Trans. Tianjin Univ. 2011, 17: 057-061
DOI 10.1007/s12209-011-1515-6

Numerical Model of Storm Surge and Inundation in Bohai Bay*

LI Daming (李大鸣)[1], FU Qingjun (付庆军)[1,2], XIE Yiyang (解以扬)[3], BAI Ling (白 玲)[1]
(1. Key Laboratory of Harbor and Ocean Engineering of Ministry of Education of China, School of Civil Engineering, Tianjin University, Tianjin 300072, China;
2. Department of Civil and Environmental Engineering, University of Houston, Houston, TX 77204-4003, USA;
3. Institute of Tianjin Meteorological Bureau, Tianjin 300074, China)

Abstract: A two-dimensional numerical model of extratropical storm surge and inundation in Bohai Bay was built based on the unsteady flow Navier-Stokes equations. The model included two sections, one was for the simulation of storm surge tidal level and the other for the simulation of storm surge inundation in the coastal area. While simulating the storm surge tidal level, the alternating direction implicit (ADI) method was applied to dispersing and solving 2D storm surge equations. In the simulation of storm surge inundation, the 2D unsteady flow equations were dispersed and solved using the structureless grids of finite volume method (FVM). A coupling calculation mode of the process of inundation and storm surge tidal level variation was proposed, therefore the storm surge inundation process and area could be calculated while simulating and forecasting the process of storm surge tidal setup. Furthermore, an extratropical storm surge and inundation in Bohai Bay were simulated using this numerical model. Simulation results are in good agreement with the measured data, which shows that this numerical model provides a new method of simulating and forecasting storm surge and inundation in Bohai Bay.
Keywords: extratropical storm surge; inundation; ADI method; structureless grid

Numerical simulation of storm surge was presented in the 1950s for the first time. Several typhoon forecasting methods were used in Japan for predicting storm surge in the 1970s[1], and then a scheme of numerical simulation of storm surge was developed in Japan[2]. Two operational methods to forecast storm surge were presented by Jelesnianski in the form of a numerical-dynamical model called special program to list amplitude of surges from hurricanes (SPLASH)[3,4]. The numerical prediction model named sea, lake and overland surges from hurricanes (SLOSH)[5] was introduced in America in the 1980s, which was used to simulate storm surge from tropical cyclones[6]. Additionally, an extratropical storm surge model was built[7]. The SLOSH model was used by National Weather Service as the standard storm surge model to calculate water elevations generated by the wind stress and atmospheric pressure in a tropical cyclone[8]. An automation extratropical storm surge predicting method (sea model) was applied in the United Kingdom[9]. In China, the research of storm surge mechanism and prediction started in the 1970s, and great progress was made in the storm surge numerical model research in the 1980s[10]. Several storm surge numerical models were carried out, and a 3D super-shallow water storm surge numerical model was applied to Bohai Sea.

A coupling model of storm surge tidal setup and inundation was built in this study, and the extratropical storm surge and inundation were simulated using this numerical model. The quasiuniform grid-division approach[11] was used both in the finite difference method (FDM) for storm surge tidal setup and finite volume method (FVM) for inundation. The water balance method[12,13] and tidal level continuous conditions were used in the simulation process of storm surge and inundation.

1 Numerical model theory of storm surge

Unsteady flow equations which are integral along water depth were used in this study, and the average

Accepted date: 2010-06-23.
* Supported by Meteorological New Technology Promotion Project of China Meteorological Administration (No. CMATG2006M22).
LI Daming, born in 1957, male, Dr, Prof.
Correspondence to LI Daming, E-mail: lidaming@tju.edu.cn.

value of integral under the effect of wind stress was deduced. The governing equations of plane 2D storm surge numerical model are

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

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}-fv+g\frac{\partial \xi}{\partial x}+\frac{gu\sqrt{u^2+v^2}}{(\xi+h)C^2}-\frac{1}{\rho H}\tau_{x,s}=0 \tag{2}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+fu+g\frac{\partial \xi}{\partial y}+\frac{gv\sqrt{u^2+v^2}}{(\xi+h)C^2}-\frac{1}{\rho H}\tau_{y,s}=0 \tag{3}$$

where ξ is tidal level setup; h static water depth; H total water depth, $H=h+\xi$; f Coriolis coefficient; g gravity acceleration; $\tau_{x,s}$ and $\tau_{y,s}$ offing wind stress in x and y direction; C Chezy coefficient, $C=\frac{1}{n}\bar{h}^{1/6}$, $\bar{h}$ average value of water depth; n roughness coefficient; u and v average velocity in x and y direction.

The alternating direction implicit (ADI) difference method was applied to dispersing and solving 2D storm surge equations in the numerical model.

2 Numerical model theory of inundation

In traditional numerical simulation of hydraulics, the discrete equations usually use regular grids difference scheme. However, in the calculation of inundation for the complex computing region, considering the influence of railway, highway, river and all kinds of flood protection dike, the FVM was used and the 2D structureless irregular grids technique was applied to this model to better reflect the inundation characteristic.

2.1 Governing equations of inundation model

The 2D unsteady flow fundamental equations were introduced as the governing equations in the numerical model of inundation to simulate storm surge and inundation. The governing equations are

$$\frac{\partial H}{\partial t}+\frac{\partial M}{\partial x}+\frac{\partial N}{\partial y}=q \tag{4}$$

$$\frac{\partial M}{\partial t}+\frac{\partial (uM)}{\partial x}+\frac{\partial (vM)}{\partial y}+gh\frac{\partial z}{\partial x}+g\frac{n^2u\sqrt{u^2+v^2}}{h^{1/3}}=0 \tag{5}$$

$$\frac{\partial N}{\partial t}+\frac{\partial (uN)}{\partial x}+\frac{\partial (vN)}{\partial y}+gh\frac{\partial z}{\partial y}+g\frac{n^2v\sqrt{u^2+v^2}}{h^{1/3}}=0 \tag{6}$$

where Z is water level, $Z=Z_0+H$, Z_0 river bed elevation; q source sink term; M and N unit width flux in x direction and y direction, $N=Hv$.

2.2 Coupling of inundation grids and storm surge grids

The junction of calculation grids was important because the model was a coupling model of storm surge and inundation. In the calculation of storm surge, the square grids were applied to domain subdivision, while in the inundation calculation structureless grids were applied. For the junction of two kinds of grids, the square grids were also applied to the inundation calculation, therefore the grids could totally coincide with each other at the junction and the boundary calculation was reduced remarkably. At the junction of ground-water boundary, the water level was determined using water balance method. If the water level in the center of storm surge calculating grid was higher than the elevation of inundation grid channel, water exchange between the two grids was calculated and so inundation was calculated.

3 Establishment of numerical model of storm surge and inundation

3.1 Establishment of storm surge model

The range of 2D storm surge numerical model covered both Yellow Sea and Bohai Sea. The storm surge which occurred in Bohai Sea was simulated using the model. The measured tidal level data of Qingdao port between Mar. 1st, 2002 and Dec. 31st, 2002 was adopted for calculating harmonic constants in the model with harmonic analysis method, and the measured tidal level data of Qingdao port from Mar. 1st, 1994 to Mar. 10th, 1994 was used as verification. The measured and calculated tidal level curves of Qingdao port are shown in Fig.1. The calculated results are in good agreement with the measured data.

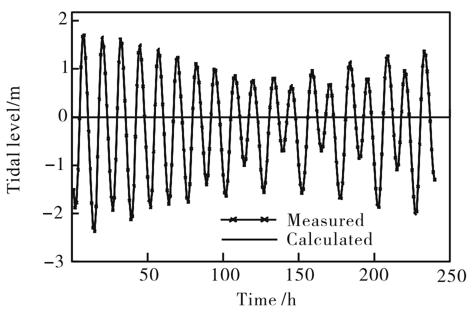


Fig.1 Verification of Qingdao port tidal level

The tidal level process of Qingdao port tidal station was used as boundary conditions, and then the tidal flow field of Bohai Sea and Yellow Sea was calculated. The measured tidal level data of Tanggu port tidal station from Mar.1st, 1994 to Mar.10th, 1994 was used as verification. The measured and calculated tidal level curves of Tanggu port by the model are shown in Fig.2, and the verification result shows a good agreement.

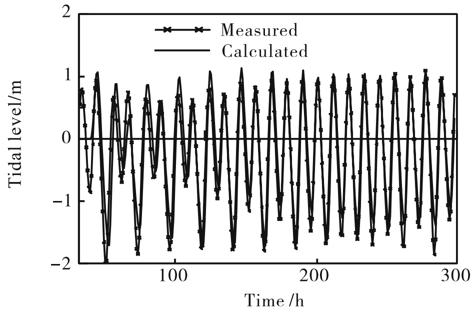


Fig.2 Verification of Tanggu port tidal level

The storm surge model was applied to Bohai Bay. In order to improve the accuracy of the simulation results, this model was firstly applied to calculating the 260-h tidal flow after 20:00 on Mar. 5th, 1994 in Bohai Bay without the influence of wind field. The tidal level process of March, 1994 which was calculated by the storm surge model was used as the water boundary conditions. The tidal level process of Tanggu station was also adopted as verification, and one point in the Bohai bay was selected for velocity verification. The velocity verification is shown in Fig.3. The calculated velocity roughly matched actual conditions, therefore the calculated results can be the foundation for further calculation of the storm surge inundation.

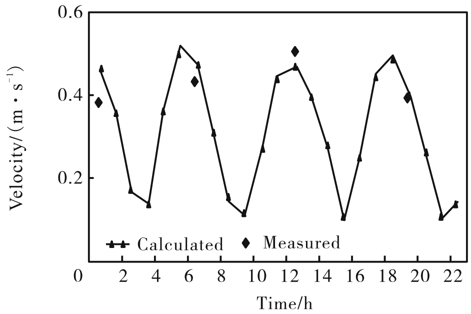


Fig.3 Verification of Tanggu port velocity

3.2 Establishment of inundation model

The topography information of inundation land is shown in Fig.4. The water level boundary of the inundation model was derived from the tidal level process of the storm surge model. The inundation occurs if the tidal level is higher than the sea wall as shown in Fig.5. The MM5 mode provided by Institute of Tianjin Meteorological Bureau was used in wind field calculation and the hourly wind stress on the grids was obtained.

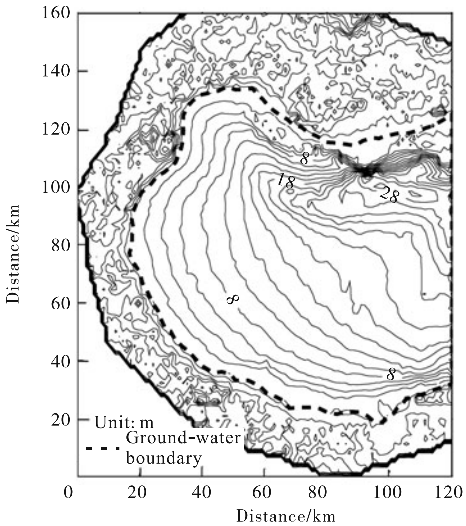


Fig.4 Topography information of inundation land

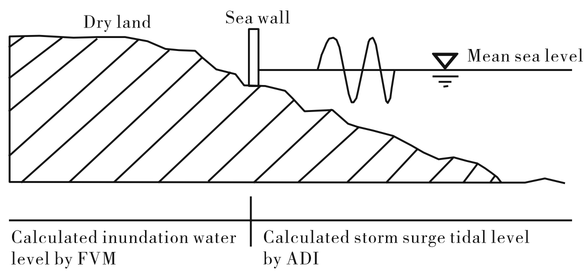


Fig.5 Coupling of inundation and storm surge

4 Application of 2D numerical model of storm surge and inundation

4.1 Simulation and verification of tidal level of storm surge

After simulating the tidal level using the storm surge numerical model, the 37-h tidal level process of a large extratropical storm surge which occurred in Bohai Bay observed at Tanggu port between 16:00 on Oct. 10th, 2003 and 4:00 on Oct.12th, 2003 was applied as verification. The measured and calculated tidal level and setup curves are shown in Fig.6 and Fig.7 respectively. The calculated high tidal level roughly matched measured value, while the calculated low tidal level was higher than the measured value because of the wind stress inaccuracy. The calculated process tendency of storm surge

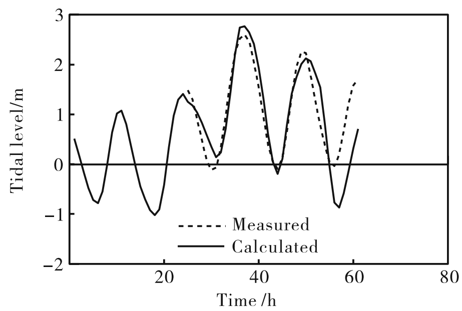


Fig.6 Verification of storm surge tidal level at Tanggu port

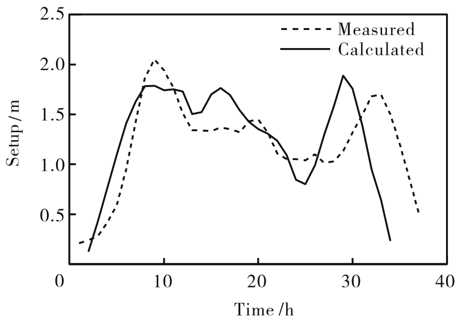
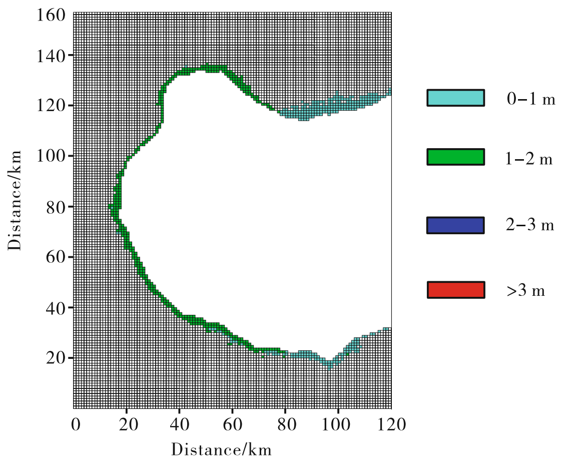


Fig.7 Verification of storm surge setup

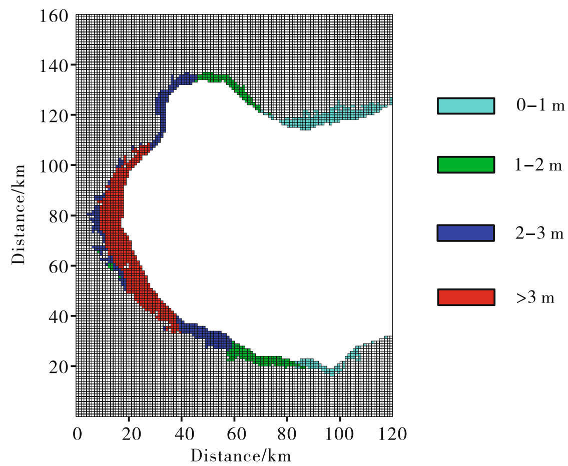
setup was correct but it had a certain lag. Therefore the calculated results can be the foundation for further calculation of the storm surge inundation.

4.2 Simulated results of storm surge inundation

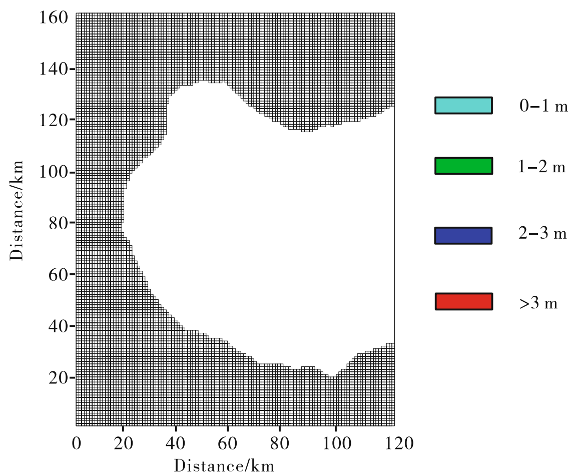
Storm surge inundation between 16:00 on Oct.10th, 2003 and 4:00 on Oct.12th, 2003 was simulated with the mean breakwater height assumed to be 2 m or without considering the breakwater height. Without considering the breakwater height, the inundation range while no storm surge occurred and the tidal level reached the maximum is shown in Fig.8(a); the inundation range while the storm surge tidal level reached the maximum is shown in Fig.8(b). Considering the 2 m high coast breakwater, the inundation range while no storm surge occurred and the tidal level reached the maximum is shown in Fig.8(c); the inundation range while the storm surge tidal level reached the maximum is shown in Fig.8(d).



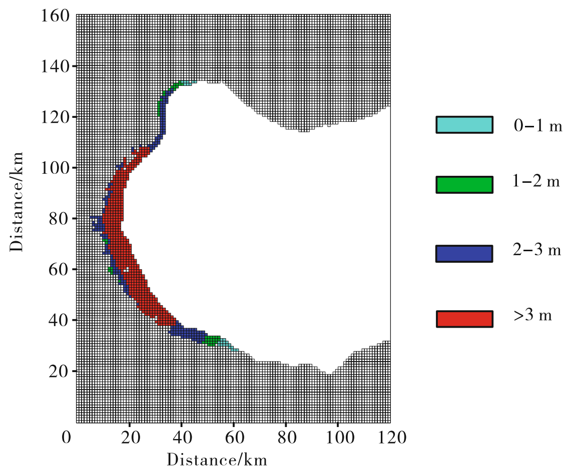
(a) Inundation range at the highest astronomic tidal level (without breakwater)



(b) Inundation range at the highest storm surge tidal level (without breakwater)



(c) Inundation range at the highest astronomic tidal level (breakwater is 2 m)



(d) Inundation range at the highest storm surge tidal level (breakwater is 2 m)

Fig.8 Simulation results of inundation range

5 Conclusions

Based on the unsteady flow equations the numerical model of storm surge and inundation was built in this study. The ADI method was applied to simulating storm surge and the FVM method was applied to simulating inundation. Tidal flow field in Bohai Bay was simulated, and the tidal level process of Tanggu port from Mar.1st, 1994 to Mar.10th, 1994 and the velocity of the tidal flow were verified. Furthermore, the large extratropical storm surge which occurred in Bohai Bay between 16:00 on Oct.10th, 2003 and 4:00 on Oct.12th, 2003 was simulated. The simulation results were consistent with the observed data. The storm surge inundation process was also simulated, and a good simulation result was obtained based on the topography information on land.

References

[1] Hino M. Theory on generation of rip currents: A simplified theory[C]. In: *Proceedings of the Twentieth Conference on Coastal Engineering in Japan*, *Japanese Society of Coastal Engineers*. 1973. 339-344.

[2] Shibaki H, Nakai K, Suzuyama K *et al*. Multi-level storm surge model incorporating density stratification and wave-setup[C]. In: *Proceedings of the 29th International Conference on Coastal Engineering*, *ASCE*. 2004. 1539-1551.

[3] Jelesnianski C P. *SPLASH Ⅰ: NOAA Technical Memorandum NWS TDL-46*[M]. National Weather Service, USA, 1972.

[4] Jelesnianski C P. *SPLASH Ⅱ: NOAA Technical Memorandum NWS TDL-52*[M]. National Weather Service, USA, 1974.

[5] Zhang Keqi, Chen Shu-Ching, Singh Peter *et al*. A 3D visualization system for hurricane storm-surge flooding [J]. *IEEE Computer Graphics and Applications*, 2006, 26(1): 18-25.

[6] Abohadima S A, Rabie A A. Numerical modeling of storm surges[J]. *Journal of Engineering and Applied Science*, 2002, 49(6): 1017-1031.

[7] Kim Soo-Youl, Yasuda Tomohiro, Mase Hajime. Numerical analysis of effects of tidal variations on storm surges and waves[J]. *Applied Ocean Research*, 2008, 30(4): 311-322.

[8] Woodruff Jonathan D, Donnelly Jeffrey P, Mohrig David *et al*. Reconstructing relative flooding intensities responsible for hurricane-induced deposits from Laguna Playa Grande, Vieques, Puerto Rico[J]. *Geology*, 2008, 36(5): 391-394.

[9] Lowe J A, Gregory J M. The effects of climate change on storm surges around the United Kingdom[J]. *Philosophical Transactions of the Royal Society A*, 2005, 363(1831): 1313-1328.

[10] Zhao Shiqing. Numerical simulation of three-dimensional tidal current in the Yangtze River estuary[J]. *Hydro-Science and Engineering*, 1985 (1): 8-20 (in Chinese).

[11] Jones Doss L, Pani Amiya K. A qualocation method for a unidimensional single phase semilinear Stefan problem[J]. *IMA Journal of Numerical Analysis*, 2005, 25(1): 139-159.

[12] Xie Lian, Liu Huiqing, Peng Machuan. The effect of wave-current interactions on the storm surge and inundation in Charleston Harbor during Hurricane Hugo 1989[J]. *Ocean Modelling*, 2008, 20(3): 252-269.

[13] Ebersole B A, Westerink J J, Bunya S *et al*. Development of storm surge which led to flooding in St. Bernard Polder during Hurricane Katrina[J]. *Ocean Engineering*, 2010, 37(1): 91-103.