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The effect of coastal geometry on the location of peak surge

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सार – शिखर महोर्मि की स्थिति पर तट रेखा का संदर्भ देते हुए वक्र तट का गतिक प्रभाव और उष्णकटिबंधीय चक्रवात पथ के आपतित कोण का अध्ययन करने का प्रयास किया गया है। भारत के पूर्व तट पर तूफान महोर्मि की प्रागुक्ति को आंकिक प्रतिदर्श के द्वारा प्रयोग किए गए हैं।

हरीकेन पवनों के एक क्रोड और भीषण चक्रवाती तूफान को दर्शाने वाले प्रबल पवन प्रतिबल बंटन का उपयोग करके भारत के पूर्व तट की ओर तीन विभिन्न स्थानों पर टकराने वाले चक्रवातों के विभिन्न पथों के परिणामों की तुलना की गई है। इन तटों की तटीय संरचना भिन्न-भिन्न होती है जैसे (1) अधिकांश सरल रेखीय तट – जो अनुमानतः दक्षिण में नागापतिनम् से उत्तर में ओंगोला तक फैले हुए हैं तथा याम्योत्तर के समानांतर हैं, (2) दक्षिण में नैलोर से उतर में मसुलीपत्नम तक फैले हुए नवचंद्राकार तट, जो चन्द्रमा के चाप से मिलते जुलते हैं और (3) दक्षिण में विशाखापतनम से उत्तर में पारादीप तक फैले हुए तिरछे तट हैं। ये तट अधिकांशतः सीधे रेखीय तट हैं जो याम्योतर पर झुके रहते हैं।

प्रयोग के परिणाम यह दर्शाते हैं कि तट के सापेक्षतया तटीय बनावट और तूफान की गति की दिशा के प्रति उच्चतम महोर्मि की स्थिति संवेदनशील होती है।

ABSTRACT. An attempt has been made to study the dynamic effect of a curving coast and the angle of incidence of the tropical cyclone track relative to shore-line on the location of the peak surge. The experiments have been performed by a numerical storm surge prediction model for the east coast of India.

Using a forcing wind-stress distribution representative of a severe cyclonic storm, with a core of hurricane winds, a comparison of the results is made for different tracks of a cyclone striking at three different places along the east coast of India which have different type of coastal configurations, *viz*., (i) almost straight line coast, running approximately from Nagapatinam in the south to Ongole in the north, which is parallel to meridian, (ii) Crescent coast running from Nellore in the south to Masulipatnam in the north, which resembles the crescent of the moon and (iii) a slant coast, running approximately from Visakhapatnam in the south to Paradeep in the north, which is an almost straight line coast inclined to meridians.

The results of the experiment show that the location of the highest surge is sensitive to the coastal geometry and the direction of motion of the storm relative to the coast.

1. Introduction

The prediction of peak surge, its location and an idea of its quantitative dispersion along the coast is very important in order to fix up the coastal stretch upto which significant surge is expected. The location of the highest surge depends predominantly on the coastal geometry of the basin. For a basin with a straight coastline, if the storm track is nearly normal to the coast, the maximum surge usually appears to the right of the landfall point in the northern hemisphere (as viewed from the sea). In an embayment, the location and intensity of peak surge is affected by the shape of the coast which is curved and/or broken by bays or estuaries. The curving coasts not only shift the peak surge position but also affect its height. Hence, the coastal geometry of a shelf needs special consideration when forecasting surges.

Another dynamic effect which has considerable bearing on surge generation and the position of highest surge occurs with the vector storm motion, for with different tracks it is possible to have maximum surge at different locations with the same cyclone and the same point of landfall. Therefore, in order to forecast accurate position of peak surge in a local area, the speed and direction of motion of the storm relative to the coast must also be precisely described.

The purpose of the present work is to study the dynamic effect of curving coast and the angle of incidence of the tropical cyclone track relative to the shore-line, on the location of the peak surge. We use the model developed by Johns *et al.* (1981) for our experiments. For this purpose the east coast of India extending from Nagapatinam in the south to Balasore in the north has been divided into three parts such that the geometry of each part is different from the other. First part consisting of Nagapatinam in the south to Ongole in the north represents an almost straight line coast which is parallel to meridian, second part of the coast extends from Nellore in the south to Masulipatnam in the north, which resembles the crescent of moon and the third portion is again a straight line coast which is inclined to meridians and extends from Visakhapatnam in the south to Balasore in the north.

Numerical experiments are performed for each of the three portions of the coast when a severe cyclonic storm of hurricane intensity strikes them from different directions. The results of our numerical experiment suggest that the location of the peak surge on the coast relative to the landfall point is significantly affected by the coastal configuration about the point of landfall and the direction from which the cyclone approaches the coast.

2. Basic equations

The basic hydrodynamic equations of continuity and momentum for the dynamical processes in a bay are given by :

$$\frac{\partial \zeta}{\partial t} + \frac{\partial}{\partial x}[(\zeta + h)u] + \frac{\partial}{\partial y}[(\zeta + h)v] = 0 \quad (1)$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} - fv = -g\frac{\partial \zeta}{\partial x} + \frac{1}{(\zeta + h)}(F_s - F_b) \quad (2)$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + fu = -g\frac{\partial \zeta}{\partial y} + \frac{1}{(\zeta + h)}(G_s - G_b) \quad (3)$$

where,

- (x,y,z) describe a system of cartesian coordinates with x taken positive eastward, y northward and z vertically upward.
- t time
- ζ elevation of the sea surface from its undisturbed state
- h depth of the sea bed
- u, v depth averaged zonal and meridional components of velocity
- f Coriolis parameter
- g acceleration due to gravity
- ρ density of the sea water
- F_s, G_s x and y components of wind stress
- F_b, G_b x and y components of bottom stress.

Following Johns *et al.* (1981), Eqns. (1)-(3) are transformed in the curvilinear coordinate system and are written in the flux form as :

$$\frac{\partial}{\partial t}[b(y)\zeta] + \frac{\partial}{\partial \xi}[b(y)(\zeta + h)U] + \frac{\partial \tilde{v}}{\partial y} = 0 \quad (4)$$

$$\frac{\partial \tilde{u}}{\partial t} + \frac{\partial}{\partial \xi}(U\tilde{u}) + \frac{\partial}{\partial y}(v\tilde{u}) - f\tilde{v} = -g(\zeta + h)\frac{\partial \zeta}{\partial \xi} + \frac{bF_s}{\rho} - \frac{F_b}{(\zeta + h)} \quad (5)$$

$$\frac{\partial \tilde{v}}{\partial t} + \frac{\partial}{\partial \xi}(u\tilde{v}) + \frac{\partial}{\partial y}(v\tilde{v}) + f\tilde{u} = -g(\zeta + h)\left[b\frac{\partial \zeta}{\partial y} - (b_1' + \xi b')\frac{\partial \zeta}{\partial \xi}\right] + \frac{bG_s}{\rho} - \frac{G_b}{(\zeta + h)} \quad (6)$$

where primes denote differentiation with respect of y, and

$b(y) = b_2(y) - b_1(y)$ is the breadth of the Bay $x = b_1(y)$ and $x = b_2(y)$ being the western and eastern coastal boundaries.

$\xi = \frac{x - b_1(y)}{b(y)}$, the transformed x-coordinate

$$U = \frac{1}{b(y)}\{u - (b_1' + \xi b')v\}$$

$$\tilde{u} = b(\zeta + h)u$$

$$\tilde{v} = b(\zeta + h)v.$$

In the above equations, the bottomn stress components are parameterised by a conventional quadratic law :

$$F_b = \rho c_f u(u^2 + v^2)^{1/2}$$

$$G_b = \rho c_f v(u^2 + v^2)^{1/2}$$

Eqns. (4)-(6) are solved subject to the following initial and boundary conditions (Johns *et al.* 1981) :

$$\tilde{u} = \tilde{v} = U = \zeta = 0 \text{ for } t \leqslant 0 \quad (7)$$

$$U = 0 \text{ at } \xi = 0 \text{ and } \xi = 1 \quad (8)$$

$$\tilde{v} + (g/h)^{1/2} b(\zeta + h)\zeta = 0 \text{ at } y = 0 \quad (9)$$

$$\tilde{v} = 0 \text{ at } y = L \text{ (northern boundary of the Bay)} \quad (10)$$

For the solution of Eqns. (4)—(6) subject to conditions (7)-(10), a conditionally stable explicit finite difference scheme with a staggered grid is used. The details of the numerical scheme are given in Johns *et al.* (1981).

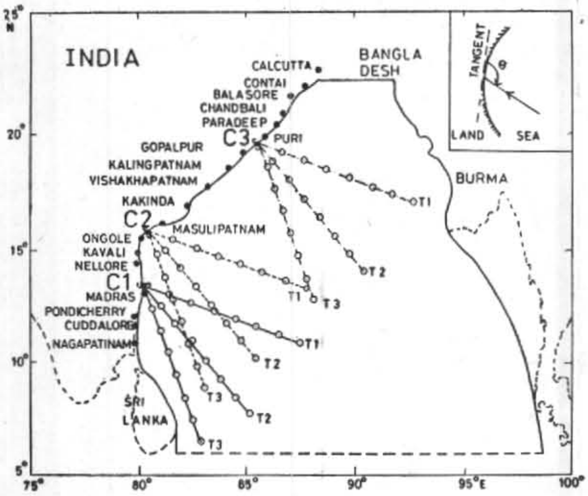

Fig. 1. Coastal regions C1, C2 and C3 along the east coast of India together with different tracks of cyclone T1, T2 and T3. The symbol § on the coast indicates the landfall point and ⊙ on the track indicates 10 hourly position of cyclone

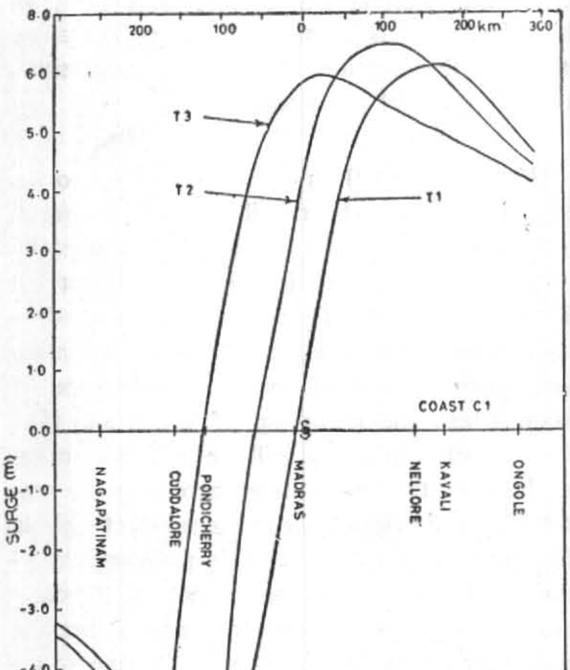

Fig. 2. Surge profile at the time of highest surge on the coast C1 for different storm tracks (The symbol § on the coast indicates the landfall point)

3. Numerical experiments

Using the model developed by Johns *et al.* (1981) numerical experiments are performed to compute the peak surge and its location along the east coast of India, which has been divided into three parts each having different coastal geometry. Surge is generated by tracking a severe cyclonic storm across the Bay of Bengal with a speed of about 11 km per hour, which strikes either of the three coastal regions from different directions. The analysis area is the whole Bay of Bengal.

Three different cyclone tracks T1, T2 and T3 used for surge computation along each of the three coastal regions C1, C2 and C3 and the places of landfall (§) are shown in Fig. 1. The angle of the storm tracks T1, T2 and T3 relative to the coast, θ is measured clockwise from the tangent drawn at the point of landfall on the curving shore-line and is shown in the top right of Fig. 1. Thus the track T1 makes an angle of approximately 110°, 60° and 60° with the coasts C1, C2 and C3 respectively, the track T2 makes an approximate angle of 140°, 90° and 90° with the coasts C1, C2 and C3 respectively and the track T3 makes an angle of 160°, 110° and 110° with the coast C1, C2 and C3 respectively. Cyclone tracks are so constructed that the places of landfall (§) are about 10 km to the north of Madras, at Chirala in Andhra Pradesh and about 45 km to the south of Puri on the coasts C1, C2 and C3 respectively (Fig. 1).

In the numerical experiments, we prescribed an initial state of rest and integrated the governing equations ahead in time as the cyclone approaches the coast. The wind distribution at any radial distance r from the centre of the core of the cyclone is computed by using the following empirically based formula :

$$\left.\begin{aligned} V &= V_m\,(r/R)^{3/2},\ 0 \leqslant r \leqslant R \\ V &= V_m\,(R/r)^{1/2},\ r \geqslant R \end{aligned}\right\}\text{(Jelesnianski 1965)}$$

where, V_m = maximum wind speed

R = radius of the maximum wind.

For our experiments, we use V_m=70 m/sec and R = 80 km, which give gale force winds (exceeding 25 m/sec) extended over a distance of 500 km from the centre of the cyclone. The associated surface wind stress is calculated by the conventional quadratic law with a uniform friction coefficient of 2.8×10^{-3}.

4. Results and discussions

Figs. 2, 3 and 4 give the coastal surge profiles at the time of highest surge on the coasts C1, C2 and C3 respectively for three types of storm tracks.

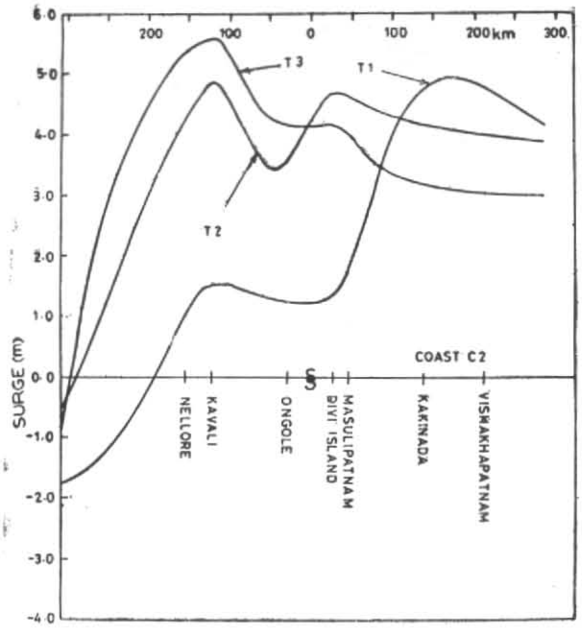

Fig. 3. As Fig. 2 except on the coast C2

Considering first the Madras region, *i.e.*, almost straight line coast C1, we find from Fig. 2 that whatever be the direction of motion of the storm relative to the coast, the maximum surge always occurs to the right of the landfall point (the observer faces the land from the sea). However, it may be seen that as the storm track becomes more southerly, *i.e.* as it is turned clockwise, the peak surge location on the coast becomes nearer to the point of landfall without any significant change in the elevations. This shift of the peak surge towards the point of landfall may solely be attributed to the clockwise change in the direction of motion of the storm since there is no effect of curving coast lines in this case.

The middle portion C2 of the east coast of India consisting of mainly Andhra region is of the shape of the crescent of moon and, therefore, its curvature is expected to play an important role in the location of peak surge. Experiments performed with cyclone striking the crescent coast, from different directions, at Chirala indicate that the position of the maximum surge on the coast shifts from extreme right to the point of landfall (as viewed from the sea) with the increase of the angle, θ of the storm track relative to the coast and as θ exceeds a critical value the peak surge location shifts to the left of the landfall point. Fig. 3 depicts the coastal surges generated by the tracks T1, T2 and T3 having the values of θ as 60°, 90° and 110°. In this case $\theta=90°$ is found to be the critical angle at which the location of the peak surge shifts from the right of the landfall to its left.

This shifting of the peak surge position to the left of the point of landfall is clearly the result of the crescent coast in this locality. It must be noted that our numerical model has vertical side-walls, therefore, the coastal stretch extending from Ongole in the south to Masulipatnam in the north forms a coastal corner of the shape of moon where the piling up of water may take place which eventually will be reflected southwards along the shore, thus increasing the sea-surface elevation at a place to the south of Chirala (the position of landfall). This phenomenon of southward wave response reflection becomes more prominent when the storm approaches the local coast making an acute angle relative to the coast. We suggest the reason for this is that when the surge waves approach the crescent coast they cannot be dispersed to the north which actually happens in the case of straight line coast. It is interesting to note here that even when the peak surge is located at a place to the right of the landfall (for $\theta < 90°$) we get a

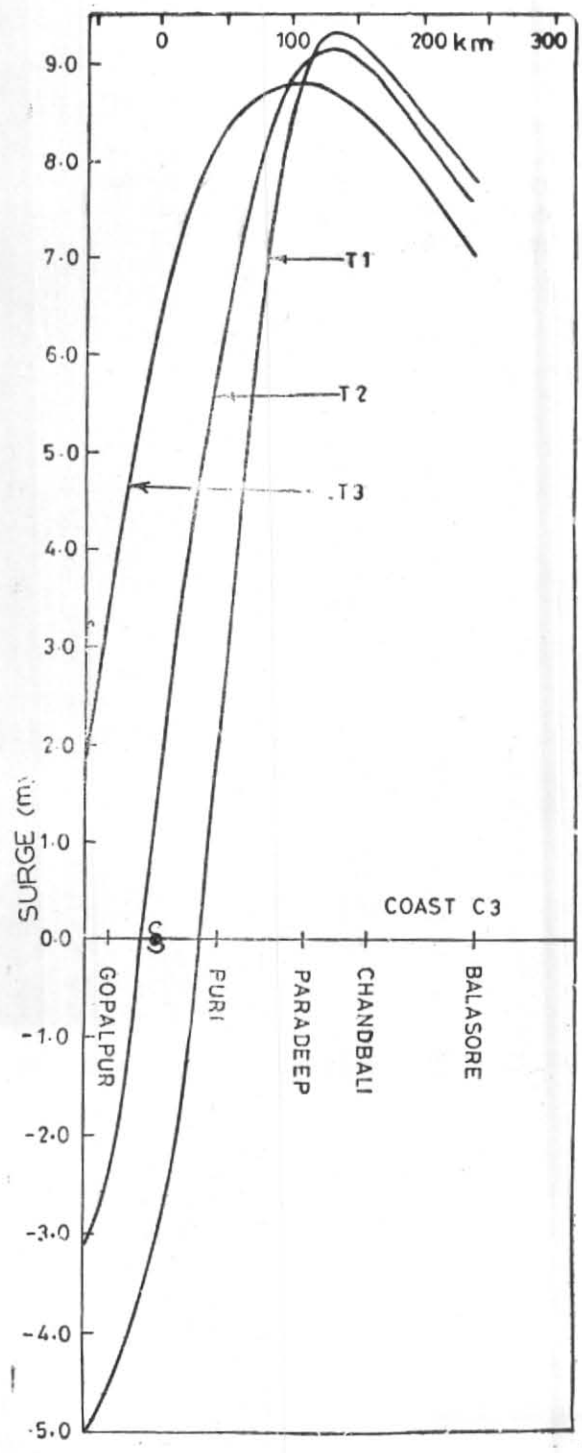

Fig. 4. As Fig. 2 except on the coast C3

secondary peak of less magnitude to the left of the landfall which again confirms the southward reflection of some of the wave response irrespective of the vector motion of the storm relative to the coast.

In order to confirm our findings that the southward (or to the left of the landfall) occurrence of the peak surge is due to the curvature of the coastal region, we finally consider the 3rd and the northern portion of the eastern coast of India, C3 (Orissa coast) which is again a straight line coast and the only difference from C1 is that it is inclined to the meridians instead of being parallel to them and, therefore, we refer to it as slant coast. It may be seen from Fig. 4 that the qualitative nature of the peak surge location along C3 is the same as along the coast C1. The maximum surge occurs always to the right of the landfall and its location shifts towards the point of landfall with clockwise turning of the track of the cyclone.

5. Concluding remarks

The surges have been generated along three coasts with different configuration when a severe cyclonic storm approaches them from different directions. On the basis of the above results the following general points may be made about the variation of the peak surge position along the coast.

(*i*) The distance to peak surge from landfall is a function of the vector motion of the storm relative to the coast. The more southerly direction of the storm track means the position of the peak surge will be more close to the point of landfall.

(*ii*) If the local coastal configuration varies considerably about the landfall point, the location of the peak surge also varies.

Hence in order to achieve greater accuracy in forecasting the coastal surges in a local area along the east coast of India, the path of the tropical cyclone and the coastal geometry of the shelf needs special consideration and, therefore, to be prescribed more precisely in a numerical storm surge prediction model.

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References

Jelesnianski, C. P., 1965, A numerical calculation of storm tides induced by a tropical storm impinging on a continental shelf, *Mon. Weath. Rev.*, **93**, 343-358.

Johns, B., Dube, S. K., Mohanty, U. C. and Sinha, P. C., 1981, Numerical simulation of the surge generated by the 1977 Andhra Cyclone, *Quart. J. Roy. met. Soc.*, **107**, 919-934.