

A study of tides and storm surges in offshore waters of the Meghna estuary using a finite element model

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सारा — मानसून ऋतु के पहले अथवा बाद के महीनों (अप्रैल-मई, अक्टूबर-दिसम्बर) में अण्डमान सागर और बंगाल की खाड़ी से उठने वाले उष्णकटिबंधीय चक्रवात, या तो पश्चिम की ओर बढ़ते हुए भारत के पूर्वी तट को प्रभावित करते हैं या फिर उत्तर अथवा उत्तर-पश्चिम की ओर घुमड़ते हुए अन्ततः बंगलादेश या म्याँमार के तट को पार करते हैं। बंगाल की खाड़ी के आस-पास का तटीय भू-भाग घनी आबादी वाला होने के कारण तूफानी लहरों से जान और माल का भारी नुकसान होता है। चक्रवात-जनित ज्वार से होने वाली क्षति अधिकतर इस बात पर निर्भर करती है कि तूफानी लहरें उच्च ज्वार के समय उठती हैं अथवा उसके आस-पास उठती हैं।

प्रस्तुत शोध-पत्र का मुख्य उद्देश्य मेघना ज्वारनद मुहाने के समीपवर्ती समुद्र में उठने वाली चक्रवातीय तूफानी लहरों के समय के संबंध में एक मिला-जुला मॉडल विकसित करना है।

यह स्पष्ट प्रतीत होता है कि सैंड्वीप के दक्षिण के साइड "ए" पर दक्षिण की ओर से आने वाली लहरों में मौलिक रूप से विस्तार होता है तथा ज्वार की ऊँचाई और धारा के प्रवाह पर इनका प्रभाव देर से पड़ता है। किन्तु ज्वार की तरंगों में इस तरह के परिवर्तन का ऊपरी विस्तार क्षेत्र अभी तक अज्ञात है। इसके अलावा यह भी कहना असंभव है कि दक्षिण की ओर तीव्रगीत से जाने वाल धाराएं संकीर्ण जेट बनाती हैं अथवा कई किलोमीटर तक चौड़ी विस्तृत धाराओं का रूप लेती हैं। किन्तु इस प्रभाव का संतोषजनक ढंग से मॉडल बनाने से पहले वस्तु स्थिति का पता लगाना आवश्यक है।

ABSTRACT. Tropical Cyclones which develop in the Andaman Sea and the Bay of Bengal during the intermonsoon months (April-May, October-December), move either westwards affecting the east coast of India or recurve to the north or northeast and eventually cross the coast of Bangladesh or Myanmar. Extensive damage is caused to the life and property by the storm surge as much of the coastal land around the Bay of Bengal is densely populated. The damage caused by a cyclone induced surge depends to a considerable extent on whether the surge peaks at or close to high tide.

The main purpose of the present study was to develop a combined time-surge model for the off-shore waters in the Meghna estuary.

It seems clear that the strong, predominantly southward current measured at Site A, south of Sandwip Island, has substantial magnifying and delaying effect on tidal elevation and current, but the areal extent of this modification of the tide is unknown at present. Further, it is impossible to say whether the fast southward current forms a narrow jet or a broad current many kilometers wide, but it is important to know which is the case before the effect can be modelled satisfactorily.

Key words — Tides, Storm surges, Meghna estuary, Site A, Off-shore

1. Introduction

In this paper we discuss some results of a recent study of tides and storm surges in eastern Bangladesh waters (Figs. 1 & 2) using a two-dimensional finite element model. Although the model reproduced tidal elevations well at the four coastal sites used for model verification and simulated surge elevations at the coast with acceptable accuracy, observations made offshore about 30 km south of Sandwip Island (where the water depth is 10m) showed that the model substantially underestimated water level and current speed in the neighbourhood of offshore measurement site A, (Fig. 2). The probable cause of this behaviour and the consequences it poses in estimating surge elevations and currents offshore is discussed.

2. Meteorological aspects

Tropical cyclones develop in the Andaman Sea and the Bay of Bengal during the inter-monsoon months (April - May, October - December) and either move westwards and impact on the east coast of India or recurve to the north or north-east and eventually cross the coast of Bangladesh or Myanmar. When a severe cyclone reaches land, the potential for damage and loss of life is huge, as much of the coastal land around the Bay of Bengal is densely populated. Figs. 3 (a-c) show the tracks of some cyclones which have affected the coastal waters of Bangladesh in recent decades.

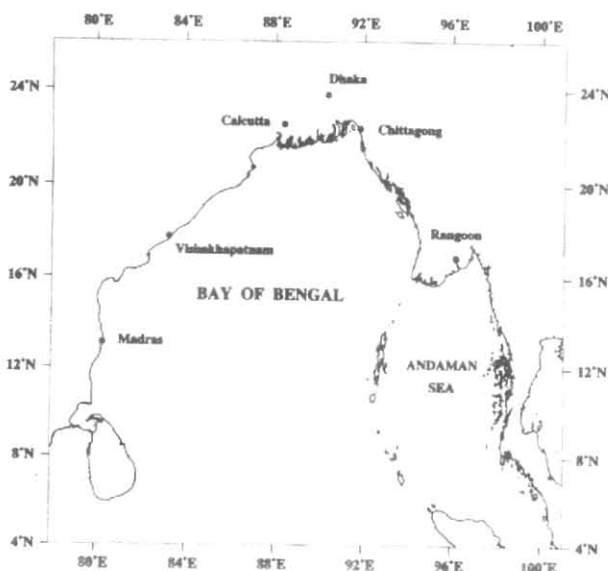


Fig. 1. Map of Bay of Bengal

Cyclones often intensify over the warm waters of the Bay and move at speeds typically ranging from 5 to 15 m/s. Useful features for classifying a cyclone are its central pressure, which can be lower than 900 hPa and its radius of maximum winds, the later being an indicator of the size of the storm, a value of 30 to 40 km denoting a tightly concentrated storm. The central pressure indicates the intensity of the storm with very high wind speeds, possibly over 200 km/h. It is only in the two decades that actual measurement of wind speeds at various heights and radii within a cyclone have been accomplished, using aircraft and radar. It has been possible to track cyclones fairly accurately since the introduction of weather satellites in the early 1960's but even today, there is no reliable way of calculating in advance the track a cyclone will follow. This uncertainty poses one of the greatest difficulties in organizing effective cyclone and storm surge warning systems.

In the northern hemisphere, the winds caused by a low pressure system rotate in the counter clockwise direction. This means that as a cyclone makes landfall, there are strong onshore winds just to the right of the track and offshore winds to the left (looking in the direction of travel). Consequently, there are likely to be excessively high water levels to the right of the track, but only moderately raised levels elsewhere along the coast. Clearly a minor change in the course as a cyclone approaches the coast can result in major differences in actual and forecast water levels at places close to the point of landfall.

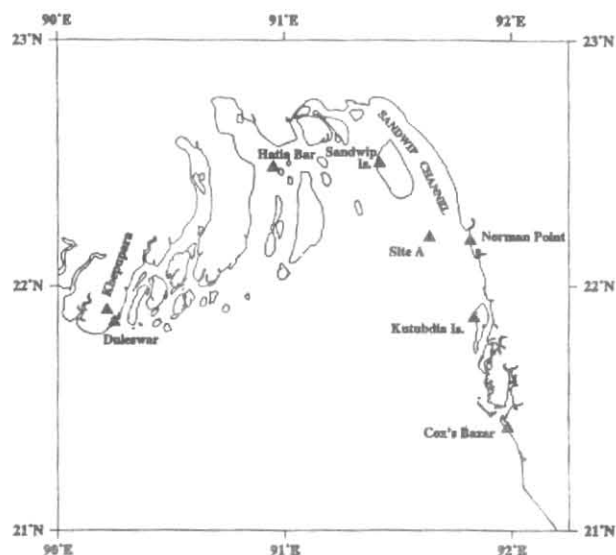
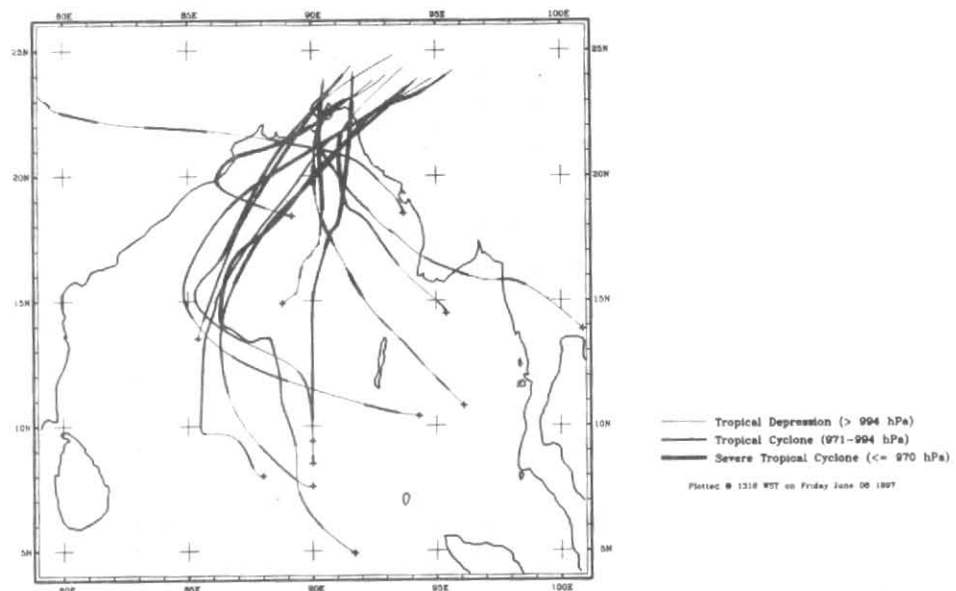
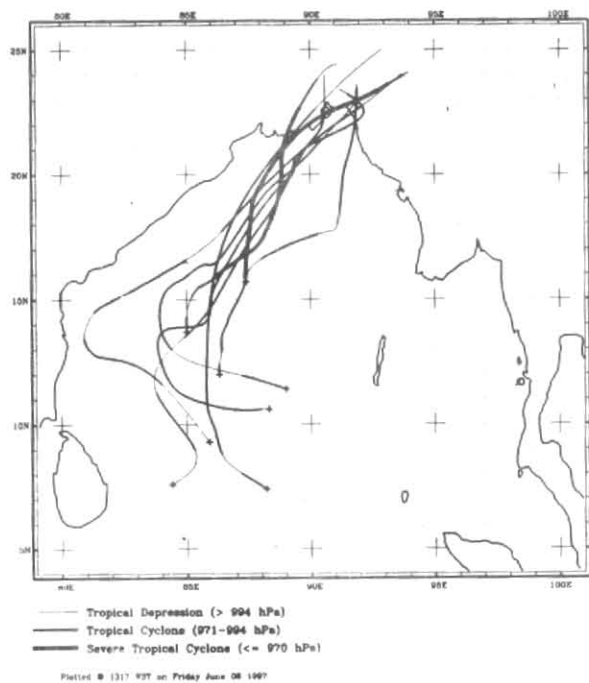


Fig. 2. Map of Meghna Estuary

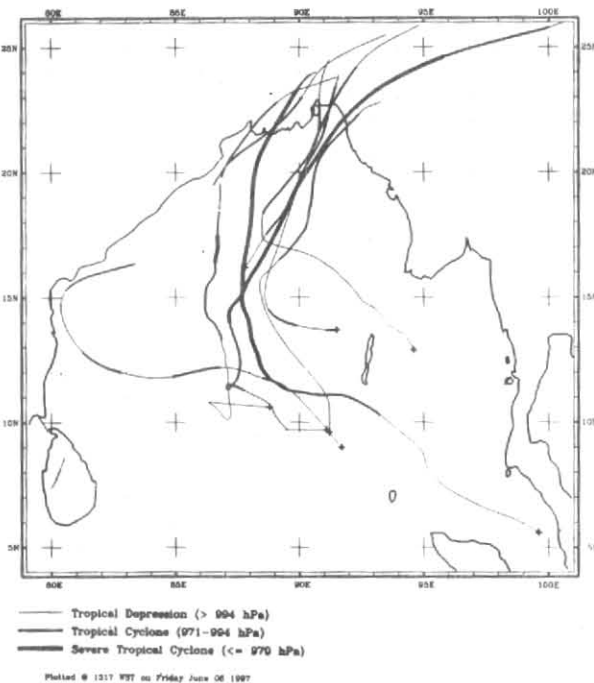
(a) Selected Tropical Cyclones during 1960-69



(b) Selected Tropical Cyclones during 1970-79



(c) Selected Tropical Cyclones during 1980-91



Figs. 3(a-c) Selected tropical cyclones during (a) 1960-69, (b) 1970-79 and (c) 1980-91

The main purpose of the present study was to develop a combined tide-surge model for the offshore waters in the Meghna estuary, in support of future hydrocarbon exploration. A total of thirty cyclones [Figs. 3 (a-c)] known to have affected the study area

in Bangladesh waters were simulated. As a first step, time histories of the tangential surface wind speed and atmospheric pressure gradient were developed for each cyclone, for the period covering its origin and development over open water until it subsided some hours after making landfall.

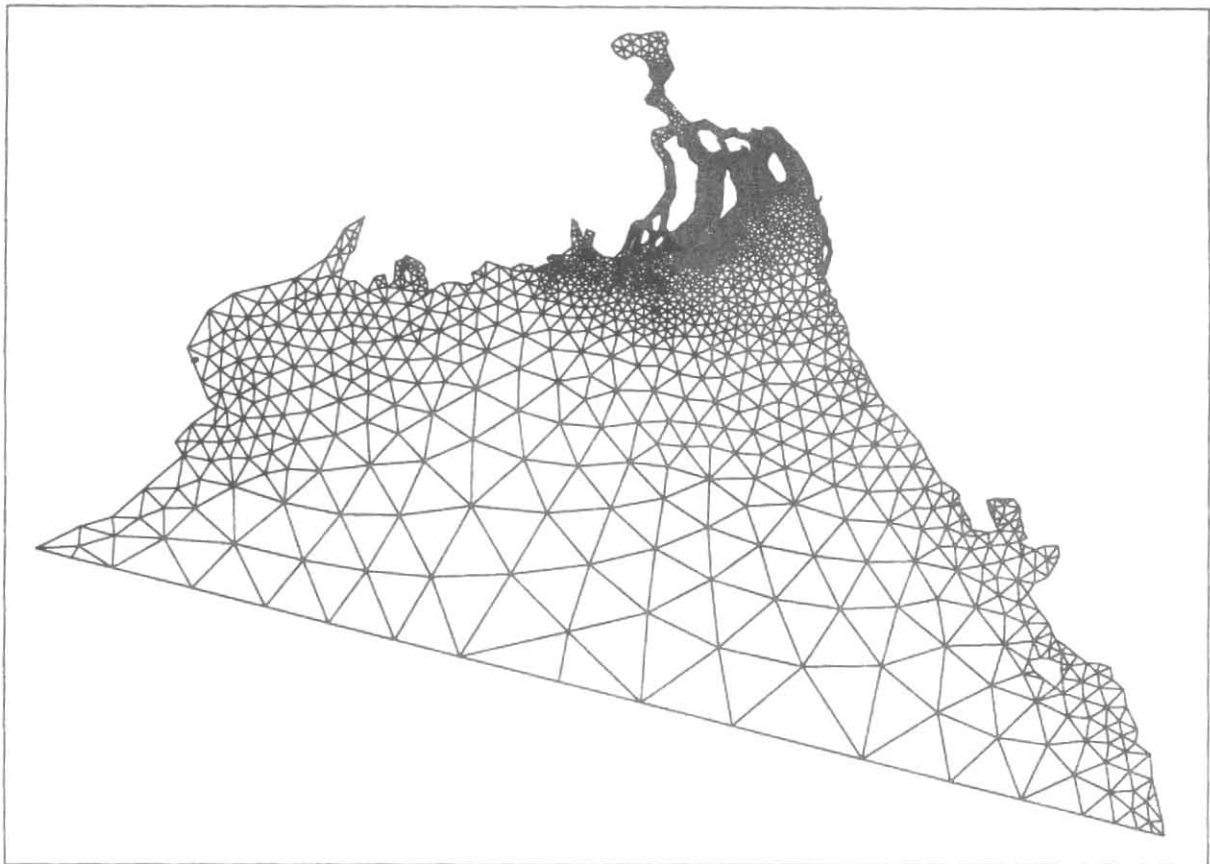


Fig. 4(a). Irregular triangular grid used for finite element model

The wind field over the ocean cannot normally be measured under cyclone conditions, but nevertheless estimated wind field *versus* time is required for any model study. Consequently, it is customary to use one of a number of formulae relating wind stress and pressure field to certain parameters of the cyclone. The Holland (1980) model was used to calculate the wind field from the prescribed pressure distribution fitted to observations. In the Holland model, surface atmospheric pressure P_a is expressed as a function of radial distance r from the cyclone center in the following form :

$$P_a = P_c + \Delta P \exp(-A/r^B) \quad (1)$$

where $\Delta P = P_a - P_c$ is the pressure deficit and A and B are empirical constants. Here P_a is the pressure field at the center of the cyclone reduced to sea level and P_c is the ambient pressure, assumed to be constant. The surface wind field was calculated

from the pressure distribution using the gradient wind equation (Flather 1994).

3. Oceanographic aspects

The damage caused at the coast by a cyclone-induced surge depends to a considerable extent on whether the surge peaks at or close to high tide. For instance, the most devastating surge recorded in Bangladesh, that of November 1970, in which several hundred thousand people were drowned, was an occasion where peak surge and high tide coincided. In contrast, the surge of May 1997 occurred close to low tide; in this case, instead of adding to the water levels produced by the surge, the tide had a moderating effect on maximum water level. This contributed to the relatively low death toll (currently estimated at about 300) during this surge. Therefore, in seas where the tidal range is comparable in magnitude with possible surges, it is essential to be able to predict tidal elevations accurately under all conditions.

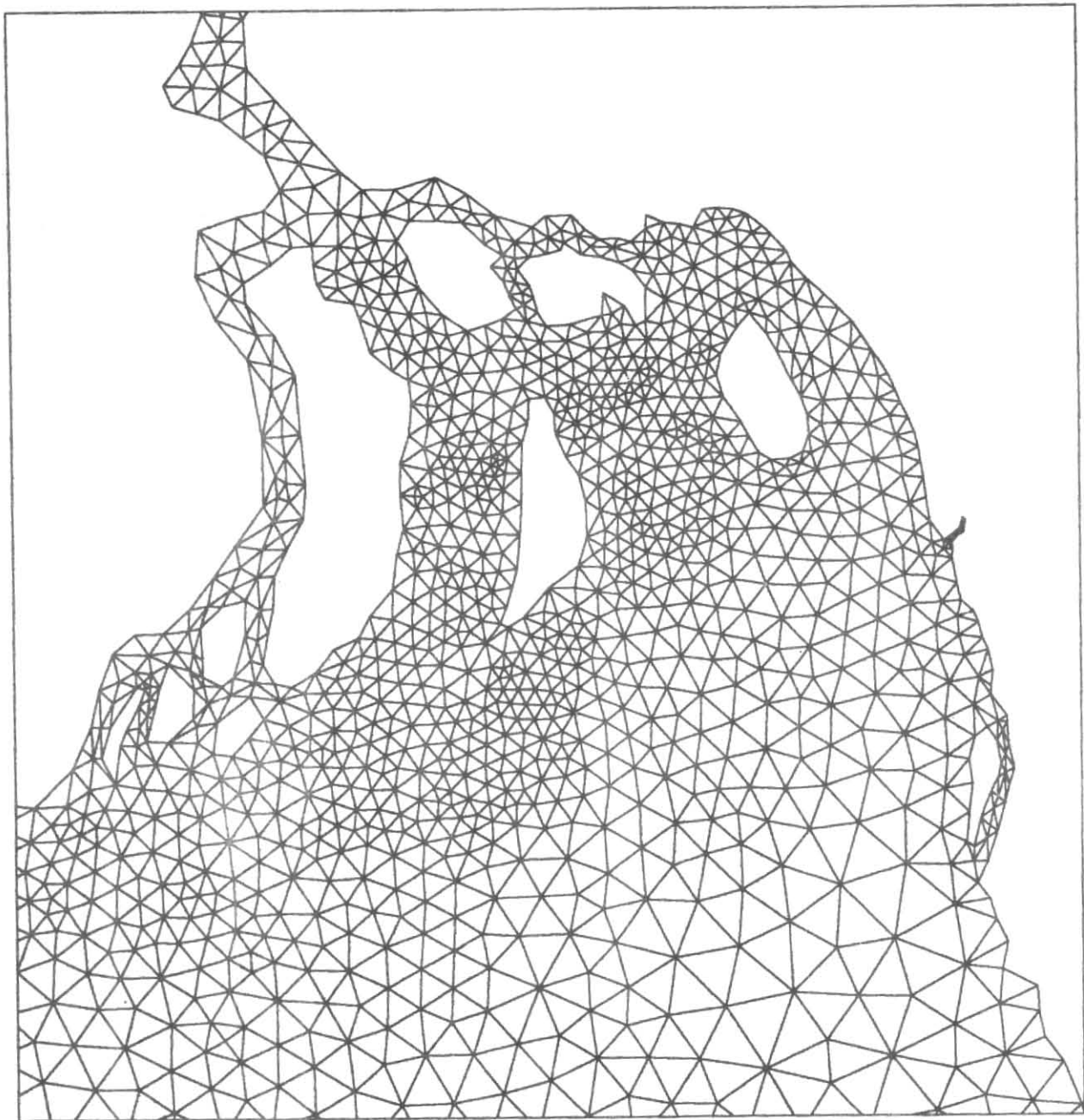


Fig. 4(b). Closeup of part of grid covering Meghna Estuary

For marine engineering purposes, it is often essential to be able to predict both water levels and currents. Apart from its obvious direct importance in design of offshore installations, such as drilling platforms and pipelines, this knowledge is required in estimation of wave height, another important design factor. Consequently, in areas subject to storm surges, it is important to be able to predict the total current due to surge and tide combined. An essential first stage in being

able to predict the combined effects of the tide and surge is to have a valid tidal model. To represent the complex bathymetry and coastal configuration, we developed a finite-element model based on the irregular triangular grid shown in Figs. 4(a & b). This type of model is well suited for accurate representation of the complicated coastlines and bathymetry of the Meghna estuary since the freedom to orient the grid elements and vary their size offers useful advantages in

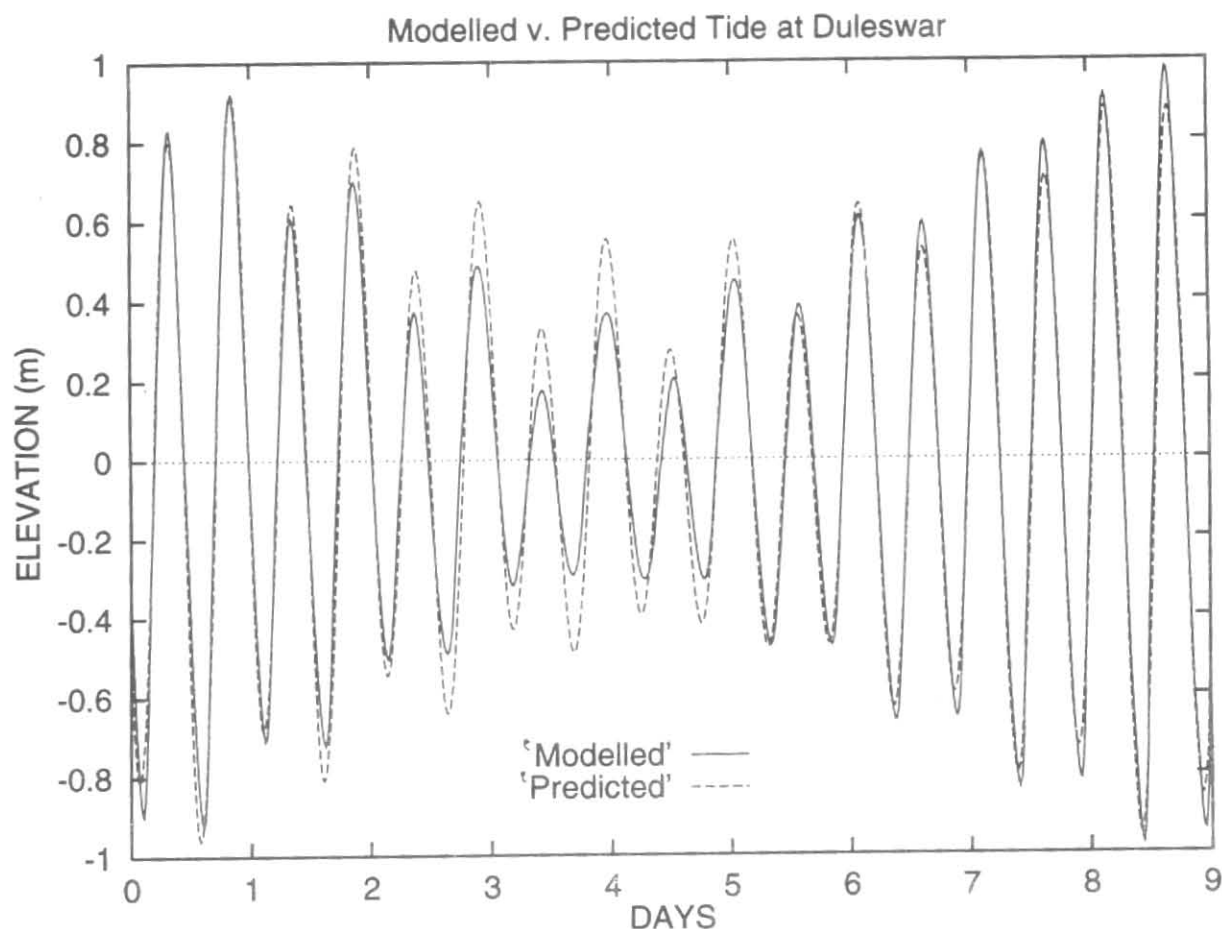


Fig. 5. Modelled and predicted tidal elevation at Duleswar

comparison with the regular grids used with finite difference models.

Tidal behaviour in a coastal sea is determined almost totally by the tidal motion in the neighbouring deep offshore waters and therefore to replicate coastal tides in a model, it is necessary to specify tidal elevation as a function of time along the open (sea) boundary of the model. Until very recently, no reliable information was available about tides in offshore regions of the Bay of Bengal. Tide gauges have been operated at sites around the coast for over a century, but it can be shown mathematically that tides in open water far from the coast cannot be calculated reliably from shore observations. As late as 1996, no long-term tidal measurements had been taken off-shore and consequently, tidal boundary conditions for models, such as

that in Fig. 4 were quite uncertain. The availability of sea level measurements from the TOPEX/POSEIDON satellite altimetry program, together with the sophisticated efforts of several teams of scientists (Le Provost *et al.* 1995) to extract tidal estimates from these observations, has largely eliminated this difficulty in applications, such as forecasting the combined effect of tides and storm surges, where knowledge of the major diurnal and semi-diurnal tidal constituents is sufficient. Estimates of diurnal constituents, K_1 , O_1 , P_1 and Q_1 and semi-diurnal constituents, K_2 , M_2 , N_2 and S_2 , which collectively account for more than 90% of the tidal signal in offshore waters are now available everywhere but in Arctic latitudes. TOPEX/POSEIDON tidal estimates are generally inaccurate in coastal seas, because of the low spatial resolution of the global numerical models used in reducing the satellite

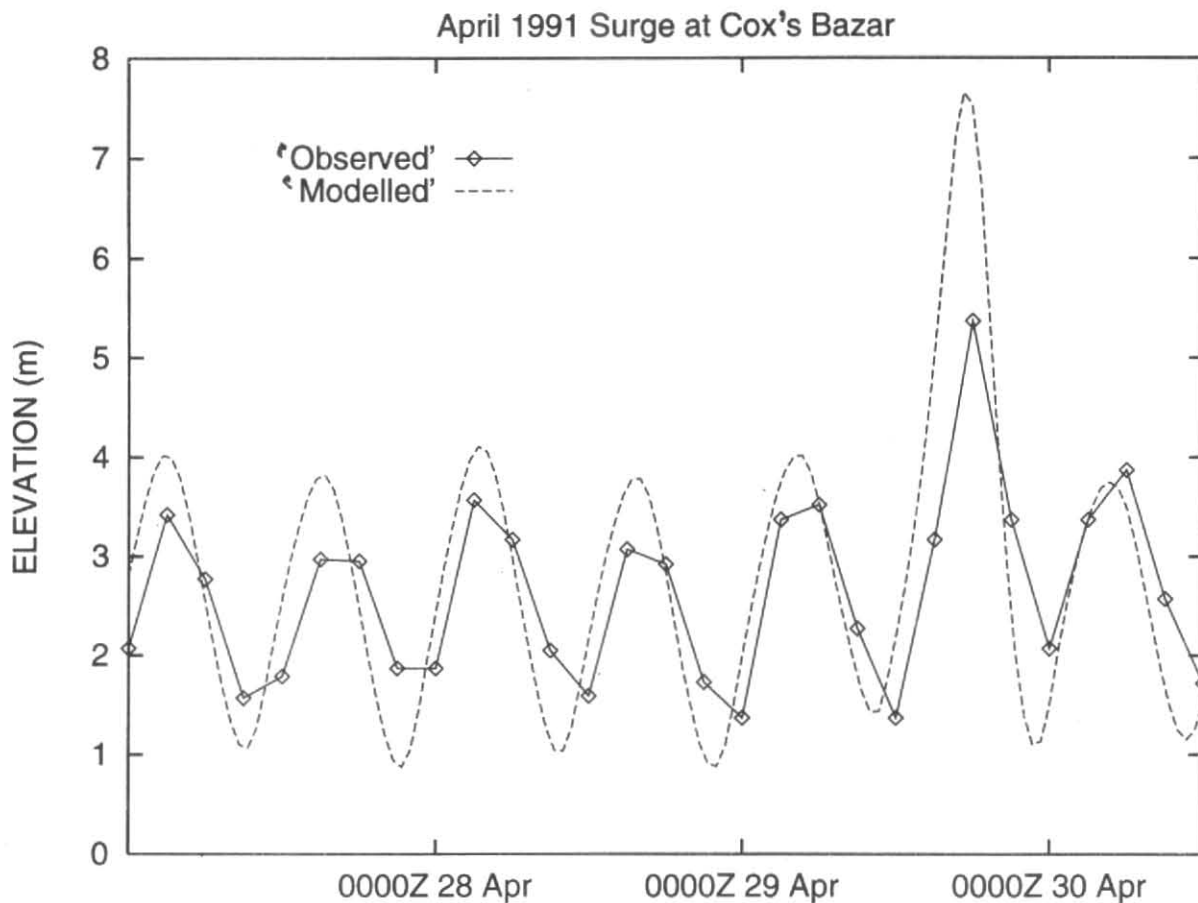


Fig. 6. Modelled and observed elevation at Cox's Bazar during April 1991 surge

observations. Thus it is still necessary to develop local numerical models in order to calculate tidal behaviour in specific coastal areas, but it is now possible to find reliable tidal elevation estimates to use as open boundary conditions for such models. Though only surface elevation as a function of time need be supplied on the open boundaries, coastal models provide estimates of velocity as well as elevation throughout the area modelled.

In view of the above developments, ability to calculate tides in shallow coastal waters is now most often limited by uncertainty about the bathymetry. The Meghna, like other major rivers debouching into the Bay of Bengal, transports huge quantities of silt year-round, with the result that island outlines, positions of shoals, and channel depths can change significantly within a year or two, and even sometimes within a few months. The high cost of conventional hydrographic

surveying rules out any possibility of getting accurate up-to-date bathymetric information for all the shallow waters of the bay. Unfortunately, remote sensing of the bathymetry, for instance, laser depth sounding, is ruled out by the opacity of the silt-laden water. In the present study, which was concerned principally with areas of interim depth (5 to 30m) some kilometers from shore, it was judged that uncertainty about the bathymetry of the very shallow parts of the Meghna estuary was unlikely to substantially affect tide and surge computations further offshore, except in so far as it limited the extent to which records of tides and surge episodes from coastal gauges at up-estuary sites, such as Sandwip Island and Hatia Bar, could be used for calibration or verification of the model.

4. The numerical model

The model is based on the shallow water equations where the continuity and momentum equations are

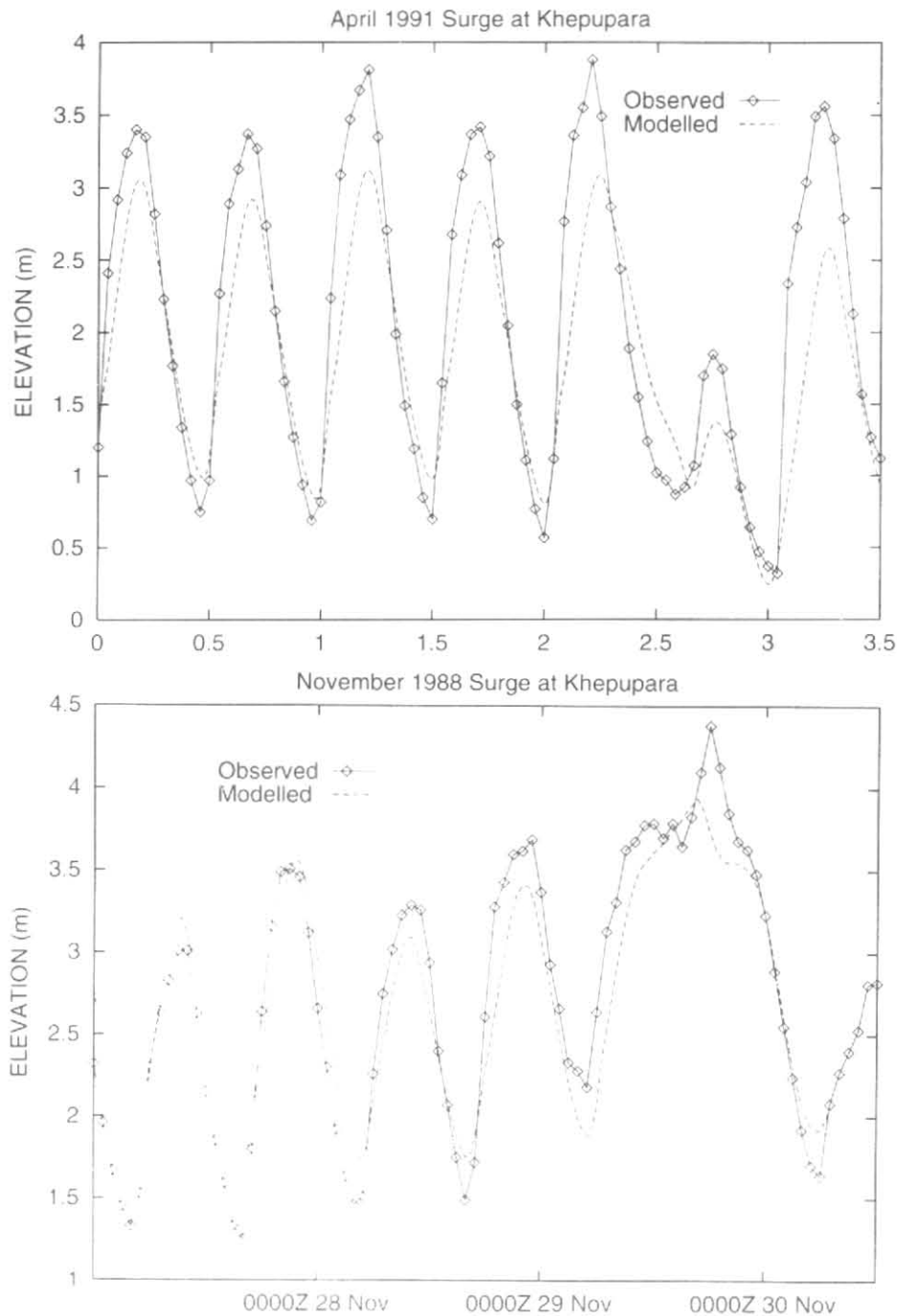


Fig. 7. Modelled and observed elevation at Khepupara during April 1991 and November 1988 surge

combined to give a wave equation that replaces the continuity equation (Kolar *et al.* 1994, Lynch and Gray 1979). The wave equation can be conveniently written as

$$\frac{\partial^2 \eta}{\partial t^2} + \gamma_0 \frac{\partial \eta}{\partial t} - \nabla \cdot (gH \nabla \eta) = \nabla \cdot R \quad (2)$$

where γ_0 is the weight of a penalty term that enforces conservation of mass, and

$$R = \nabla \cdot (H \bar{u} \bar{u}) + f \times H \bar{u} - \nabla \cdot (H A_h \nabla \bar{u}) - \gamma_0 H \bar{u} - \frac{\tau_s}{\rho} + \frac{\tau_b}{\rho} - HF \quad (3)$$

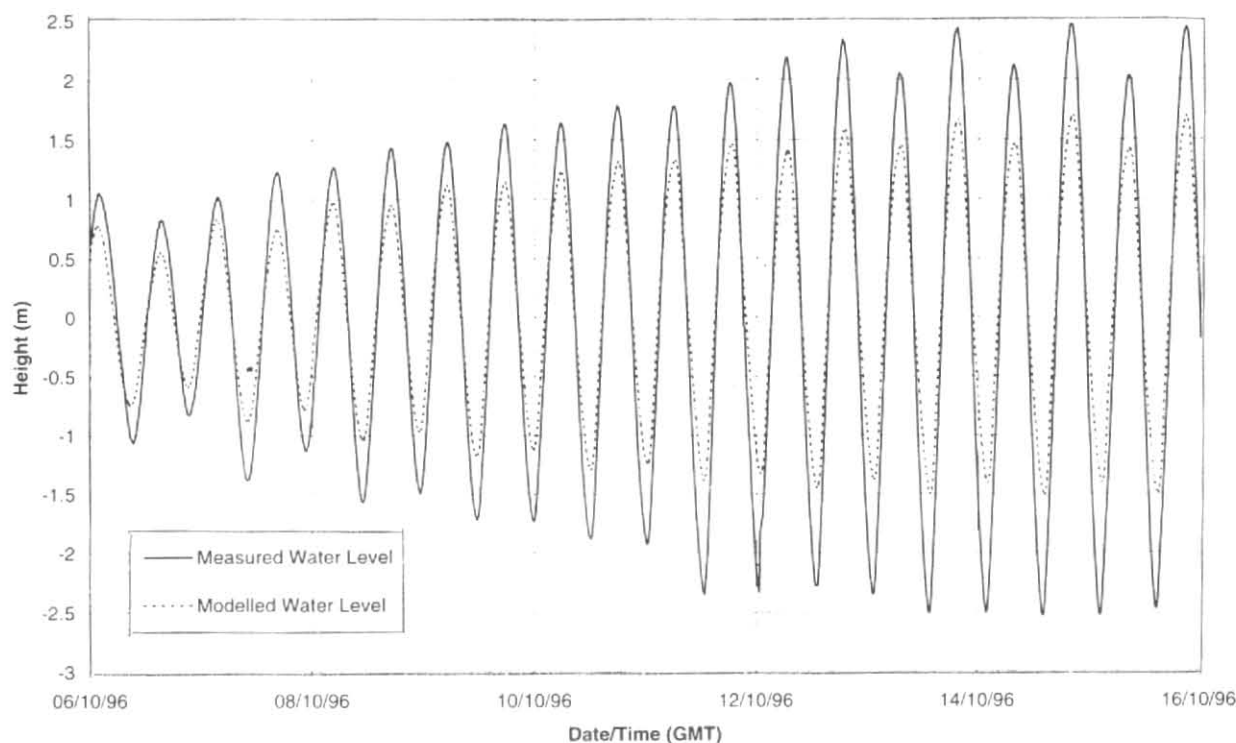


Fig. 8. Observed and modelled elevation at offshore Site A

Surface and bottom boundary conditions are given as,

$$\frac{\tau_s}{\rho} = C_a |W| W \quad (z = \eta) \quad (4)$$

$$\frac{\tau_b}{\rho} = C_f |u| u \quad (z = -h) \quad (5)$$

essential boundary conditions on η are set at open boundaries, and $(\bar{u} \cdot \hat{n}) = 0$ (no normal flow, where \hat{n} is the unit vector normal to the boundary) is applied on land boundaries.

The various terms appearing in these equations are defined as follows. The surface elevation relative to mean sea level is given as $\eta(z, y, t)$, $u(x, y, t)$ is the horizontal velocity, and $\bar{u}(x, y, t)$ is the vertical or depth average of u . The water depth from mean sea level is given as $h(x, y)$, while $H(x, y)$ is the total water depth, $h = h + \eta$. f is the Coriolis parameter and g is the gravitational acceleration. The surface stress is denoted as τ_s and τ_b denotes the bottom stress, C_a is the surface drag coefficient; W is the wind speed, C_f is the bottom stress coefficient and ρ is the density. F represents body forces, such as density gradient

forces, and ∇ is the horizontal gradient operator $\left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}\right)$. $A_h(x, y, z, t)$ is the coefficient for the horizontal component of viscous stresses. In many models, A_h is usually assumed to vanish. However, in the present model, this term is retained to dissipate small-scale features near fronts or other step gradients.

The equations are approximated using standard Galerkin techniques. The spatial domain is discretized by defining a set of 2-dimensional triangular elements in the horizontal plane. A standard Lagrange basis of polynomial degree p is defined on the master element and this basis is used to interpolate variable quantities within each element. In this study, linear bases ($p = 1$) are used.

The wave equation is discretized in time using a 3-level difference approximation with time level $k + 1$, k and $k - 1$. All terms are centred at time level k and the scheme can be made implicit or explicit. The momentum equations are centered between levels $k + 1$ and k , with the exception that the dispersion term and the advection term are evaluated at level k . Normally, this would produce a fully 2D matrix problem. However, it is possible to obtain a much simpler problem by

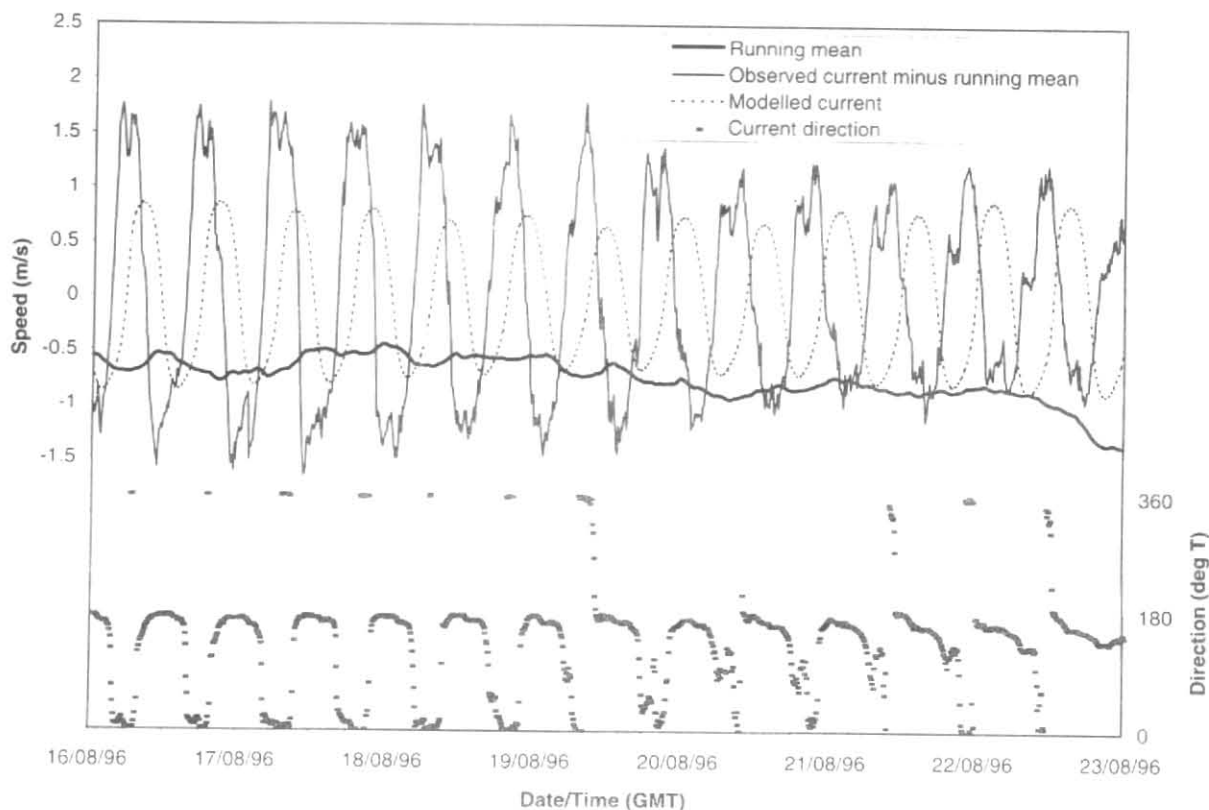


Fig. 9. Observed and modelled current speed at offshore Site A

applying node-point integration in the horizontal and using linear bases in the explicit version of the model. This effectively diagonalizes the mass matrix. This procedure results in very good computational efficiency, but has poorer phase accuracy. The implicit version has a consistent mass matrix and the system of equations is solved with a frontal solver (Waters 1980).

The approach used here for a moving boundary is that elements are active or inactive depending whether they have dry nodes. Following this approach, nodes are checked for water depth to determine if they are wet or dry and the element calculations handled accordingly. Dry nodes are identified by $H \leq \epsilon_h$, where ϵ_h is a minimum water depth determined from a computational stability criterion or other means. Then an element with a dry node is omitted from the calculations and a slip condition applied at the wet nodes. The water level in the inactive element is retained until the element is rewetted. In this case there is conservation of mass but momentum is neglected. A more detailed description of these equations and the finite element approximation are

contained in Walters and Takagi (1997). There one may find references to a wide range of other related works.

5. Calibration and verification of model

Having set up a model with TOPEX/POSEIDON tidal constituents as boundary conditions, results are compared with observed tides in order to examine whether adjustments to model parameters, such as friction, or to the boundary conditions improve the agreement between observed and modelled tides. In the present case, only coastal gauge data was available for this calibration stage, as the observations from offshore Site A did not become available till later in the project. Since offshore waters were of principal interest, it was considered appropriate to compare the model with sites adjacent to open water. Chittagong, for instance, is unsuitable, as it is sited well up-river; extensive shoal areas separate Sandwip and Hatia Bar sites from the open sea and besides, tides at these sites are subject to large seasonal fluctuations, as much as 50% in the case of M_2 . The only observations

judged likely to be representative of open water conditions were Cox's Bazar, Kutubdia Island, Norman Point and Duleswar. As the constituents for Kutubdia Island given in the Admiralty Tide Tables (Anonymus 1995) appeared to be inconsistent with those from other gauges on the mainland coast, Kutubdia was accorded very little weight during model calibration. However, a revised analysis for Kutubdia obtained later agreed satisfactorily with the calibrated model.

By applying small corrections to the constituents amplitudes and phases used on the open boundary and adjusting the friction coefficient, C_f , a satisfactory fit was achieved to the observations from the calibration sites used: Cox's Bazar, Norman Point and Duleswar. The agreement between modelled and observed tides at Duleswar shown in Fig. 5 is typical of all three sites. The fact that the published analyses for Norman Point and Duleswar are based on records of only 29 days meant that further calibration effort was hardly justified. The best value of C_f was found to be 0.0018, considerably less than the value of 0.0026 frequently used in tidal models elsewhere. It is probable that stratification in the Meghna estuary results in a lower rate of frictional loss than that occurs in well-mixed water. Flather (1994) settled on a friction coefficient of 0.0015 and also allowed a small amount of horizontal friction.

Very few time histories of water level are available for major surge episodes in the area studied. The few permanent gauges were apparently not designed to function at extreme water levels or were destroyed by the surges or accompanying cyclone. Fig. 6 shows the record from the gauge at Cox's Bazar during a surge which occurred in April 1991, together with the elevation computed using the finite element model. It can be seen that the model overestimated maximum water level in this instance. No attempt was made to calibrate the model, *e.g.*, to adjust the wind stress coefficient C_a using this record, because the difference between modelled and observed values is in all likelihood caused by the fact that we did not include inundation (even though the model can simulate it) due to lack of land orographic data. Inclusion of inundation would reduce maximum levels at the coasts, but was judged unlikely to affect computed water levels and currents offshore to any significant extent. Fig. 7 shows surges in April 1991 and November 1988

recorded at Khepupara. For lack of bathymetric and coastline data, the inlet in which the Khepupara gauge is sited was not included in the model and the modelled elevation time history shown in Fig. 7 pertains to a location on the open coast about 50 km from Khepupara. Agreement between observed and modelled elevations is nevertheless quite good. It is likely that inclusion of this inlet in the model would produce a computed surge peak at the gauge site somewhat larger and later than that on the coast, resulting in even better agreement with the observed elevations. More coastal and offshore records of elevation *versus* time during surge episodes are needed before calibration of meteorological factors in surge models of the Bay of Bengal can proceed. For the present, it is only possible to use parameter values which have proved satisfactory in similar applications elsewhere.

All 30 cyclones shown in Fig. 3 were simulated in the course of this study. The computed surface winds, water levels and currents were used in estimation of significant wave height at various locations during each storm, but discussion of these results will be deferred for the present. The remainder of this paper is concerned with recent observations indicating the existence of currents which have a significant influence on offshore tidal behaviour.

6. Offshore elevation and current observations

Towards the end of the project, approximately two months of tide gauge and current meter records from offshore site A became available. The current meter was positioned 2m above bottom in 10m of water. Observed elevations for a 5-day period in October 1996 are shown in Fig. 8, together with elevations computed at Site A using the calibrated model. It is clear that the observed elevations are substantially greater in magnitude than the computed elevations, quite unlike the situation at the coastal gauges, where the observed and computed elevations are of similar magnitude. At Site A, the computed elevation also lags the observed elevation slightly.

Fig. 9 shows observed current speed and direction for a 7-day period in August 1996, together with current speed as computed by the model. In order to assist comparison of observed and modelled currents, a 12hr 40 min (approximate M_2 period) running mean has been subtracted from the observed current and

plotted separately. Looking first at the oscillatory portion of the current, it is clear that the magnitude of the modelled current is substantially less than that of the observed current and in addition is delayed by about three hours. From this diagram and other presentations of the observed current, it is apparent that there was a mean southward current of about 1 m/s at Site A throughout the measurement period. This surprisingly high current must presumably be due to discharge from Sandwip Channel. It seems that this strong southward flow, which is not simulated in the present model, has a substantial effect on tidal elevation and current in the neighbourhood of Site A but has little effect on tidal elevations at the coast, judging by the good agreement between observed and modelled values there. It would obviously have been desirable to include such flow in the model once its importance became obvious, but insufficient data is available about the magnitude of the flow through Sandwip Channel. Measurements of this flow and observations of the extent of the current seawards of Sandwip Channel are necessary before models of the area can be improved significantly. At present, it is impossible to say whether the fast southward current forms a narrow jet or a broad current many kilometers wide, but it is important to know which is the case before the effect can be modelled satisfactorily.

7. Conclusions

It seems clear that the strong, predominantly southward current measured at Site A, south of Sandwip Island, has substantial magnifying and delaying effect on tidal elevation and current, but the areal extent of this modification of the tide is unknown at present. It apparently does not extend to the coast, since observed elevations there agree well with results from the present model, from which river discharge is omitted. More current measurements have to be made in and at locations seaward of Sandwip Channel and other main branches of the Meghna estuary before it will be possible to compute the effects of the large mean

currents with any useful degree of accuracy. When enough measurements become available to include mean currents satisfactorily in tidal computations, the model will at that stage be potentially capable of simulating tides, surges, mean currents simultaneously, taking into account their mutual interactions. However, final calibration and verification will require measurement of elevations and currents offshore during several surge episodes, an undertaking which will require very robust instruments to be in place for a number of years.

Acknowledgements

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