density and the Smagorinsky formulation for eddy viscosity were used in the model. Bed resistance was included in the model in the form of Manning's number. Varying Coriolis forces were applied to the model. A timestep of 900s was used in the model.

Model validation

Information on the maximum storm surge during the 1991 Cyclone was obtained from public domain through literature search. Numerical modelling of the 1991 Cyclone was also carried out by [14] using the MIKE21 Flow Model of DHI and by [15] using the ADCIRC Model. Storm surge values were also reported by [15] from [16] and [17]. Numerical modelling of storm surge was also carried out by [18]. Storm surge values from these sources are summarised in Table 4 and are compared with the findings from this study and generally a good agreement was found.

A storm surge of 5.8m was reported by [10] at the affected areas along the Patuakhali-Cox's Bazar coast.

Measured data for direct verification of the model hindcast results is very limited. The Bangladesh Inland Water Authority, which maintains an extensive network of tide gauges, reported that no data for the cyclone period had been recovered [18]. However, they provided a map to [18] showing the areas affected by the cyclone. The map reproduced by [18] shows that Sandwip Island and the Chittagong were the worst affected areas. This is in agreement with the model results presented in Table 4 which shows that the higher surges (of 5.4m and 5.3m respectively) were found in these two areas.

As reported in [18] from [19], the time of flooding was "between 12 and 1 o'clock in the morning of 30 April (local time)" which is equivalent to 18:00 to 19:00 UTC 29 April. This timing agrees well with those in Figure 4.

Model results and discussions

Model results are provided over a wider area particularly the landfall areas that were affected the most by the cyclone. Besides the model results at selected key locations, two-dimensional plots of model results are provided in the paper to allow researchers and practitioners to extract model results anywhere within the wider region.

Figure 3 indicates that the highest positive surges occurred in the south-eastern coastal waters of Bangladesh where the cyclone made landfall.

The temporal variation of surge at selected locations during the cyclone is shown in Figure 4. The maximum surge at these locations are provided in Table 5 (copied from Table 4) with the coordinates of the locations and the timings. The highest surge of approximately 5.4m was found in Chittagong on 29 April 1991 19:45 where the cyclone made landfall. Higher surges were also found at its neighbouring areas (i.e. 5.4m at Sandip Island and 5.1m at Anwara). Areas further away from the landfall location were subjected to smaller surges (i.e. 4.2m at Hatia Island and 4.4m at Kutubdia Island). Cox's Bazar is far away from the landfall location and therefore a small surge of about 2.7m was found there. Figure 5 indicates that surges higher than 1m, 2m, 3m and 4m in Chittagong were sustained for duration of about 17.5 hours, 11.7 hours, 7.7 hours and 5.5 hours respectively.

The south-western coastal waters in Bangladesh were less affected due to the distance from the main path of the cyclone.

Figure 5 shows that the largest negative surge of up to 1.5m occurred in the south-eastern coastal waters of Bangladesh.

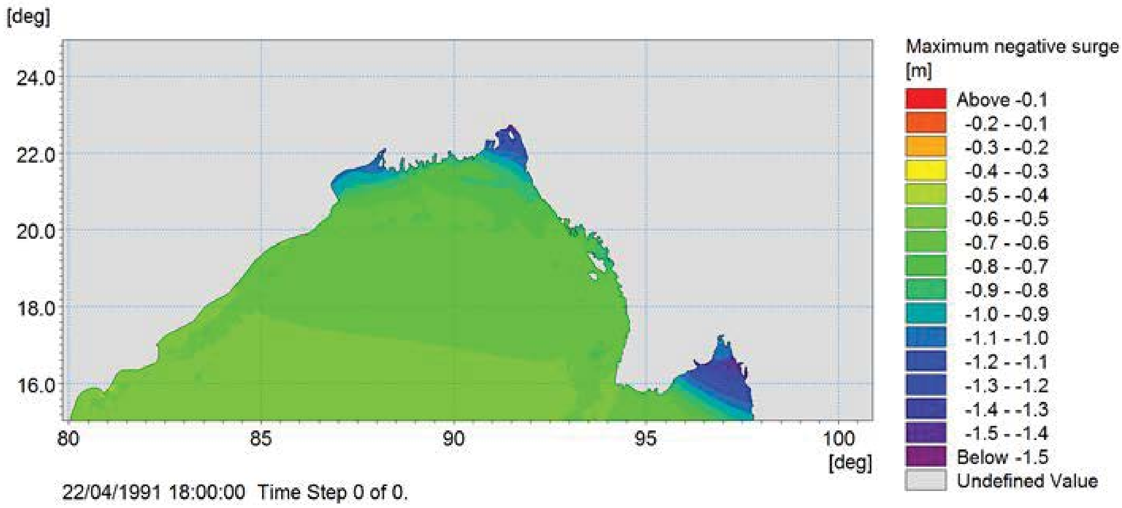

Figure 5: Maximum negative surge during the entire duration of the 1991 Cyclone.

Locations	Latitude (°N)	Longitude (°E)	Maximum surge (m)	Time on 29 April 1991
Hatia Island	22.46	91.11	4.2	20:00
Sandip Island	22.55	91.52	5.4	20:15
Chittagong	22.36	91.74	5.4	19:45
Anwara	22.18	91.80	5.1	19:30
Kutubdia Island	21.89	91.89	4.4	19:00
Cox's Bazar	21.42	91.96	2.7	15:45

Table 5: Maximum positive surge at selected locations along the coastline of Bangladesh.

Recommended Design Considerations

The potential impact of a cyclone event on the design of coastal and marine facilities may be summarised as follows:

1) Shoaling results in an increase in water levels and stronger currents inshore. Measures will be required to protect structures from scouring of the foreshore and sea bed and limit damage to the crest if heavy overtopping occurs;

2) The foreshore will be subjected to flooding as the cyclone waves and surge approach; and

3) Facilities located on the landward slope are at risk from cyclone wave run-up and surge.

Cyclone Risk Reduction Measures

Damage due to a cyclone depends on the strength and proximity of the cyclone as well as local bathymetry and topography and the location of people, structures and facilities.

It is almost impossible to fully protect people and settlements from major cyclone events. However, various soft and hard measures (independently or in combination) could be adopted to reduce fatalities and damage to key infrastructure.

Some potential measures to reduce the risk of damage and deaths from major cyclone events are highlighted below:

1) Detection, early warning systems and real-time observation systems are of great importance;

2) Appropriate awareness and understanding among the general public;

3) Mitigation plans and evacuation and rescue preparedness by responsible authorities;

4) Cyclone risk assessment, flood risk and inundation hazard maps;

5) Cyclone shelters;

6) Developing artificial forest such as mangroves and casuarinas of appropriate width behind the shoreline to reduce cyclone wave energy;

7) Maintaining natural sand dunes;

8) Regulations for development in the coastal zone;

9) Saline embankments to prevent salt-water entering into fertile lands;

10) Raising ground levels of important structures and facilities such as warehouses, terminals and quays; and

11) Constructing cyclone defence structures such seawalls, dykes, gates, nearshore breakwaters and offshore barriers. However, these structures are substantial and very expensive.

For major coastal infrastructure, the adoption of appropriate design parameters, a proper assessment of structural loads, forces and stability in combination with a detailed understanding of cyclone processes will reduce the level of damage resulting from these events. Furthermore, physical modelling of major coastal and marine structures and mooring systems to investigate their stability under severe conditions will be helpful to reduce damage due to cyclones.

Risks Reduction from Mudslides and Landslides

High tides and heavy and prolonged rains during a cyclone may cause floods and submergence of low-lying areas which may lead to mudslides and landslides in mountainous areas causing loss of life and property. Landslides and mudslides are downhill earth movements that move slowly and cause gradual damage. They can also move rapidly destroying property and taking lives suddenly and unexpectedly. They typically carry heavy debris such as trees and boulders which cause severe damage together with injury or death. Faster movement of mudslides makes them deadly.

It is not possible to prevent a mudslide or a landslide. However, preparatory steps can be taken to lessen the impact of a mudslide. Some guidelines are briefly mentioned below:

1) Carrying out risk assessment;

2) Creating public awareness and practicing an evacuation plan;

3) Staying up-to-date on storm/rainfall/cyclone warnings during times of increased risk;

4) Watching for any visible signs such as cracks on land, debris flows or trees tilting or boulders knocking;

5) Staying alert and awake;

6) Moving out of the path of the landslide or debris flow; and

7) Some erosion control measures might be helpful (such as installing barrier walls, improving drainage system and planting trees with deep and extensive root systems).

Summary and Findings

This paper illustrates how a tidal model can be used to simulate the impacts of cyclones on coastal developments and facilities. The MIKE21 Flow Model FM was coupled with the MIKE21 Spectral Wave (SW) model to improve accuracy in model prediction. Unstructured flexible (triangular) mesh was used to allow use of fine mesh at areas of importance. The higher order numerical scheme was used to improve model prediction.

Model results are provided over a wider area particularly the landfall areas that were affected the most by the cyclone. Besides the model results at selected key locations, two-dimensional plots of model results are provided in the paper to allow researchers and practitioners to extract model results anywhere within the wider region.

The findings from the modelling study which focused on the 1991 cyclone in the Bay of Bengal are summarised below:

1) The maximum surge was generated off the south east coastal areas of Bangladesh;

2) The highest surge of approximately 5.4m was found in Chittagong where the cyclone made landfall;

3) Surges higher than 1m, 2m, 3m and 4m in Chittagong were sustained for a duration of approximately 17.5 hours, 11.7 hours, 7.7 hours and 5.5 hours respectively;

4) The impact on the Indian coast and the south-western coast of Bangladesh was limited; and

5) The largest negative surge of up to 1.5m occurred in the south-eastern coastal waters of Bangladesh.

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