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Calibration of a finite element surge prediction model for the east coast of India

G. Latha*, E.P. Rama Rao* & R. Mahadevan

National Institute of Ocean Technology, Velachery-Tambaram Main Road, Pallikaranai, Chennai – 601 302, India

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Real time simulation of storm surges using numerical models requires calibration and validation of the model before being used for operational forecasts. The main objective of this paper is to present the calibration studies carried out on an operational level storm surge prediction model developed at NIOT using finite element method. The primary requirement for calibration of surge prediction model is the actual data on bathymetry, past cyclones and the observed surges. The bathymetric contours along the shelf of east coast of India were digitized from the hydrographic charts and the data on cyclones which crossed the east coast of India for the past fifty years were collected from India Meteorological Department. The sensitivity studies showed that the wind stress coefficient is the key sensitive parameter for the model and so the model is calibrated for this parameter. The surge simulations using the calibrated parameter compare very well with the observed surges and illustrate the predictive capability of the model.

[**Key words** : Storm surge, finite element method, calibration]

Coastal regions are generally vulnerable to storms and associated surges and the inundation caused by the surges have devastating impacts. To minimize damages, it is essential to have a forecasting model for storm surges and for estimation of coastal inundation.

Among the various numerical methods available for surge prediction[1-5], the finite element method is the most suited due to its flexibility to represent irregular boundaries and complex topographies with greater accuracy. Though finite element models for surge prediction were developed in the past[3,6], to reduce the computation significantly, an efficient model using explicit finite element scheme for surge simulation was developed at NIOT[7,8] and benchmarked using the international standard software MIKE21 of Danish Hydraulic Institute. Then sensitivity studies were carried out on the model[9] and the wind stress coefficient was found to be the key calibrating parameter.

This finite element model needs to be calibrated before it is used for operational forecasts. Calibration of the numerical model requires actual data of all the inputs that go into the model. The objective of this paper is to present the calibration carried out on the finite element model using actual data of bathymetry of the domain and cyclones that crossed east coat of India over the last fifty years (Fig. 1).

[#] E-mail: latha@niot.ernet.in
[*]Present address: Indian National Centre for Ocean Information Services, Hyderabad-500 033, India

Materials and Methods

Governing equations

The vertically integrated form of the shallow water equations governing the ocean flow field in an ocean shelf, in a Cartesian co-ordinate frame fixed to the rotating earth, are the continuity equation.

$$q_{x,x} + q_{y,y} + \zeta_{,t} = 0 , \qquad \ldots (1)$$

and the momentum equations in the x and y directions:

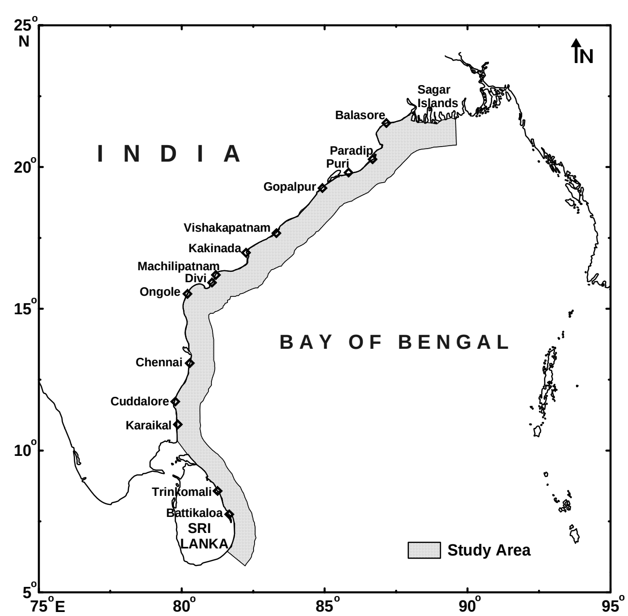

Fig. 1 — Study area in the ocean shelf region along the east of coast of Sri Lanka and India.

$$q_{x,t} + H^{-1} q_x q_{x,t} + H^{-1} q_y q_{x,y} - f q_y = -\rho^{-1} H p_{a,x} - gH\zeta_{,x} + \rho^{-1}\left(\tau_{ax} - \tau_{bx}\right), \qquad \ldots (2)$$

$$q_{y,t} + H^{-1} q_y q_{y,x} + H^{-1} q_y q_{y,y} + f q_x = -\rho^{-1} H p_{a,y} - gH\zeta_{,y} + \rho^{-1}\left(\tau_{ay} - \tau_{by}\right) \qquad \ldots (3)$$

Here the origin of the coordinate system was chosen at the undisturbed sea surface and *z* was measured positive upwards. The pressure was assumed hydrostatic and the astronomical tide generating forces were neglected. The volume transport (q) and volume transport components are defined as $q_x = \int u dz$ and $q_y = \int v dz$, where the integration limits vary from -h to ζ; *(u, v)* are the components of velocity in the *(x, y)* directions respectively and *t* is the time. The suffixes preceded by comma indicate partial derivatives. $H = h + \zeta$ is the total depth of water, *h* is the undisturbed depth of water and ζ is the elevation of the sea surface, measured from the undisturbed sea surface; p_a is the atmospheric pressure, f is the Coriolis parameter, ρ is the density of water and g is the acceleration due to gravity; (τ_{ax}, τ_{ay}) and (τ_{bx}, τ_{by}) are the stresses at the air-sea interface (wind stresses) and at the bottom surface (bottom stresses) respectively.

Table 1 — Statistics of grid spacing (km)

Area	Average	Minimum	Maximum
A Between Sri Lanka &Paradip			
Across the shelf	5.64	1.97	11.60
Along the shelf	8.76	6.35	17.20@
B. Between Paradip & Bangladesh			
Across the shelf	6.52	1.97	15.00
Along the shelf	8.90	6.35	20.00@

(@ The grid spacing is large only at a few places along the coast, where the coast line is highly irregular)

The wind and the bottom stresses were evaluated using the conventional quadratic law as follows:

$$\tau_a = K_a \rho_a |W| W, \quad \tau_b = K_b \rho |q| q, \qquad \ldots (4a,b)$$

where, K_a and K_b are the wind and bottom stress coefficients respectively, ρ_a is the air density, $W \equiv (W_x, W_y)$ is the wind velocity measured 10m above the sea level and the volume transport $q \equiv (q_x, q_y)$.

Initial and boundary conditions

The usual practice in storm surge simulation studies is to assume the ocean to be initially at rest, before the introduction of the wind stresses at the ocean free surface, i.e. ζ, q_x, $q_y = 0$ for $t \leq 0$. Along the open ocean boundary the clamped condition ($\zeta = 0$) is used in view of the earlier observations[4]. The conventional impermeable vertical wall assumption is made along the coastal boundary.

Wind field estimation

The wind estimates based on pressure distribution over ocean regions are considered to be more reliable, since the pressure observations are relatively free from noise unlike wind observations. In the present surge simulation model, we used the pressure distribu-

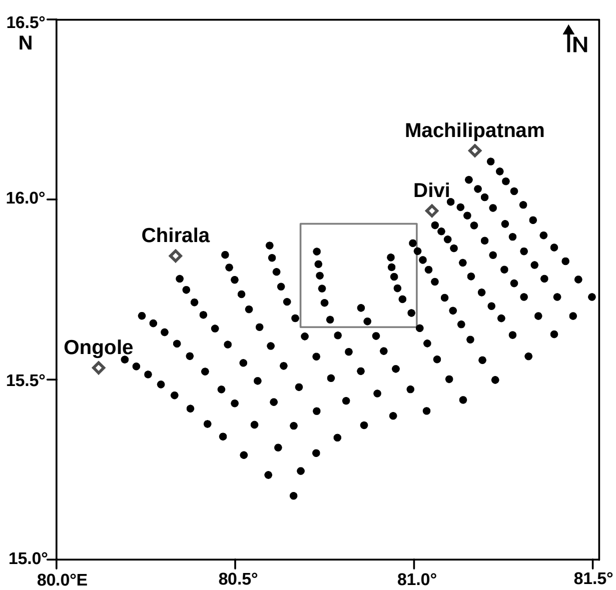

Fig. 2 — Finite element grid near Machilipatnam area.

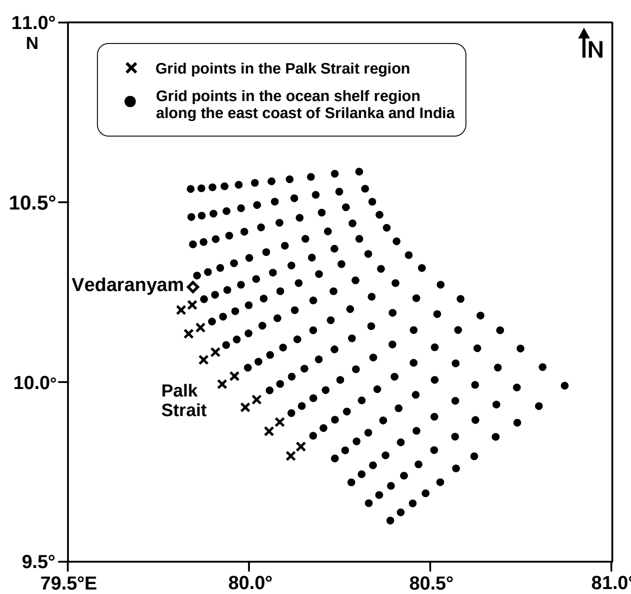

Fig. 3 — Finite element grid in the Palk Strait

Table 2 — Cyclone parameters and location of peak surges for past cyclones along the east coast of India

Cyclone	Land fall (°N)	Location of peak surge observed	Peak surge distance from landfall (km)	Δp (hPa)	Rad. of max wind (km)
Machilipatnam (1949)	16.3	Machilipatnam	87	80	25
Kakinada (1969)	16.7	Kakinada	49	45	25
Sriharikota (1972)	14.0	Sriharikota	33	80	25
Divi (1977)	15.8	Machilipatnam	26	97	45
Kavali (1979)	14.8	Ongole	61	60	35
Sriharikota (1984)	14.0	Sriharikota	17	60	25
Kavali (1989)	14.8	Near Ongole	23	70	20
Divi (1990)	15.7	Machilipatnam	26	80	40
Madras (1994)	13.0	Madras	14	30	25
Kakinada (1996)	16.7	Kakinada	49	35	20
Paradip (1982)	20.7	Dhamra port	60	40	50
Orissa (1985)	21.0	Chandbali	22	25	42
Orissa (1989)	21.8	Near Dariapur	75	40	33

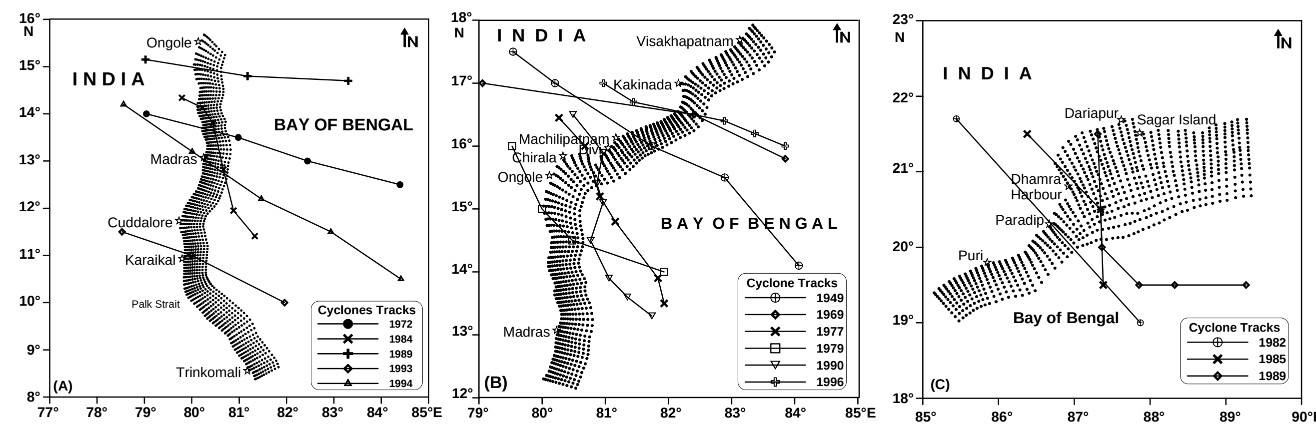

Fig. 4 — Tracks of the cyclones which crossed (A) Tamilnadu coast (B) Andhra Coast and (C) Orissa Coast

tion given by Basu & Ghosh[10] to derive the wind field, since it requires only one parameter 'n' to define the pressure distribution and for a fixed 'n' the wind field derived from this formulation coincided well with observed winds for past cyclones. Basu & Ghosh[10] compared the computed and measured pressure distributions for four cyclones and observed that the parameter 'n' varies between 1.3 and 2. Fixing the value of 'n' as 1.7, they computed the maximum wind for thirty-seven past cyclones and found them to match well with observed maximum winds. Hence in this study, we used their formulation with the parameter 'n' as 1.7.

Explicit finite element method

In this model the finite element method[11] was adopted and flow domain was first divided into 9-noded quadrilateral elements. The variables (ζ, q_x, q_y)

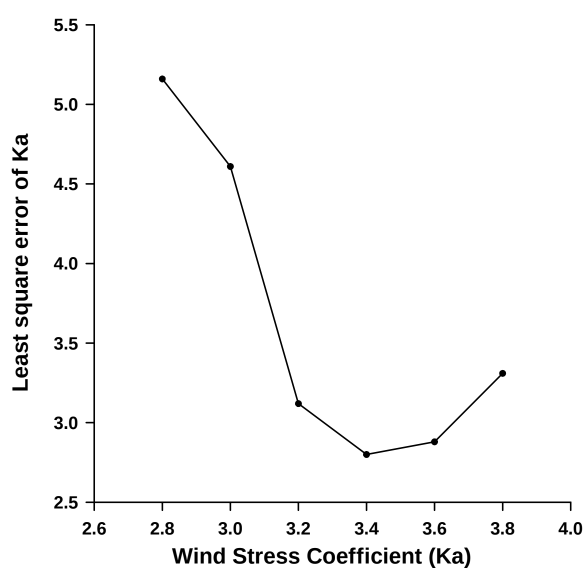

Fig. 5 — Wind coefficient (Ka) vs. least square error of K_a.

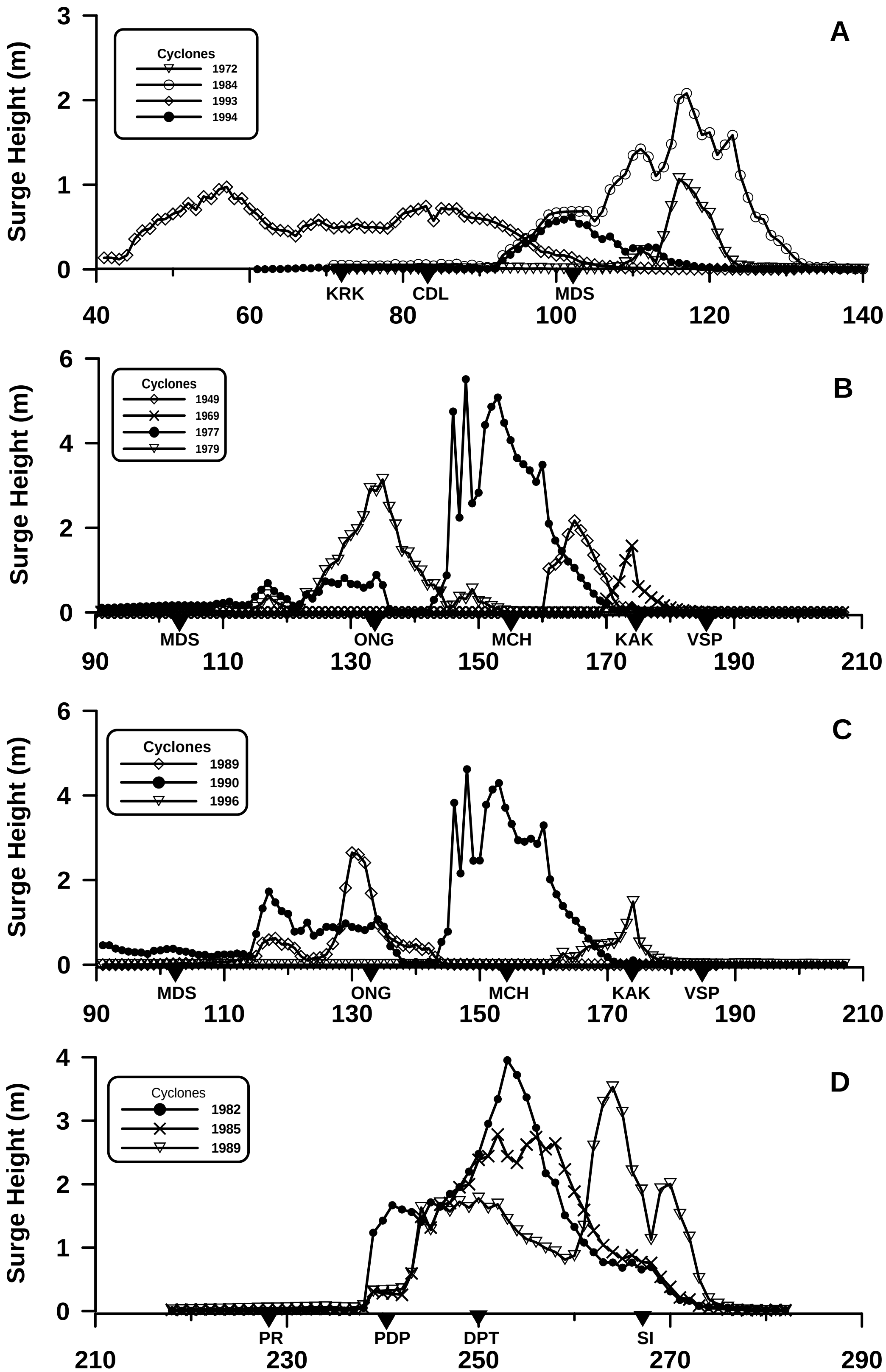

Fig. 6 — Surge envelopes for the cyclones that crossed (A) Tamilnadu coast, (B,C) Andhra coast and (D) Orissa coast. (Coastal stations are given as KRK — Karaikal, CDL — Cuddalore, MDS — Madras, ONG — Ongole, MCH — Machilipatnam, KAK — Kakinada, VSP — Visakhapatnam, PR — Puri, PDP — Paradip, DPT — Dhamra Port and SI — Sagar Island).

Table 3 — Comparison of surge estimates for past cyclones

Cyclone	Peak Surge height (m)		
	Observed	Predicted-IITD[12]	Predicted-NIOT
Machilipatnam (1949)	2.50	2.09	2.16
Kakinada (1969)	2.60	2.82	1.57
Sriharikota (1972)	1.00	1.23	1.07
Divi (1977)	5.00	4.93	5.07
Kavali (1979)	3.00	3.30	3.14
Sriharikota (1984)	2.00	2.40	2.08
Kavali (1989)	3.00	3.80	2.65
Divi (1990)	4.50	4.41	4.30
Karaikal (1993)	1.50[@]	1.85	0.97
Madras (1994)	1.00	0.83	0.62
Kakinada (1996)	1.50	1.60	1.49
Paradip (1982)	4.00	3.50	3.90
Orissa (1985)	3.00	-	2.70
Orissa (1989)	4.00	-	3.50

([@]Observed by the members of Hazard Mitigation Project of IIT, Madras, 1993)

over the elements are represented by Lagrangian quadratic basis functions (i.e. piece-wise continuous polynomials) in the form,

$$\zeta(x,y,t)\approx\sum_{j=1}^{N} \zeta_j(t)\phi_j(x,y) \quad \ldots (5a)$$

$$q_x\approx\sum_{j=1}^{N} q_{xj}(t)\phi_j(x,y) \quad \ldots (5b)$$

$$q_y\approx\sum_{j=1}^{N} q_{yj}(t)\phi_j(x,y) \quad \ldots (5c)$$

where, ζ_j, q_{xj}, q_{yj} are the unknown nodal values of the dependent variables in an element, $\phi_j(x,y)$ are the shape functions and N is the number of nodes in each element. The approximate solutions (Eqs. 5a-c) were substituted into the governing equations (Eqs.1-3) and the Galerkin's method of weighted residuals was employed to get the element equations. In this scheme, nine-nodded Lagrangian isoparametric elements were used to discretise the variables in the problem. The use of Lagrangian interpolation functions in combination with Simpson's rule of integration of dependent variables over an element makes the coefficient matrices of the flow variables diagonal as against a banded matrix, which normally results from other forms of finite element schemes. This leads to an explicit time integration scheme avoiding matrix inversion and hence a reduction in computation, which is a primary requirement in real time storm surge prediction

Finite element grid generation

The ocean shelf along the east coast of Sri Lanka and India, which is the analysis area for the storm surge prediction model, is shown in Fig. 1. The southern boundary of the analysis area is 6°N and the northern boundary is 22°N. The length and the average width of the shelf are nearly 2600 km and 50 km respectively.

The software "DIGI" (from MIKE21 Package) and "FASTTABS" were used to generate the finite element grid over the analysis area. Using the software "DIGI", the depth contours 0 m (coastline), 5 m, 10 m, 20 m, 30 m, 50 m, 100 m, 150 m and 200 m, in the hydrographic charts were digitized and a bathymetry file was created. The bathymetry file forms the input to the software "FASTTABS". Using this software, the finite element grid was generated interactively and the depth at the grid points was determined.

Initially the finite element grid was generated for the shelf region from Sri Lanka to Paradip consisting of 236 points along the shelf and 11 grid points across the shelf. The mesh consists of a total number of 2596 points. The statistics of the grid spacing for this stretch is shown in Table 1A. The finite element mesh for the shelf region between Paradip and Bangladesh was carried out separately as the width of the shelf in this region is high. The grid points across the shelf are 21 for the region from Paradip to Sagar islands and 17 beyond Sagar islands. Along the coast there are 27 points and the total number of nodes in this mesh is 514.

The grids used in the region near Krishna river delta and in the Palk Straight are shown exclusively below due to the following reasons:

1. In the Krishna river Delta the coast line has a deep curvature and the number of points across the shelf were reduced accordingly.
2. In the shelf region between Sri Lanka and Tamil Nadu, the Palk Strait is an open ocean region. Additional grid points were introduced to handle the open ocean condition.

Figure 2 shows the grid distribution used in the present model over the shelf region near the Krishna River delta. As this delta region extends into the shelf, only 7 grid points are considered across the shelf. The channel between Sri Lanka and Vedaranyam (Fig. 3) that connects the Bay of Bengal and the Palk Strait can be kept open or closed by switching on or off a parameter in the software. When the channel is kept open the software automatically generates 14 extra grid points in the Palk Strait region (Fig. 3).

Model calibration

While calibrating the surge model and then using it for forecasting, we have to be aware of the quality of the input data used in calibration experiments. Many uncertainties in the specification of cyclone parameters, which go as input to the surge model, are discussed below.

Pressure difference

- Determination of the maximum atmospheric pressure difference (Δp) from the T-number of a cyclone was based on an empirical relation between them. Error involved in the estimation of Δp from the T-number of a cyclone is $\approx \pm 10$hPa, when T-number = 5.
- T-number estimation from satellite imagery of cloud pattern is subjective in nature.

Pressure and wind distribution

Empirical functions fitted to the pressure and wind fields are again subjective in nature. When wind fields were derived from the atmospheric pressure fields, approximate force balance relations were used.

Results and Discussion

The present model was calibrated using the data of 11 past cyclones which crossed the east coast of India in the stretch of Andhra and Tamil Nadu. The tracks of these cyclones are shown in Fig. 4 and the parameters of the cyclone are listed in Table 2. Using the finite element model, the peak surges generated by these cyclones were computed for values of K_a varying from 2.8×10^{-3} to 3.8×10^{-3}. The error in the surge estimates defined as the difference between the observed and the model predicted peak surges for each K_a were computed for all the cyclones. The sum of squares of these errors over all the cyclones for each K_a is shown in Fig. 5, and it can be seen that it has the least value for $K_a = 3.4 \times 10^{-3}$. Hence the value of K_a was fixed as 3.4×10^{-3} and the surge generated along the coast for the 11 past cyclones were computed. The surges caused by cyclones that crossed the Orissa coast are simulated using the same K_a and the results are compared with the observed surges. The surge envelopes are shown in Fig. 6 and the peak surges are presented in Table 2.

The average error in the predicted surge by NIOT model when compared with the observed surge is 6 % for 11 cyclones and it is 35% for the other three cyclones, over the coast of Tamil Nadu and Andhra. The average error for the Orissa cyclones is 12%. It may be noted that the observed surges of past cyclones are not instrument recorded values and they are based on post storm surveys. Also the uncertainties in the input parameters of an approaching cyclone are mentioned earlier. Even with all these limitations, Table 3 illustrates that the predictive capability of our model is good. So it is concluded that the model can be validated once the instrument recorded surge data is available and then it can be used for forecasting the surges.

References

1 Das P K, Sinha M C & Balasubramaniam V, Storm surges in the Bay of Bengal. *Quart. J. Mat. Soc.,* 100 (1974) 439-449.
2 Johns B, Dube S K, Mohanty U C & Sinha P C, Numerical simulation of the surge generated by the 1977 Andhra Cyclone. *Quart. J.R. Met. Soc*., 107 (1981) 919-934.
3 Murty T S & Henry R F, Tides in the Bay of Bengal. *J. Geophy. Res*., 88 (1983) 6069-6076.
4 Jossy P M, Mahadevan R, Bharatkumar B H & Subramanian V, Numerical simulation of open coast surges, Part I: Experiments on offshore boundary conditions. *J. Coast Res,* 12 (1996) 112-122.
5 Jossy P M & Mahadevan R, Numerical simulation of open coast surges, Part II Experiments with storm parameters and shelf geometry. *J Coast Res,* 12 (1996) 123-132.
6 Ajoykumar, *Finite element simulation of shallow water flow field,* MS-thesis, Indian Institute of Technology, Madras, India, 1994.
7 Mahadevan R. & Aswathanarayana P A, *Development of an operational level storm surge model*, Project Report, (NIOT, Chennai, India), 1998.
8 Latha G & Mahadevan R, Development of operational level software for prediction of coastal flooding due to storm surges, Technical Report, (NIOT, Chennai, India). 1999
9 Latha G & Mahadevan R, Sensitivity and predictive capability studies on a finite element surge simulation model. *Indian J Mar Sci*, 29 (2000) 89-95.
10 Basu B K & Ghosh S K, A model of surface wind field in a tropical cyclone over Indian seas, *Mausam*, 38 (1987) 183-192.
11 Gray W G, An efficient finite element scheme for two-dimensional surface water computations, in *Proceedings of the first International Conference on Finite Elements in Water Resources*, edited by Gray W G. *et al.* (Pentech Press, London) 1976, pp. 4.33-4.49.
12 Rao Y R, Chitti Babu P, Dube S K, Rao A D and Sinha P C. Storm surge prediction and frequency analysis for Andhra Coast of India, *Mausam*, 48 (1997) 555-566.