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Storm surge prediction and frequency analysis for Andhra coast of India

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सार — भारत के पूर्वी समुद्री तट पर भीषण चक्रवातीय तूफानों के आने के समय तूफानी समुद्री लहरों का उठना साधारण बात है । आंध्र प्रदेश के तटीय जिलों में काफी ऊँची तूफानी लहरें नहीं उठती हैं । इस क्षेत्र में तूफानी लहरों तथा चक्रवातों के कारण होने वाली वर्षा तटीय क्षेत्र में आने वाली बाढ़ का मुख्य कारण है । इस शोध पत्र में 1891 से 1996 के दौरान आंध्र प्रदेश के तटीय भागों में आए भीषण चक्रवातों के कारण उठी तूफानी लहरों के अनुरूपण का प्रयास किया गया है । मूलानुपाती सूत्र की सहायता से लहरों के कारण होने वाले अंतःस्थलीय आप्लावन का भी आकलन किया गया है । प्राप्त हुए परिणामों की उपलब्ध प्रेक्षणों से पुष्टि की गई है । तूफान के बाद की सर्वेक्षण रिपोर्ट पर आधारित विचार-विनिमय पर्याप्त रूप से अच्छा रहा है और इससे यह भी पता चलता है कि ये मॉडल ऊँची लहरों के आयाम और उनकी अवस्थिति का पूर्वानुमान लगाने में सक्षम है । जोखिम विश्लेषण के उद्देश्य से विभिन्न तटीय क्षेत्रों में आने वाले तूफानों और उठने वाली लहरों के बीच आवृत्ति संबंधों का भी पता लगाया गया है ।

ABSTRACT. Storm surges associated with severe cyclonic storms are common occurrences along the east coast of India. The coastal districts of Andhra Pradesh have experienced major surges in the past. Storm surges and the rains associated with cyclones are major causes for coastal flooding in this region. An attempt has been made, in this paper, to simulate surges along the Andhra coast that would have occurred due to severe cyclones during 1891-1996. Inland inundation due to surges is also estimated by using an empirical formula. The computed results are validated with the available observations. The comparison using post-storm survey reports, appears reasonably good to assert that the model is capable of predicting the peak surge amplitude and its location. Frequency of occurrence relationships is obtained for various zones along the coastal region for the purpose of risk analysis.

Key words — Storm surges, Coastal flooding, Return period, Risk analysis, Model validation and Bay of Bengal.

1. Introduction

The destruction caused by storm surges associated with severe tropical cyclones, along the Indian coast line is a serious problem. Several techniques based on empirical and numerical modelling have been developed for predicting storm surges in India. However, the numerical models based on solving the nonlinear hydrodynamic equations have gained wider acceptance due to the increased computing power. The first numerical model to predict storm surges in the Bay of Bengal was developed by Das (1972). Subsequently, Das *et al.* (1974) conducted numerical experiments to compute surges generated by tropical cyclones impinging on three coastal areas (north-eastern sector, northern sector and north-western sector of head Bay). Nomograms for estimation of storm surges were prepared as a function of pressure drop (30-50 hPa) and speed of the movement of storm (15-40 kmph) for these three regions. Ghosh (1977) has evolved an objective method to predict the storm surges on the entire east coast of India north of 10°N. He developed a set of nomograms by using SPLASH model (Jelesniaski 1972) to the northern part (20°N to 21°36′N) and the remaining coast, separately. However, these nomograms have their limitations as they are based on idealized storms with a specific structure. Murty *et al.* (1986) and more recently Das (1994) and Dube *et al.* (1997) have reviewed the problem of storm surges in Bay of Bengal.

Rao (1968) classified the Indian coastline into three categories based on combined storm surges and wind waves. According to him the Andhra coast from 14°N to 16.5° N falls in the B-category (2 to 5m) with a short C-type belt (> 5m) near Nizampatnam bay. The rest of the coastline is categorized under A-type (< 2m). However, the cyclones which struck to the north of 16.5°N have also produced surges more than 2m on few occasions. A severe cyclonic storm which struck the Andhra coast near Divi on 19 November 1977 has initiated a series of systematic storm surge modelling studies in this region (Johns *et al.* 1981, Dube *et al.* 1982, Johns *et al.* 1985 etc). These studies paved the way for the development of a real-time prediction system for east coast of India (Dube *et al.* 1994).

Storm surges are generated by cyclonic winds and atmospheric pressure drop associated with cyclone. In recent years, there has been considerable concern to estimate the vulnerability of coasts due to cyclones and associated surges in view of projected global warming and sea level rise. Although not in this context, Mooley and Mohile (1983) identified significant trends in storm frequency, notably a highly significant increase in mean frequency of storms incident on Andhra coast during the period 1965-80. In addition to this, the recent disastrous cyclone in 1996 which struck the coast near Kakinada has further emphasised the need for better forecasting of cyclones and associated storm surges in this region.

In view of the adverse effects of storm surges, various programs are being developed to protect the coastal regions against damages from surges. Design of adequate measures require reliable estimates of maximum storm surge elevation *versus* frequency of occurrence relationships. This is usually achieved by the frequency analysis of climatological data on sea level elevation on meteorological elements. However, in the major coastal stretch of Andhra region such data is either non-existent or of very poor quality. Thus, it may be desirable to generate such data by using a reliable numerical model for all historical storms which may have generated surges along the coast.

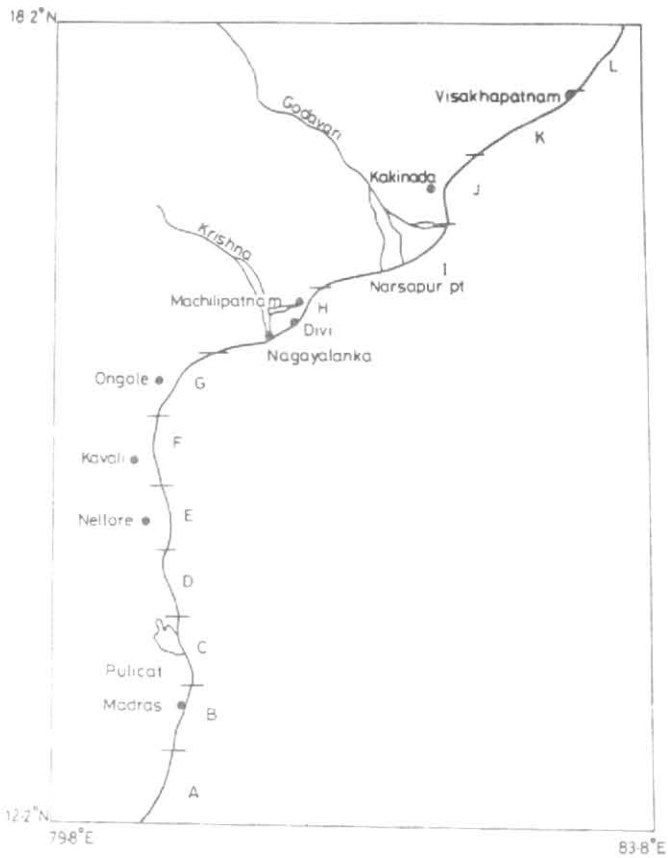


Fig. 1. Analysis area

The vertically integrated numerical storm surge model of IIT Delhi (IITD) has been applied along the east coast of India with reasonable success (Dube *et al.* 1994). This model uses a smoothed bathymetry generated from spot depths obtained from coarse hydrographic charts. Although, the model can accommodate high resolution near the coast, it precludes the consideration of finer coastal geometry of Andhra region due to its coarse resolution in alongshore direction. This may have significant impact on the location and magnitude of peak surge (Dube *et al.*1982).

In the present study, we develop a location specific fine resolution model for Andhra coast (Fig. 1) on the lines similar to that of IITD storm surge model. One of the important features of the model is that instead of generating a smoothed bathymetry by using a function

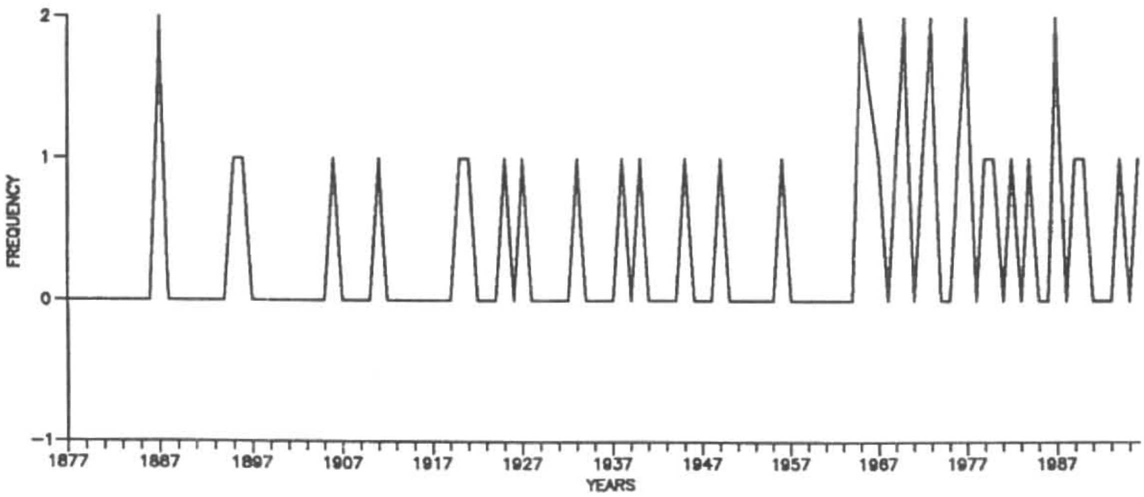


Fig. 2. Frequency of severe cyclonic storms which have struck Andhra coast during 1877-1996

from spot depths, we use the actual bathymetry extracted from a very fine resolution naval hydrographic charts for the region extending from the south of Nizampatnam bay to Kakinada bay. A simple drying scheme has also been included in the model in order to avoid the exposure of land near the coast due to strong negative surges. Attempt has also been made to test the reliability of the model by validating it for various cyclones which struck the Andhra Coast over the years.

Using this model, numerical experiments are performed to simulate the storm surge heights associated with all the historical severe cyclonic storms which have struck the coast during 1891-1996. This information has then been used to calculate the frequency of occurrence of storm surge heights at different locations of the coast. Assessment of the risk associated with a major storm surge for a given location is also given in this paper.

In section 2, we discuss the trends and mean frequency of severe cyclonic storms that hit the Andhra coast. The IITD storm surge model and the modifications adopted in this study are succinctly discussed in section 3 with validation experiments in the later section. A method to estimate the inland flooding associated with storm surges has been delineated in section 5. The frequency of occurrence relationships and the risk due to surges are briefly described in the last section.

2. Frequency of severe cyclonic storms

Fig. 2 gives the frequency of severe cyclonic storms which have struck Andhra coast during 1877 to 1996. It may be seen from the figure that the Andhra coast has been subjected to frequent severe cyclonic storms. Mooley (1980) studied the cyclonic storms which formed over Bay of Bengal and those made landfall at various locations along the Indian coastline. Mooley and Mohile (1983) have identified the location of storms in the Bay of Bengal which may landfall along the Andhra Coast. They also found significant trend in storm frequency, notably a highly significant increase in the mean frequency of storms incident on the Andhra coast during the period 1965-80. After 1980, eight severe cyclonic storms crossed Andhra coast at various locations with a mean frequency of 0.5, which is significant at 10% level. We have computed the changes in the mean frequency by using the analysis similar to that of Mooley and Mohile (1983) for 120 years (1877-96) by taking four equal periods. Change in the mean frequency in the last quarter (1967-96) over its previous quarter (1937-66) is found to be significant at 10% level. The analysis further confirms that the incidence of severe cyclonic storms during 1965-96 is at higher level in comparison to the preceding years.

3. The storm surge model

We use the IITD surge model (Dube *et al.* 1994) to predict storm surge elevations along the coastal strips of Andhra and Tamil Nadu (12.2°N to 18.2°N). Only a brief description of the model and modifications adopted in the present study will be given here. For complete details regarding the model we refer the readers to a series of publications which are reviewed by Dube *et al.* (1997).

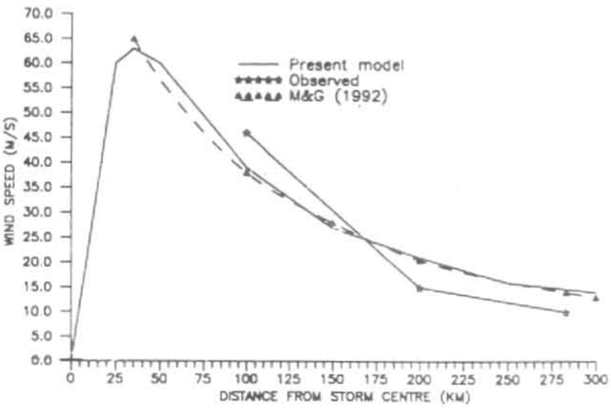


Fig. 3. Comparison of wind profile computed by the present model with that of Mandal and Gupta (1992)

The vertically integrated numerical model (IITD Surge Model) is fully nonlinear. The surface and bottom stresses are parameterized by conventional quadratic law. The treatment of coastal boundaries in the model involves a procedure leading to a realistic curvilinear representation of both the western and the eastern boundaries. A desirable feature of storm surge simulation scheme is the ability to incorporate increased resolution adjacent to the coastline. This has been achieved by using a variable grid which leads to a substantial refinement of resolution near the coast and a coarser resolution in the deeper waters. This type of grid assists in the incorporation of a more detailed bathymetric specification in the important coastal region.

The atmospheric forcing is provided by Jelesnianski and Taylor (1973) storm model. This model uses as input the radius of maximum sustained wind and pressure drop. By taking pressure drop as 70 hPa and the radius of maximum wind as 35 km for May 1990 Andhra cyclone, Fig. 3 depicts the wind profile as computed by the present model. Profile computed by Mandal and Gupta (1992) who used Holland (1980) wind model and the available observations are also shown in the figure. It may be seen that a reasonably good match is obtained between the Mandal and Gupta (M&G) fit and the wind profile of this model. The observations reported are only available at distances more than 100 km from the centre. This model as well as M&G fit slightly over-estimates the winds in the outer periphery of the cyclone. Since, these over-estimated winds in the outer region may not significantly influence the peak surge, we have not made any attempt to modify the present model.

The coastal boundaries of the model are taken as a side walls across which the normal transport vanishes. The normal currents across the open sea boundaries are prescribed by a radiation type of condition given by Heaps (1973). A conditionally stable semi-explicit finite difference scheme on a staggered grid is used for the numerical solution of model equations. The model integration starts from an initial state of rest.

The analysis area for the present study extends from 12.2°N to 18.2° N and 300 km in the offshore direction. North-south extent of the region has been divided into 49 points with a grid distance of 12.8 km while there are 20 points in offshore direction. Due to the stretching function in the model, we attain a fine resolution ranging from about 2 km near the coast to 15km at 7th grid point in offshore direction. These meridional and zonal grid spacings ensure a reasonably enough resolution to take care of the observed topographical and depth variations in the major part of the region. Fine Naval Hydrographic Chart (No. 355) of Nizampatnam and Kakinada bays, has been used to extract the depth values from mean sea level. For the rest of region we have taken depth from another naval Hydrographic Chart (No. 7706). This way we are able to incorporate the realistic bathymetry in the first offshore 30 to 50 km (continental shelf width). After the continental shelf, we use coarser bathymetry till 100km, and subsequently we keep the bathymetry as constant.

A drying scheme is necessary to deal with strong negative surges are produced to the south of landfall point in this finer version of the model. IITD surge model has been modified by incorporating a simple and appropriate drying scheme. Before each u and v computation this scheme tests whether the grid is wet or dry by checking the local water depth. If the grid point is dry, then the current is set to zero and if it is wet, then the currents are updated by solving momentum equations.

4. Model validation

The verification of model results is an onerous task because of inadequate number of tide gauges. Infact, only two permanent tide gauges, Madras and Visakhapatnam are functioning in the domain of our analysis region. Therefore, we rely on the post storm survey estimates of India Meteorological Department, and the historical surges reported in different publi-

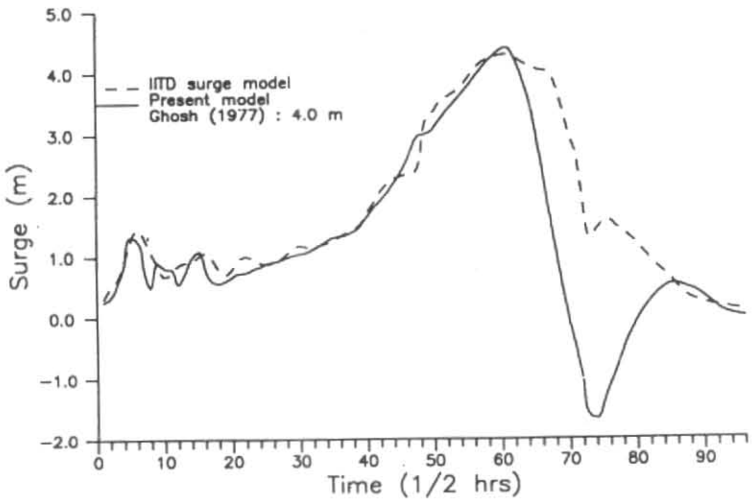


Fig. 4(a). Comparison of the computed time history of surge amplitude at the landfall point by the present model and IIT-D surge model for May 1990 cyclone

cations (Murty *et al.* 1986, Dube *et al.* 1994). In addition to it, whenever surge has been reported in a range of estimates, we employed the average of it as the observed value. This section has been divided into two parts. In part I, we present complete details of the surges produced by two recent cyclonic storms (May 1990 and November 1996). We also compare this model results with other estimates. For any storm surge predictive model, it is highly desirable to check for its aptness, suitability and reliability for a range of cyclonic storms. In part II, we validate the model for eleven cyclonic storms for which reliable surge information is available. Computed surge elevations have been subjected to various statistical tests.

(a) *May 1990 Cyclone*

A severe cyclonic storm with a core of hurricane winds crossed the Andhra coast at the mouth of Krishna river on the evening 9 May 1990 at about 1330 UTC. Detailed track history of the cyclone is given in Dube *et al.* (1994). The model is integrated from 0300 UTC on 8 May to 0300 UTC of 10 May. Fig. 4(a) shows the surge history from 0300 UTC of 8 May till 0300 UTC of 10 May at the landfall point Divi. Figure also depicts the surge amplitudes as computed by IITD surge model and the estimates from nomograms prepared by Ghosh (1977). It may be seen from Fig. 4(a) that the forerunners of a period of 1 to 1.5 hrs before the main surge and the resurgence phase are well simulated by the model. The comparison of the present model although of only peak surge value, is reasonably well with other estimates. The improvement in peak surge is mainly due to the better representation of bathymetry and geometry. In Fig. 4 (b), we depict the peak surge envelop along the Andhra coast. The affected region predicted by the model is around 40 km which is in good agreement with post storm survey reports. Although, the affects of estuaries, causeways etc. are important in any surge forecast, these aspects have not been taken care of in the present model, and we restrict ourselves to open coast surge.

(b) *November 1996 Cyclone*

A low pressure system developed around 16°N and 85°E on 4 November 1996 and moved westward. This system intensified into severe cyclonic storm by 6 November at 0300 UTC and started moving slightly in northwesterly direction. It further intensified as a severe cyclonic storm with hurricane winds and crossed the Andhra coast near Kakinada on 6 November at 1200 UTC. This severe cyclonic storm is reported to have perished large population and caused significant damages to the property in the coastal districts of Andhra Pradesh. Satellite reports indicated the storm to be of intensity T-4.5 with a pressure drop of 30 hPa and radius of maximum sustained winds of 20-40 km. The peak wind speeds recorded in this cyclone are around 80-100 knots. Hence, for the surge computations we take the pressure drop as 35 hPa and radius of maximum winds as 20km. The cyclone attained the wind speeds of severe cyclonic storm only 200km away from the coast and attained the strength of the hurricane winds very near the continental shelf.

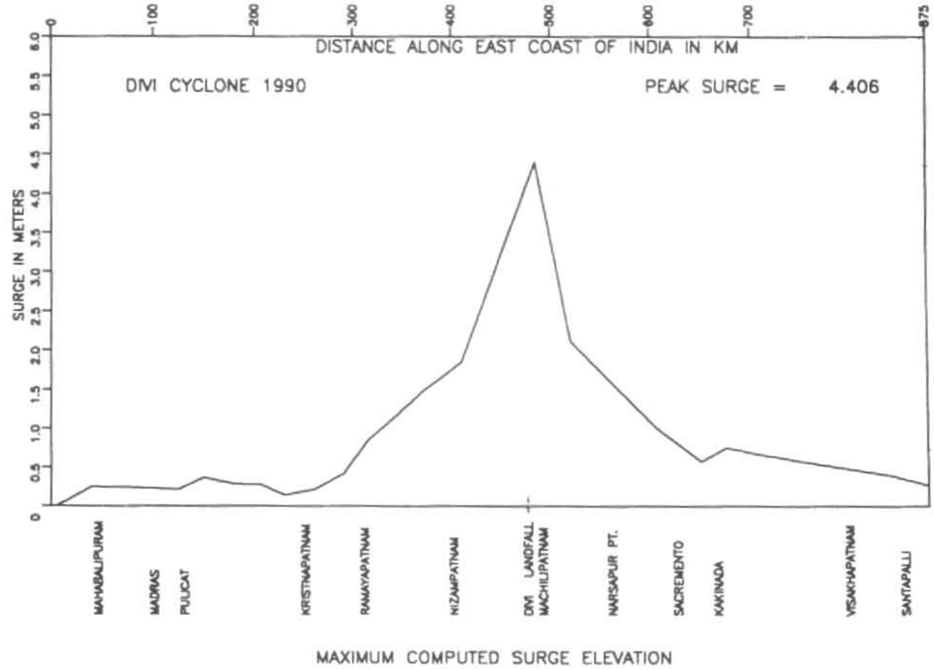


Fig. 4(b). Peak surge envelop along the Andhra coast associated with May 1990 cyclone

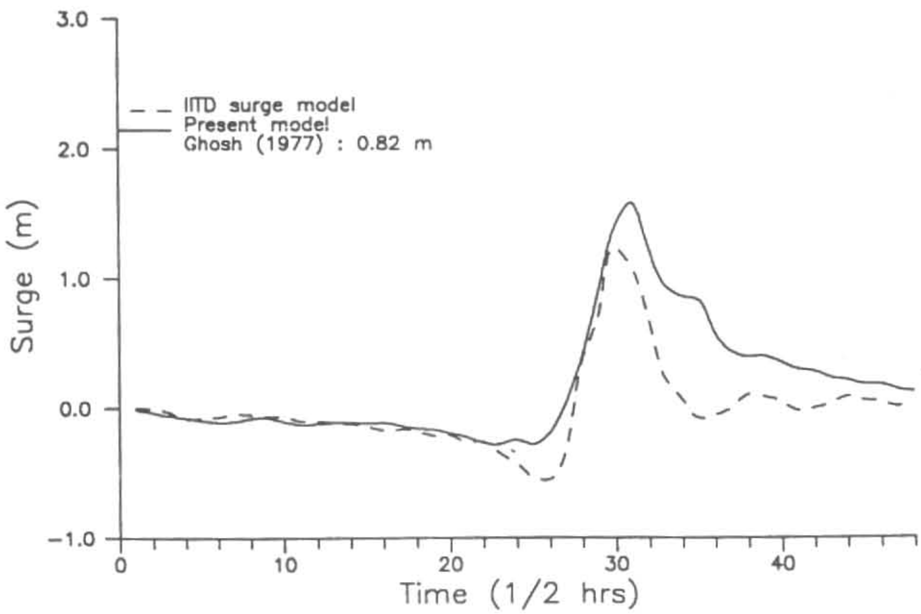


Fig. 5(a). Same as Fig. 4(a) except for 1996 Kakinada cyclone

India Meteorological Department (IMD) estimated a peak surge of 1.5 m due to this cyclone. Model simulated peak surge of 1.6m near Kakinada is in good agreement with the post storm survey estimates. Performance of the present model in the simulation of the surges associated with the November 1996 cyclone is apparently better than the IITD surge model [Fig. 5(a)]. This improvement may be attributed to the refinement in grid and near coastal bathymetry. The peak surge envelop for November 1996 cyclone

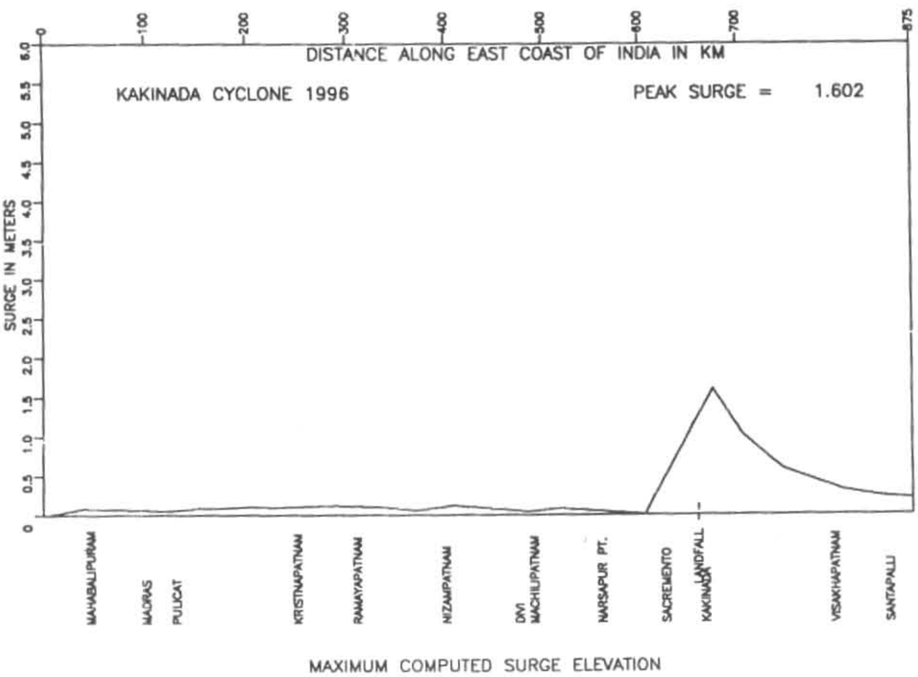


Fig. 5(b). Same as Fig. 4(b) except for 1996 Kakinada cyclone

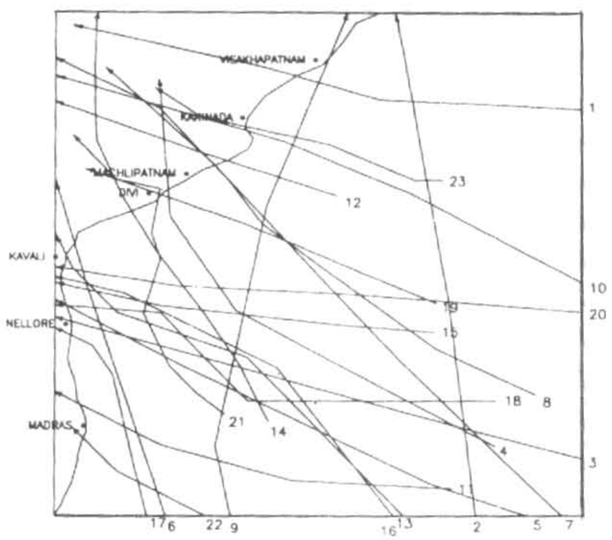


Fig. 6. Tracks of the severe cyclonic storms which struck Andhra coast during 1877-1996

has been shown in Fig. 5(b). This is in accordance with various visual post-storm surveys reporting a surge of 2 to 2.5 m just to the south of Kakinada.

However, it should be mentioned here that the development of storm surge is mainly because of wind stress with significant effects from depth variations, coastal geometry etc. Hence, any error in the wind speed would greatly modify the surge. Since the winds are estimated through an analytical model which uses pressure drop and radius of maximum winds as input, utmost care has to be adhered in prescribing these parameters.

4.1. *Comparison of computed and observed surges*

In Fig. 2, we have shown the frequency distribution of 39 severe cyclonic storms which have struck Andhra coast during 1877-1996. Among these, there are atleast 23 cyclones which appear to have potential of producing a peak surge of more than 1 m (Fig. 6). Table 1 lists these 23 cyclones with various parameters and landfall latitude. The information in respect of the tracks of severe cyclonic storms and the landfall locations along the Andhra Coast upto 1970 has been obtained from India Meteorological Department (IMD), and subsequently from the yearly accounts given in Mausam. The cyclone parameters have been taken from a report on the impact of cyclonic storms and tidal wave near Visakhapatnam prepared by India Meteorological Department and publications in Indian Journal of Meteorology, Hydrology and Geophysics (Mausam). The cyclonic storms with a star superscript have been

TABLE 1

Severe cyclonic storms having potential of producing significant surges along the Andhra coast during 1891-1996

S. No.	Cyclone	ΔP (hPa)	R (km)	Landfall (Lat°N)	Maximum wind speed (knots)
1.	1895 Kakinada	35	18	17.2	70
2.	1906 Vizag	25	15	17.9	60
3.	1921 Nellore	30	15	14.3	60
4.	1925 Machili	60	20	16.1	108
5.	1927 Nellore*	80	25	14.3	100
6.	1940 SH	30	22	14.0	60
7.	1945 Machili	50	19	16.3	90
8.	1949 Machili*	60	25	16.3	110
9.	1965 Vizag	30	15	17.9	62
10.	1969 Kakinada*	45	25	16.7	96
11.	1972 SH*	30	15	13.8	80
12.	1976 Machili	30	15	16.1	70
13.	1976 Kavali	28	15	14.8	60
14	1977 Divi*	80	40	15.8	135
15.	1977 Kavali	26	15	14.8	55
16.	1979 Kavali*	60	35	14.8	100
17.	1984 SH*	60	25	14.0	102
18.	1987 Nellore	26	15	14.4	50
19.	1987 Machili	26	15	15.9	50
20.	1989 Kavali*	70	20	14.8	110
21.	1990 Divi*	80	40	15.7	136
22.	1994 Madras*	30	25	13.0	75
23.	1996 Kakinada*	35	20	16.7	90

*Cyclonic storms used for validation of the model

used for the validation of our model as post-storm surveys surge information could be procured only for these cyclones.

TABLE 2

Comparison of observed and computed peak surge amplitude and their locations

Cyclone	Surge (m)		Location of peak surge	
	Observed/ Reported	Computed	Observed	Computed
1927 Nellore	3.0	3.07	North of Nellore	Nellore
1949 Machili	2.5	2.093	Machili-patnam	10 km north of Machili-patnam
1969 Kakinada	2.6	2.82	Kakinada	Kakinada
1972 SH	0.8-1	1.23	Srihari-kota	Srihari-kota
1977 Divi	5.0	4.93	Divi	Divi
1979 Kavali	3.0	3.3	Kavali	10 km north of Kavali
1984 SH	2.0	2.4	Srihari-kota	Srihari-kota
1989 Kavali	3-4	3.8	40 km north of Kavali	48 km north of Kavali
1990 Divi	4.5	4.41	Divi	Divi
1994 Madras	1-1.5	0.83	Madras	20 km north of Madras
1996 Kakinada	1.5	1.6	Kakinada	Kakinada

SH-Sriharikata

In Table 2, the computed and observed peak surges and their locations of landfall have been listed for the eleven cyclones (shown by superscript '*') in Table 1. It may be seen from Table 2 as well as from Fig. 7 that in most of the cases, the model is able to reasonably predict the amplitude and location of the peak surge.

In order to check the aptness and suitability of the model for future prediction we have also carried out error (residual) analysis of the model results. Residual is defined as $e_i = O_i - E_i$ where, O_i (i = 1, ... 11) are the observed peak surge values and E_i (i = 1, ... 11)

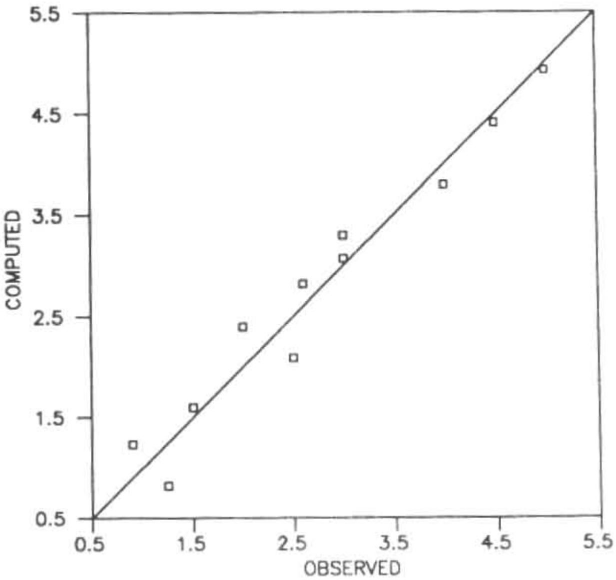


Fig. 7. Comparison of observed and computed peak surge amplitudes

are the computed surges (Neter *et al.* 1978). In Fig. 8 the residuals are plotted against the computed surge values. Figure do not indicate any pattern of systematic departure of the points around the zero line. Thus it may be inferred that the model is apt for peak surge estimation. The normality of the residuals is also checked by taking the standardized residuals as

$$e_i' = \frac{e_i}{\sqrt{\text{MSE}}} \qquad (1)$$

where MSE, (mean square error) is given by

$$\text{MSE} = \frac{\Sigma e_i^2}{n-2}, \; n \text{ being the number of data} \qquad (2)$$

This, e_i' follow t-distribution with (n-2) degrees of freedom. In the t-distribution central 50% of it falls between –.703 and .703. All the computed standardized residuals fall in this range, and five of these are positive and six are negative. This analysis therefore provides no evidence of any departure from normality. Further, the simple bias (Murphy and Katz 1985) of the predictions can be given as $\overline{O}/\overline{C}$, where $\overline{O}$ and $\overline{C}$ are arithmetic means of observed and computed surges. The computed bias (0.99) show a good agreement between observations and computations. However, the residual plot show a slight over-prediction of surges which are not very severe (< 2.0).

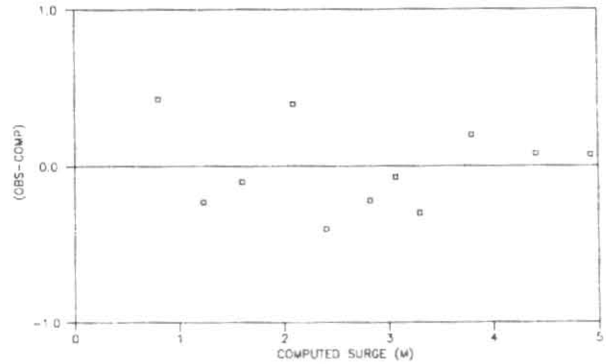


Fig. 8. Residuals and computed surge values of severe cyclonic storms

The deviations from observed and computed surges are in the interval of tidal ranges in this region (Murty and Henry 1983), which have not been included in the model. It may also be mentioned that the seasonal water level changes are not included in the computation of storm surges. These effects are small in comparison with the main surge, nevertheless, they would be included in our future modelling studies. Although the model is able to predict peak surge elevations, we are in no position to validate the time history of surges and associated currents due to non-availability of observations. The validation experiments and the error analysis provided in this section gives the necessary confidence to use this model for generating the storm surge elevations at various locations along the Andhra coast.

5. Storm surge associated inland flooding

In the earlier sections the prediction of surges using numerical model is demonstrated with a reasonable confidence limit. However, for the purpose of evacuation of population from those regions where it may cause inland flooding, it would be necessary to develop some objective method to estimate the affected area. The movement of surge water over the coastal land is very complex. Numerical models have been developed in many parts of the world to simulate the inland penetration of surges (Flather and Heaps 1975). Johns *et al.* (1982) used a continuously deforming lateral boundary to simulate the coastal flooding associated with 1977 Andhra cyclone. Dube and Rao (1991) used the similar type of model to simulate the coastal inundation due to sea level rise and storm surges. This model may be of use when the onshore topographic profile in the coastal region has a linear slope, thus

TABLE 3

Intrusion distances due to surge water for various cyclones at different locations along Andhra coast

Zone	Surge (m)	Slope	Inundation (km)
A	0.5	.0025	Nil
B	.83	.0025	0.5
C	1.3	.002	3.0
D	1.4	.002	3.1
E	3.15	.002	4.8
F	3.07	.001	6.6
G	3.85	.0017	5.8
H	4.95	.0015	8.5
I	1.8	.002	3.0
J	2.82	.002	3.6
K	1.05	.0027	2.3
L	0.8	.0025	0.6

leading to the inland advance of shoreline as surge height rises. Since the details of topographic charts of this region are presently not available, we use an empirical technique (Ali 1992) to estimate the inland inundation.

The inland flooding is calculated by using the formula, which is given as follows :

$$L = \frac{4(h + 1.5\,\zeta)^2}{3(h + \zeta)\,(s + c/8)} \tag{3}$$

where, L is the maximum distance travelled by surge, h is the depth of the water at which ζ storm surge height is calculated, s is the bed slope and c is the friction factor.

In the absence of information on onshore topography, s, has been computed by assuming that it is same as the sea floor gradient of the offshore region. Table 3 gives the slopes and the calculated inland inundation distances for various zones along the coastal region of Andhra Pradesh. Maximum computed surges have only been considered in the calculation of inland flooding for a constant friction factor (c = 0.01). The computed inland distances for major surges are in reasonable agreement with available estimates. However it may be noted that for the accurate prediction of inland flooding, the details of onshore topography, the structures, information regarding causeways, estuaries etc. are needed. Present method may give some reasonable estimates with proper choice of friction and slope factors for emergency management.

6. Frequency analysis

Storm surges associated with all the 23 cyclonic storms listed in Table 1 are simulated with the present model to produce peak surge elevations at all the 49 grid points along the coast. The entire coastal region is divided into 12 zones (A, B, ... L) containing 4 grid points in each zone for the sake of convenience as shown in Fig. 1. Frequency of occurrence relationships for these twelve zones has been analysed in detail. Further, we have chosen the maximum surge elevation due to a cyclone in a zone as the representative peak surge of that zone.

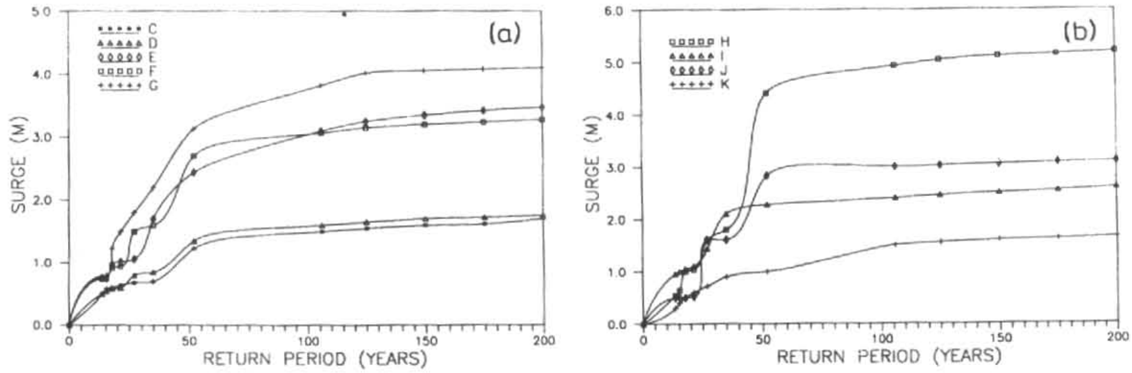
Estimates of frequency of occurrence is made by calculating a cumulative distribution function (CDF) for the storm surge associated with the concerned cyclone. If $X_1, X_2, \ldots X_n$ be the peak surge values for a particular zone, a CDF may be written as follows:

$$P[X \leq\,] = F_x(x) \tag{4}$$

where, $P[\ ]$ represents that probability that X less than or equal to some value x and $F_x(x)$ is the cumulative probability function ranging from 0 to 1. Following Scheffner *et al.* (1996) we estimate F_x without introducing any parametric relationship. The n surge values are ranked in increasing order of size, so that the value $X_{(1)}$ is the smallest in the series and $X_{(n)}$ represents the largest value. If r denote the rank of the value $X_{(r)}$ such that rank 1 is the smallest and rank $r = n$ is the largest, $F_x(X_{(r)})$ may be estimated as (Gumbel 1954) below,

$$\hat{F}_x(X_{(r)}) = \frac{r}{n+1} \text{ for } \left\{ X_{(r)}, r = 1, 2, \ldots, n \right\} \tag{5}$$

This form of estimate allows for future values of x to be less than the smallest value $x_{(1)}$ with the probability $1/(n + 1)$, and to be larger than the largest value $X_{(n)}$ also with probability of $1/(n + 1)$. The CDF defined by Eqn. (5) has been used to



Figs. 9 (a&b). Computed surge frequency of occurrence relationships for zones (a) C to G and (b) H to K

develop surge frequency relationships. The CDF for a storm surge corresponding an n-year return period is determined as,

$$F(x) = 1\text{-}1/n \tag{6}$$

where $F(x)$ is simulated CDF of n year surge. Frequency of occurrence relationships is obtained by linearly interpolating a surge from Eqn. (5) corresponding to the CDF associated with the return period specified in Eqn. (6).

Figs. 9 (a & b) show the plots of computed surge frequency of occurrence relationships for the zones C to G and H to K respectively. The return periods are calculated according to the approach discussed previously. It may be noticed that the calculated return periods are based on only for those cyclones that have made landfall as severe cyclonic storms in this region. Further, in this calculation we have not included hypothetical events that would have occurred, and therefore these relationships may be viewed as realistic.

In this paper, an attempt has also been made to estimate the risk of a storm surge to exceed a particular level on the basis of calculated return periods. If T_R (return period) is in years, the probability than an event x equals or exceeds a level 'Q' in a year is given by,

$$P(X \geq Q) = 1/T_R \tag{7}$$

The non-failure probability may then be written as,

$$P(X \geq Q) = 1 - 1/T_R \tag{8}$$

TABLE 4

Risk (%) of exceedence of storm surge heights at Divi (Zone 'G')

Years	Surge height (s)				
	≥ 1	≥ 2	≥ 3	≥ 4	≥ 5
10	50	22	20	18	8
20	75	40	36	34	15
50	97	92	67	65	36
160	99.9	99.4	89	87	59
200	99.99	99.99	98.8	98.5	83.9

Hence, the risk in an n-year period may be given by,

$$P(X > Q) = 1 - \left(1 - \frac{1}{T_R}\right)^n \tag{9}$$

By using these relations one can estimate the risk of storm surge levels for various locations along the coastal stretch. We present here only the estimated percentage of risk for Divi (Table 4). It may be noticed from the table that in 50 year period the surge of 4m expected to be exceeded with a probability of 65% and 5m with 36%. Although, the probability associated with return periods are based on certain assumptions such as random variable x are independent, the estimates given by this method may be used for coastal zone management.

7. Conclusions

A storm surge forecast model has been described for the Andhra coast. The modifications regarding the drying of grid points due to negative surges and incorporation of actual bathymetry in earlier version of IITD surge model is briefly discussed. The model results reported in this paper are in good agreement with available peak surge observations/estimates. This paper also demonstrates the suitability of a fine resolution surge mode for reasonable prediction of surges along the Andhra coast. Development of fine resolution location specific numerical models with actual bathymetry are probably a better option than the models covering the entire east coast of India. A simple formula is used to compute the inland inundation due to storm surges. More sophisticated techniques based on conti- nuously deforming coastal boundaries are under inves- tigation.

Frequency of occurrence relationships are obtained on the basis of all the major historical storms which have struck different segments of Andhra coast during the period 1891-1996. These results are used to estimate the risk of a surge to exceed a particular level. The results are well suited for storm surge risk analysis.

The storm surge prediction model for Andhra coast, although performing reasonably well, has still certain limitations of not taking into account nonlinear interaction of tides, waves and surges. These aspects are proposed to be included in near future, so that the overall objective of producing forecasts by taking into account all possible surge generating mechanisms may be achieved.

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