

# Numerical Simulation of Open Coast Surges. Part II: Experiments with Storm Parameters and Shelf Geometry

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## ABSTRACT

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Storm surge simulation studies are carried out with a numerical hydrodynamic model which uses conformal mapping technique suggested by WANSTRATH *et al.* (1976) for transforming the irregular shelf region into a rectangle. The flow field is simulated by solving the depth averaged shallow water equations in the transformed plane. The 1977 Andhra Cyclone is considered as a test case for these simulation studies. The shelf region influenced by this storm is along the east coast of India between Madras and Kalingapatnam.

This study indicates, the sensitivity of the model to the near shore shelf bathymetry and to the wind stress coefficient; the importance of the tangential wind stress field over atmospheric pressure field; and the negligible influence of non-linear terms and the momentum entering the ocean waters outside the shelf region on surge estimates.

**ADDITIONAL INDEX WORDS:** *Numerical simulation, storm surges, east coast of India, 1977-Andhra Cyclone, conformal mapping, coastal flooding.*

## INTRODUCTION

The east coast of India has been frequently affected by cyclonic storms which form in the Bay of Bengal and move towards the Indian coast. Some of them have generated very high surges near the coast. A number of numerical model studies have been carried out by several investigators for the simulation of observed surges during some of the past storms which crossed the Indian coast (DAS, 1972; DAS *et al.*, 1974; JOHNS *et al.*, 1981, 1985; DUBE *et al.*, 1981, 1985). In most of these studies, the open ocean boundary of the analysis area is fixed at nearly 300 km east of the east coast of India, either the stair step approximation or the curvilinear treatment of JOHNS *et al.* (1981) is used to represent the irregular boundaries and a representative bathymetry is introduced in the analysis area.

The ocean shelf along the east coast of India, however, is very narrow with its width varying between 30 to 50 km over a major portion of its length and the flow field in the open ocean region beyond the coastal shelf is likely to have least

influence on the storm induced surges near the coast. In view of this, in the present study, we developed a software for surge simulation introducing the actual geometry and also a more realistic bathymetry of the shelf region along the east coast of India between Madras and Kalingapatnam, the shelf adjacent to Andhra coast. This simulation model uses the conformal mapping technique suggested by WANSTRATH *et al.* (1976) to transform the shelf region into the interior of a rectangle and numerically solves the transformed governing equations in the transformed region.

Numerical experiments are performed using the software developed for surge simulation to study the model performance and to identify the important parameters of the model. The 1977-Andhra cyclone is considered as a test case in these experiments. The results of these experiments are presented in this paper. This study forms an essential step in the development of a simulation model for real time prediction of surges along the east coast of India. Once the model is made perfect, the atmospheric input to this model could be derived from weather forecasting models available for this region.

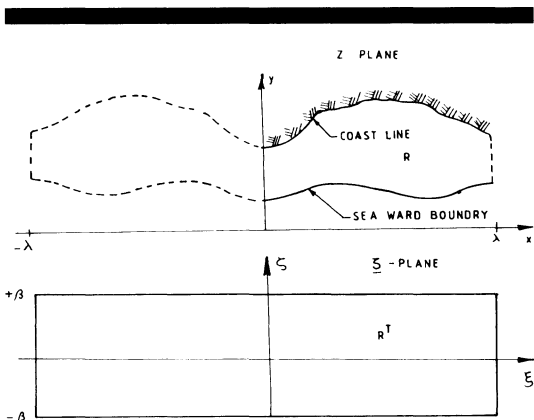


Figure 1. A typical shelf region in the real plane and in the transformed plane.

### CONFORMAL MAPPING OF THE SHELF REGION

In this section the algorithm of WANSTRATH *et al.* (1976) for generating the transformation function to transform any specified region into a rectangular region is discussed. This is an alternative approach to the curvilinear treatment of the boundaries proposed by JOHNS *et al.* (1981).

Figure 1 shows a typical shelf region *R* in the *Z*-plane, bounded by the coastline, the seaward boundary and two parallel lateral boundaries, to be transformed into the interior of a rectangle in  $\zeta$ -plane. The problem now is to find a suitable transformation function,

$$Z = F(\zeta) \tag{1}$$

where  $Z = x + iy$ ,  $\zeta = \xi + i\zeta$  and  $i = \sqrt{-1}$ , such that the coastline and the seaward boundary are mapped as isolines of the coordinate  $\zeta$  (*i.e.* the coastline maps on to the isoline  $\zeta = \beta$ , and the seaward boundary on to the isoline  $\zeta = -\beta$ ; see Figure 1) and the two lateral boundaries in the *Z*-plane are mapped as isolines of the coordinate  $\xi$ . The functional form considered for the transformation is the truncated Fourier series (WANSTRATH *et al.*, 1976),

$$\begin{aligned} x(\xi, \zeta; B_0, B_n, C_n) \\ = \xi + \sum_{n=1}^N \\ \times (B_n \sinh nk\zeta + C_n \cosh nk\zeta) \sin nk\xi \end{aligned} \tag{2a}$$

$$\begin{aligned} y(\xi, \zeta; B_0, B_n, C_n) \\ = B_0 + \zeta + \sum_{n=1}^N \\ \times (B_n \cosh nk\zeta + C_n \sinh nk\zeta) \cos nk\xi \end{aligned} \tag{2b}$$

where  $k = \pi/\lambda$  and  $\lambda$  is the length of the shelf in the *x*-direction.  $B_0$  and the set of coefficients  $B_n$  and  $C_n$  are the unknowns in this transformation, which are determined such that the Equations 2a and b give the best fit, in a least square sense, to the coastline, when  $\zeta = \beta$  and to the seaward boundary, when  $\zeta = -\beta$ .

### EQUATIONS GOVERNING THE OCEAN FLOW FIELD

The depth averaged form of the shallow water equations governing the shelf flow field, in a Cartesian co-ordinate frame fixed to the rotating earth are,

$$(uH)_{,x} + (vH)_{,y} + \eta_{,t} = 0 \tag{3}$$

$$\begin{aligned} \rho_w((uH)_{,t} + (uuH)_{,x} + (vuH)_{,y} - fvH \\ + gH\eta_{,x}) \\ = -Hp_{,x} + (\tau_{ax} - \tau_{bx}) \end{aligned} \tag{4}$$

$$\begin{aligned} \rho_w((vH)_{,t} + (uvH)_{,x} + (vvH)_{,y} + fuH \\ + gH\eta_{,y}) \\ = -Hp_{,y} + (\tau_{ay} - \tau_{by}). \end{aligned} \tag{5}$$

Here the origin of the coordinate system is chosen at the undisturbed sea surface and  $(u, v)$  are the depth averaged velocities in the  $(x, y)$  directions respectively and  $t$  is the time. The suffixes preceded by ‘,’ indicate the partial derivatives.  $H = h + \eta$  is the total depth of water,  $h$  is the undisturbed depth of water and  $\eta$  is the sea surface elevation measured from the undisturbed sea surface. ‘ $f$ ’ is the Coriolis parameter =  $2\Omega \sin \phi$ ,  $\Omega$  is the angular velocity of earth,  $\phi$  is the latitude of the place,  $\rho_w$  is the density of water and  $g$  is the acceleration due to gravity.  $(\tau_{ax}, \tau_{ay})$  and  $(\tau_{bx}, \tau_{by})$  are the stresses at the air-sea interface and the ocean bottom surface respectively and they are evaluated using the conventional quadratic law as follows:

$$\tau_a = K_a \rho_a |W|W \tag{6}$$

and

$$\tau_b = K_b \rho_w |V|V \tag{7}$$

where  $K_a$  and  $K_b$  are the wind and bottom stress coefficients respectively.  $\rho_a$  is the air density taken as  $1.29 \text{ kg/m}^3$ ,  $V \equiv (u, v)$  and  $W$  is the wind velocity measured 10 m above the mean sea level.

For a cyclonic wind forcing, the wind velocity  $W$  in Equation 6 is computed using the model suggested by JOHNS *et al.* (1985).

$$|W| = \begin{cases} W_m (r/r_o)^{1.5} & \text{for } 0 \leq r \leq r_o \\ W_m \exp[(r_o - r)/\alpha] & \text{for } r_o < r \leq r_1 \\ W_m \exp[(r_o - r_1)/\alpha] \\ \quad \times \exp[(r_1 - r)/\beta] & \text{for } r > r_1 \end{cases} \quad (8)$$

where  $W$  is the tangential wind velocity at a radial distance  $r$  from the centre of the cyclone,  $W_m$  is the maximum wind speed,  $r_o$  is the radius of maximum wind speed and the other parameters  $r_1$ ,  $\alpha$ ,  $\beta$  are constants with dimensions of length.

The pressure distribution is calculated for this cyclonic wind forcing using the model suggested by HOLLAND (1980),

$$p = P_o + (P_\infty - P_o) \exp[-(r_o/r)^B] \quad (9)$$

where  $p$  is the pressure at a radial distance  $r$  from the centre of the cyclone,  $P_o$  is the pressure drop at the centre of the cyclone,  $P_\infty$  is the ambient pressure or the pressure at the outer periphery of the cyclone and  $B$  is a constant.

### Initial and Boundary Conditions

In the present study the ocean is assumed to be initially at rest before the introduction of wind stresses at the ocean free surface, *i.e.*

$$\eta, u, v = 0 \quad \text{for } t \leq 0$$

Across the lateral boundaries of the shelf, JELESNIANSKI (1965) and WANSTRATH *et al.* (1976) applied the zero gradient condition in open coast storm surge simulation problems, since the wind and the ocean current velocities and their gradients will be small near these boundaries which are generally placed far from the cyclone centre. In a later study CHAPMAN (1985) recommended the application of radiation condition along these boundaries, since zero gradient condition behaves like a perfect reflector of disturbances propagating out of the study area. Hence in the present study, along the lateral boundaries of the shelf, the radiation condition is used in the form,

$$v_{n,n} \pm \sqrt{g/h} \eta_{n,n} = 0$$

where  $n$  is along the normal to this boundary. However, MATHEW *et al.* (1995) have observed that, when the zero gradient and radiation conditions are applied independently at the lateral boundaries of the shelf, the surge histories simulated remain the same over a major portion of the shelf except near the lateral boundaries.

Along the open ocean boundary the clamped condition ( $\eta = 0$ ) is assumed in view of the observation of MATHEW *et al.* (1995) and the conventional impermeable vertical side wall assumption is made along the coastal boundary.

### Governing Equations in the Transformed Plane

Consequent to the transformation of the study region in the  $Z$ -plane into a rectangular region in  $\zeta$ -plane, the equations governing the flow field need to be solved in the transformed plane. The linearised form of the governing equations in the transformed plane are as follows,

$$\eta_{,\zeta} + \frac{1}{G^2} [(Gu_\zeta H)_{,\zeta} + (Gv_\zeta H)_{,\zeta}] = 0 \quad (10)$$

$$\rho_w \left[ (u_\zeta H)_{,\zeta} - fv_\zeta H + \frac{gH}{G} (\eta - H_b)_{,\zeta} \right] = \tau_{a\zeta} - \tau_{b\zeta} \quad (11)$$

$$\rho_w \left[ (v_\zeta H)_{,\zeta} + fu_\zeta H + \frac{gH}{G} (\eta - H_b)_{,\zeta} \right] = \tau_{a\zeta} - \tau_{b\zeta} \quad (12)$$

where  $(u_\zeta, v_\zeta)$  are the depth averaged velocities in the  $\xi$  and  $\zeta$  directions respectively,  $G$  is the transformation scale factor of the curvilinear co-ordinate system given by

$$G^2 = \left( \frac{\partial x}{\partial \xi} \right)^2 + \left( \frac{\partial y}{\partial \xi} \right)^2. \quad (13)$$

$H_b$  is the atmospheric pressure anomaly in units in which  $\eta$  is expressed,  $(\tau_{a\zeta}, \tau_{a\xi})$  are wind stress components and  $(\tau_{b\zeta}, \tau_{b\xi})$  are bottom stress components. Except for the inclusion of the scale factor  $G$ , the above equations are the same as the depth averaged linear shallow water equations in the  $(x, y)$  co-ordinate system.

### NUMERICAL SCHEME

The governing equations are solved numerically using the leap-frog scheme at discrete grid points and time instants defined by

$$\xi = \xi_n = n\delta\xi, \quad n = 0, 1, 2, \dots, N,$$

$$\begin{aligned} \zeta &= \zeta_m = m\delta\zeta, & m &= 0, 1, 2, \dots M, & & - H_b(n, m + 1, k - 1) \\ t &= t_k = k\delta t, & k &= 0, 1, 2, \dots K, & & + H_b(n, m - 1, k - 1)] + 2\delta t\tau_{af} \end{aligned} \quad (19)$$

where  $\delta\xi$ ,  $\delta\zeta$  specify the grid spacing and  $\delta t$  the time increment. The computations are performed on a staggered grid in space and time. Then the finite difference analog of the governing equations are

$$u_\xi(n, m, k) = \hat{H}^{-1}(GA.GB + f\delta t.GC)/[GA^2 + (f\delta t)^2] \quad (14)$$

$$v_\zeta(n, m, k) = \hat{H}^{-1}(GA.GC - f\delta t.GB)/[GA^2 + (f\delta t)^2] \quad (15)$$

$$\begin{aligned} \eta(n, m, k + 1) &= \eta(n, m, k - 1) \\ &- [G(n + 1, m)Hu_\xi(n + 1, m, k) \\ &- G(n - 1, m)Hu_\xi(n - 1, m, k)] \\ &\times (\delta t/\delta\xi)/G^2(n, m) \\ &- [G(n, m + 1)Hv_\zeta(n, m + 1, k) \\ &- G(n, m - 1)Hv_\zeta(n, m - 1, k)] \\ &\times (\delta t/\delta\zeta)/G^2(n, m) \end{aligned} \quad (16)$$

where  $n$ ,  $m$  and  $k$  are indices related to  $\xi$ ,  $\zeta$  and time respectively and

$$GA = 1 + K_b\delta t|V(n, m, k - 2)|\bar{D}^2, \quad (17)$$

$$\begin{aligned} GB &= \hat{H}u_\xi(n, m, k - 2) \\ &\times [1 - K_b\delta t|V(n, m, k - 2)|]/\bar{D}^2 \\ &+ f\delta tv_\zeta(n, m, k - 2) \\ &- (\delta t/\delta\xi)[g\bar{D}/G(n, m)] \\ &\times [\eta(n + 1, m, k - 1) \\ &- \eta(n - 1, m, k - 1) \\ &- H_b(n + 1, m, k - 1) \\ &+ H_b(n - 1, m, k - 1)] + 2\delta t\tau_{af} \end{aligned} \quad (18)$$

$$\begin{aligned} GC &= \hat{H}v_\zeta(n, m, k - 2) \\ &\times [1 - K_b\delta t|V(n, m, k - 2)|]/\bar{D}^2 \\ &- f\delta tu_\xi(n, m, k - 2) \\ &- (\delta t/\delta\zeta)[g\bar{D}/G(n, m)] \\ &\times [\eta(n, m + 1, k - 1) \\ &- \eta(n, m - 1, k - 1) \end{aligned}$$

where  $|V(n, m, k - 2)| = [u_\xi^2(n, m, k - 2) + v_\zeta^2(n, m, k - 2)]^{1/2}$  and  $\bar{D}$  is the average depth of four neighboring points.  $\hat{H}$  is the average of depths at adjacent grid points, in the  $\zeta$ -direction in Equations 14 and 18, and in the  $\xi$ -direction in Equations 15 and 19. In the above numerical scheme the Coriolis acceleration and the friction terms are evaluated implicitly.

### NUMERICAL EXPERIMENTS AND DISCUSSION OF RESULTS

A software is developed to solve the depth averaged shallow water equations in the shelf region adjacent to the Andhra coast. Such depth averaged models are justifiable only in the absence of strong velocity structure in the vertical column. Such a situation may not strictly exist in surge phenomena, since the momentum supporting the flow field is transferred across the sea surface from atmospheric winds and is communicated to greater depths. However, for operational forecasting of surges, the depth averaged models are used, since the final prediction of surges depends more on the quality of the input data than on the model sophistication. There are too many uncertainties in the estimation of storm parameters and storm track which are used as input to the surge model. Further, requirement of an operational level model is that it should involve less computational resources, efforts and time.

Using the software developed for the surge simulation in the shelf region along the east coast of India, numerical experiments are carried out by varying the following parameters: the shelf bathymetry, shelf width, pressure field and wind and bottom stress coefficients. The influence of these parameters on surge level ( $\eta$ ) along the coast, a variable of prime importance in surge simulation studies, is examined. In these experiments, the sea level along the coast at any time and the envelope of the highest water level at each point on the coast for all time, referred to as the surge profile and surge envelope respectively, are computed. The highest surge on the surge profile and on the surge envelope are referred to as the maximum surge and the peak surge respectively.

The test cyclone considered is the 1977-Andhra cyclone which caused extensive coastal flooding near Machilipatnam, a coastal town on the east coast of India. A surge elevation of around 5 m

Table 1. Parameters of wind and pressure models for the 1977-Andhra cyclone.

Maximum wind speed $W_m = 70$ m/sec
radius of maximum wind $r_0 = 80$ km
Radius of the cyclone eye wall $r_1 = 175$ km
$\alpha = 200$ km, $\beta = 10$ km
Central pressure $P_0 = 925$ millibars
The ambient pressure $P_\infty = 1,005$ millibars
$B = 1.75$

above the mean sea level was estimated near the coastal regions of Machilipatnam, by a post-cyclone survey conducted over the surge affected regions. In the present simulation model, following JOHNS *et al.* (1981), the cyclone is positioned at  $83.7^\circ\text{E}$  longitude and  $10^\circ\text{N}$  latitude on the 17th November 1977 midnight (*i.e.* 0 hr). From 17th November the cyclone is moved along an idealized straight line track shown in Figure 2 with the landfall occurring at Chirala after 60 hr.

The difficult part of surge prediction model is the specification of the surface stress  $\tau_a$ , an important term in the momentum equations. It is expressed as a function of wind velocity ( $W$ ) and stress coefficient ( $K_a$ ). But neither  $W$  nor  $K_a$  can be estimated with consistent accuracy and obviously, the estimation of  $\tau_a$  is sensitive to errors in the estimates of  $W$  and  $K_a$ .

In the present simulation experiments, the wind and pressure fields associated with the 1977-Andhra cyclone are computed using Equations 8 and 9 respectively. The model parameters for this cyclone are given in Table 1 and they were chosen such that the wind and pressure fields estimated from the model are close to the measured values. For real time surge models, JELESNIANSKI and TAYLOR (1973) recommend the indirect method of estimating the wind field from the pressure field since pressure observations generally have much less noise than wind observations.

The ocean shelf region considered in this model is nearly 700 km long and 30–50 km wide, extending from Madras to Kalingapatnam along the east coast of India with the storm landfall point nearly at the centre of this coastal stretch. The co-ordinates of the shore and the seaward boundaries for this region are read from the hydrographic charts. The seaward boundary is taken at a place where the depth of the sea bed increases rapidly, *i.e.* at the shelf break and the 200 m depth contour is assumed to represent the shelf break. The transformation coefficients  $\beta$ ,  $B_s$ ,  $B_n$  and  $C_n$

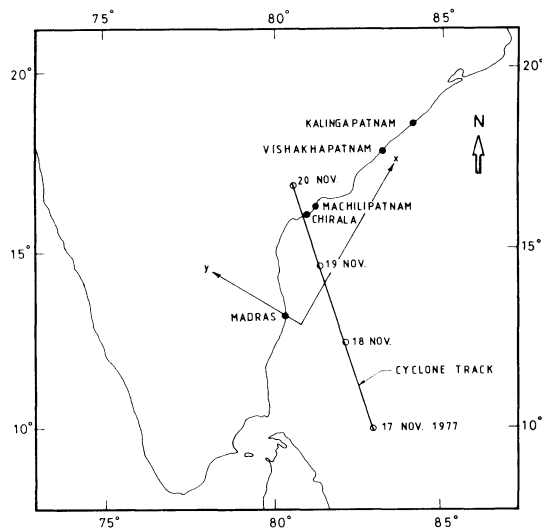


Figure 2. Idealized track of 1977-Andhra cyclone.

are computed to map this shelf region into a rectangular region.

This transformed shelf region is discretized into 232 and 10 equal segments along the  $\xi$  and  $\eta$  axes respectively, for the finite difference solution of the governing equations. A time step of 40 sec is used for a stable time integration.

In all the experiments otherwise stated following JOHNS *et al.* (1981), the wind and the bottom stress coefficients are taken as,  $K_a = 2.8 \times 10^{-3}$  and  $K_b = 2.6 \times 10^{-3}$  respectively.

### Bathymetry

In the numerical experiments, we used shelf profiles which, when normalized with respect to the local shelf width, have the same form over the entire length of the shelf. Three such profiles, *viz.* profiles ACEF, ABDEG and ACEG used in the present study are shown in Figure 3. Profile ACEF defines a constant depth shelf (20 m deep). The other two profiles are formed from the average shelf profile (ADEG) around Chirala, the landfall point for the 1977-Andhra cyclone, where rapid variations in the sea level were observed during this cyclone. The depth of the shelf at the coast in the profiles ABDEG and ACEG are taken as 10 m and 20 m respectively, to accommodate the expected negative surges on the left side of the cyclone track at the time of landfall. Further re-

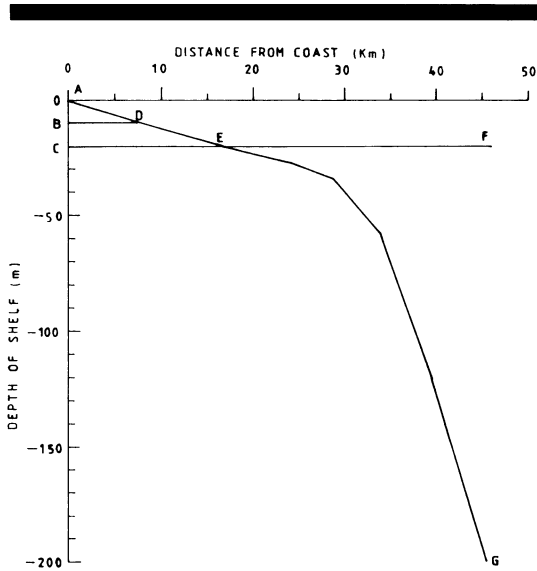


Figure 3. An average cross section of the ocean shelf near Chirala.

duction in coastal height below 10 m would lead to a retreat of the coastline into the ocean. To accommodate this feature in the surge simulation a continuously deforming boundary model with very small spatial grids should be considered. But the extra efforts and computational resources involved in this will be too large to serve the requirements of an operational level model.

The peak surges estimated for 1977-Andhra cyclone using these profiles are given in Table 2. The peak surges can be seen to vary from 2.38 to 3.23 m for these profiles. The profile ABDEG (see Figure 3) which is the closest to the average shelf profile (ADEG) near Chirala, gives the highest peak surge. These experiments show that the surge height at the coast is strongly influenced by the near shore bathymetric features. For the shelf profile ABDEG, Figures 4 and 5 show the surges along the coast and surge contours in the shelf region respectively, 30 minutes before the landfall. The distance along the x-axis in Figure 4 is with reference to the rotated coordinate system shown in Figure 2.

In these experiments only the storm induced tangential wind stress field is introduced in the model, the atmospheric pressure anomalies are neglected and the linearised form of the momentum equations are solved.

Table 2. Peak surge estimates for the 1977-Andhra cyclone for different shelf profiles.

	Peak Surge Estimates (m)	
	Linear	Non Linear
Variable depth shelf having a depth of 20 m at the coast (Profile ACEG in Figure 3)	2.39	2.38
Shelf with constant depth of 20 m (Profile ACEF in Figure 3)	2.99	3.00
Variable depth shelf having a depth of 10 m at the coast (Profile ABDEG in Figure 3)	3.22	3.23

Note: The pressure field is neglected in the simulation

### Non-linear Inertia Terms

DAS (1981), by examining the order of magnitude of different terms in the equations governing the flow field, has shown that the ratio between the non-linear and the local acceleration terms in momentum equations is of order  $(Z/\tilde{H})$ . Here  $Z$  and  $\tilde{H}$  are the scales of sea level variation ( $\eta$ ) and water depth ( $h$ ) respectively. This implies that the momentum equations can be linearised in regions where surge height is small compared to the water depth. In storm surge phenomenon,  $(\eta/h)$  is generally small over a major portion of the shelf, except over small regions along the coast where the water depths are small and simultaneously wind velocities are high. It is also observed that (Table 2), when non-linear terms are introduced into the surge simulation model without the pressure anomaly terms, the estimated peak surge is not significantly different from those of the earlier experiments. This suggests that the non-linearity of the equations governing this flow field is very weak. Hence, in subsequent experiments, the non-linear terms are neglected in the simulation model.

### Pressure Field

In this experiment both the tangential wind stress and the atmospheric pressure fields are introduced together in the simulation model. Figure 4 shows the surges along the coast with and without including the pressure field in the simulation model (for the shelf profile ABDEG). It is observed (Table 3) that there is no significant difference in the magnitude of the maximum surge which occurs at the coast nearly 80 km to the right of the landfall point, where the wind velocity is

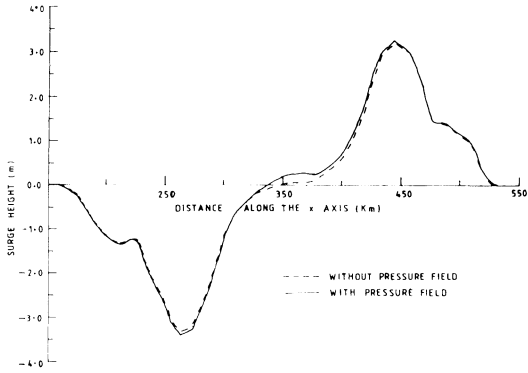


Figure 4. Surges along the coast 30 minutes before the time of landfall for the 1977-Andhra cyclone. Linearised governing equations are used in the simulation. Shelf profile considered is ABDEG.

maximum. This is because, the regions of maximum wind and the maximum pressure anomaly do not coincide for the pressure field to significantly contribute to the maximum surge, and the wind stress is the dominant factor responsible for generating the surges. Also the application of the clamped condition along the open ocean boundary which prevents the normal response of the sea level along this boundary to the pressure field, may have its influence on the peak surge at the coast. Though the maximum surge heights are not significantly changed by the introduction of the pressure field, the surge heights near the landfall point are increased, where the pressure anomaly is maximum.

#### Shelf Width

The estimated peak surge for the 1977-Andhra cyclone in all the above simulation experiments, are much less than the peak surge of 5 m documented in the post-cyclone survey reports. The possible reasons for this underestimation of peak surge height are: (a) the radius of the region coming under the influence of this cyclone wind field at any moment is nearly 200 km whereas the shelf region considered in the present model is only 30–50 km wide, and (b) during the cyclone, though the sea level variations in the deeper ocean will be insignificant, the momentum transferred from the atmosphere to the ocean waters in the deeper regions and advected into the shelf region which might amplify the surges near the coast is ignored

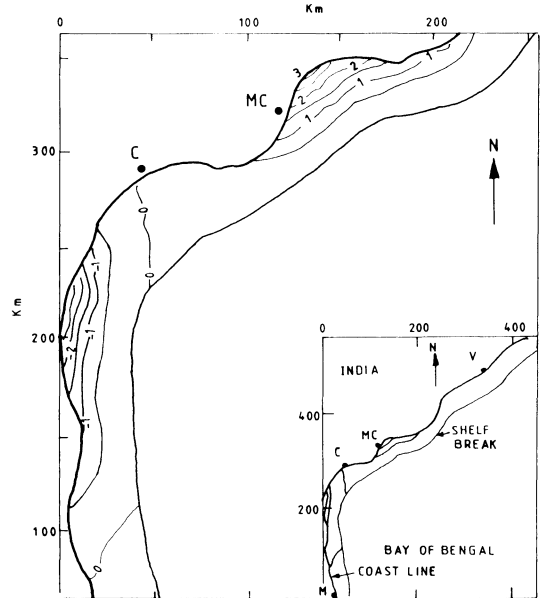


Figure 5. Surge contours in the shelf 30 minutes before the time of landfall. Linearised governing equations are used in the simulation and the pressure field is neglected. Shelf profile considered is ABDEG. (M) Madras; (C) Chirala; (MC) Machilipatnam; (V) Visakhapatnam.

in the model. In view of this, the study area bounded between the shoreline and the 200 m depth contour, is extended seaward by 200 km throughout the length of the shelf. The depth of water in the extended region is taken as constant (200 m).

It can be seen (Table 4) that, in the case of wider shelf, with only the tangential wind stresses introduced in the model, the peak surge is less

Table 3. Maximum surge estimates for the 1977 Andhra cyclone with and without pressure field.

	Maximum Surge Estimates (m)	
	Without Pressure Field	With Pressure and Wind Fields
Shelf with constant depth (20 m)	2.99	3.02
Shelf with varying depth (Profile ABDEG in Figure 3)	3.22	3.27

Note: Linearised governing equations are used in the simulation

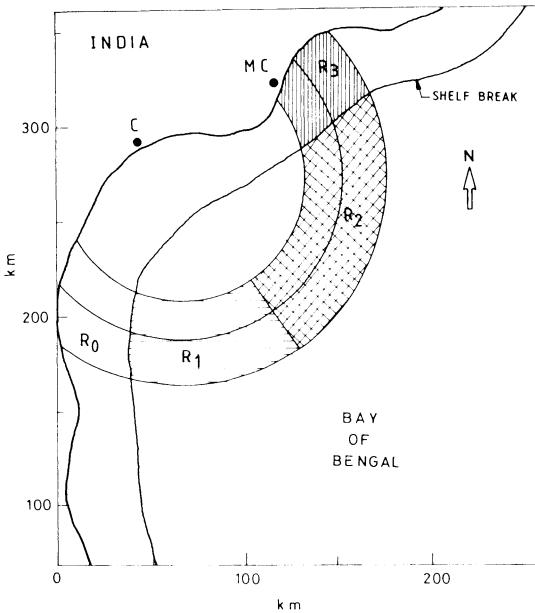


Figure 6. Regions of ocean ( $R_0$ ,  $R_1$ ,  $R_2$  and  $R_3$ ) subjected to strongest winds 30 minutes before the cyclone landfall.

than that estimated for the actual shelf. This has perhaps resulted from the different grid systems used in the actual and the wider shelves. Though the average grid spacings were maintained the same for both the shelves, the transformation functions used in the two cases have led to different grid spacings over the shelves. We have already observed that the peak surges are influenced by the bathymetry near the coast and hence, different grid spacings across the shelf is bound to influence the peak surge. Except for this small difference that has been observed in the peak surge estimates due to different grid systems used, they are not significantly influenced by the momentum transferred to the ocean waters by tangential wind stresses outside the actual shelf region.

Though we anticipated initially significant increase in the peak surge near the coast in the case of wider shelf, the above result is not surprising if we examine the regions of the ocean subjected to strongest winds (see Figure 6). The momentum from the atmosphere transferred into the ocean waters in the region  $R_1$  (region of the strongest winds) obviously will not contribute to the peak surge along the coast near Machilipatnam (MC). The momentum transferred into the ocean waters

Table 4. Peak surge estimates for the 1977-Andhra cyclone with different shelf widths.

	Peak Surge Estimate (m)	
	Without Pressure Field	With Pressure and Wind Fields
Actual shelf (Profile ABDEG)	3.22	3.27
Wider shelf*	3.07	3.64

Note: Linearised governing equations are used in the simulation

\*Profile ABDEG extended beyond the shelf break with a constant depth of 200 m

over the region  $R_2$  is also likely to be deflected by the Coriolis force away from the coast near MC. Only the wind stresses over the region  $R_3$  seems to have the maximum influence on the surges generated along the coast near MC where the surge is observed to reach the maximum height.

Then we introduced both the tangential wind stress and the pressure fields in the model and the peak surge was observed to be 3.64 m (Table 4). In this case we may note that, the clamped open ocean boundary is far from the coast and the sea surface response to pressure anomaly field contributes 0.37 m (nearly 10%) over the estimated value for the actual shelf. Even with this contribution from pressure anomaly over a wider shelf, the surge estimates were much less than the post storm survey estimate of 5 m.

#### Wind Stress and Bottom Stress Coefficients

The results so far presented were obtained by treating the wind and bottom stress coefficients as constants in the model, though they are primarily functions of wind and current speeds respectively. With constant stress coefficients ( $K_a = 2.8 \times 10^{-3}$  and  $K_b = 2.6 \times 10^{-3}$ ), the model estimate of peak surge for the 1977-Andhra cyclone is seen to be significantly lower than the recorded surge. Therefore, simulation experiment is repeated, expressing  $K_a$  as a function of wind speed  $|W|$  and assuming  $K_b$  as constant ( $2.6 \times 10^{-3}$ ), to see if it improves the model prediction. Though estimates of  $K_a$  show significant scatter (WANG and CONNOR, 1975; WHITAKER, 1973; LARGE and POND, 1981), in the present experiment,  $K_a$  is expressed in the form (WANG and CONNOR, 1975),

$$K_a = (1.1 + 0.0536|W|) \times 10^{-3}, \quad (20)$$

then the predicted peak surge (4.94 m) is observed



Table 5. Peak surge estimates for the 1977-Andhra cyclone with different bottom stress coefficients.

Bottom Stress Coefficient ( $K_b$ )	Peak Surge Estimates (m)
$0.5 \times 10^{-3}$	5.11
$1.0 \times 10^{-3}$	5.04
$1.5 \times 10^{-3}$	5.00
$2.0 \times 10^{-3}$	4.98
$2.5 \times 10^{-3}$	4.97
$3.5 \times 10^{-3}$	4.95

Note: Linearised governing equations and Variable  $K_b$  as defined in Eqn. 10 are used in the simulation. The pressure field is neglected. Shelf profile considered is ABDEG

to compare well with the recorded peak surge of 5.0 m. Figure 7 shows the surge envelopes along the coast for constant and variable wind stress coefficients. In this and in subsequent experiments the actual shelf with the depth profile ABDEG is used.

In the next experiment,  $K_b$  is varied from  $0.5 \times 10^{-3}$  to  $3.5 \times 10^{-3}$ , and the wind stress coefficient as defined in Equation 20 is used. No significant variation is observed in the peak surge estimates (Table 5), showing that  $K_b$  is not an important parameter in storm surge phenomenon.

### CONCLUDING REMARKS

Numerical experiments are carried out using the software developed for solving the depth averaged shallow water equations in the shelf region, adjacent to the Andhra coast. Some of the model parameters are varied to examine their influence on surge level ( $\eta$ ) along the coast, which is an important variable in surge simulation studies. Idealized wind and pressure fields having the general features of the 1977-Andhra cyclone are considered as the forcing functions in these experiments. Only the clamped condition along the offshore boundary is used in the present study and the influence of the other possible offshore boundary conditions are not examined. This choice of the boundary condition is based on the observations of MATHEW *et al.* (1995). They have recommended the use of clamped condition along this boundary after examining the influence of several offshore boundary conditions on surge simulation in a rectangular shelf.

In surge simulation studies the wind stress coefficient (one of the important model tuning parameters) is chosen by comparing the model simulated surges with the observed values. But ar-

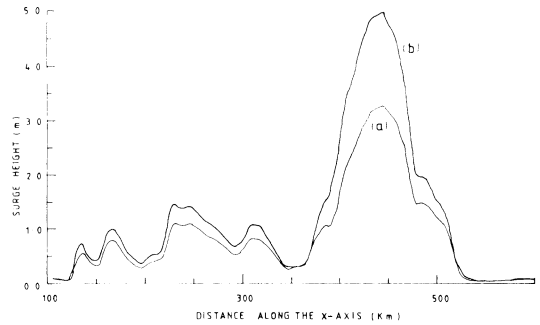


Figure 7. Predicted surge envelopes for the 1977-Andhra cyclone with (a) constant wind stress coefficient and (b) varying wind stress coefficient (Equation 20). Linearised governing equations are used in the simulation and the pressure field is neglected. Shelf profile considered is ABDEG.

chived data on surges are limited, since tide gauges along the coast are few and these gauges frequently become inoperative during severe storms. There are large inherent errors in the available data on both surge and meteorological observations. Hence, determining the tuning parameters of a model from one storm event should be avoided. But in the present study the wind stress coefficient is determined from single surge event. Before the software developed here could be used for real time prediction of storm surges, more generalized tuning parameters of the model should be determined employing a suitable data assimilation technique and utilizing the available data on historical storms and surges, to serve all future storms in that region.

With these limitations on the scope of this study the results of the present experiments can be summarized as follows:

The bathymetry of the shelf region near the coast is an important factor affecting the surges.

The surge estimates are not altered by the introduction of the non-linear inertia terms in the numerical scheme.

The momentum transferred by the tangential wind stress to the waters outside the shelf region has no significant influence on the peak surge near the coast.

Among the two components of the cyclonic wind forcing, *viz.* the tangential wind stress and pressure fields, the former is observed to be the dominant forcing responsible for the estimated peak surge near the coast.

In surge simulation studies the wind stress coefficient is the most important model tuning parameter which has to be chosen by comparing the model simulated surges with the observed values. When the wind stress coefficient is treated as a linear function of wind velocity the predicted peak surge is comparable with the reported peak surge.

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