Storm Surge Forecasting In the Bay of Bengal and Arabian Sea

S K DUBE
Indian Institute of Technology, Kharagpur 721- 302
E mail : skdube@iitkgp ernet in

Abstract

India and its neighborhood are threatened by the possibility of storm surge floods whenever a tropical cyclone approaches About 300 ,000 lives were lost in one of the most severe cyclone that hit Bangladesh (then east Pakistan) in November 1970 The Andhia cyclone devastated the eastern coast of India, killing about 10, 000 persons in November 1977. More recently the Orissa coast of India was struck by a severe cyclonic storm in October 1999, killing more than 15000 people besides enormous loss to the property in the region These and most of the world s greatest human disasters associated with the tropical cyclones have been directly attributed to storm surges.

Storm surge disasters cause heavy loss of life and property damage to the coastal structures and the losses of agriculture which lead to annual economic losses in these countries.Thus the real time monitoring and warning of storm surge is of great concern for this region.

The main objective of the present paper is to highlight the current activity in surge prediction in India .The paper also describes the mitigation measures for storm surge hazards.

Introduction

Storm surges associated with severe tropical cyclones constitute the world s worst coastal marine hazard Storm surge disasters cause heavy loss of life and property, damage to the coastal structures and the losses of agriculture which lead to annual economic losses in affected countries .Death and destruction arise directly from the intense winds characteristics of tropical cyclones blowing over a large surface of water which is bounded by a shallow basin. As a result of these winds the massive piling of the seawater occurs at the coast leading to the sudden inundation and flooding of coastal regions.

Storm surges are extremely serious hazards along the east coast of India Bangladesh Myanmar and Sri Lanka About 300,000 lives were lost in one of the most severe cyclone that hit Bangladesh (then East Pakistan) in November 1970. Recent Paradip Cyclone devastated the eastern coast of India, killing more than 10,000 persons in October 1999. These two and most of the world's greatest human disasters associated with the tropical cyclones have been directly attributed to storm surges.

During the last 109 years, 263 cyclones had struck the east coast of India, leaving severe damage and causalities mostly because of the strong winds and storm surges. Statistics show that 37% of the total cyclones hitting the east coast of India have crossed the Orissa coast. Notable storm surges that have affected the Orissa coast have been during October 1967, October 1971, June 1982 October 1985 and October 1999 of which the recent Paradip cyclone of October 1999 was the worst. The storm surge due to the October 1999 event was more than 7 meters over and above the normal astronomical tide. The surge penetrated through Mahanadi river system and caused serious inland flooding. Thus the real time monitoring and warning of storm surges is of great importance to Orissa.

A detailed review of the problem of storm surges in the Bay of Bengal is given by Ali (1979), Rao (1982), Roy (1984), Murty (1984), Murty et al. (1986), Das (1994 a, b), Dube et al. (1997, 1999, 2000a) and Chittibabu (1999).

The purpose of the present paper is to give a review of recent developments in predicting the storm surges in the Bay of Bengal and Arabian Sea. A real time storm surge prediction system is also proposed here for disaster management (Dube et al. 1994).

Destruction Potential of Strom Surge

Although the frequency of tropical cyclones in the Bay of Bengal is not quite high, the coastal regions of India, Bangladesh and Myanmar suffer most in terms of loss of life and property caused by the surges. The reason besides the inadequate accurate prediction, are the low lands all along the coasts and considerably low-lying huge deltas, such as, Gangetic delta and Irrawaddy delta Table I lists the number of deaths associated with several deadly cyclone disasters in India and Bangladesh where death tolls were in excess of 5000 lives. These major surges usually occurred unexpectedly.

There can be little doubt that the number of casualties would have been considerably lower if the surge could have been predicted, say, 24 hours in advance allowing effective warnings in the threatened area. The prediction, must, of course, be accurate enough so that one can distinguish between the dangerous surges and the surges that cause little harm, as people cannot be evacuated from exposed areas for every approaching storm. Some success has been achieved in predicting storm surges by computer oriented numerical models.

TABLE I

DEATHS IN TROPICAL CYCLONES

Year	Countries	Deaths
1970	Bangladesh	300,000
1737	India	300,000
1876	Bangladesh	200,000
1897	Bangladesh	175,000
1991	Bangladesh	140,000
1833	India	50,000
1864	India	50,000
1822	Bangladesh	40,000
1965	Bangladesh	19,279
1999	India	15,000
1963	Bangladesh	11,520
1961	Bangladesh	11,466
1985	Bangladesh	11,069
1971	India	10,000
1977	India	10,000
1960	Bangladesh	5,149
1973	India	5,000

Data Input for Surge Prediction Models

In order to achieve greater confidence in surge prediction in the Indian Seas one should have the good knowledge of the input parameters for the model. These parameters include the oceanographic parametets meteorological parameters (including storm characteristics) hydrological input basin characteristics and coastal geometry wind stress and seabed friction and information about the astronomical tides. It has been seen that in many casts these input parameters strongly influence the surge development.

Most of the northern Bay of Bengal is very shallow and is characterized by sharp changes in seabed contours. The shallowness of water may considerably modify the surge heights in this region. Therefore, accurate bathymetry maps are needed for improved surge prediction.

Operational Prediction Models

In India, the study of the numerical storm surge prediction was pioneered by Das (1972). Subsequently several workers attempted the prediction of storm surges in the Bay of Bengal (Das et al. 1974; Ghosh, 1977, John and Ali, 1980; Johns et al. 1981; Murty and Henry, 1983; Dube et al. 1985 etc.)

Operational numerical storm surge prediction models have been developed and are being routinely used for several coastal region of the world such as North Sea, the Gulf of Mexico and Atlantic coast, Hong Kong, China etc.

Most of the operational models require large computing power. Therefore for routine forecasting of storm surges, especially providing multiple forecast scenarios, the models cannot be used in the absence of access to sufficient computing facility. To overcome this difficulty, most of the forecasting offices use the nomogram methods of JELESNIANSKI (1972) for prediction of storm surges associated with tropical cyclones. The nornograms have been developed from modelling studies of a large number of bathymetnes and approach angles.

Advent of powerful personal computers has set up a trend to run storm surge models in real time on PC-based workstations in an operational office. In fact, a PC-based work station (the Automated Tropical Cyclone Forecasting System, ATCF) is already in operation at the Joint Typhoon Warning Centre, Guam for the past many years. The Australian Bureau of Meteorology Research Centre, together with their Bureau Severe Weather Programme Office has also developed an Australian workstation for storm surge forecasting.

Meal Time Storm Surge Prediction System for the Bay of Bengal

In India, Dube et al (1994) described a real time storm surge prediction system for the east coast of India. The forecasting system proposed by the authors is based on the vertically integrated numerical storm surge models that were developed earlier by the group (Johns et al. 1981; 1983; Dube et al. 1985). Surface winds associated with a tropical cyclone are derived from a dynamic storm model (Jelesnianski and Taylor, 1973). The only meteorological inputs required for the model are the positions of the cyclone, pressure drop and radii of maximum winds at any fixed interval of times. The model can be run in a few minutes on a PC in an operational office. The system is operated via a terminal menu and the output consists of the two -dimensional and three-dimensional views of peak sea surface elevations with the facility of zooming the region of interest. One of the significant features of this storm surge predication system is its ability to investigate multiple forecast scenarios to be made in real time. This has an advantage because the meteorological input needed for surge prediction can be periodically updated with the inflow of data on fast telecommunication links. The model has extensively been tested with severe cyclonic storms, which struck the east coast of India during the period 1960-1999. Detailed case studies by using this model may be seen in Dube and Gaur (1995). This version of the model was tested in near real time during the cyclone periods of 1992-1993 (Dube and Gaur, 1995).

Validation Experiments

In order to validate the model, using the data of severe cyclonic storms hitting the east coast of India has performed several simulation experiments. An attempt has been made to compare the simulated sea surface elevations with observations from local tide gauges. wherever possible or with post storm survey estimates of India Meteorological Department. The model results reported in the present study are in good agreement with available observations/estimates.

In the present paper we will give the results of the model computed storm surges associated with October 1999 Orissa cyclone.

Real Time Prediction of Storm Surge Associated with 1999 Super Cyclone

A depression formed in the Bay of Bengal near 12° N and 98.5° E at 0600 UTC of 25th October 1999. It became a cyclonic storm in the early hours of 26th and located at 13.5° N and 96. 5° E. The cyclone moved further in a northwesterly direction and lay centered at 16° N and 92°E. It became a severe cyclonic storm with a core of hurricane winds on 27th at 0300 UTC. The cyclone further intensified into a very severe cyclonic storm and lay centered at 17.5° N and 89.5° E on 28th. Cyclone crossed the Orissa coast of India close to Paradip between 0430 and 0630 UTC of 29 October. For the track land falling near Paradip the pressure drop is 97 hPa and radius of maximum winds is 40 km. The track of the cyclone is shown in Figure 1.

Forecast experiments weie performed for the following scenarios:

Scenario I

In this case the expected landfall is near Puri. The numerical integration is carried out for 36 hours. A maximum surge of 4.6 m is predicted to the north of Konark. The region between Konark and Paradip is affected by a surge of more than 3 m (Fig. 2a).

Scenario II

For this scenario the landfall of the cyclone is now taken as Balasore.The maximum computed surge of 4.2m occurs 30km to the south of Balasore (Fig.2b).

Scenario III

For this experiment the tentative best track of the cyclone is taken from the IMD after the cyclone ciossed few km south of Paradip. The model is integrated with 98 hPa and 40 km ladius of maximum winds. Fig. 2 (c) shows the model computed peak surge envelope along the Orissa coast. It can be seen that a maximum surge of about 7. 8m occurred close to the landfall point (Dube et al. 2000). The coastal legion between Konark and Chandbali is affected by a surge of more than 5m Post- storm survey reports also show that the surge is more than 7m, near Paradip.

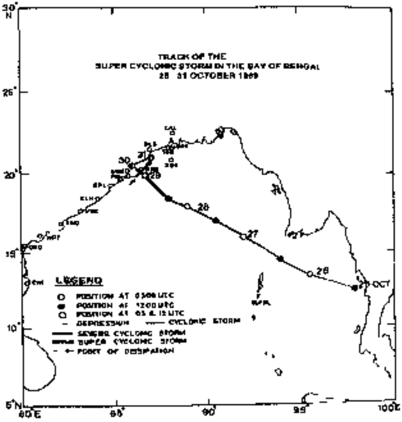

Fig. 1. *Track of October 1999 Orissa Cyclone*

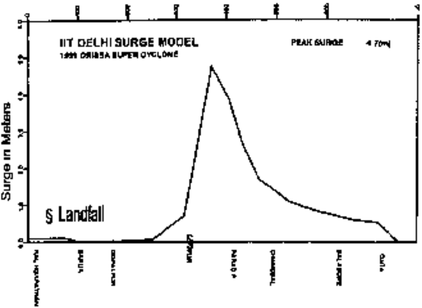

Fig. 2(a) *Peak Surge -Scenario I :Landfall at Puri(Dube et al, 2000b).*

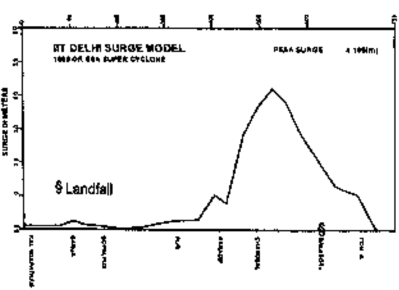

Fig 2(b) *Peak surge- Scenario II :Landfall at Balasore (Dube et al, 2000b).*

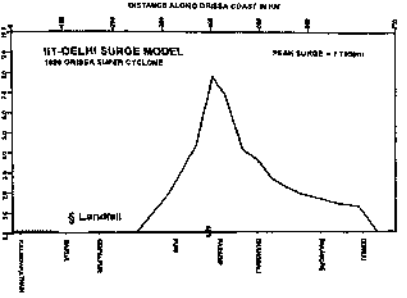

Fig.2(c) *Peak surge envelop - Scenario III Actual Landfall at Paradeep (Dube et al. 2000b).*

Some Future Directions

The damage from cyclones is mainly due to two factors. About 90% of the damage is due to inundation of land by sea water and also flooding of the river deltas from the combined effects of tides and surges from the sea penetrating into the rivers, while at the same time excess water in the rivers due to heavy rains from the cyclone is trying to flow through the rivers into the sea. The balance 10% of the damage is from the very strong winds from the moving cyclones. At this time, science is not capable of controlling cyclones but is capable of eliminating practically 90% of the damage and the loss of life. The only recourse to minimizing the damage from the strong winds is to design buildings with stronger roofs, and wind - proofing electric power poles, etc. Still one has to expect damage to trees.

This general pattern of damage worldwide appears to apply for the recent event in Orissa as well. The cyclone of October 25 - 29, 1999 made landfall near Paradip in Orissa and the peak TWLE was about 12 meters.

It should also be noted that almost all the loss of life is due to inundation and flooding. Thus there is need for a plan, which should practically eliminate 90% of the damage but also eliminate almost all the loss of life as well. Following are some of the recommendations in this regard:

Use extremely sophisticated state of the ait computer models to calculate maximum possible stoim surge and maximum possible total water level envelope (MPTWLE) foi the Onssa coast, undei a variety of scenarios

Through very detailed soil surveys one can determine for each segment of the Onssa coastline which of the following protection measure is most appiopnate

(a)	Earth dykes	(d)	Bieakwateis
(b)	Sea walls (conciete)	(e)	Stoirn surge buffer zones (vegetation reed grass)
(c)	Mangrove forests	(f)	Sand dunes

Sometimes a combination of two or thiee o(the above may be moic appropriate

To mitigate the damage from the oveiflow and flooding Irom uvus a combination of the following schemes, should be considered

(a) Storm surge bamers to pievent the surge from the ocean to penetiatc into the avers

(b) A system of diy canals ioi each river and estuary Duiing a flooding event, excess water can be diverted into these

References

ALI A (1979) Storm surges in the Bay of Bcng-il and some rehlcd problems Ph D rhesis University of Reading England pp 227

CHITTIBABU P (1999) Development of storm bulge prediction models for the Bay of Bcnyil and the Arabian Sea Ph D Thesis IIT Delhi Indii pp 262

DAS P K (1972) A prediction model for stoim surges in the Bay of Bengal Nituic v *2V)* pp 211 213

DAS P K (1994a) Prediction of stoim suiges n the Bay of Bengal Proc Indian Nat Sci Ac id v 60 pp 513 533

DAS P K (1994b) On the Prediction of storm suiges Sadhana v 19 pp 583 595

DAS P K DUBE S K MOHANTY U C SINHA P C ind RAO A D (1983) Numuicil simulation of the surge generated by the June 1982 Onssa cyclone Mausam v 34 pp 359 366

DAS P K SINHA M C and BALASUBRAMANYAM V (1974) Stoim Suiges in the Bay of Bengal Quart J Roy Met Soc v 100 pp 437 449

DUBE S K and GAUR V K (1995) Real time storm surge piediction system for the Bay of Bengal Current Science v 68 pp 103 113

DUBE S K SINHA P C and ROY G D (1985) The numerical sunuldt on of storm suiges along the Bangladesh coast Dyn Atmos Oceans v 9, pp 121 133

DUBE, S K RAO A D, SINHA, P C and CHITTIBABU, P (1994) A real time storm surge piediction system An Application to east coast of India Proc Indian Nat Sci Acad \ 60 pp 157 170

DUBE, SK, RAO, A D, SINHA, P C MURTY, T S and BAHULAYAN, N (1997) Storm sutge in the Bay of Bengal and Arabian Sea The pioblem and its Prediction Mausam \ 48, pp 283-304

DUBE, S K, SINHA, P C, RAO, A D and CHITTIBABU, P (1999) Recent developments in storm surge modeling and future trends (In) A K Bhatnagar, S Raghavan R N Keshavamurthy, G S Gdnesan, J Shanmugasundram, S Rajarathnam N Jayanthi S K Subramanian, R Suiesh and Y E A Raj (Eds), Meteorology Beyond 2000 Indian Meteorological Society, Chennai, India pp 521-531

DUBE S K, RAO, A D SINHA, P C and CHITTIBABU, P (2000a) Storm surge modeling and piediction, (In) A P Dwivedi (Ed), Mathematical Analysis and Applications, Narosa Publishing House, New Delhi, India, pp 109 124

DUBE, S K, CHITTIBABU, P, RAO, A D, SINHA, P C and MURTY, T S (2000b) Extreme sea levels associated with severe tropical cyclones hitting Onssa coast of India Marine Geodesy, v 23, pp 75-90

DUBE, S K, CIIITTIBABU, P, RAO, A D, SINHA, P C and MURTY, T S (2000c) Sea levels and coastal inundation due to tiopical cyclones in Indian coastal regions of Andhra and Onssa Maune Geodesy, v 23, pp 65 73

GI-IOSH S K (1977) Piediction of Storm suiges on the coast of India Ind J Meteo Geophys v 28, pp 157-168

HEAPS, N S (1973) Three dimensional numerical model for the Irish Sea Geophys J Roy Astron Soc, v 35, pp 99 - 120

JELESNIANSKI C P (1972) SPLASH I Landfall storms, NOAA Tech Memo NWS TDL-46 Washington D C, pp 52

JBUESNIANSKI C P and TAYLOR, A D (1973) A preliminary view of storm surges before and altei storm modification NOAA Technical Memorandum ERL WMPO-3, pp 33

JOHNS B and ALI, A (1980) The numerical modelling of storm surges in the Bay ot Bengal Quart J Roy Mel Soc, v 106, pp 1 8

JOHNS B DUBE S K, MOHANTY U C and SINHA, PC (1981) Numerical simulation of the suige geneiated by the 1977 Andhra Cyclone Quart J Roy Met Soc, v 107, pp 915 934

JOHNS B SINHA, P C, DUBE S K, MOHANTY, U C and RAO, A D (1983) Simulation of storm surges using a three dimensional numencal model an application to the 1977 Andhi a Cyclone Quart J Roy Met Soc v 109, pp 211224

LWIN, T (1980) Review of methods of storm surge piediction currently used in Burma Report to the WMO Workshop on Storm Surges, November 10 - 15, Rangoon, Burma, pp 8

VtURTY, T S (1984) Storm surges Meteorological Ocean Tides Department of Fisheries and Oceans, Ottawa, Canada, pp 897

MURTY T S TLATHER R A and HENRY R F (1986) The stoim singe pioblcm in the Bay of Bengal Prog Oceanog v 16 pp 195 233

MURTY T S and HENRY R F (1983) Tides in the Bay of Beng il J Geophys Res v 88 pp 6069 6076

RAO A D (1982) Numerical storm surge piediction in India Ph D Thesis Indian Institute of Technology Delhi pp 211

RAO A D DUBE S K and CHITTIBABU P (1994) Tmite difference techniques applied to the simulaton of surges and currents mound Sri Linki ind Southern Indnn Peninsula Corap Fluid Dyn v 3 pp 71 77

RAO Y R CHITTIBABU P DUBE S K RAO A D ind SINHA P C (1997) Storm suige prediction and frequency analysis for Andhra coast of India Mius-un v 48 pp 5'55 566

ROY G D (1984) Numerical storm surge prediction in Bangladesh Ph D Thesis Indi in Institute of Technology Delhi pp 188

SIELECKI A (1968) An energy conserving difference scheme foi the stoim suigc cqiutions Mon Weather Rev v 96 pp 150 156