Hydrodynamic numerical simulation on Baimao shoal section of Yangtze River under the impact of Typhoon Winnie

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Abstract: Baimao shoal is the key barrier in the project of 12.5m deep-water channel of the Yangtze estuary extending upward to Nanjing. Meanwhile a large number of wetlands locate along the riverbank of Baimao shoal North waterway. It is important to develop an analysis about the hydrodynamic influence by regulation project as well as by the impact of terrible typhoons around Baimao shoal. In this study, a 2-D numerical model was employed and verified with observed datasets. The hydrodynamic conditions on Baimao shoal section under the impact of Typhoon Winnie were simulated. Influences from channel regulating structures towards water level and flow velocity under the typhoon were also analyzed by the numerical model. It shows that regulation project has smaller impact towards hydrodynamic condition on Baimao shoal section. While, typhoon Winnie may cause water level and flow velocity increase by a large margin at wetland area and groin head. The significant increases of water level and flow velocity induced by typhoon need to be considered properly.

1. Introduction

In December 2015, the first-stage project of 12.5m deep-water channel in the lower reach of the Yangtze River had executed the completion acceptance. By building channel regulating structures in the range of 56km from Taicang to Nantong, the deep-water channel had extended upward to Nantong (Tiansheng Port). Baimao shoal is the first encountered navigation-obstructing waterway in the project of 12.5m deep-water channel of the Yangtze estuary extending upward to Nanjing. Based on the topography data and hydrodynamic condition, the riverbed evolution characteristics and navigation-obstructing features of Baimao shoal had been studied [1]. On this basis, the corresponding regulating structures had been put forward and applied to practice. The actual situations indicate that the regulation project has achieved obvious effects. The regulating structures have curbed the unfavorable change trend of the channel. With the effective control measures to channel erosion applied on Baimao shoal, there has been a significant improvement for channel condition [2].

Along with the rapid development of large construction projects in the Yangtze River, some researchers have raised concerns about the possible effects on the hydrodynamic conditions along the river and its coasts. Chen [3] analyzed the velocity and sediment characteristics under the influence of regulating project in Sheyang Port channel according to the results of a numerical model, the computed results revealed the distribution characteristics of back silting in the Sheyang estuary. Sediment ejection method proposed by Zhao [4] which based on the mechanism for sediment deposition has been widely used in 12.5m Yuanyuansha reach deep-water channel. Although the
previous studies have demonstrated the effect of regulation project from various aspects, there has been very little quantitative research in the evaluation of hydrodynamic conditions of regulation project in extreme circumstances. Typhoon-induced storm surge is a serious natural hazard caused by tropical storm, which can raise the water level and flow velocity dramatically and result in flooding [5]. Baimao shoal, as an intertidal zone under the interactive effects of both the runoff and the tide, the regulation project effect on which should be considered under the impact of typhoon. Meanwhile, there are large numbers of wetlands along the riverbank of Baimao shoal north waterway. Wetlands have a good coast mudflat protection function, but the sharp rise of water level and flow velocity has a great impact on wetland ecosystem [6]. Hence there is a pressing need to simulate and analyze the hydrodynamic changes in the regulation area of Baimao shoal under the impact of typical typhoon.

In this paper, with the data of water level boundaries and time series flow rate during a typical typhoon period, the delft3D model is employed to simulate the hydrodynamic conditions on Baimao shoal section. According to the result of numerical model, the water level and flow velocity changes generated by typhoon may be shown to analyze their influences.

2. Study Area and Typical Typhoon

2.1 Study Area

As shown in Figure 1, the study area is located in the lower reach of the Yangtze River, which is an intertidal zone under the interactive effects of both the runoff and the tide. Baimao shoal, located at this area, is the key barrier in the project of 12.5m deep-water channel of the Yangtze estuary extending upward to Nanjing, the depth of which is less than 12.5m caused by unstable hydrodynamic force and sediment transport. The first-stage project of 12.5m deep–water channel in the lower reach of the Yangtze River began in August 2012 and executed the completion acceptance in December 2015. Baimao shoal wetlands occur along the riverbank of North waterway. The famous Xisha National Wetlands Park is located here. Many of these wetlands are exposed to daily tidal action. These wetland areas are characterized by an assemblage of plants and animals, an ecological community, adapted to the particular conditions of this transition area between river and land [6].

2.2 Typical Typhoon

Typhoon Winnie is selected to analyze the hydrodynamic variation before and after regulation project under extreme conditions. Typhoon Winnie (NO. 9711), which was a tropical cyclone occurred in the
western Pacific in August 1997, caused a serious impact on the China mainland. The details of typhoon including hourly typhoon tracking, central pressure as well as the maximum wind speed were downloaded from the NOAA (National Oceanic and Atmospheric Administration) website. The data of water level boundaries and time series flow, used for simulating the velocity changes caused by Typhoon Winnie in the study area, can be calculated though a verified 2-D outer model in Yangtze Estuary.

3. Model Descriptions

3.1 Delft3D Hydrodynamic Model

Delft3D-FLOW solves the Navier Stokes equations for an incompressible fluid, under the shallow water and the Boussinesq assumptions [7]. The continuity equation is calculated as:

\[
\frac{\partial \zeta}{\partial t} + \frac{1}{\sqrt{G_{\xi \xi} G_{\eta \eta}}} \left( \frac{\partial ((d + \zeta) U \sqrt{G_{\eta \eta}})}{\partial \eta} + \frac{\partial ((d + \zeta) V \sqrt{G_{\xi \xi}})}{\partial \xi} \right) = (d + \zeta) Q
\]

(1)

With U and V the depth-averaged velocities, Q representing the contributions per unit area due to the discharge or withdrawal of water, precipitation and evaporation.

The momentum equations in horizontal direction are given by:

\[
\frac{\partial u}{\partial t} + \frac{u}{\sqrt{G_{\xi \xi} G_{\eta \eta}}} \frac{\partial G_{\eta \eta}}{\partial \eta} + \frac{v}{\sqrt{G_{\xi \xi} G_{\eta \eta}}} \frac{\partial G_{\xi \xi}}{\partial \xi} + \frac{w}{\sqrt{G_{\xi \xi} G_{\eta \eta}}} \frac{\partial G_{\xi \xi}}{\partial \xi} + \frac{v^2}{\sqrt{G_{\xi \xi} G_{\eta \eta}}} \frac{\partial G_{\eta \eta}}{\partial \eta} - f v = - \frac{1}{\rho_0 \sqrt{G_{\xi \xi}}} P_\zeta + F_\zeta + \frac{1}{(d + \zeta)^2} \frac{\partial}{\partial \sigma} (v, \frac{\partial v}{\partial \sigma}) + M_\xi
\]

(2)

\[
\frac{\partial v}{\partial t} + \frac{u}{\sqrt{G_{\xi \xi} G_{\eta \eta}}} \frac{\partial G_{\eta \eta}}{\partial \eta} + \frac{v}{\sqrt{G_{\xi \xi} G_{\eta \eta}}} \frac{\partial G_{\xi \xi}}{\partial \xi} + \frac{w}{\sqrt{G_{\xi \xi} G_{\eta \eta}}} \frac{\partial G_{\xi \xi}}{\partial \xi} + \frac{uv}{\sqrt{G_{\xi \xi} G_{\eta \eta}}} \frac{\partial G_{\eta \eta}}{\partial \eta} + f u = - \frac{1}{\rho_0 \sqrt{G_{\eta \eta}}} P_\zeta + F_\zeta + \frac{1}{(d + \zeta)^2} \frac{\partial}{\partial \sigma} (v, \frac{\partial v}{\partial \sigma}) + M_\eta
\]

(3)

With u, v flow velocity in \( \xi, \eta \) direction (m/s), f the Coriolis parameter (1/s), \( \rho_0 \) the reference density of water (kg/m\(^3\)). \( P_\zeta \) and \( P_\eta \) are the gradient hydrostatic pressure in \( \xi, \eta \) direction, respectively. \( F_\zeta \) and \( F_\eta \) represent the unbalance of horizontal Reynold’s stresses. \( M_\xi \) and \( M_\eta \) represent the contributions due to external sources or sinks of momentum. \( v_e \) is the vertical eddy viscosity (m\(^2\)/s).

3.2 Model Setup

The model domain is shown in Figure 1, which covers the Yangtze River next to the estuary from Tiansheng Port to Nanmen Port. It consists of three open boundaries, including three types of boundaries, namely, the inlet, outlet and solid walls. The bathymetry of model domain is obtained from observed data in October 2011. The structured grids with a resolution approximately 100m are designed in the study area, which consists of 374×689 orthogonal grids. The model mesh of this studied domain is developed as shown in Figure 2. Cartesian co-ordinate system is adopted in this model.
3.3 Model Verification

Observed datasets from four measuring stations were used to verify the hydrodynamic model. The stations are shown in Figure 1. The model is ran from 2011/10/1 00:00 to 2011/10/13 00:00, Manning coefficient is from 0.016 to 0.03 in accordance with the bathymetry of study area, and the time step is 12 s.

The hydrodynamic model is verified by comparing the observed water level and flow velocity datasets with the model simulation results in October 2011. As shown in Figure 3, the water levels and flow velocities match well with the observed datasets. The verified hydrodynamic model can be used in the following sections.

![Figure 2 Model mesh](image)

![Figure 3 Verification of water level and flow velocity](image)

3.4 Model Simulation

The corresponding regulating structures on Baimao shoal section had been applied to practice in the first-stage project of 12.5m deep-water channel in the lower reach of the Yangtze River. Through the
model setup, the regulating structures can be loaded into the model to simulate the hydrodynamic condition after the regulation project. Time series flow rate along the inlet boundary and water level along the outlet boundary during Typhoon Winnie period are considered to be the boundary input data. The start time and stop time of Simulation are set to 1997/8/18 16:00 and 1997/8/19 16:00, respectively. Three feature stations are selected in order to further analyze the impact from typhoon and regulating structures towards water level and flow velocity. Layout of regulation project and location of feature stations for hydrodynamic analysis are shown in Figure 4. Station A is located near groin head, station B is located near the channel line of south waterway on Baimao shoal section, and station C is located near Xisha National Wetlands Park.

Figure 4 Layout of regulation project and location of feature stations

4. Analysis of water level changes on Baimao shoal section under Typhoon Winnie

4.1 Analysis of water level field variations
Compared with the normal condition, the overall increase of water level occurs in computing area under the impact of Typhoon Winnie, and the maximum increase of water level is 1.42m. Under typhoon action, the change of water level is not obvious before and after the regulation project, and the range of change is within 0.02m. The problems of flood control and wetland destroy caused by water level rise are worth considering.

4.2 Analysis of water level changes at feature stations
Since the variations of three stations are similar, only station C is picked for analyzing here. It shows that water level rise caused by typhoon Winnie at station C is much obvious, the maximum value of which is 1.42m. By contrast, under the impact of typhoon, regulation project causes less water level rise which is 0.02m on average at station C. Regulation project has smaller impact towards water level in wetland areas on Baimao shoal section, while impact towards wetland environment from typhoon causing water level increasing by a large margin needs to be considered properly. The variations of water level (under normal condition, under typhoon action, under the combined action of typhoon and regulation project) at station C are shown in Figure 5.
5. Analysis of flow velocity changes on Baimao shoal section under Typhoon Winnie

5.1 Analysis of flow velocity field variations

Compared with the normal condition, the overall increase of flow velocity occurs in computing area under the impact of Typhoon Winnie, and the maximum increase of flow velocity is 0.5m/s. The velocity of shield area in the regulating structures tends to decrease, but there is a general increase of flow velocity on groin head. The velocity direction under typhoon, mostly upstream, is different from the normal condition because of typhoon-induced water level at the lower reach of Yangtze River. Extra attention needs to be paid upon issues like sediment erosion problems happening in extreme weather conditions due to the increasing of general velocity of flow as well as the change of velocity direction caused by typhoon.

5.2 Analysis of flow velocity changes at feature stations

At station A, flow velocity has increased widely under the impact of Typhoon Winnie, and the maximum value of flow velocity rise is 0.3m/s. Under typhoon action, flow velocity rise caused by regulation project is obvious, the average value and the maximum value of which are 0.11m/s and 0.29m/s, respectively. It indicates that a significant increase in flow velocity occurs near groin head due to the protective effect of regulating structures towards the shield area. The variations of flow velocity at station B show that, flow velocity rise caused by Typhoon Winnie is much obvious, and the maximum value of which is 0.45m/s. Under typhoon action, regulation project causes less flow velocity rise which is 0.01m/s on average at station B. Variation of flow velocity from regulating structures under Typhoon Winnie is basically consistent with corresponding results without typhoon by Wen [8], it shows that impact from regulating structures towards flow velocity near channel line is rather small under the action of typhoon. Station C is located near Xisha National Wetlands Park. According to the results at station C, Typhoon Winnie causes a general increase in flow velocity in wetland areas, the maximum value of flow velocity rise is 0.6m/s. under the impact of typhoon, flow velocity rise caused by regulation project is relatively small, the average value and the maximum value of which are 0.02m/s and 0.15m/s, respectively. Regulation project has smaller impact towards flow velocity in wetland areas, but the effect of flow velocity rise caused by typhoon on wetland ecology needs to be noticed.

The variations of flow velocity (under normal condition, under typhoon action, under the combined action of typhoon and regulation project) at station A, station B and station C are shown in Figure 6. In summary, impact towards wetlands and groin head from increased flow velocity should be paid more attention.

Figure 5 Variations of water level (under normal condition, under typhoon action, under the combined action of typhoon and regulation project)
6. Conclusion
A 2-D numerical model is employed and verified to simulate the hydrodynamic changes on Baimao shoal section under the impact of 12.5m deep-water channel project and Typhoon Winnie in this paper. Research from numerical model demonstrates that, under the action of typhoon, impact from regulating structures towards water level and flow velocity is small. Extra attention needs to be paid upon issues like sediment erosion problems happening in extreme weather conditions due to the increasing of general velocity of flow as well as increased flow velocity on groin head caused by the typhoon. Regulation project has smaller impact towards hydrodynamic condition in wetland areas on Baimao shoal section. Impact towards wetland environment from typhoon causing water level and flow velocity increasing by a large margin needs to be considered properly.

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