CHAPTER THIRTEEN

NUMERICAL SIMULATION OF STORM SURGES INDUCED BY TROPICAL STORMS IMPINGING ON THE BANGLADESH COAST

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ABSTRACT: In the present paper a vertically integrated coastal zone numerical model has been described for the simulation of the surges generated by the tropical storms striking the Bangladesh coast. The model is fully nonlinear and uses a conditionally stable explicit finite-difference scheme for solving the relevant equations of motion. In this model the analysis area extends from 87°E to 93°E along the south coast of Bangladesh and there are three open-sea boundaries situated along 87°E, 93°E and 19°N. The model utilises a curvilinear boundary treatment to represent the coastline and uses a non-uniform off-shore grid spacing adjacent to the coastal boundary. This allows an increased resolution near the Bangladesh coast.

Using a forcing wind-stress distribution representative of the 1970 Chittagong cyclone, we compare the model predicted surges with the observed sea-surface elevations along the Bangladesh coast. The predicted peak surge elevation above mean sea level compares well with the observed values at Chittagong port. A comparison of the results has also been made with those obtained from the corresponding model having uniform off-shore grid spacing.

INTRODUCTION

The tropical storms and the associated surges are very common occurrences along the coastal regions of Bangladesh. These systems directly affect the life and property of the habitants which is a heavy burden on the country's exchequer. About 500,000 lives were lost in one of the most severe cyclones that hit Bangladesh (then East Pakistan) in November, 1970. There can be little doubt that the number of casualities would have been considerably lower if the storm surges could have been predicted well in advance to allow effective warnings in the threatened areas.

In an earlier paper, Dube et al.(4) have developed a vertically integrated coastal zone numerical model for the simulation of storm

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surges along the Bangladesh coast. This model uses a staggered finite-difference grid on which the sea-surface elevation and components of velocity are computed at different computational points. The sea-surface elevations are not directly carried out at points along the coastline. Thus, the coastal surge elevations are derived by extrapolating from the computed elevations of those adjacent off-shore grid points at which they are carried. In this model the grid spacing across the coastal zone is uniform and relatively coarse. Consequently, the extrapolated coastal surge elevations may not be very realistic as these are dependent on the elevations computed directly at those off-shore points which are far away from the coast. This deficiency may be overcome by overall increasing the off-shore resolution in the model which would lead to a substantial increase in the computational overheads and is, in any case, unnecessary far away from the coastline.

Accordingly, in the present paper, the model described by Dube et al.(4) has been extended to allow for an increased resolution near the Bangladesh coast. The noteworthy difference in our method from those earlier used by Jelesnianski (5), Das et al. (1) and Johns and Ali (6) is that it does not depend on the patching together of computational regions having different uniform grid spacings. Our approach is analogous to that used by Johns et al.(8) for the simulation of surges along the east coast of India. The model uses a continuously contracting non-uniform off-shore grid spacing adjacent to the coastal boundary which permits an increased resolution near the Bangladesh coast.

The model covers an analysis area lying between 87°E and 93°E, and between 19°N and the south coast of Bangladesh. There are three open-sea boundaries situated along 87°E, 93°E and 19°N. Numerical experiments performed with this model for simulating the surge generated by the November 1970 Chittagong cyclone lead to a surge response along the Bangladesh coast which is in good agreement with the observed values.

FORMULATION OF THE MODEL

The sphericity of the earth's surface is neglected and we use a system of rectangular Casterian coordinates in which the origin, o, is in the equilibrium level of the sea-surface. ox points towards the south, oy points towards the east and oz is directed vertically upwards. The displaced position of the sea-surface is given by $z = \zeta\ (x,y,t)$ and the position of the sea-floor by $z = -h(x,y)$. A northern coastal boundary (the south coast of Bangladesh) is situated at $x = b_1(y)$ and the southern open-sea boundary is at $x = b_2(y)$. The western and the eastern open-sea boundaries are at $y = 0$ and $y = L$ respectively. This configuration is shown in Fig.1.

The basic equations of continuity and momentum in the vertically integrated form may then be given by

$$H_t + (Hu)_x + (Hv)_y = 0 \tag{1}$$

$$u_t + uu_x + vu_y - fv = -g\ \zeta_x + \frac{1}{H\rho}\ \{\ \tau_x^{\zeta} - c_f\ \rho\ u(u^2 + v^2)^{\frac{1}{2}}\} \tag{2}$$

$$v_t + uv_x + vv_y + fu = -g\ \zeta_y + \frac{1}{H\rho}\ \{\ \tau_y^{\zeta} - c_f\ \rho\ v(u^2 + v^2)^{\frac{1}{2}}\} \tag{3}$$

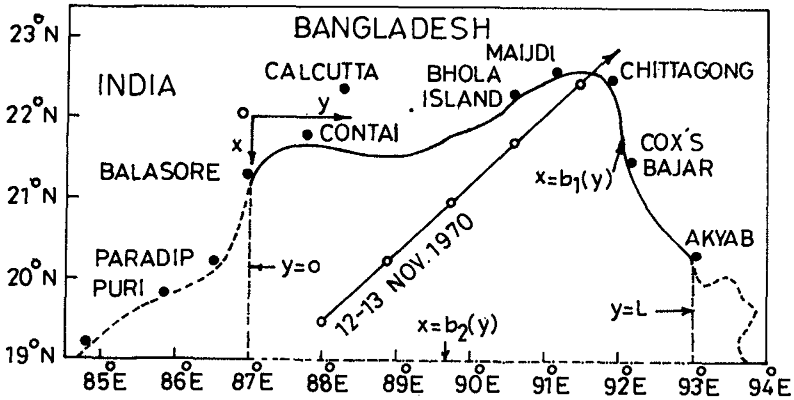

Fig.1 The analysis area and idealised track,
—.—.— open-sea boundaries
o 5 hourly positions of the centre of the cyclone (on the track)

where f denotes the Coriolis parameter, the pressure is taken as hydrostatic and H is the total depth ζ +h. (τ^{ζ}_{x}, τ^{ζ}_{y}) denotes the applied surface wind-stress and the bottom stress is parameterised in terms of a quadratic law. ρ denotes the water density and the friction coefficient, c_f, is taken as 2.6×10^{-3}.

Following Dube et al.(4), the appropriate boundary conditions are given by

$$u - v\,(b_1)_y = 0 \qquad \text{at } x = b_1(y) \tag{4}$$

$$u - v\,(b_2)_y - (g/h)^{\frac{1}{2}}\,\zeta = 0 \qquad \text{at } x = b_2(y) \tag{5}$$

$$v + (g/h)^{\frac{1}{2}}\,\zeta = 0 \qquad \text{at } y = 0 \tag{6}$$

$$v - (g/h)^{\frac{1}{2}}\,\zeta = 0 \qquad \text{at } y = L \tag{7}$$

COORDINATE TRANSFORMATION

In order to facilitate the numerical treatment of an irregular boundary configuration and to incorporate increased resolution adjacent to the coastline, we introduce the following coordinate transformations (Das et al.(3)).

$$\xi = \{ x - b_1(y)\} / b(y) \tag{8}$$

$$\eta = \xi + \varepsilon \ln(1 + \xi / \xi_o) \tag{9}$$

where $b(y) = b_2(y) - b_1(y)$ is the breadth of the basin and, ε and ξ_o are disposable parameters.

Taking η, y and t as new independent coordinates, Eqs.(1)-(3)may be transformed to

$$(b\zeta)_t + F(\eta)(bHU)_\eta + \tilde{v}_y = 0 \tag{10}$$

$$\tilde{u}_t + F(\eta)(U\tilde{u})_\eta + (v\tilde{u})_y - f\tilde{v} = - gHF(\eta)\zeta_\eta + b\,\tau^\zeta_x/\rho - c_f\tilde{u}(u^2 + v^2)^{\frac{1}{2}}/H \tag{11}$$

$$\tilde{v}_t + F(\eta)(U\tilde{v})_\eta + (v\tilde{v})_y + f\tilde{u} = - gH\{b\zeta_y - (b_{1y} + \xi b_y) F(\eta)\zeta_\eta\} + b\,\tau^\zeta_y/\rho - c_f\tilde{v}(u^2+v^2)^{\frac{1}{2}}/H \tag{12}$$

where,

$$bU = u - (b_{1y} + \xi b_y)v \tag{13}$$

$$(\tilde{u}, \tilde{v}) = bH(u,v) \tag{14}$$

$$F(\eta) = 1/\xi_\eta = 1 + \varepsilon/(\xi + \xi_o) \tag{15}$$

The boundary conditions (4) and (5) become

$$U = 0 \qquad \text{at } \eta = 0 \tag{16}$$

$$bU - (g/h)^{\frac{1}{2}}\zeta = 0 \text{ at } \eta = \eta_m \tag{17}$$

where $\eta_m = 1 + \varepsilon \ln(1+1/\xi_o)$.

Eqs. (10)-(12) form the basic set for the numerical solution process.

NUMERICAL PROCEDURE

For the solution of the Eqs. (10)-(12) subject to the relevant boundary conditions, a conditionally stable explicit finite-difference scheme with a staggered grid is used. The details of the discretization procedure and the finite-difference grid selection are completely analogous to those reported in Das et al.(3).

The stability characteristics of this computational scheme have been discussed in detail by Johns et al.(7). In fact, stability is only conditional upon the time step being limited by the space increment and the gravity wave speed.

NUMERICAL EXPERIMENTS

Numerical experiments are performed by using the analysis area which extends from 87°E to 93°E along the south coast of Bangladesh and there are three open sea boundaries situated along 87°E, 93°E and 19°N (Fig.1). Thus, on an average, the width of the coastal zone is about 168 miles (270 km) while the east-west extent, L, of the analysis area is about 375 miles (600 km). An idealised cyclone moves along the indicated straight-line track with uniform speed of translation for about 21 hours before landfall near Chittagong port (Fig.1). The five hourly positions of the centre of the cyclone is also indicated in the figure.

The wind field associated with this cyclone is simulated by applying the following empirically based formula suggested by Jelesnianski (5)

$$V = \begin{cases} V_o\ (r/R)^{3/2} & \text{for } r \leqslant R \\ V_o\ (R/r)^{\frac{1}{2}} & \text{for } r > R \end{cases}$$

where V_o is the maximum sustained wind, R the radius of maximum wind and r is the distance from the centre of the cyclone. Following Das et al.(1), we take

$$V_o = 164 \text{ ft s}^{-1}(50 \text{ ms}^{-1}) \text{ and } R = 25 \text{ miles}(40 \text{ km}).$$

The optimum grid resolution in the computational plane is chosen with $m = 10$, $n = 21$, $\varepsilon = 0.04$ and $\xi_o = 0.001$. Thus, $\eta_m \approx 1.27$ and $\Delta\eta \simeq 0.14$. This is obtained as a result of several experiments performed with the 1970 Chittagone cyclone for testing the adequacy of the resolution. It may be seen that with the above selection of parameters, the first off-shore grid point at which the elevation is computed is, on an average, about 3 miles (5 km) from the coastline and $\Delta y \simeq 18.5$ miles (30 km).

In our numerical experiments we prescribed an initial state of rest and integrated the governing equations ahead in time for a period of 50 hours. A time-step of 3 min. was found to be consistent with the computational stability. We also considered the sea-surface response during several hours after landfall when the system starts to enter the resurgence phase.

RESULTS AND DISCUSSIONS

The surges associated with the 1970 Chittagong cyclone have been computed by using a number of off-shore grid resolutions. However, the results are presented only for two resolutions corresponding to $m = 10$, $n = 21$ and $m = 20$, $n = 21$ for comparison and for an optimal selection of the grid size.

In Fig.2 we give the distribution of the predicted maximum sea-surface elevation (peak surge envelope), its time of occurrence and the

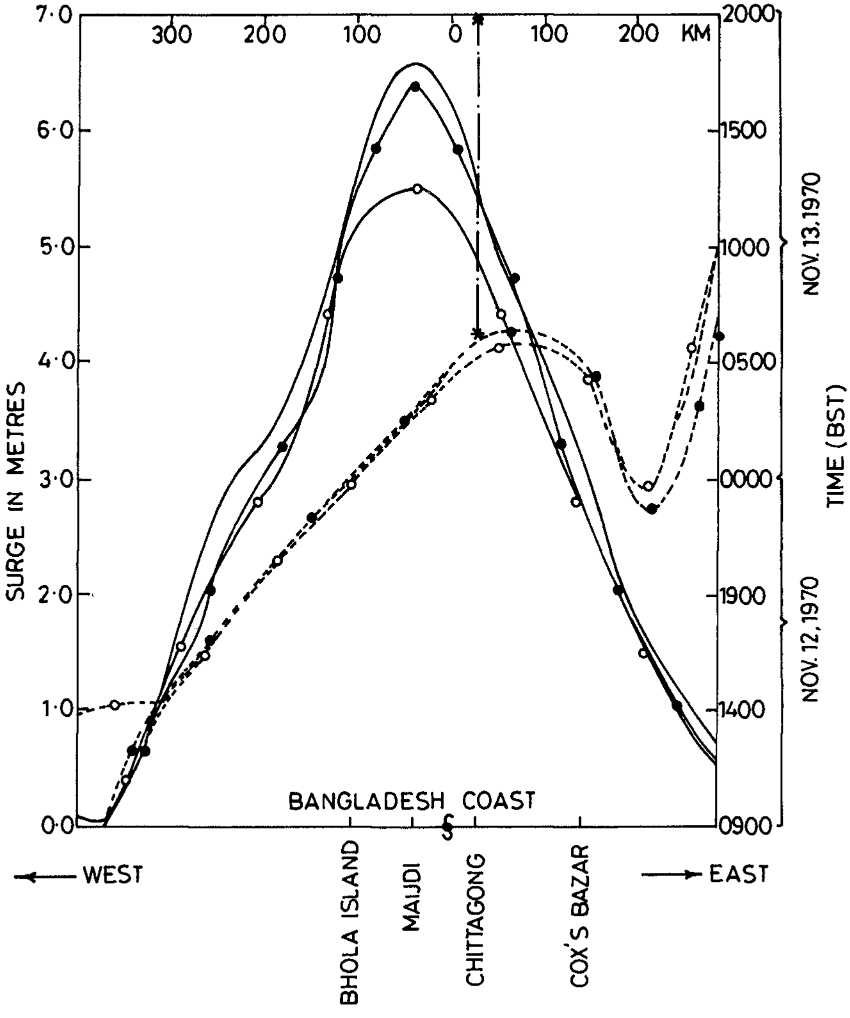

Fig.2 Maximum predicted surge and its time of occurrence
§ Place of landfall ● Time of landfall (on time axis)
—— Peak surge envelop (m=10) --- Time of occurrence (m=10)
—●— Peak surge envelop (m=20) -●- Time of occurrence (m=20)
—o— Peak surge envelop (m=20 , obtained in (4))
-o- Time of occurrence (m=20, obtained in (4))

observed surge along the Bangladesh coast. It may be seen from the figure that by increasing the number of off-shore grid points from 10 to 20 the maximum change in the peak surge values at various coastal stations is within two percent. Further, the time of occurrence of the peak surge in the two cases is almost same. A further increase in the number of off-shore grid points also show similar results.

The adequacy of the alongshore resolution has also been tested by increasing the value of n, which has not resulted in any significant change in the elevations and their time of occurrence along the coastal stations.

These tests on the selection of optimum resolution indicate that there is insignificant quantitative change in the results for the two resolutions (10X21 and 20X21). However, the computer overheads in the later case are much higher. Keeping these facts in view, it is appropriate to use a 10X21 grid for the present numerical experimentation.

The Fig.2 provides an idea of the coastal stretch upto which the significant surge may be expected. It may be seen from the figure that the maximum surge height of 21.6 ft (6.6m) is predicted at Maijdi which is about 25 miles (40 km) to the left of the landfall. A maximum surge of about 18.0 ft (5.5m) is predicted at Chittagong port (about 17.5 miles (28 km) to the right of the landfall point) at 0540 hrs BST on 13 November, 1970. A peak elevation of 19.7 - 29.5 ft (6-9 m) was reported at this tidal station on the morning of 13 November while according to the Tide-Table the predicted astronomical tide was 5.9 ft(1.8m) at about the same time. Thus, if we assume that the total sea-surface elevation is the result of purely linear superposition of surge and tide, it may be noted that the observed sea-surface elevation at Chittagong was in excess of 13.8 - 23.6 ft(4.2 - 7.2m) over the usual high-tide (Das et al.(2)). Hence, it may be seen that our predicted surge of 18.0 ft (5.5m) is in good agreement with the observed range of maximum surge of 13.8 - 23.6 ft (4.2 - 7.2 m) at Chittagong.

Further, it is worthwhile to compare the results of the present study with those obtained by Dube et al.(4) who have used a uniform off-shore grid spacing for the simulation of surges along the Bangladesh coast. It may be seen from Fig.2 that there is significant improvement in the computed surge heights by using a non-uniform off-shore grid spacing which allows an increased resolution adjacent to the coast.

Fig.3 depicts the time variation of the storm surge at four stations along the Bangladesh coast. All the three stages of the surge-forerunner, the main surge, and the resurgence phase may clearly be seen from the temporal variation of the coastal sea-surface elevations. The maximum surge height of 21.6 ft (6.6m) is predicted at Maijdi. The peak occured at 0240 hrs BST on the morning of 13 November. This main surge remains for a very short period (about 30 min.) and is followed by the resurgence phase. During resurgence phase the sea-surface elevation falls rapidly from its maximum value and becomes negative after about the next 6 hours period and a sea-surface depression of 10.2 ft (3.1m) is predicted at 1700 hrs BST on 13 November.

The predicted surge height at Chittagong is about 18.0 ft (5.5m) which occurs in the morning of 13 November at about 0540 hrs BST. It may be seen that the time of occurrence of the peak surge is in excellent agreement with the time of landfall. This main surge persists for about half an hour before falling rapidly and becoming negative at 1430 hrs BST. At Chittagong, a maximum sea-surface depression at 7.2ft (550mm) is predicted at about 1800 hrs BST on 13 November with a subsequent increase in the water height leading to a depression of about 15 cm in the early morning of 14 November.

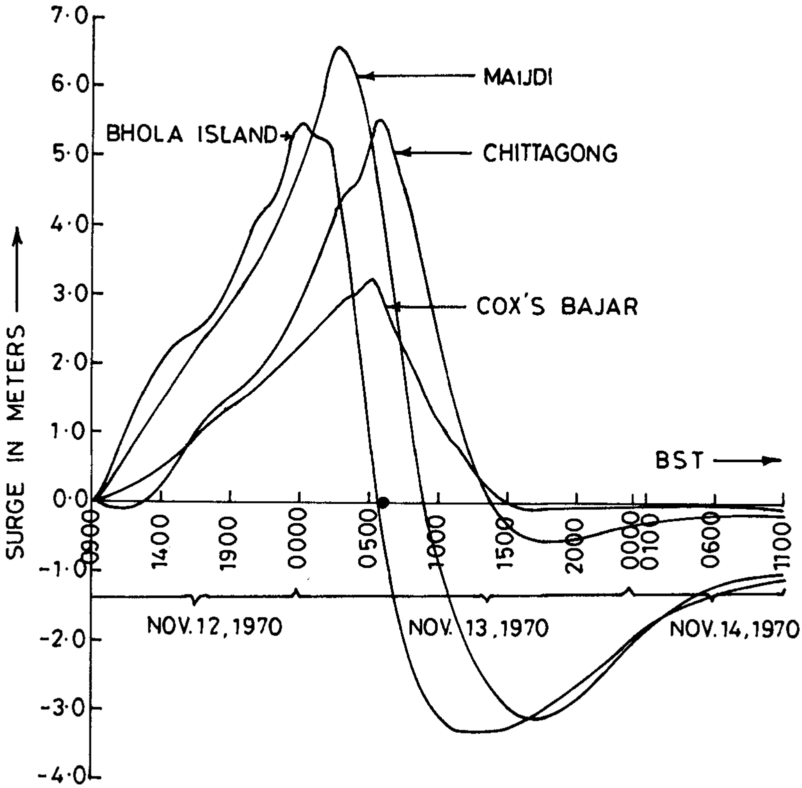

Fig. 3. Time variation of the predicted sea-surface elevation at four coastal stations.

● Time of landfall

At Bhola Island which is about 68 miles (110 km) to the west of landfall, the sea-surface elevation rises gradually to attain its peak value of about 18.0 ft (5.5m) at 0000 hrs BST on 13 November. Here again the main surge is short-lived (about 40 min.) and the surge becomes negative within 6 hours of the occurrence of its peak value. A sea-surface depression of about 10.8 ft (3.3m) is predicted at 1230 hrs BST on 13 November.

The predicted time history of the surge at Cox's Bazar which is about 87 miles (140 km) to the SE of landfall, indicate a maximum sea-surface elevation of 10.5 ft (3.2m) in the morning of 13 November at about 0500 hrs BST. This main surge is again very short-lived and it falls gradually to become negative in the afternoon of 13 November.

APPENDIX - REFERENCES

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