Assessment of Sudden Siltation in port area based on numerical simulation

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Abstract. During the typhoon period, sudden silting is easy to happen in the port area, which will affect the normal operation of the ship. It is an important reference for port maintenance to evaluate the Sudden Siltation after typhoon. In this study, a coupled mathematical model of wave, tidal current and sediment is established to simulate the sudden deposition of Ruoshan port area under the action of typical typhoon. The results show that the sediment concentration in the typhoon period is much higher than that in the normal weather because of the larger current velocity and the obvious wave action. The research results can provide design support for dredging and maintenance of Ruoshan port.

1. Introduction

Under the typhoon weather, the sediment concentration in the port area increases, and the port area is prone to a large amount of sediment deposition in a short time, that is, "sudden sediment deposition". It is very important to evaluate the amount of sudden sediment deposition accurately for ensuring the normal passage of the channel and maintaining the normal operation of the port area. At present, there are two main methods to evaluate the sudden sediment deposition: empirical formula method and model test method. The model test method is divided into mathematical model method and physical model method. Lin-Yun S[1] developed the physical model of sediment under the joint action of wave and current. Sudden siltation in the approach channel caused by storm surge was successfully reproduced in this physical model. Bai[2] summarized the mechanism of sudden sediment deposition, and theoretically defined and deduced the sediment carrying capacity under the action of waves. Based on cjk3d mathematical model, Lu Chuanteng[3] et al. carried out numerical simulation on the Sudden Siltation of the Yangtze River Estuary under the action of typhoon waves. It was found that typhoon waves have a great influence on the sediment concentration in the shallow waters of -15 m isobath.

In this study, Ruoshan port in Wenling City, Zhejiang Province, China is selected as the research object, and the Sudden Siltation of the port under the typical typhoon is discussed based on the mathematical model. The research results can provide design support for dredging and maintenance of Ruoshan port, as well as technical reference for the estimation of Sudden Siltation amount of other semi closed port areas in China.

2. Research area

Ruoshan port is one of the three major ports of Wenling national central fishing port in Zhejiang Province, China(Figure 1). The port is located in the west of Ruoshan, east of Shitang port, west of aiwan bay, with a water area of about 7 million m². The breakwater of Ruoshan fishing port blocks the waves in the open sea, which makes Ruoshan fishing port an important harbor area and shelter anchorage.
for fishing boats in and around the area. However, due to the semi closed port construction, sediment is difficult to be brought out of the port with the falling tide. Since the construction of Ruoshan fishing port, it has been silted up. At present, the siltation of Ruoshan port due to the construction of breakwater has affected the entry and exit operations of local fishing boats to a certain extent, and local fishermen can only take the tide to enter and exit the port, which is extremely inconvenient. In order to ensure the normal operation of the port area and respond to the call of fishermen, the local government plans to start the dredging project of Ruoshan port area of Wenling central fishing port.

Wenling city faces the East China Sea, with frequent typhoons in summer and autumn. Therefore, it is necessary to pay attention to the sudden silting in the harbor area during the typical typhoon period after the implementation of dredging project.

Figure 1. Geographical location of Ruoshan port

3. Mathematical model introduction
In order to study the problem of sudden deposition in typhoon period in Ruoshan port, a coupling mathematical model of storm surge, wave, sediment transport and bed erosion and deposition is needed. The model is described below.

3.1. Hydrodynamic mathematical model
Continuity equation,

$$ \frac{\partial h}{\partial t} + \frac{\partial hu}{\partial x} + \frac{\partial hv}{\partial y} = q \tag{1} $$

Momentum equation in X direction,
Momentum equation in Y direction,

\[
\frac{\partial hu}{\partial t} + \frac{\partial (hu^2 + \frac{1}{2} gh^2)}{\partial x} + \frac{\partial huv}{\partial y} = S_x
\]

(2)

\[
\frac{\partial hu}{\partial t} + \frac{\partial (hu^2 + \frac{1}{2} gh^2)}{\partial x} + \frac{\partial huv}{\partial y} = S_y
\]

(3)

Where \( h \) is the depth of water, \( u \) is the velocity in \( x \) direction, \( v \) is the velocity in \( y \) direction; \( S_x \) and \( S_y \) are called source terms, and the expression is,

\[
S_x = -\frac{h}{\rho} \frac{\partial p_a}{\partial x} - gh \frac{\partial z_b}{\partial x} + \frac{\tau_{ax} - \tau_{bx}}{\rho} + c_x
\]

(4)

\[
S_y = -\frac{h}{\rho} \frac{\partial p_a}{\partial y} - gh \frac{\partial z_b}{\partial y} + \frac{\tau_{ay} - \tau_{by}}{\rho} + c_y
\]

(5)

In formula (4)-(5), \( p_a \) is the surface atmospheric pressure; \( c_x, c_y \) are the Coriolis forces; \( z_b \) is the bed elevation; \( \tau_{bx}, \tau_{by} \) are the bottom resistance, \( \tau_{ax}, \tau_{ay} \) are the wind stress components in direction \( x \) and \( y \).

3.2. Wind field and pressure field model

In the calculation of storm surge, the calculation of typhoon is very important. In this calculation, the model wind field and pressure field of Jelesianski\(^4\) are selected, and the formula is as follows:

\[
W = \begin{cases} 
\frac{r}{r+R} \left( V_{0x} \hat{r} + V_{0y} \hat{j} \right) + W_R \left( \frac{r}{R} \right)^{\beta} \left( A \hat{r} + B \hat{j} \right) / r, & (0 < r \leq R) \\
\frac{R}{r+R} \left( V_{0x} \hat{r} + V_{0y} \hat{j} \right) + W_R \left( \frac{R}{r} \right)^{\beta} \left( A \hat{r} + B \hat{j} \right) / r, & (r > R)
\end{cases}
\]

(6)

\[
P_a = \begin{cases} 
P_0 + \frac{1}{4} (P_\infty - P_0) \left( \frac{r}{R} \right)^3, & (0 < r \leq R) \\
P_\infty - \frac{3}{4} (P_\infty - P_0) \frac{R}{r}, & (r > R)
\end{cases}
\]

(7)

Where, \( R \) is the maximum wind speed radius; \( r \) is the distance from the calculation point to the typhoon center; \( V_0 \) is the typhoon moving speed; \( WR \) is the maximum wind speed of the typhoon; \( A = -[(x-xc) \sin\theta + (y-yc) \cos\theta]; B = (x-xc) \cos\theta - (y-yc) \sin\theta; (x, y), (xc, yc) \) is the coordinates of calculation point and typhoon center respectively; \( \theta \) is the inflow angle (when \( r \leq R, \theta \) is 10°; when \( r > 1.2R, \theta \) is 25°; the rest \( \theta \) is linear interpolation between 10° and 25°; \( P_0 \) is the typhoon center pressure, \( P_\infty \) is the atmospheric pressure at infinity (1010hpa in calculation). \( \beta \) is the attenuation coefficient of typhoon wind speed distance.

The maximum wind speed is calculated using the wind-pressure relationship proposed by Atkinson-hollidy\(^5\) (8).

\[
W_R = 3.029 \left( P_\infty - P_0 \right)^{0.644}
\]

(8)

The maximum wind speed radius is given by empirical formula, see formula (9).

\[
R = R_k - 0.4 (P_0 - 900) + 0.01 (P_0 - 900)^2
\]

(9)

In(9), \( P_0 \) is the central air pressure(\( hPa \)), \( R \) is the maximum wind speed radius. \( R_k \) is the empirical constant.
3.3. Wave model
SWAN model is used for wave calculation in typhoon period. The wave model is wind wave spectrum model, which is generally suitable for large-scale wind wave field simulation. Based on the principle of wave energy conservation, the model theory can consider wave diffraction, refraction, bottom friction, foam dissipation, wind energy input, wave breaking and other factors. For detailed model introduction of SWAN model, please refer to the literature[6].

3.4. Mathematical model of suspended sediment transport
The vertical average two-dimensional unbalanced sediment transport equation is adopted for suspended sediment transport, and its basic equation is (10).

\[
\frac{\partial}{\partial t} \left( h_s \right) + \frac{\partial}{\partial x} \left( h u_s \right) + \frac{\partial}{\partial y} \left( h v_s \right) = \frac{\partial}{\partial x} \left( h \varepsilon_s \frac{\partial s_i}{\partial x} \right) + \frac{\partial}{\partial y} \left( h \varepsilon_s \frac{\partial s_i}{\partial y} \right) - \alpha \sigma_{sl} (s_i - s) \]

(10)

Where: \( s_i \) is the sediment concentration of the group \( l \); \( s \) is the sediment carrying capacity of the group; \( \alpha \) is the coefficient of recovery saturation; \( \sigma_{sl} \) is the settling speed of the group \( l \); \( \varepsilon_s \) is the sediment diffusion coefficient.

3.5. Bed erosion and deposition model
The deformation equation of bed surface is shown in the formula:

\[
\gamma_s \frac{\partial z_0}{\partial t} = \alpha_j \omega_j (s_i - s) \]

(11)

4. Establishment and verification of mathematical model
4.1. Model calculation area
In order to ensure the full development of storm surge model, the calculation scope of the model includes the whole East China Sea. The water boundary of the calculation domain extends to Shantou, Guangdong Province in the west, to the Taiwan Island in the south, to the Ryukyu Islands in Japan and Jeju Island in South Korea in the East, with an approximate range of 21.5°N-41°N, 116.5°E-127°E. The calculation range of the model is shown in Figure 2.
4.2. Selection of typical typhoon

This paper analyzes the typhoons landing in Zhejiang Province in the past 50 years, among which 9711 has the greatest impact on Wenling City. After the Typhoon 9711 was formed in the Western Pacific Ocean on August 10, 1997, it moved to the coast of China, and its intensity increased continuously. On August 18, the typhoon landed in Wenling, Zhejiang Province. The maximum wind force near the center reached 54 meters per second, belonging to the super typhoon level. At the time of landing, the wind force was still more than 40 meters per second, the radius of level 10 wind circle reached 180 kilometers, and that of level 7 wind circle reached 500 kilometers. After the typhoon passed through Zhejiang, Anhui, Jiangsu and Shandong provinces, it had a great impact on the relevant areas, all of which had strong winds and rainstorms, and had a great impact on the surrounding areas such as Shanghai. Because Typhoon 9711 landed at the high tide and the landing point was very close to the Ruoshan port area, Typhoon 9711 was used as a typical typhoon in this paper to analyze the sudden deposition after the excavation of Ruoshan port area. The path of Typhoon 9711 is shown in Fig3.
4.3. Verification of storm current
Because there is no measured flow data during the typhoon, only the process of storm surge level can be verified. See Figure 4 for the wind field and pressure field before the landing of 9711 typhoon. See Figure 5 for the verification of storm surge water level process.
4.4. Typhoon wave verification
See Figure 6 for wave height verification of wave stations during 9711 typhoon. It can be seen from the figure that the mathematical model successfully reproduced the current and wave conditions during the typhoon. This is the basis of the calculation of sudden deposition.

5. Analysis of calculation results of sudden sediment deposition in Ruoshan port
The calculation range of sediment model is consistent with that of storm surge and typhoon wave model. After the model is stable, the three days before and after the typhoon are calculated, and then the sudden deposition in the typhoon period is counted. Because the storm current velocity is large in typhoon period, and the sand lifting effect of wave is obvious, the sediment concentration in typhoon period is much higher than that in normal weather. Through calculation, the peak sediment concentration of Ruoshan approach channel in typhoon period can reach more than 2.0 kg/m³, which is more than 10 times of that in normal period. The terrain change of Ruoshan port area during the typhoon is shown in Figure 7. It can be seen from the figure that during the typhoon, the deposition of the Northeast branch channel is relatively serious, ranging from 0.03 to 0.07m. On the north side of luoxingshan and in the center of Ruoshan port area, the deposition is also relatively large, ranging from 0.05 to 0.07m. As a whole, the sedimentation volume gradually decreases from northwest to Southeast.
6. Conclusion

In this study, a two-dimensional coupled model of storm surge, typhoon wave and sediment transport is established. The storm surges and waves during the 9711 typhoon were simulated successfully. On this basis, the Sudden Siltation amount of Ruoshan port area during a typhoon is calculated. The calculation results show that after a typhoon, the sedimentation in the middle of the port area is large, and the sedimentation amount can reach 0.05-0.07m.

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