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A Study on Storm Surge and Flooding Over the Coastal Area of Bangladesh

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Abstract: This paper articulates causes of storm surge, the many factors that influence storm surge, mathematical modeling of storm surge in three dimension, determination of areal average maximum surge height in the coastal area, determination of risk of storm surge, susceptibility to storm surge disaster due to socio economic and physical environmental factor and coastal flooding. According to discussion this paper has classified coastal flooding into five categories and risk areas into four categories.

MSC: 47A63.

Keywords: Storm surge, boundary conditions, risk index, hazard factor, vulnerability factor.

1. Introduction

Storm surge and the coastal flooding are a damaging phenomenon in Bangladesh. Wind-setup is the rise of sea level relatively to the normal still water level in great lakes or seas when wind is blowing to the shore. Wind-setdown is the falling of sea level when wind is blowing from the shore. In the sea affected by tides, wind setup or storm surge is the rise of water level above the tidal level. Tide, topography, earth's rotation, wind speed, storm movement velocity, atmospheric pressure, precipitation but here the important factors are air pressure and wind patterns. When wind speed exceeds 74 mph (during storms, hurricanes) the rise of water level is very significant and it is called storm surge. This is the short term response of water body to the pressure and wind fields over the sea. If the storm surge is coincident with the high water during spring tide it gives rise of strong damages on humanity and properties in the storm attack region and vicinity. Bangladesh is extremely prone to damage from storm surge. Every year, on average, at least one major cyclonic storm surge attacks Bangladesh. During the past forty years there have been two very large disaster with intensive flooding and loss of life. There is further effect of coastal flooding on the productivity of agricultural land; that is the intrusion of saltwater into fresh ground and surface water resources.

Causes of storm surge:

Storm surge is caused primarily by the strong winds in a hurricane or tropical storm. The low pressure of the storm has minimal contribution. The wind circulation around the eye of a hurricane blows on the ocean surface and produces a vertical

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circulation in the ocean. In deep water, there is nothing to disturb this circulation and there is very little indication of storm surge. Once the hurricane reaches shallower waters near the coast, the vertical circulation in the ocean becomes disrupted by the ocean bottom. The water can no longer go down, so it has nowhere else to go but up and inland. In general, storm surge occurs where winds are blowing onshore. The highest surge tends to occur near the "radius of maximum winds," or where the strongest winds of the hurricane occur.

The Many Factors that Influence Storm Surge:

There are several factors that contribute to the amount of surge a given storm produces at a given location:
Lower pressure will produce a higher surge. However, the central pressure is a minimal contributor compared to the other factors. Stronger winds will produce a higher surge. A larger storm will produce higher surge. There are two reasons for this. First, the winds in a larger storm are pushing on a larger area of the ocean. Second, the strong winds in a larger storm will tend to affect an area longer than a smaller storm. Size is a key difference between the surge generated by storms. On the open coast, a faster storm will produce a higher surge. However, a higher surge is produced in bays, sounds and other enclosed bodies of water with a slower storm. The angle at which a storm approaches a coastline can affect how much surge is generated. A storm that moves onshore perpendicular to the coast is more likely to produce a higher storm surge than a storm that moves parallel to the coast or moves inland at an oblique angle. Storm surge will be higher when a hurricane makes landfall on a concave coastline as opposed to a convex coastline. Higher storm surge occurs with wide, gently sloping continental shelves, while lower storm surge occurs with narrow, steeply sloping shelves. Storm surge is highly dependent on local features and barriers that will affect the flow of water.

2. Mathematical Modeling of Storm Surge in Three Dimension

(1). **The Three Dimensional Equations:** The governing equation of the three dimensional model can be exhibited in the orthogonal Cartesian coordinate systems which includes the Reynold's averaged equations of mass, momentum, temperature and salinity conservations. The equations not only indicate the effect of the gravitational/buoyancy forces but the effect of the Coriolis pseudo–force is also expressed. The equations can be written as follows.

Continuity equation:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{1}$$

x-momentum equation:

$$\frac{du}{dt}=-\frac{1}{\rho_\circ}\frac{\partial p}{\partial x}+f_v+\frac{\partial}{\partial z}\left(A_{mv}\frac{\partial u}{\partial z}\right)+F_x \tag{2}$$

y-momentum equation:

$$\frac{dv}{dt}=-\frac{1}{\rho_\circ}\frac{\partial p}{\partial y}-f_u+\frac{\partial}{\partial z}\left(A_{mv}\frac{\partial v}{\partial z}\right)+F_y \tag{3}$$

z-momentum or hydrostatic equation:

$$\frac{\partial p}{\partial z}=-\rho g \tag{4}$$

Temperature equation:

$$\frac{dT}{dt}=\frac{\partial}{\partial z}\left(A_{hv}\frac{\partial T}{\partial z}\right)+F_T \tag{5}$$

Salinity equation:

$$\frac{dS}{dt}=\frac{\partial}{\partial z}\left(A_{hv}\frac{\partial S}{\partial z}\right)+F_S \tag{6}$$

The terms $\frac{d()}{dt}$, F_x, F_y, F_T and F_S presented in the equations (2), (3), (5) and (6) represent the total derivative terms, these unresolved processes and in analogy to the molecular diffusion can be described as :

$$F_x = \frac{\partial}{\partial x}\left[2A_m \frac{\partial u}{\partial x}\right] + \frac{\partial}{\partial y}\left[A_m \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)\right] \tag{7}$$

$$F_y = \frac{\partial}{\partial y}\left[2A_m \frac{\partial v}{\partial y}\right] + \frac{\partial}{\partial x}\left[A_m \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)\right] \tag{8}$$

$$F_{T,S} = \frac{\partial}{\partial x} A_h \frac{\partial (T,S)}{\partial x} + \frac{\partial}{\partial y} A_h \frac{\partial (T,S)}{\partial y}. \tag{9}$$

where u, v are the horizontal components of the velocity vector, w is the vertical component of the velocity vector, g is the gravitational acceleration, p is the local pressure, $\rho(x, y, z, t, T, S)$ is the local density, ρ_0 is the reference water density, A_m is the horizontal turbulent diffusion coefficient, A_{mv} is the vertical turbulent diffusion coefficient, $f = 2\Omega \sin\varphi$ is the coriolis parameter, where Ω is the speed of angular rotation of the earth by $\Omega = 7.2921 \times 10 - 5$ rad s^{-1} and φ is the latitude, T is the potential temperature, S is the potential salinity, A_h is the horizontal thermal diffusivity coefficient, A_{hv} is the vertical thermal diffusivity coefficient, the terms F_x and F_y are the horizontal viscosity terms and the terms F_T and F_S are the horizontal diffusion terms of temperature and salinity respectively.

The main assumptions used in the derivation of above equations are that: (a) the water is incompressible $\left(\frac{d\rho}{dt} = 0\right)$; (b) the density differences are small and can be neglected, except in buoyant forces. Consequently, the density ρ_0 used in the x and y momentum equations (2) and (3) is a reference density that is either represented by the standard density of the water or by the depth averaged water density as follows:

$$\rho_0 = \frac{1}{\eta + h}\int_{-h}^{\eta} \rho dz = \frac{1}{D}\int_{-h}^{\eta} \rho dz \tag{10}$$

Where the total depth D is expressed as: $D = \eta + h$ that is, the sum of the sea surface elevation η above the mean sea level (MSL) plus the depth h of the still water level. The density ρ used in the z-momentum is represented by the sum of the reference density ρ_0 and its variation ρ' $(\rho = \rho_0 + \rho')$. The last assumption (c) is that, the vertical dimensions are much smaller than the horizontal dimensions of the water field and the vertical motions are much smaller than the horizontal ones. Consequently, the vertical momentum equation reduces to the hydrostatic law (hydrostatic approximation) and the Coriolis term $2\Omega(v \sin\varphi - w\cos\varphi)$ reduces to $2\Omega v \sin \varphi$ [see the equation(2)]. The vertical integration of the equation (4) from the depth z to the free surface η yields the pressure at the water depth z as:

$$\begin{aligned} p|_\eta - p|_z &= g\int_z^\eta \rho dz' \\ &\Rightarrow p = p_{atm} + g\rho_0(\eta - z) + g\int_z^\eta \rho' dz' \end{aligned} \tag{11}$$

where z' is a dummy variable for integration, η is the sea surface elevation above the MSL, $p|_z = p = p(x, y, z, t)$ and $p|_\eta = p_{atm}$ is the standard atmospheric pressure.

(2). **Boundary conditions:**

(i). **Surface boundary conditions:** The continuity, momentum and temperature surface boundary conditions describe the interaction of the water surface with the atmosphere. They are de?ned as:

$$w|_\eta = \left[\frac{\partial \eta}{\partial t} + u\frac{\partial \eta}{\partial x} + v\frac{\partial \eta}{\partial y}\right]_\eta \tag{12}$$

$$A_{mv}\begin{bmatrix}\delta u/\delta x\\ \delta v/\delta z\end{bmatrix}_{\eta}=\begin{bmatrix}\tau_{sx}/\rho_0\\ \tau_{sy}/\rho_0\end{bmatrix} \tag{13}$$

$$\dot{T}=\rho_0 A_{hv}\left.\frac{\partial T}{\partial z}\right|_{\eta} \tag{14}$$

$$\dot{S}=\rho_0 A_{hv}\left.\frac{\partial S}{\partial z}\right|_{\eta} \tag{15}$$

The equation (12) represents the surface boundary condition for the continuity equation (1), as expressed by the kinematic free surface condition. At free surface, the kinematic boundary condition can be derived considering the fact that the free surface is a material boundary for which a particle initially on the boundary will remain on the boundary. Assuming that there is no water penetrating the free surface, then the material or total derivative at the free surface $(\eta - z)$ is zero, therefore:

$$\begin{aligned}\frac{D(\eta-z)}{Dt}&=\frac{D\eta}{Dt}-\frac{Dz}{Dt}=0\\ \Rightarrow\left[\frac{\partial\eta}{\partial t}+u\frac{\partial\eta}{\partial x}+v\frac{\partial\eta}{\partial y}+w\frac{\partial\eta}{\partial z}\right]_{\eta}-\left[\frac{\partial z}{\partial t}+u\frac{\partial z}{\partial x}+v\frac{\partial z}{\partial y}+w\frac{\partial z}{\partial z}\right]_{z}&=0\end{aligned} \tag{16}$$

Since, $\frac{\partial\eta}{\partial z}=\frac{\partial z}{\partial t}=\frac{\partial z}{\partial x}=\frac{\partial z}{\partial y}=0$ and $\frac{\partial z}{\partial z}=1$, the equation (16) reduces to the equation (12). The equation (13) represents the surface boundary condition for the z-momentum or the hydrostatic equation (4) with the surface wind stresses given by the drag law (bulk formula) as:

$$\begin{bmatrix}\tau_{sx}\\ \tau_{sy}\end{bmatrix}=\rho_{air}C_M W\begin{bmatrix}W_x\\ W_y\end{bmatrix};\quad \tau_s=\rho_{air}C_M\left|W\right|W;\quad W=\left(W_x^2+W_y^2\right)^{\frac{1}{2}} \tag{17}$$

Where W is the wind speed at $10m$ above the sea water surface, W_x and W_y are two components of the wind speed vector, ρ_{air} is the density of air at the standard atmospheric conditions, C_M is the bulk momentum transfer (drag) coefficient and τ_s is the wind imposed surface stress. The equations (14) and (15) represent the surface boundary condition for the temperature and salinity equations (see the equations (16) and (17)).

$\dot{T}$ represents the net surface heat flux and $\dot{S}\equiv S(0)\left[\dot{E}-\dot{P}\right]/\rho_0$, where $(\dot{E}-\dot{P})$ represents the net evaporation $\dot{E}$-precipitation $\dot{P}$ fresh water surface mass flux rate and $S(0)$ represents the surface salinity.

(ii). **Bottom boundary conditions:**

$$w|_{-h}=-\left[u\frac{\partial h}{\partial x}+v\frac{\partial h}{\partial y}\right]_{-h} \tag{18}$$

$$A_{mv}\begin{bmatrix}\delta u/\delta z\\ \delta v/\delta z\end{bmatrix}_{-h}=\begin{bmatrix}\tau_{bx}/\rho_0\\ \tau_{by}/\rho_0\end{bmatrix} \tag{19}$$

$$\rho_0 A_{hv}\left.\frac{\partial T}{\partial z}\right|_{-h}=0 \tag{20}$$

$$\rho_0 A_{hv}\left.\frac{\partial S}{\partial z}\right|_{-h}=0 \tag{21}$$

The equation (18) represents the bottom boundary condition for the continuity equation (1), as expressed by the kinematic boundary condition. At the bottom, the kinematic boundary condition reflects the fact that there is no flow normal to the boundary, therefore, the material derivative $z + h$ is zero:

$$\begin{aligned}\frac{D\left(z+h\right)}{Dt}&=\frac{Dz}{Dt}+\frac{Dh}{Dt}=0\\ \Rightarrow\left[\frac{\partial z}{\partial t}+u\frac{\partial z}{\partial x}+v\frac{\partial z}{\partial y}+w\frac{\partial z}{\partial z}\right]_{-h}+\left[\frac{\partial h}{\partial t}+u\frac{\partial h}{\partial x}+v\frac{\partial h}{\partial y}+w\frac{\partial h}{\partial z}\right]_{-h}&=0\end{aligned} \tag{22}$$

and since, $\frac{\partial z}{\partial t}=\frac{\partial h}{\partial t}=\frac{\partial z}{\partial x}=\frac{\partial z}{\partial y}=\frac{\partial h}{\partial z}=0$ and $\frac{\partial z}{\partial z}=1$, the equation (22) reduces to the equation (18).

The equation (19) represents the bottom boundary condition for the z-momentum or the hydrostatic equation (4). The bottom shear stresses are parameterized as follows:

$$\begin{bmatrix}\tau_{bx}\\ \tau_{by}\end{bmatrix}=\rho_0 C_D\left|u\right|\begin{bmatrix}u\\ v\end{bmatrix};\quad \tau_b=\rho_o C_D\left|u\right|u;\quad \left|u\right|=\left(u^2+v^2\right)^{\frac{1}{2}} \tag{23}$$

Where u and v are the horizontal flow velocities at the grid point closest to bottom and C_D is the bottom drag coefficient determined as the maximum between a value calculated according to the logarithmic law of the wall and a value equal to 0.0025:

$$C_D=\max\left[k^2\left(ln\frac{h+z_b}{z_0}\right)^{-2},0.0025\right] \tag{24}$$

Where z_0 is the bottom roughness height in the present application $z_0=1cm$, z_b is the grid point closest to bottom, and $k=0.4$ is the VonKarman's constant. If, on the side walls and bottom, the normal gradients of T and S in the equations (20) and (21) are zero. Then there are no advective and diffusive heat and salt ?uxes across these boundaries.

(iii). **Lateral boundary conditions:** Without inflow or outflow from the rivers, the lateral conditions for the wall boundary are specified that: (a) there is no flow normal to the wall ($\partial u_n/\partial n=0$), and (b) the no slip conditions tangential to the wall are valid ($u_\tau=0$), where u represents the velocity vector, and n and τ are the normal and tangential directions.

(3). **Wind stress and atmospheric pressure conditions:** The typhoon pressure ?eld and surface wind velocity created by the pressure gradient were modeled following the relationships:

$$\frac{\partial p_{air}}{\partial \eta}=-\rho g \tag{25}$$

$$\frac{\partial \eta}{\partial x}=\frac{\rho_{air}C_M W^2}{\rho g D} \tag{26}$$

Where p_{air} is the atmospheric pressure, η is the sea surface elevation from the reference level of undisturbed surface, ρ is the density of sea water in the z-momentum, g is the gravitational acceleration of the earth, x is the coordinate in the east-west direction, ρ_{air} is the density of air C_M is the drag coefficient, W is the wind profile that results from the typhoon pressure gradient and D is the total depth of sea water. According to the equation (25), the pressure reducing for $1mb$ corresponds to about a $1cm$ rise in the sea level. The total water depth D inversely affects the sea surface elevation η, whereas the wind speed at the specific height ($10m$) directly affects the sea surface elevation.

Determination of areal average maximum surge height in the coastal area:

The surge height may be computed by equation (27) developed by Reid and Bretschneider and Tareque & Chowdhury as:

$$h_R=\frac{BV^2}{\left(5*10^6+LV^2\right)^{0.2}} \tag{27}$$

where h_R is the areal average surge height in m, L is the length of the continental shelf in km up to $200m$ depth of contour, B is a parameter related to L, and V is the cyclonic wind speed in kmh^{-1}.

The value of L is taken to be $245km$, the average of 230 and $260km$ and similarly the value of B is taken as $32*10^{-4}$ as the average of $30*10^{-4}$ and $34*10^{-4}$. Applying the values of B and L, and the values of V for various periods, the surge height for coastal area for different periods can be calculate. Maximum surge height with respect to mean sea level can be found from the relation $h_m=h_R+M_2+S_2+h_0$, where h_0 is the mean tide level, and M_2 and S_2 are the tidal constituents: $M_2=1.3$ and $S_2=0.43$.

Determination of intrusion distance of storm surge:

The storm surge intrusion distance can be computed using equation (28) developed by Freeman & Le Mehaute and Multi-purpose Cyclone Shelter Program as:

$$X = \frac{4(4 + 1.5h)^2}{3\,(4 + h)\,(S_b + f/8)} \tag{28}$$

where h = surge height, f = friction factor, and S_b = land slope. Applying the values of h, f and S_b in the above equation the storm surge intrusion distance for coastal area can be calculate.

Determination of risk of storm surge:

The risk of a storm surge for a particular area depends mainly upon depth of inundation, population density and land use. A method to assess the risk from a natural disaster is given by the risk index:

$$\text{risk index (RI)} = HF * VF \tag{29}$$

where HF = hazard factor and VF = vulnerability factor. HF and VF are defined as:

$$HF = \frac{10 * \text{hazard index of an area}}{\text{highest hazard index}} \tag{30}$$

$$VF = \frac{10 * \text{importance index of an area}}{\text{highest importance index}} \tag{31}$$

The hazard index is defined as the element that causes the risk and in this case the depth of the storm surge is the hazard index. The importance index is defined as the element that indicates the economic value of the area flooded and in this case the land-use type is the importance index. In this method the higher the value of the risk index the higher the degree of risk.

Susceptibility to storm surge disaster due to socio economic and physical environmental factor:

Bangladesh has the eighth largest population of the world this high population density increases the susceptibility to storm surge disasters. Another factor which increases the susceptibility is the migration of workers to the southern parts of the country in the months of April, May, October and November. These are favorable months for getting a job at aman paddy fields, but these months coincide with two cyclone seasons (see fig. 1).

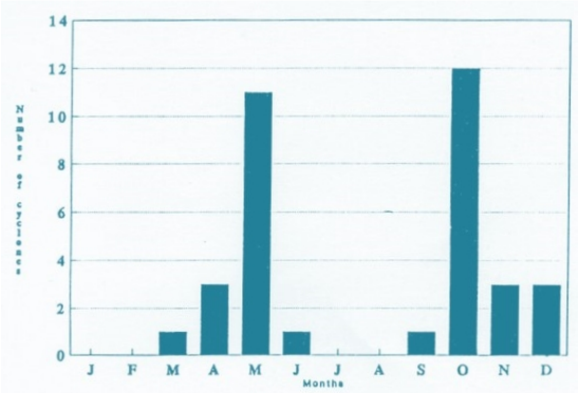

Figure 1. **Monthly distribution of 35 Major Cyclones in Bangladesh**

The coastal areas and off-shore islands of Bangladesh are low lying and very flat. The height above mean sea level of the coastal zone is less than 3m. The range of astronomical tide along the coast of Bangladesh is so large that the storm induced sea level is apt to become very high. The normal tidal range is about 3m near the Indian border in the west and becomes higher to the east (central coastal part) to about 5m near Sandwip Island at the mouth of the Meghna estuary (Figure 2). The tidal range in the southeastern part is about 3.5 to 4m. If storm surges are superimposed on high tides, the situation becomes disastrous.

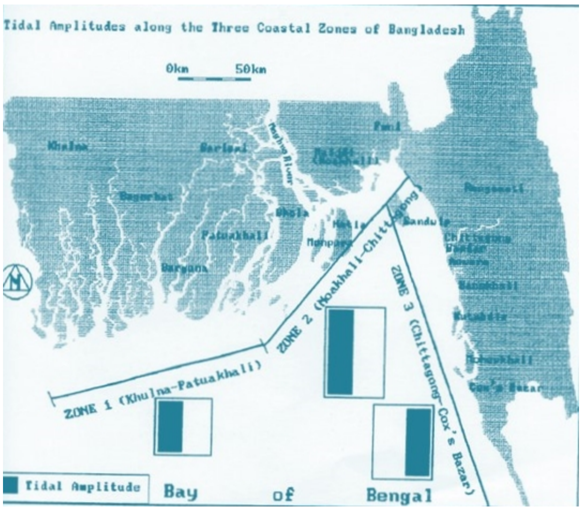

Figure 2. **Average tidal amplitudes in the three coastal zones of Bangladesh**

A funneling coast line reduces the width of storm induced waves and increases the height. Also, the fact that the coasts are situated at right angles in the northern corner of the Bay of Bengal (figure 2.) causes higher storm induced waves compared to a straight coast line.

Coastal flooding

Accelerated sea level rise, driven by global climate change, will continue to affect Bangladesh coast through permanent inundation, drainage congestion in the polders, storm surge inundation and increased salinity intrusion of low-lying areas. As a result, a wide range of impacts on socio-economic and natural systems is anticipated, including increased damage to property and infrastructure, net loss of coastal wetlands and coastline, declines in coastal bird and wildlife populations. When Sea water over topped and breached the polder and then flooded a vast region of the coastal area of Bangladesh. Storm water destroyed the existing crops, shrimp farm, vegetation, livestock etc. and increased the salinity of the land and interior water bodies. The affected people have taken their shelter on the polders. Flood of storm surge depends on the flowing factors on which the devastation depends:

- Height of storm surge including tidal level and sea level rise.
- Duration of storm surge hazards expose to the susceptible area.
- Slope drag factor and land use pattern of the hazardous area.

Result and Discussion:

- Normal coastal flooding - no damage on crops.
- Moderate coastal flooding - very limited damage on crops.

- Moderately high coastal flooding - high damage on crops but relatively low damage on properties and lives.
- High coastal flooding - large scale damage on crops, properties and lives.
- Severe coastal flooding - severe damage on crops, properties and lives.

On the basis of the above discussion, the risk areas are classified into the following four categories:

- Low risk area with risk index value $0 < RI <= 19$;
- Risk area with risk index value $20 < RI <= 39$;
- High risk area with risk index value $40 < RI <= 60$;
- Severe risk area with risk index value $RI > 60$.

3. Conclusion

Storm surges can happen at any time. As storm surges become a greater concern in Bangladesh communities, municipalities have realized the need to take a greater responsibility to provide protection for their residents. In the event of a storm surge, vital community resources could be damaged, wiped out, or become inaccessible. Planning for potential coastal flooding is the best way to minimize the damaging that communities can face. The accurate prediction of storm surge makes a lot of contribution in protection and mitigation of natural damages occurred in the coastal areas of Bangladesh. So, to protect the human wealth, crop, agricultural land, domestic animals etc. from damage it is very essential for everybody to take a careful study and management of the aspects of the storm surge and coastal flooding.

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