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Cyclones in the Bay of Bengal and its Risk Reduction Measures – A Numerical Modelling Case Study of Waves Generated by Cyclone Bhola (1970)

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ABSTRACT

Significant loss of life and damage to properties, marine facilities and ecosystems are caused by cyclones. Cyclone modelling results are used for deriving robust design conditions for coastal and marine structures and facilities. They 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 has set up a regional model covering the Bay of Bengal and its wider surroundings to address these issues. Major cyclones in the Bay of Bengal that have affected the Bangladeshi coastline since 1970 was initially identified. The Cyclone Bhola (8-13 November 1970) was found to be the deadliest tropical cyclone ever recorded and one of the world's deadliest humanitarian disasters affecting the coastal areas of Bangladesh. Less information is available on numerical modelling of waves from Cyclone Bhola. This paper, therefore, concentrates on Cyclone Bhola to illustrate the use of numerical modelling to simulate waves generated by cyclones. Effects of white capping on predicted wave heights were also investigated. The MIKE21 Spectral Wave and Flow Models developed by DHI were used in the numerical modelling study. Sample results of waves 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 originating in the Bay of Bengal and its surroundings. The methodology described in this paper for modelling cyclone waves in the Bay of Bengal could also be applied to simulate cyclones at other sites around the world.

Key words: Numerical modelling, natural hazards, cyclones, extreme waves, port development, Bay of Bengal, 1970 Cyclone, Cyclone Bhola

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1. INTRODUCTION

1.1 Formation of Cyclones

Tropical cyclones (also known as hurricanes or typhoons) are associated with warm and moist air and hence they form only over warm ocean waters near the equator (within latitude 30° north and south). They need some 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. Warm ocean waters of at least 27°C throughout a depth of about 50m from sea surface is required for cyclone formation.

The warm and moist air rises causing an area of lower pressure beneath. Cooler air moves into the lower pressure area and becomes warm and moist and rises too. When the warm and moist air rises, it cools down and forms clouds. The whole system of clouds and winds spins and grows and is fed by ocean's heat and evaporated water continuously. Cyclones that form north of the equator spin counterclockwise whereas cyclones south of the equator spin clockwise due to the difference in Earth's rotation on its axis.

Storm surges from cyclones are generated due to an interaction between air and water. The atmosphere forces the water body and consequently oscillations are generated in the water body with periods ranging from a few minutes to a few days. A cyclone becomes deadly by causing inundation along the coastline if the maximum surge coincides with a high astronomical tide. There are essentially two major forcing factors when a weather system moves over a water body. 1) Atmospheric pressure gradient normal to the sea surface. This is known as "inverse barometer effect" or "static amplification" or "the static part of the storm surge". A decrease of one hectopascal (hPa) in the atmospheric pressure raises the sea level by one centimeter (cm). This static part has only about 5-15% contribution in the magnitude of a surge. 2) The dominant factor, known as "dynamic amplification", is caused by the tangential wind stress (associated with the wind field of the weather system) acting over the sea surface which pushes the water towards the coast resulting to a pile-up of water at the coast.

1.2 The Saffir-Simpson Hurricane Wind Scale

The Saffir-Simpson Hurricane Wind Scale is designed to help determine wind hazards of an approaching hurricane easier for emergency officials. The scale is assigned five categories with Category 1 assigned to a minimal hurricane and Category 5 to a worst-case scenario. The Saffir-Simpson Scale classifying depression, tropical storm and hurricane is given in Table 1.

Table 1: Saffir-Simpson Hurricane Classification

Storm type	Category	Pressure (hPa)	1-min peak wind speed (knots)	1-min peak wind speed (mph)	1-min peak wind speed (km/h)
Depression	TD	-	< 34	<39	< 63
Tropical Storm	TS	-	34 – 63	39 – 73	63 – 118
Hurricane	1	> 980	64 – 82	74 – 95	119 – 153
Hurricane	2	965 – 980	83 – 95	96 – 110	154 – 177
Hurricane	3	945 – 965	96 – 113	111 – 130	178 – 210
Hurricane	4	920 – 945	114 – 135	131 - 155	211 - 250
Hurricane	5	< 920	> 135	> 155	> 250

1.3 Damages from Cyclones

Cyclones are associated with high-pressure gradients and consequently generate strong winds, torrential rain and storm surges at landfall making these one of Earth's most destructive natural phenomena. The destruction from a tropical cyclone depends on its intensity, size and location. Very strong winds may damage installations, dwellings, transportation and communication systems, trees etc. and cause fires resulting in considerable loss of life and damage to property and ecosystems. Cyclones also impose significant risks during construction and operation of seaports and other marine structures and facilities.

Cyclones have been responsible for the deaths of about 1.9 million people worldwide during the last two centuries. It is estimated that 10,000 people per year perish due to tropical cyclones [1]. Bangladesh is especially vulnerable to tropical cyclones with around 718,000 deaths from them in the past 50 years [2]. The deadliest tropical cyclone in Bangladesh was Cyclone Bhola (1970), which had a death toll of at least 300,000 [3] possibly as many as 500,000 [4, 5]. An estimated over 138,000 people were killed [6] with an equal number of injured [7] and about 13.4 million people were affected [7] by the 1991 Cyclone in Bangladesh.

During the 50 years since Cyclone Bhola, 1942 disasters were attributed to tropical cyclones which killed 779,324 people and caused US$ 1,407.6 billion in economic losses with an average of 43 deaths and US$ 78 million in damages every day [8].

Maximum damages from a cyclone occur if landfall takes place at high tide. There was a severe cyclone in the Bay of Bengal in October 1960 which claimed only over 5,000 lives [9] although the strength of this cyclone was similar to that of Cyclone Bhola (November 1970). The significant difference in fatalities is due to the fact that the November 1970 cyclone crossed the coast at high tide while the October 1960 storm moved onshore at low tide [10].

1.4 Benefits from Cyclones

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

1.5 Major Cyclones in the Bay of Bengal

The Bay of Bengal is located in the north-east corner of the Indian Ocean and is surrounded by India, Bangladesh, Myanmar, Sri Lanka and the western part of Thailand. It has an area of approximately 2.2 million km², with an average water depth of 2,600m and a maximum depth of 5,258m. It is a semi-enclosed tropical basin which experiences seasonal changes in circulation and weather due to the monsoons. The Bay of Bengal is responsible for the formation of some of the strongest and deadliest tropical cyclones in the world. It is a potentially energetic region for the development of cyclonic storms accounting for about 7% of the global annual total number of tropical storms [11]. Approximately 40% of the blow of total storm surges in the world occur in Bangladesh but about 80% of the global casualties occur in this area [11]. These cause huge loss of life and damage to property every year to the coastal population of Bangladesh. Among the countries that share the Bay of Bengal coastline, Bangladesh is the most vulnerable based on the number of landfalls since 1970. Among all the natural hazards, tropical cyclones along with storm surges are the most catastrophic in nature along the coastal regions of Bangladesh.

During 1960-2007 around 18 severe cyclones have hit the coast of Bangladesh causing enormous disruptions, damages and a remarkable number of deaths. On an average a severe cyclone hits Bangladesh every three years [12] and this has been rising at the rate of 1.18 cyclones per year from 1950-2000 [13]. No less than 14 severe cyclones form over the Bay of Bengal in every ten years [14]. About 154 cyclones (consisting of 43 cyclonic storms, 43 severe cyclonic storms, and 68 tropical depressions) affected Bangladesh during 1877-1995 [15] and more than 70 of these were major hazards [16]. About 5% of the global tropical storms and 80% of the global casualties happen in the Bay of Bengal. The deadliest events include Cyclone Bhola (1970), 1991 Tropical Cyclone, Orissa Cyclone (1999) and the Cyclone Sidr (2007).

Cyclone Bhola (1970) had a calculated central pressure between 950 and 960 mb [10]. It should be noted that Cyclone Bhola was not the most intense storm to ever afflict Bangladesh. The 1876 Bengal Cyclone (the Great Backerganj Cyclone, 29 October – 1 November 1876) devastated the coast with an estimated 40-ft storm surge and killed between 100,000 and 400,000 people [10]. A ship within the eye of that storm recorded a pressure of 930 mb [10].

The coastline of the Bay of Bengal ranks as one of the most susceptible to tropical cyclonic storm surge risk. The coastal areas are affected by these major natural calamities due to its geographical setting and population density as well as the size of the surges which are the largest in the world. There are various reasons why cyclones are more disastrous to the Bangladesh coastline namely, northward cyclone tracks, funnelling of the Bay of Bengal, high astronomical tide levels with long tidal range, shallow coastal water, long continental shelf and the presence of low-lying islands and the delta systems.

The Bay of Bengal records a higher number of cyclones than the Arabian Sea. Most of the time sea surface temperature in the Bay of Bengal exceeds 28°–30°C which is warmer than the Arabian Sea due to high stratification and less mixing. This is because the Bay of Bengal receives enormous volumes of fresh water from rains and has inflows from the world's largest river system – Ganges, Brahmaputra and Meghna. Since fresh water is lighter than the salty waters in the Bay of Bengal, it forms a thin layer on the sea surface. This thin layer of fresh water is heated more easily than the extremely salty waters of the Arabian Sea and these higher sea surface temperatures create favourable conditions for convection in the overlying atmosphere. Furthermore, the remnant depressions of the cyclones that form over the West Pacific Ocean sometimes cross into the Bay of Bengal from the South China Sea with minimal weakening. The reason is that the Kra Isthmus which connects Malaysia to rest of Asia is narrow and the landmass does not have a significant influence on the strength of tropical cyclones travelling into the Bay of Bengal. Finally, the smaller difference in wind speed with respect to altitude (weak vertical wind shear of horizontal wind) over the Bay of Bengal creates a favourable condition for the formation of cyclones.

Cyclones are common in the coastal areas of Bangladesh consisting of over 700km of coastline on the mainland and several offshore islands in the Bay of Bengal. Approximately one-tenth of the global total cyclones occur in the Bay of Bengal. However, not all the tropical cyclones formed in the Bay of Bengal move towards Bangladesh. Approximately one-sixth of the tropical storms generated in the Bay of Bengal usually hit the coastline of Bangladesh. The above information was obtained from [17].

The Bay of Bengal is vulnerable to cyclones predominantly in the pre-monsoon months of April-May (early summer) and the post-monsoon months of October-December (late rainy season). The highest number of cyclones occur in May, October and November. The monsoon season is from June to September when the formation of cyclones is less likely. Cyclones of the pre-monsoon and post-monsoon seasons are the most destructive due to great instability of 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 the north and finally to north-east across Bangladesh. The monthly variation of tropical cyclones over the Bay of Bengal and Bangladesh during 1974 to 2003 is shown in Figure 1 obtained from [18] which suggests that the highest number of cyclones form in May, October and November.

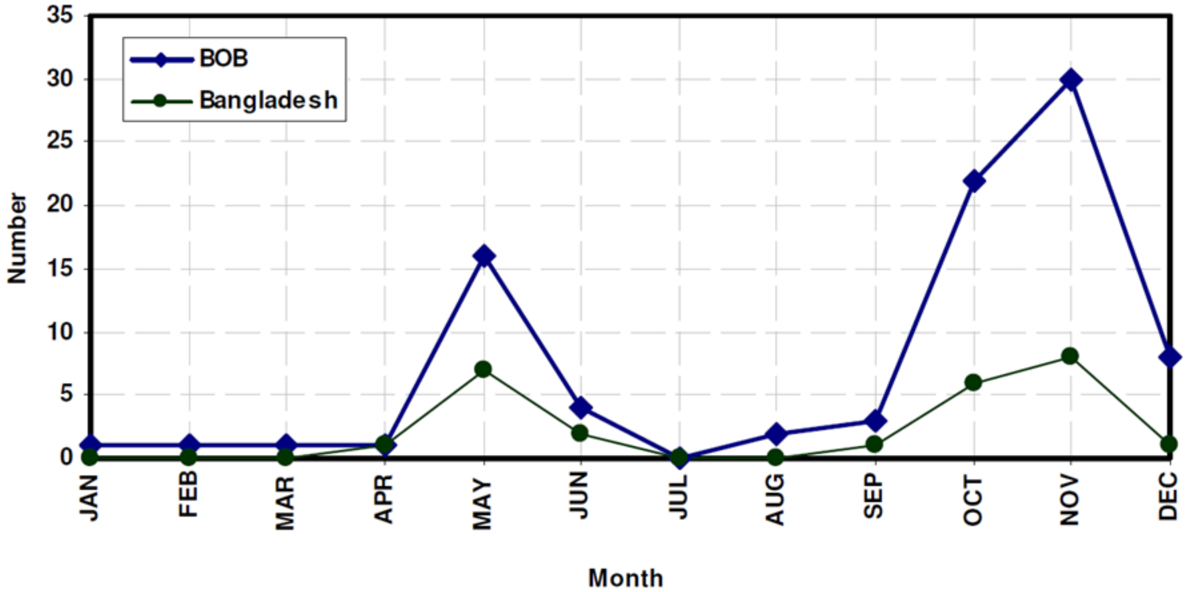

Figure 1: Monthly variation of tropical cyclones over Bay of Bengal (BOB) and Bangladesh during 1974 to 2003 [18]

The monthly distribution of 34 severe cyclones with winds in excess of 54 mph during the 190 years (before Cyclone Bhola) was presented by [10] which clearly reveals a double maximum of activity with the primary maximum occurring in October and a secondary peak in May. Bangladesh is lashed by a severe cyclone one out of every 5 years on an average; however, the distribution is certainly not evenly spaced in time [10].

Workers from other parts of Bangladesh travel to the southern parts for getting a job at aman paddy fields during the months of April, May, October and November [19]. These migrant workers are susceptible to cyclones as these months coincide with the two cyclone seasons (March-June and September-December). The highest number of cyclones occur in October and the second highest number of cyclones occur in May.

Coastal areas and offshore islands in Bangladesh are low lying and very flat. The height of the coastal zone above mean sea level is less than 3m [19]. The astronomical tidal range in Bangladesh is large which is about 3m in the west, 5m in the central part and 3.5-4.0m in the south-eastern part of the country's coastline [19]. Damage from a cyclone at a location becomes disastrous if its landfall coincides with the local high tide.

A funnelling coastline reduces the width of storm induced waves and thereby increases the height. The coasts are situated at right angles in the northern corner of the Bay of Bengal which causes higher storm induced waves compared to a straight coastline [19].

There is a disproportional large impact of storm surges on the coast of Bangladesh due to various local reasons such as re-curvature of cyclones in the Bay of Bengal, shallow continental shelf, high tidal range, triangular shape at the head of the Bay of Bengal, almost sea-level topography of the coastal land and high density of population and coastal defence system [19].

A detailed chronological list of major cyclones in Bangladesh along with associated storm surge and approximate loss and damage is available in [19] who compiled it from [20, 21, 22]. Data on number of deaths for some years are missing from that chronological list. Some of the selected cyclones with number of deaths in Bangladesh are provided in Table 2. Data on cyclones until 1991 in Table 2 were obtained from [19] and data on cyclones thereafter were obtained from [15].

Table 2: Selected cyclones and associated number of deaths in Bangladesh [15, 19]

Year	Deaths
1876	400,000
1970	300,000
1897	175,000
1991	145,000
1911	120,000
1917	70,000
1962	50,000
1919	40,000
1822	40,000
1965a	19,270
1958	12,000
1965b	12,000
1963	11,520
1961a	11,468
1961b	11,466
1985	11,069
1971	11,000
1960a	8,149
1941	7,000
1960b	6,000
1988	5,708
2007	4,234
1965c	870
1966	850
1997	410
1973	183
1969	175
1967	128
1983	43
1974	20
1986	14
1975	5

1.6 The Present Study

Royal HaskoningDHV carried out a literature search on major cyclones in the Bay of Bengal that affected the Bangladeshi coastlines since 1970. Cyclone Bhola (8-13 November 1970) was found to be the deadliest tropical cyclone ever recorded and one of the world's deadliest humanitarian disasters affecting the coastal areas of Bangladesh. Cyclone Bhola is the most devastating natural disasters in human history but there is little to no meteorological research conducted on the event due to the lack of available measured data. As less information is available on Cyclone Bhola (1970), this paper has concentrated on this major event to illustrate the use of numerical modelling to simulate waves generated by cyclones. It was found from literature search that some numerical modelling studies on surge from Cyclone Bhola were carried out by various researchers. On contrary, less information is available on numerical modelling of waves from Cyclone Bhola. Therefore, numerical modelling of waves from Cyclone Bhola was carried out in the present study to illustrate the use of numerical modelling to simulate waves generated by cyclones. Effects of white capping on predicted wave heights were also investigated.

A large regional model is required to simulate cyclone waves and surge. Given the above risks, Royal HaskoningDHV has set up regional wave and tidal hydrodynamic models covering the Bay of Bengal and its wider surroundings to support their project work in the region. The MIKE21 Spectral Wave Model and the Flow Model FM have been used in the study. Sample results of waves from the modelling studies are presented in this paper for illustration purposes only. Structural design considerations and cyclone risk reduction measures are also discussed. The model could be used to simulate the passage of a cyclone anywhere within the Bay of Bengal and its surroundings. The methodology described in this paper for modelling cyclone waves in the Bay of Bengal could also be applied to simulate this type of events at other sites around the world.

2. CYCLONE BHOLA (1970)

2.1 Formation of Cyclone Bhola

Cyclone Bhola (known as the Great Cyclone of 1970) was a devastating tropical cyclone in the Bay of Bengal region that struck Bangladesh and India's West Bengal. On 1 November, Tropical Storm Nora developed over the South China Sea, in the West Pacific Ocean. The system lasted for four days, before degenerating into a remnant low over the Gulf of Thailand on 4 November, and subsequently moved west over the Malay Peninsula on 5 November 1970 [17, 23]. The remnants of this system contributed to the development of a new depression in the central Bay of Bengal on the morning of 8 November. The depression intensified as it moved slowly northward and IMD [24] upgraded it to a cyclonic storm the next day. The storm became nearly stationary that evening near 14.5° N, 87° E, but began to accelerate toward the north on 10 November [25]. The storm further intensified into a severe cyclonic storm on 11 November and began to turn towards the northeast, as it approached the head of the bay. It developed a clear eye and reached its peak intensity later that day, with three-minute sustained winds of 185 km/h (115 mph), one-minute sustained winds of 240 km/h (150 mph) [26], and a central pressure of 960 hPa. The cyclone made landfall on the Bangladeshi coastline during the evening of 12 November around the same time as the local high tide. As the storm made landfall, it caused a 10-metre (33 ft) high storm surge at the Ganges Delta [18]. In the port at Chittagong, the storm tide peaked at about 4 m (13 ft) above the average sea level, 1.2 m (3.9 ft) of which was the storm surge [10]. The enormous destruction from Cyclone Bhola was primarily due to storm surge. The above information was obtained from the "Wikipedia" website for "1970 Bhola Cyclone".

2.2 Damages from Cyclone Bhola

Cyclone Bhola remains the deadliest tropical cyclone ever recorded and one of the world's deadliest natural humanitarian disasters in modern history. At least 300,000 [3] people died in the storm, possibly as many as 500,000 [4, 5], primarily as a result of the storm surge that flooded much of the low-lying islands of the Ganges Delta. The storm surge devastated many of the offshore islands, wiping out villages and destroying crops throughout the region. In Bangladesh, over 3.6 million people were directly affected by the cyclone, and the total damage from the storm was estimated at US$86.4 million (US$450 million in 2006 dollars) [27]. The survivors claimed that approximately 85% of homes in the area were destroyed or severely damaged, with the greatest destruction occurring along the coast [28]. Ninety percent of marine fishermen in the region suffered heavy losses, including the destruction of 9,000 offshore fishing boats. Of the 77,000 onshore fishermen, 46,000 were killed by the cyclone, and 40% of the survivors were affected severely. In total, approximately 65% of the fishing capacity of the coastal region was destroyed by the storm, in a region where about 80% of the protein consumed comes from fish. Agricultural damage was similarly severe with the loss of US$63 million worth of crops and 280,000 cattle [18]. Three months after the storm, 75% of the population was receiving food from relief workers, and over 150,000 relied upon aid for half of their food [28]. Cyclone Bhola also led to increased cholera and typhoid cases in the region due to the contamination of the water supply due to the storm. Many attempts of sending aid to the region were impeded by the prevalent cholera, and as a result, medical aid was delayed [29]. The above information was obtained from the "Wikipedia" website for "1970 Bhola Cyclone".

2.3 Track and Data of Cyclone Bhola

The track (route) of Cyclone Bhola was obtained from [30] and is shown in Figure 2. The cyclone data was obtained from IBTrACS [31]. The IBTrACS archived cyclone data contains 3 hourly information including date and time, track (path) and the maximum sustained wind speeds (1-minute mean). However, the IBTrACS website does not provide the minimum central pressures and the radius of maximum sustained wind speeds for this old cyclone. Therefore, these missing parameters were estimated using the two equations provided below derived by the author (M A Sarker) solely for the use in the present study. Data from the JTWC website [32] on recent major cyclones in the Bay of Bengal was used to derive these two equations.

P = -0.8161W + 1027 (1)

R = -0.2561W + 45.353 (2)

Where,

W is the maximum sustained wind speeds (knots)

P is the minimum central pressure (mb)

R is the radius of maximum wind speed (nm)

Empirical relationships between the maximum wind speed and the central pressure in tropical cyclones were determined for Atlantic hurricanes and Pacific typhoons by several scientists such as those cited in [10]. These relationships should also be valid for cyclones in the Bay of Bengal as cyclones do not differ dynamically from hurricanes or typhoons [10].

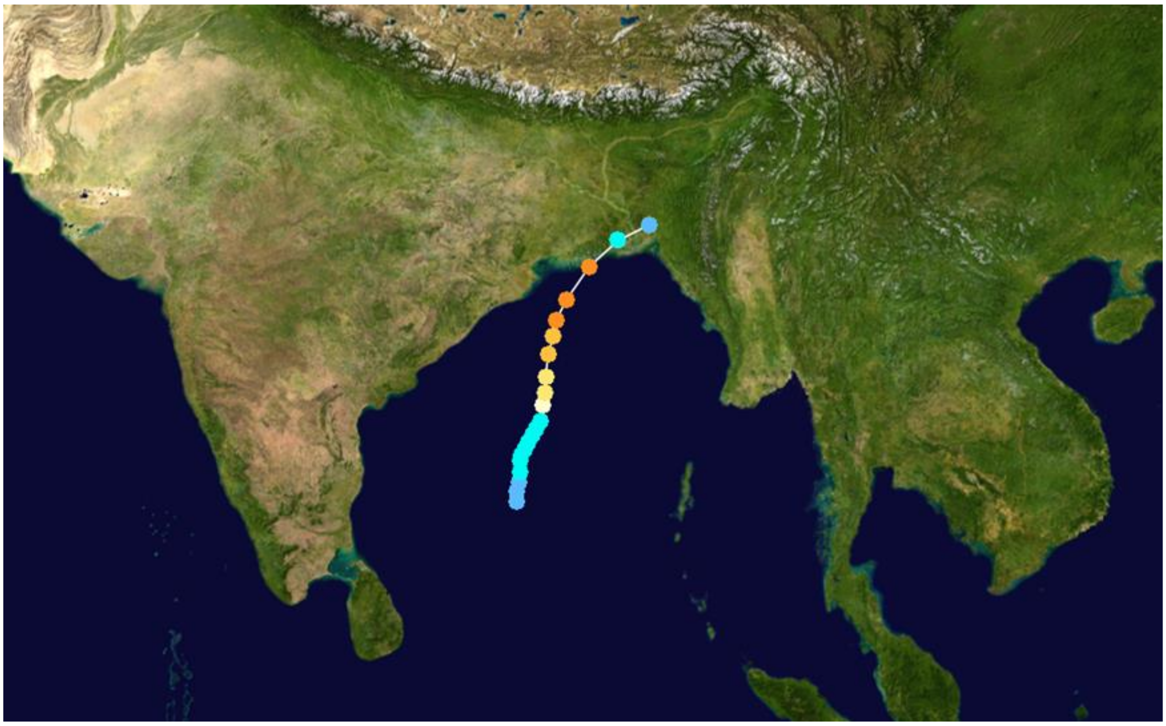

Figure 2: Track of Cyclone Bhola (1970) [30]

Data on Cyclone Bhola is provided in Table 3 [31]. It should be noted that the 1-minute mean wind speeds in Table 3 were converted into 1-hour mean using the methodology described in [33] for use in the numerical model.

Table 3: Track and Data of the Cyclone Bhola (1970) [31]

Date and time (UTC)	Time (hour)	Longitude (°E)	Latitude (°N)	Max 1-minute wind speeds (knots)
08/11/1970 00:00	0	86.3000	12.3000	25
08/11/1970 03:00	3	86.2925	12.3925	25
08/11/1970 06:00	6	86.3000	12.5000	25
08/11/1970 09:00	9	86.3500	12.6500	25
08/11/1970 12:00	12	86.4000	12.8000	25
08/11/1970 15:00	15	86.4075	12.8925	25
08/11/1970 18:00	18	86.4000	13.0000	25
08/11/1970 21:00	21	86.4000	13.2000	30
09/11/1970 00:00	24	86.4000	13.4000	35
09/11/1970 03:00	27	86.3925	13.5075	35

09/11/1970 06:00	30	86.4000	13.6000	35
09/11/1970 09:00	33	86.4425	13.7500	35
09/11/1970 12:00	36	86.5000	13.9000	35
09/11/1970 15:00	39	86.5500	14.0000	35
09/11/1970 18:00	42	86.6000	14.1000	35
09/11/1970 21:00	45	86.6425	14.2425	35
10/11/1970 00:00	48	86.7000	14.4000	35
10/11/1970 03:00	51	86.7850	14.5350	35
10/11/1970 06:00	54	86.9000	14.7000	35
10/11/1970 09:00	57	87.0574	14.9275	35
10/11/1970 12:00	60	87.2000	15.2000	35
10/11/1970 15:00	63	87.2651	15.5000	35
10/11/1970 18:00	66	87.3000	15.8000	35
10/11/1970 21:00	69	87.3575	16.0500	50
11/11/1970 00:00	72	87.4000	16.3000	65
11/11/1970 03:00	75	87.4001	16.5700	65
11/11/1970 06:00	78	87.4000	16.9000	65
11/11/1970 09:00	81	87.4350	17.3425	65
11/11/1970 12:00	84	87.5000	17.8000	65
11/11/1970 15:00	87	87.6000	18.1725	65
11/11/1970 18:00	90	87.7000	18.5000	65
11/11/1970 21:00	93	87.7352	18.7925	65
12/11/1970 00:00	96	87.8000	19.1000	65
12/11/1970 03:00	99	87.9405	19.4474	65
12/11/1970 06:00	102	88.2000	19.9000	65
12/11/1970 09:00	105	88.5972	20.5350	65
12/11/1970 12:00	108	89.1000	21.2000	65
12/11/1970 15:00	111	89.6276	21.7524	50
12/11/1970 18:00	114	90.2000	22.2000	35
12/11/1970 21:00	117	90.7947	22.5329	30
13/11/1970 00:00	120	91.4000	22.8000	25

3. WIND AND PRESSURE FIELDS GENERATION

The MIKE21 Cyclone Wind Generation Tool developed by DHI [34] was used to generate the cyclonic wind and pressure fields. The tool allows users to compute wind and pressure data due to tropical cyclones. Several cyclone parametric models are included in the tool such as Young and Sobey model (1981), Holland – single vortex model (1981), Holland – double vortex model (1980) and Rankine vortex model. The Young and Sobey model was used in the study. The Young and Sobey model requires six input parameters (i.e. time, track, radius of maximum wind speed, maximum wind speed, central pressure and neutral pressure). The other models require some additional parameters (such as Holland parameter B and Rankine parameter X) that need to be calculated using empirical relationships. This adds further uncertainty to the generated wind and pressure fields. Therefore, the other models were not used for the study. Figure 3 shows an example of wind and pressure fields from Cyclone Bhola on 12/11/1970 09:45 when it generated the maximum significant wave heights. These wind and pressure fields were used to drive the cyclone model described later.

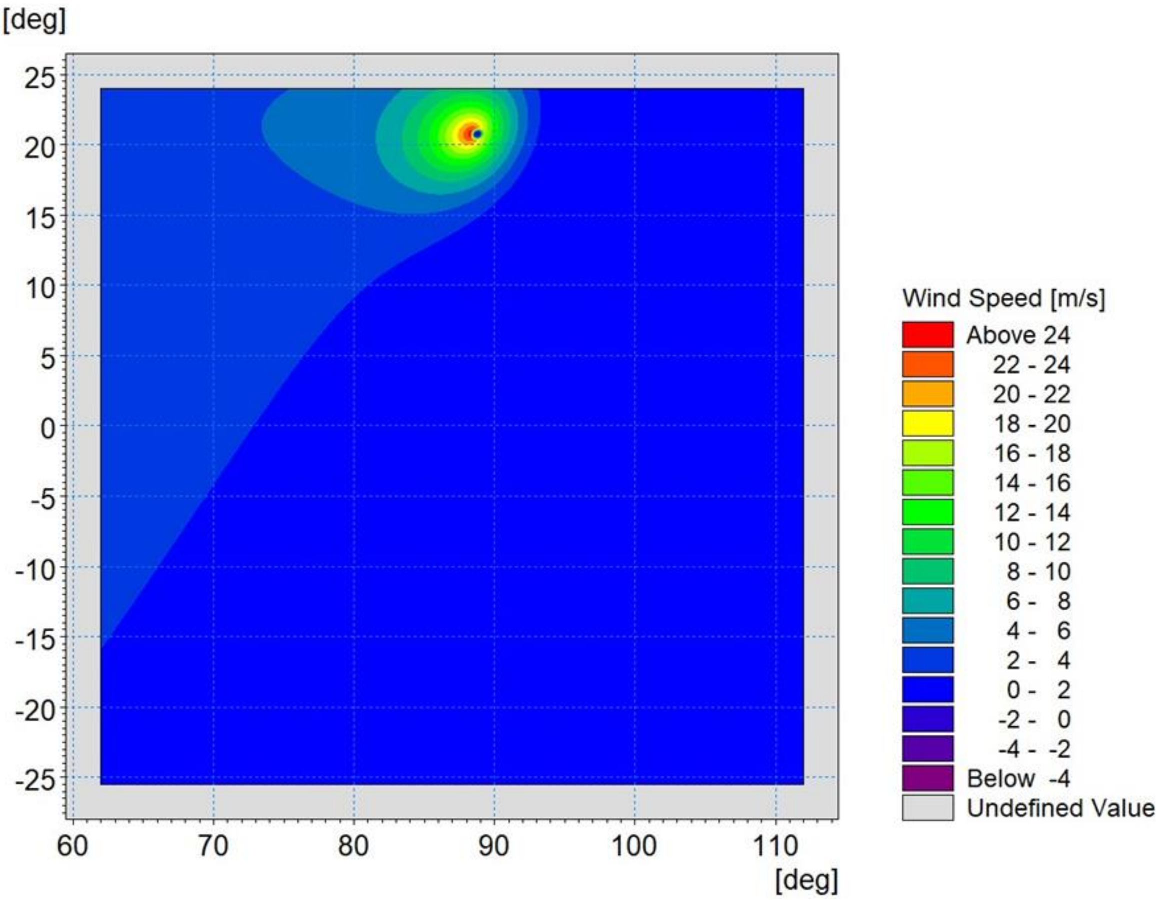

Figure 3(a): Wind fields of Cyclone Bhola on 12/11/1970 09:45

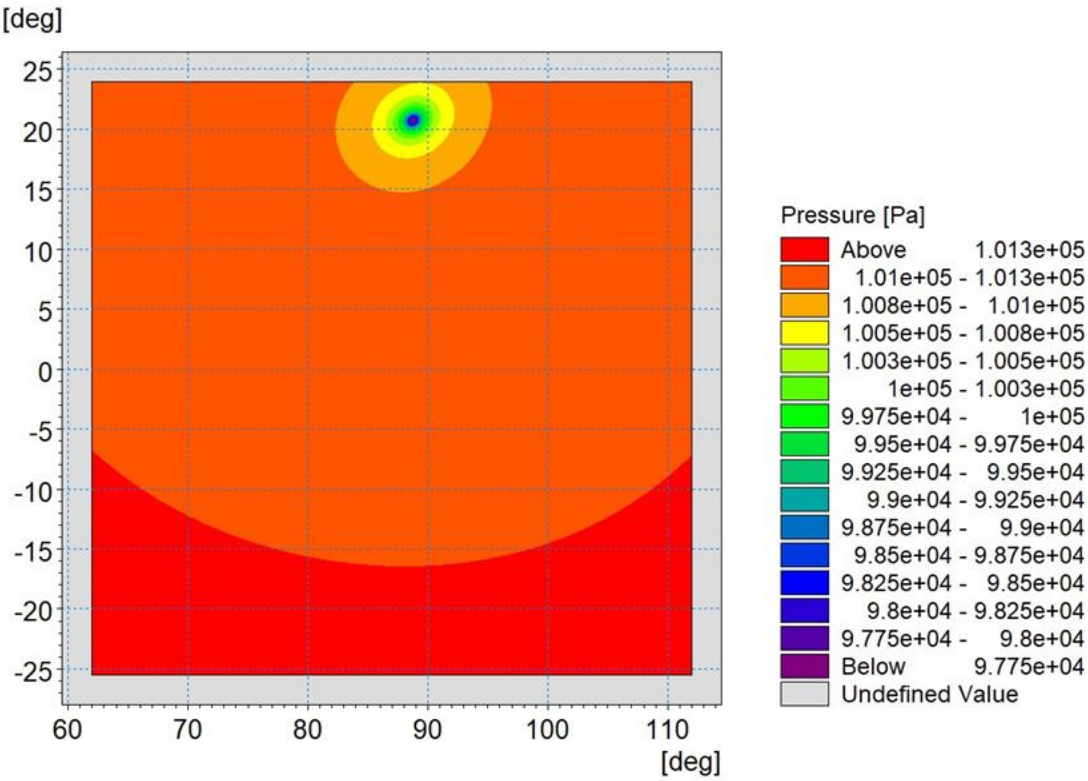

Figure 3(b): Pressure fields of Cyclone Bhola on 12/11/1970 09:45

Figure 3: Wind and pressure fields of Cyclone Bhola on 12/11/1970 09:45

4. BAY OF BENGAL REGIONAL MODEL SET UP BY ROYAL HASKONINGDHV

Royal HaskoningDHV has set up a two-dimensional Regional Model for the Bay of Bengal and surroundings. The regional model covers the coastlines of six countries – India, Sri Lanka, Bangladesh, Myanmar, Malaysia, and Indonesia (see Figure 4). An unstructured flexible mesh (with variable cell sizes) was used in the study. The model bathymetry (as shown in Figure 4) was obtained from the C-Map Global Database [35].

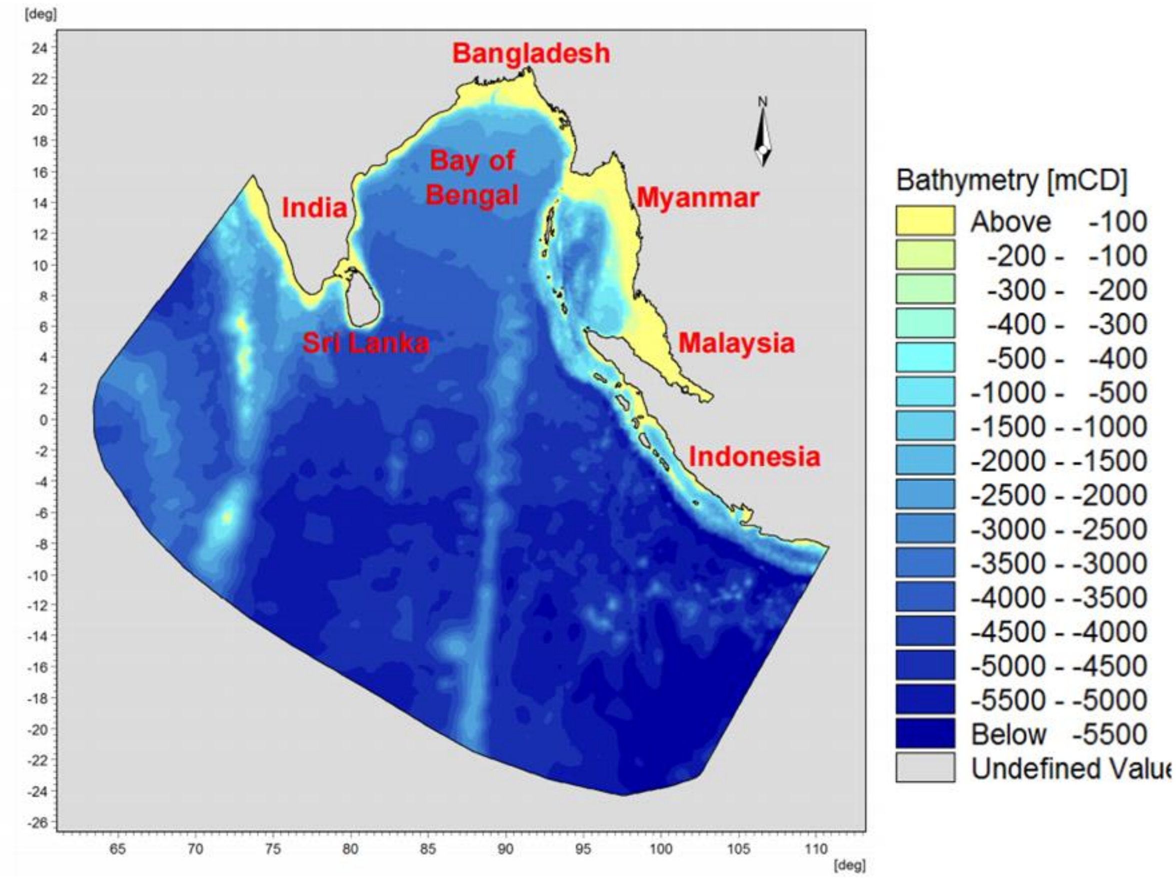

Figure 4: Extent and bathymetry of the regional model set up by Royal HaskoningDHV

5. NUMERICAL MODELLING OF WAVES FROM CYCLONE BHOLA

5.1 The Regional Wave Model

The regional wave model set up by Royal HaskoningDHV based on the MIKE21 Spectral Wave (SW) Model developed by DHI [36] was used to simulate the generation and propagation of cyclone waves. The fully spectral formulation was used with in-stationary time formulation. Wave diffraction, wave breaking, bottom friction and white capping were included in the model simulations. Quadruplet wave interaction was included together with the JONSWAP fetch growth empirical spectral formulation. The higher order numerical scheme was used to improve accuracy in model results. This regional wave model was used to derive cyclone waves.

5.2 The Regional Tidal Model

Royal HaskoningDHV has also set up a two-dimensional regional tidal hydrodynamic model for the Bay of Bengal and its surroundings using the MIKE21/3 Flow Model FM developed by DHI [37]. The model is based on the numerical solution of the two/three-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 higher order numerical scheme was used in the study to improve accuracy in model results. Standard “Flood and Dry” were included in the model to consider flooding and drying processes. Barotropic density type and Smagorinsky eddy viscosity type were used. Coriolis forcing was included in the model as varying in domain. A constant bed resistance as

Manning's number (n = 1/44 $m^{1/3}/s$) was used throughout the model domain. This regional tidal model was used to derive cyclone surge.

5.3 Methodology

The cyclone wave model was driven by the wind and pressure fields as shown in Figure 3. A constant water level of +2.6mCD was used in the tidal model as an initial condition as well as boundary conditions along all open boundaries. The model simulations covered the entire passage of the cyclone across the Bay of Bengal.

The model simulation was carried out in a coupled mode where the wave model and the tidal model were run simultaneously. This allowed the wave model to obtain water levels from the tidal model and the tidal model to obtain radiation stress from the wave model automatically during a simulation and thus improving accuracy in model results.

5.4 Model Validation

No measured wave data was found from literature search on Cyclone Bhola. Therefore, model parameters were selected based on Royal HaskoningDHV experience on cyclone modeling and guidelines provided in the DHI manual.

A series of sensitivity runs were also carried out with various values of white capping (dissipation coefficient, C_{dis}). Model results were extracted at various locations (as shown in Figure 5) along the Bangladeshi coastline at different water depths. Results from the sensitivity runs are provided in Table 4. It was found that the modelled wave heights both at the shallow and the deep waters are sensitive to white capping with higher wave heights for lower white capping.

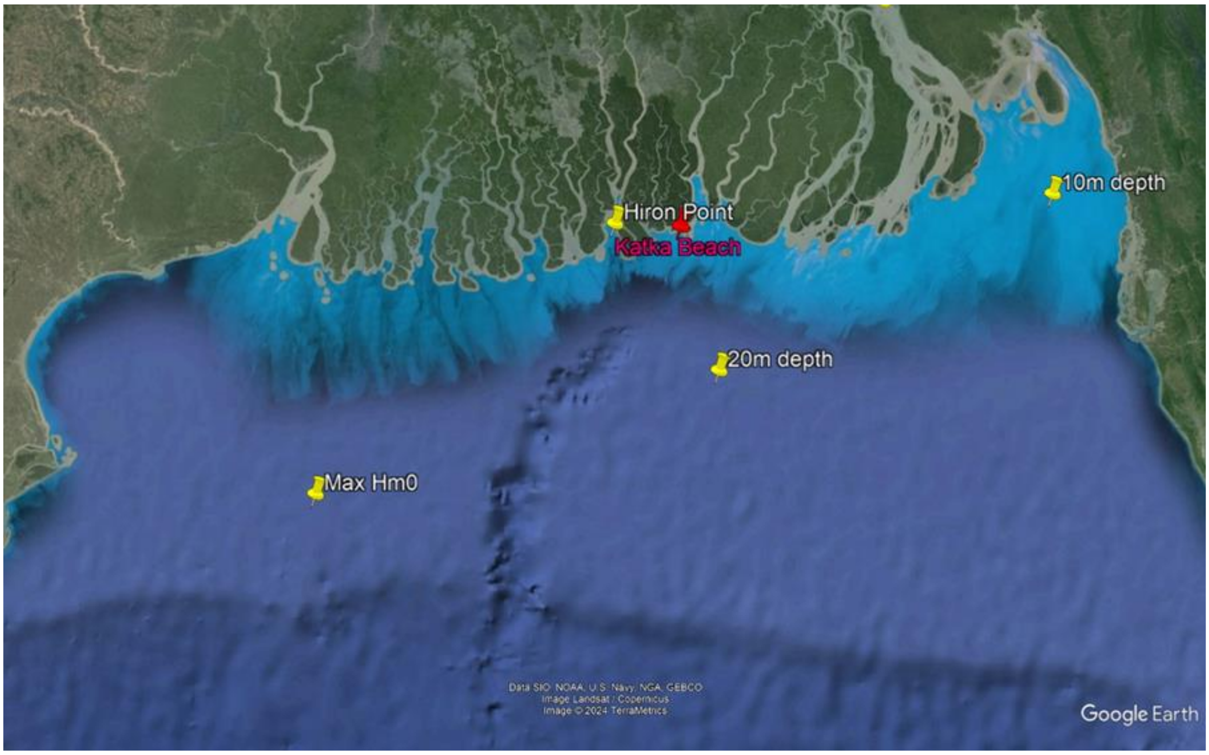

Figure 5: Output locations for sensitivity runs (background image from Google Earth)

Table 4: Sensitivity results on white capping from the present study

White capping	Significant wave heights (H_{m0})				
	Maximum H_{m0} (88.2°E, 20.6°N)	**Hiron Point (89.5°E, 21.8°N)**	**Katka SeaBeach (89.8°E, 21.8°N)**	**At 10m depth (91.5°E, 22.0°N)**	**At 20m depth (91.0°E, 21.2°N)**
4.5	14.8m	2.9m	1.7m	2.1m	5.8m
6.0	13.2m	2.8m	2.3m	2.0m	5.2m
8.0	11.6m	2.8m	2.2m	1.9m	4.7m

Numerical modelling of waves from Cyclone Gonu (2007) in the Arabian Sea was carried out by [38] who found that the modelling wave height matched with the measured value for white capping of 6.0. The Arabian Sea and the Bay of Bengal both lie in the northern Indian Ocean and have some similarities in cyclone processes. Therefore, white capping 6.0 was used in the present study to carry out the model production runs.

5.5 Model Results and Discussions

The model results for Cyclone Bhola indicate that the maximum hindcast significant wave height (H_{m0}) of approximately 13.2m (with associated peak wave period of 13.7s) occurred at location of 88.2°E, 20.6°N (107m depth) on 12 November 1970 at 09:45. The two-dimensional distribution of wave height contours is shown in Figure 6 for this time-step. The figure indicates that the maximum significant wave heights were generated near the south-western coastal waters of Bangladesh. The temporal variation in significant wave height and peak wave period at this location is shown in Figure 7. The figure indicates that significant wave heights higher than 10m were sustained for approximately 8.5 hours and wave heights higher than 12m were sustained for approximately 4.2 hours.

Further statistical analyses of model results were carried out using the MIKE21 Tool to derive maximum significant wave heights over the Bay of Bengal. The maximum significant wave heights over the model domain are shown in Figure 8. Maximum significant wave heights at various locations along the Bangladeshi coastline were extracted from the model results. These locations are shown in Figure 5 and the maximum significant wave heights at these locations are provided in Table 4.

The modelling results for Cyclone Bhola indicate that it was a major event that generated waves up to 13.2m at the height of the storm. The storm took a north-easterly track and travelled into the south-west coastal waters of Bangladesh resulting in high waves off the coast. The impact of the cyclone was at its highest at the north-west corner of the Bay of Bengal affecting mostly the northern coast of India and the south-western coast of Bangladesh.

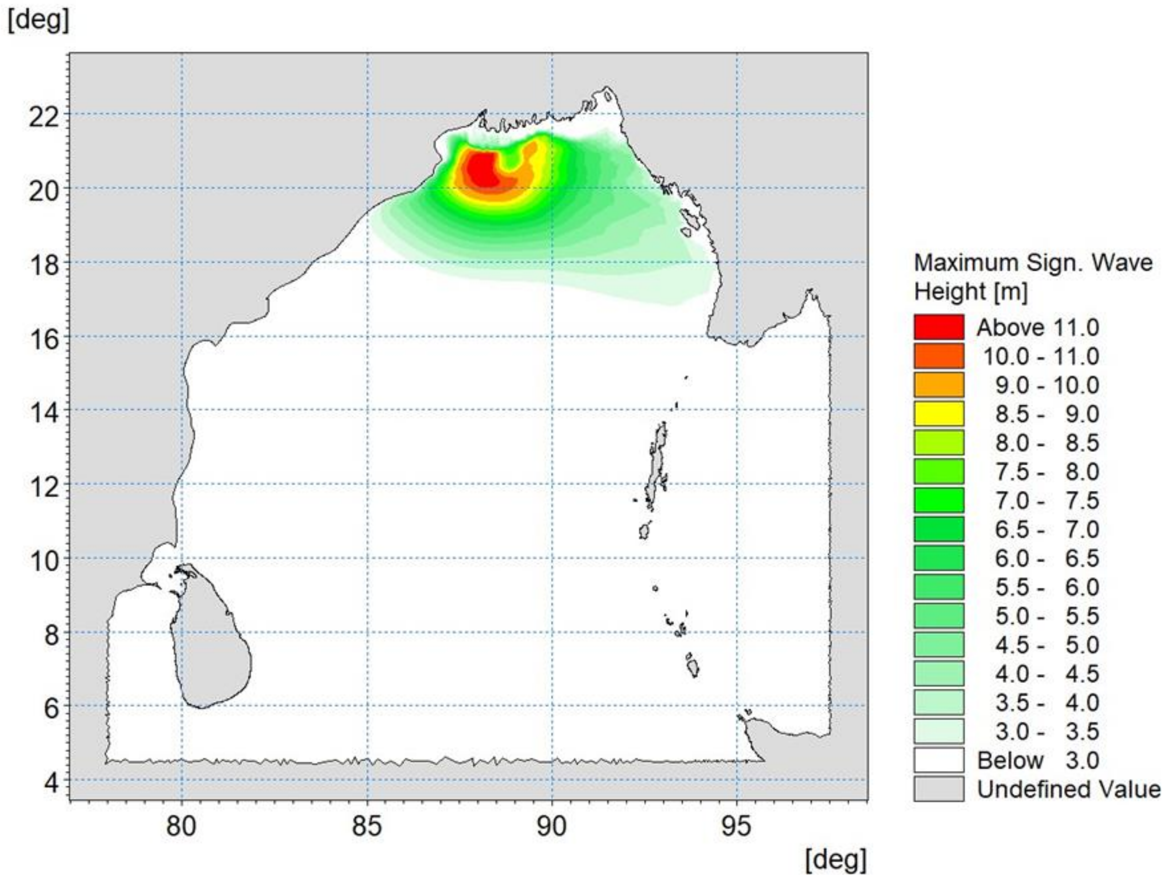

Figure 6: Significant wave heights (H_{m0}) of Cyclone Bhola on 12/11/1970 09:45

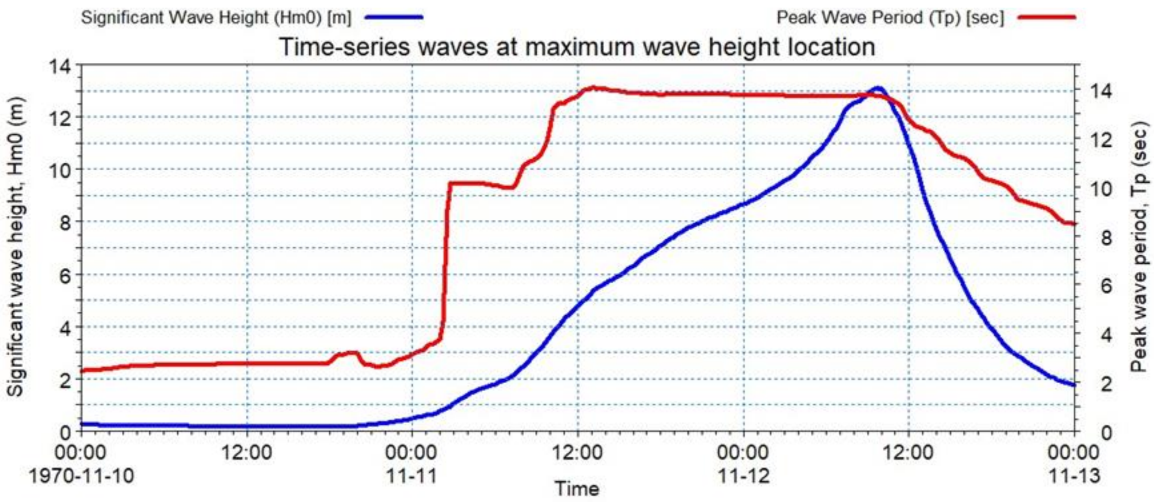

Figure 7: Time-series of waves over the entire duration of Cyclone Bhola at the maximum wave height location [88.2°E, 20.6°N, 107m depth]

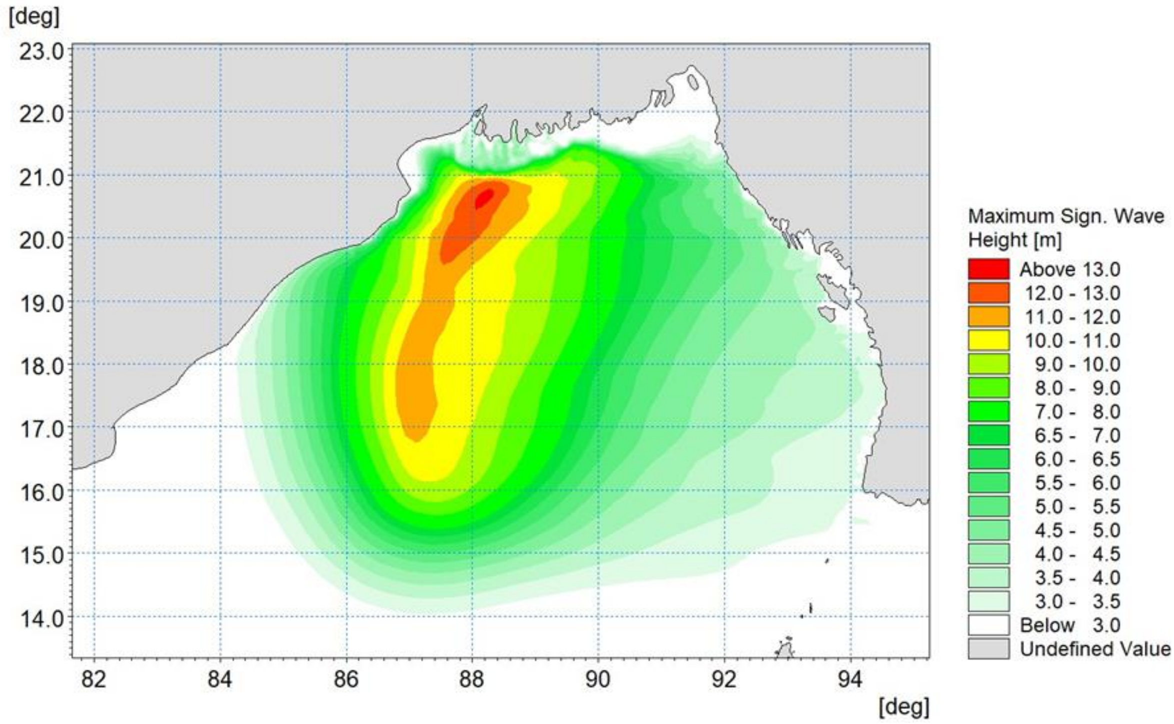

Figure 8: Maximum significant wave height (H_{m0}) over the entire duration of Cyclone Bhola

6. LIMITATIONS ON THE MODEL RESULTS

Model results presented in this paper are for illustration purposes only. These should not be used for any practical project work for which use of local survey bathymetric data and detailed local calibration and validation are essential.

The missing parameters of Cyclone Bhola were estimated using the two equations provided earlier derived by the author solely for the use in the present study.

7. 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 seabed 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.

8. CYCLONE RISK REDUCTION MEASURES

8.1 Risks Reduction from Cyclones

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 cyclonic 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 cyclonic 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.

8.2 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).

9. SUMMARY AND FINDINGS

Numerical modelling of waves from cyclones was carried out to illustrate the application of numerical models in simulating historical cyclones. Cyclone Bhola was a great devastating tropical cyclone in the Bay of Bengal region that killed up to 500,000 people in Bangladesh with widespread damages of properties and crops. Full information on this event is not available. Therefore, this cyclone was selected for the numerical modelling. The MIKE21 models and tools developed by DHI were used in the study. Missing information on the cyclone was filled up by analysing characteristics of recent cyclones in the Bay of Bengal.

The model results for Cyclone Bhola indicate that the maximum hindcast significant wave height (H_{m0}) of approximately 13.2m (with associated peak wave period of 13.7s) occurred at location of 88.2°E, 20.6°N (107m depth) on 12 November 1970 at 09:45. The maximum significant wave heights were generated near the south-western coastal waters of Bangladesh. Wave heights higher than 10m were sustained for approximately 8.5 hours and wave heights higher than 12m were sustained for approximately 4.2 hours. The impact of the cyclone was at its highest at the north-west corner of the Bay of Bengal affecting mostly the northern coast of India and the south-western coast of Bangladesh. It was found that the modelled wave heights both at the shallow and the deep waters are sensitive to white capping with higher wave heights for lower white capping as shown in Table 4.

The methodology described in this paper for modelling cyclone waves in the Bay of Bengal could also be applied to other sites around the world that are affected by this type of event.

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