Model for water circulation in tidal dominated estuarine regions

Dinh Van Uu[3] **and Ha Thanh Huong**[4]

Abstract: The litho-hydrodynamic and environmental conditions in the Vietnamese coastal estuarine basin are significantly affected by the land-ocean-atmosphere interaction processes whish tide has a determining role. Application of the coupled 1D, 2D and 3D modeling system could resolve this complicated problem but it requires other solutions related with the boundary and coupling conditions.

A fully three-dimensional (3D) baroclinic hydrodynamic model was developed and applied for tidal dominated open estuarine regions. The Marine Hydrodynamic and Environmental Center (MDEC) model is enable simulate the hydrodynamic features of the coastal estuarine basin with a minimum requirement of the river and tidal boundary conditions.

The model was tested and calibrated by simulating total water circulation and level in the Haiphong estuarine region. The results show good agreement between the numerical simulation and field measurement. The model could be developed and coupled with environmental model to future coastal ocean monitoring and prediction system for Vietnamese coastal waters.

Keywords: hydrodynamics; numerical modeling; estuaries; circulation;

1. Introduction

The physical processes in the estuarine and coastal region are complex and involve advection, diffusion and mixing within the water column as well as the dynamics of bottom boundary layer (BBL). The bottom stresses depend on the BBL conditions formed under forcing factures as tide, wind and surface wave. To include these processes into circulation model for water column an adequate description of the BBL is required. The interaction processes between waves and currents play an important role and the moving sediment affects both on the flow and on the bed form.

This study is based on a modeling system which links a 3D coastal circulation model, surface forcing model, bottom boundary layer model and opens boundary conditions.

Aims of the present paper are to compute spatial distribution patterns of water circulation, water level and bottom shear stresses in response to different hydrodynamic and forcing conditions in the Hai Phong Port estuarine region.

2. The modelling system

The numerical modeling system consists of following components: a PE coastal hydrodynamic model, a surface forcing model, a bottom boundary layer model, an computational procedure for open boundaries with tide dominated conditions.

2.1 The PE coastal hydrodynamic model

The temporal evolution of sea elevation, currents, temperature and salinity in response to atmospheric forcing and river discharges is calculated with a thermodynamic model

[3] Marine Dynamics and Environment Centre, Vietnam National University; 334, Nguyen Trai, Thanh Xuan, Hanoi; Tel: 84 4 8584945; E-mail: uudv@vnu.vn

[4] Marine Dynamics and Environment Centre, Vietnam National University; 334, Nguyen Trai, Thanh Xuan, Hanoi; Tel: 84 4 8584945; E-mail: huonghat@yahoo.com

MDEC developed from GHER (University of Liege) coastal ocean model. This model has been described in details in the -work of Dinh Van Uu and his co-workers [5, 6, 7], where the parameterization scheme of the turbulent viscosity is expanded in the horizontal and vertical direction differently. We use a wind-wave interaction model to compute the surface wave parameters and wind stress in different wind condition.

The wind-wave interactive model in the near surface atmospheric boundary is used in the computation of the wave characteristics and wind stress in the wavy condition. In this model, the wind stress contains two components: purely turbulent component τ_{at} and the wave force component τ_{aw}:

$$\tau_a = C_D \rho_a u^2{}_{10} = \rho_a u^2{}_* = \tau_{at} + \tau_{aw} \tag{1}$$

We can parameterize these interaction through the surface friction coefficient C_D, considering as a function of the wind velocity at a distance z from the sea surface. The wind velocity profile change is due to the surface roughness parameters in the normal (no wave) z_0 and under wavy condition z_e (Jansen, 1992):

$$u_z = \frac{u_*}{\kappa} \ln\left(\frac{z + z_e - z_0}{z_e}\right) \tag{2}$$

Where z_e and z_0 could be calculated by semi-empirical formula depending of the ratio between wave and wind speed c/V or c/u* (Dinh Van Uu, 1981).

We use and analytical boundary layer model to calculate the total bottom stress from the lowermost velocity point in the circulation model. The total stress is given by the current and the wave contribution (Grant and Madsen 1979, WAMDI, 1988):

$$\tau_b = \rho C_b v^2 = \tau_c + \tau_w = \rho C_c v^2 + \rho C_w u^2{}_w = \rho u^2{}_{*cw} = \rho\left(u^2{}_{*c} + u^2{}_{*w}\right) \tag{3}$$

where

$$u_{*c} = \left[\frac{\tau_c}{\rho}\right]^{\frac{1}{2}}, \quad u_{*w} = \left[\frac{\tau_w}{\rho}\right]^{\frac{1}{2}}$$

For the pure current stress, we can use the following formula:

$$\tau_c = \rho C_c v^2, \; C_c = \frac{1}{2} f_c = \frac{\kappa^2}{\left(\ln(30z/k_{bc})\right)^2} \tag{4}$$

where k_{bc} is an apparent bottom-roughness caused by the turbulent in the wavy boundary layer.

$$k_{bc} = k_b \left[24 \frac{u_{*cw}}{u_w} \frac{A_b}{K_b}\right]^{\beta} \tag{5}$$

In the normal condition without wave (only current) $k_{bc} = k_b = \frac{z_0}{30}$ and the flow friction coefficient is

$$C_c = \frac{1}{2} f_c = \frac{\kappa^2}{\left(\ln(z/z_0)\right)^2}. \tag{6}$$

For the wave stress, we use the formula:

$$\tau_w = \rho C_w v^2 = \frac{1}{2}\rho f_w u^2{}_w . \quad (7)$$

Where the formula for computing the wave friction f_w, the osculating amplitude A_b and velocity u_w are taken from the theory of linear wave.

2.2 Procedure to deal with the river-estuary open-river boundary condition

For the tide dominated estuarine region, the demand for establishing the boundary conditions for open boundary connecting river and estuary becomes extremely necessary and require special technique or procedure. For the currently known techniques, the variation of river discharge and water level often lead to the confliction results in the flow field near the open boundary. To resolve this confliction, we propose a new procedure which allows us to eliminate the possibility of confliction.

Based on the hydraulic energy conservation principle along the estuary, we can assume that the effects of the flow increase the water level at the estuary a quantity depending on the river discharge. The water level in the estuary will be the combination of the water level due to tide and the added water level from the river discharge $\xi = \xi_t + \delta_\xi$, where the added water level δ_ξ will be decreased in offshore direction. For the river-estuary section, we have the following formula for the river-added water level: $\delta_\xi = \alpha \frac{v^2}{2g}$, where the coeficient ratio α depending on the location of the river-estuary boundary and the shape of studied basin.

So the the river-estuary boundary conditions for the tide dominated area can be given in the form of water level consisting of two components: the tidal water level based on the data observation of tide and the river-added level due to the river discharge.

3. Results and discussions

Besides the application results for all Bien Dong area, the MDEC model has been carried out for the Tonkin bay, the Vietnamese South-East waters and the Quang Ninh-Hai Phong coastal zone simulating the water circulation, temperature, salinity, suspended mater, oil and sediment fields in the monthly and seasonal time scale. In the scope of this report, we concentrate on analyze of some results for the water and elevation fields in the estuarine area of Hai Phong port.

The Haiphong estuarine region is a tidal dominated basin with large seasonal variation of water discharge from river system. In this region, as principal marine port of Vietnam, there are two navigation channels: Nam Trieu and Lach Huyen (Figure 1). After construction of the Dinh Vu dike Nam Trieu became the largest river mouth entering in the open part of estuary. The problem of sedimentation is the most important for the Haiphong port management. Beside the problem of sedimentation the process of coastal erosion is also urgent for Cat Hai coastal region especially during storm wind condition in the south-west monsoon season.

The 3D model MDEC has been implemented for the studied area with the grid dimension of 200m and five layer depending on the double sigma variation. The study of the model has been carried out in different conditions of each interaction: surface wind, river discharge and the more realistic features of topography and tidal oscillation.

To verify our model, we have carried out the model under the condition without wind forcing. The current and water level have been simulated in the time of seven days with the conditions of water level on the open boundary Nam Trieu, Lach Huyen, South Cat Ba and East Hon Dau. The next step, the boundary conditions on the river discharge into basin and the wind conditions on the surface have been tested to estimate the circulation picture and water level on the region.

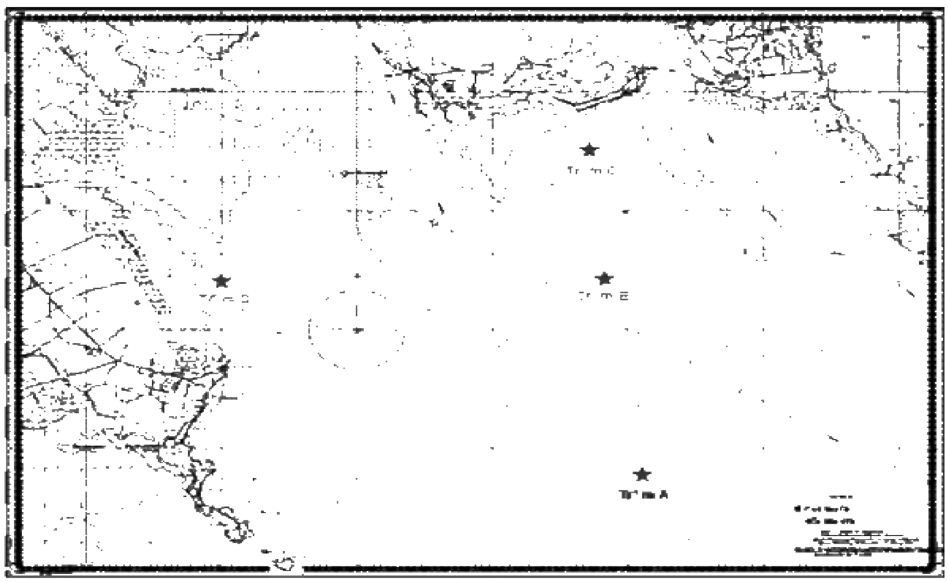

Figure 1. Topograpgy map and hydrographic station in the Haiphong Port Estuarine area

The simulated water level fields describe quite well the propagation phenomenon in the shallow and topographic complicated basin. With the harmonic constant for 4 main components in the estuary and seashore stations, the model shows that the differences in the water level between areas at the same moment are very small, not bigger than 0.3m. Considering the maximum distance between points in the grid not exceed 30km, this difference is quite agrees with the reality of the tide characteristics.

Analyzing the circulation fields, we can see the difference between the water level regime and tidal currents at different locations. The most recognizable phenomenon is the opposite phase of the current in the estuary of Nam Trieu and Lach Huyen (Figure 2). While the variation of the tidal current in the deep sea have the similarity in both phase and amplitude (Figure 3).

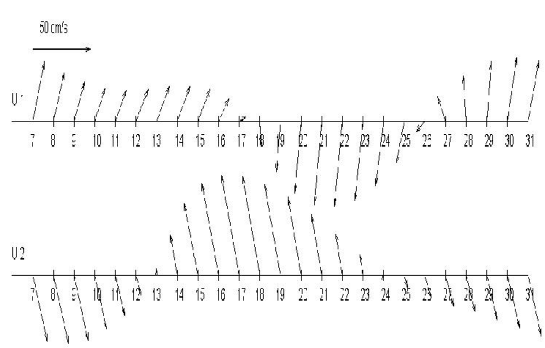

Figure 2. The variation of the tidal current in the Nam Trieu (above) and Lach Huyen navigation channels

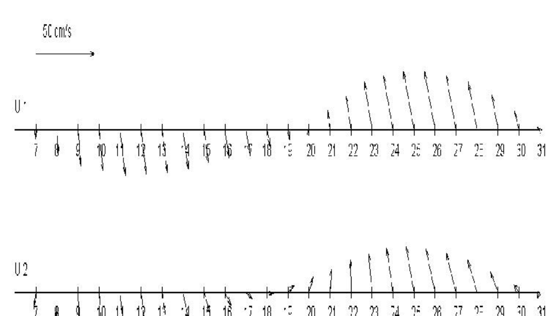

Figure 3. Tidal current variation in area offshore Do Son (above) and Cat Hai

With the above mentioned features of tidal current field, it forms a special tidal regime for this region. A remarkable phenomenon is the deformation of the tidal current ellipse with the tendency of changing the tidal current in the east-west direction corresponding to the boundary of the narrow water offshore Cat Hai. In the high or low phase tide, the current is parallel to the Cat Hai shore often connects to the inflow or outflow of the Nam Trieu and Lach Huyen navigation channels with the opposite direction, it forms reversing current starting from corresponding estuaries. In Figure 4, we show two tide current fields correspond to two cases analyzed above.

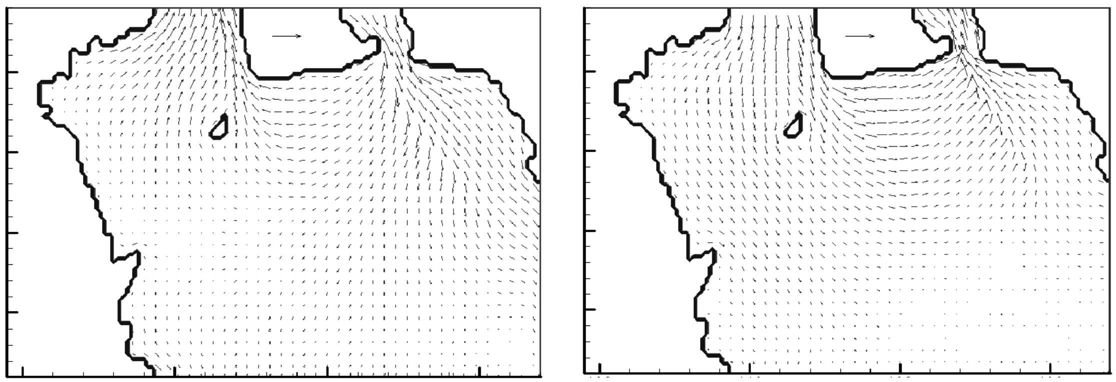

Figure 4. Typical water circulation filed in the high (left) and low (right) tidal phase

Figure 5 shows the day-night variation of the tidal current at two locations in the shallow water area offshore of Cat Hai.

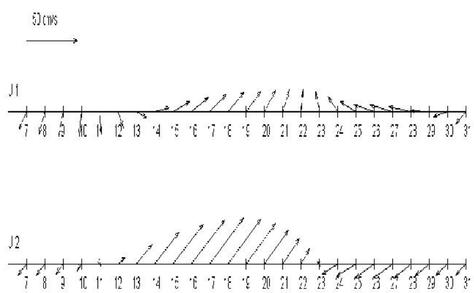

Figure 5. Tidal current variation in the near shore Cat Hai shallow water (above) and Ben Got tidal inlet.

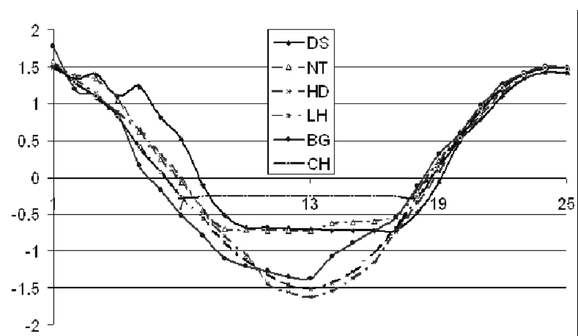

Figure 6. Simulation water level in area estuary Hai Phong with storm condition: DS- dike Do Son, NT- Nam Trieu chanel, HD- offshore Hon Dau, LH- Lach Huyen Chanel, BG- Ben Got inlet, CH- Cat Hai shallow water.

We can notice the difference between the variation characteristics of the tidal currents in the shallow and deep areas (Figures 3 and 5). Besides, there is the phenomenon of increasing of the current parallel to the shore in the direction of Ben Got. This could be the cause of the bed erosion and the forming of a inlet connecting Lach Huyen and offshore Cat Hai (Figure 1)

The results from the modeling have been verified by comparing with the characteristics of the water level and current obtained from the field survey in 2007 and 2008 of the project QGTD 04.07 and KC09.23/06-10.

The effect of river discharge to the current only happens strongly in the tidal current phase and river current phase both have inward direction. However this can only be noticeable on a limited region and therefore do not change the tide dominated circulation picture.

For the wind effect, we can confirm the weak role of this factor in the normal wind condition it does not change the direction of the tide dominated circulation. However, it can change the value of the total current. During storm, the variation of the direction of the wind is significantly influenced on the location of the maximum storm surge: at the eastern and northern storm wind the coastal region along Haiphong-Doson protection dike is more affected by the storm surge (Figure 6). In the storm surge affected regions the water level mays be about 50cm more than in the offshore. This local storm surge contribution mays be affected the dike protection system is these regions.

We can see that the storm surge phenomenon is due mainly to accumulative water. however with the value of 50-60 cm is a very dangerous case if combined with tide and storm surge coming from offshore.

4. Conclusion

The simulated results from the 3D hydrodynamic model MDEC of the estuarine region in Hai Phong port have confirm the possibility of application for the similar litho-hydrodynamic complicated basin of Vietnam. From the analysis of the results, we can see two areas where the chance of erosion and storm surge is very high: Cat Hai and dike 14 in Do Son. This should be considered in the process of planning and costruction of the shore protection system in Hai Phong.

The hydrodynamic model mays be coupled with different environmental models in the a monitoring and prediction environmental system for the estuarine and coastal region with the comlexity of the hydrodynamic, topographic and forcing conditions.

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