NUMERICAL SIMULATION AND DEPOSITION PREDICTION FOR NEW DEVELOPED DEEP WATERWAY IN SILTING SHOALS

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ABSTRACT: There are many silting shoals distribution in China coast. And more and more harbours have been built in this areas, because of the demand of port for industry development. The deposition on waterway is essential factor for such ocean engineering. In this paper, a study will be taken as an example for the new developed channel using Lianyungang deep channel. It takes investigation, data analysis, numerical simulation and model of sediment deposition measures in silting shoals or new developed waterway to study the construction of deep channel. Firstly, flow variations after harbour layout and deep channel are discussed. It shows that the suitable distribution of harbour is essential for regulation the crosscurrent to keep the safety of ship sailing in new developed channel. The depth of channel has also certain effect on current. On the basis of sediment study, the prediction model is built to study the deposition in new developed waterway. And silting distribution along the channel are given for different schemes. It suggests that, the gate of harbour should be positioned at the outside of wave broken zone to avoid the strong deposition at gated of channel under strong storm. The study case is useful for selection of channel position, the gate of harbour, and regulation of crosscurrent in new developed harbour zone and channel selection.

Keywords: deep waterway; silting shoals; deposition; crosscurrent; numerical simulation

INTRODUCTION

The silting coasts not only have mild cross-shore slope, but also have broad silting shoals. In order to meet the region’s economic development and implement the coastal opening-up strategy, the construction of deep harbour at the silting coasts is a practical problem which have to be faced by China’s port and waterway engineering. As the open waters of silting coast, the shoals in the Lianyungang seas are broad, the underwater terrain slope is about 1/1500, and the length of -5m-above (relative to the Lianyungang theoretical base surface) shoals excess 8km; the construction of 300 thousand tons waterway requires the excavation length and depth have to excess 50km and 20m, respectively. As a developed harbour, flow dynamics, wave conditions and sediment deposition after the harbour construction have become great concern issues. In this paper, based on the characteristics of natural conditions of Lianyungang seas, tidal current and sediment deposition are calculated by mathematical model according to the designing institute’s schemes. The schemes are evaluated from the perspective of current and sediment, and the corresponding proposal and suggestions are made in order to provide a reference for the suitable distribution of harbour channel similar to the silting coasts.

PROJECT BACKGROUND

Referring to the measured data(Yangtze River hydrology and water resources survey Bureau,2005), the tidal type near the Lianyungang seas belongs to semidiurnal tide, the flood duration is not equal to the ebb, and the latter is larger than the former, the average tidal range is about 3.4m. The obvious rotation current appears at the south reach of Lianyungang in the west of Guanhe mouth, the main current gradually transiting from SW-NE to SE-NW in the west to east direction. Moreover, the flood velocity is larger than the ebb. The radio of them is generally 1:1.3, and the tidal averaged velocity is within range of about 0.4-0.6m/s.

Lianyungang locates at the end of the longshore sediment current, and the sea bed is nearly under the equilibrium condition, somewhat erosion(Shanghai Waterway Engineering Design and Consulting Co., Ltd.,2009). The sediment transport along the harbour coast mainly belongs to the suspended sediment. Based on the measured data, the sediment concentration is about 0.05-0.20kg/m3 under the normal weather condition, and is gradually reduced from the coast to the open seas. Table 1 shows the measured statistics under the different depths and weather conditions. The medium sediment diameter in the coastal areas is between 0.006
mm and 0.008mm, while in the deep waters of -10m-below is generally 0.008-0.01mm.

Table 1 The statistics of sediment concentration in the Xuwei seas

<table>
<thead>
<tr>
<th>Region</th>
<th>Mild Wind</th>
<th>Medium Wind</th>
<th>Strong Wind</th>
<th>Annual Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>3m</td>
<td>0.08-0.10</td>
<td>0.6-1.0</td>
<td>1.5-2.1</td>
<td>0.15-0.22</td>
</tr>
<tr>
<td>5-5.5m</td>
<td>0.05-0.09</td>
<td>0.45-0.65</td>
<td>1.0-1.7</td>
<td>0.10-0.16</td>
</tr>
<tr>
<td>7m</td>
<td>0.04-0.07</td>
<td>0.3-0.5</td>
<td>-1.0</td>
<td>0.07-0.11</td>
</tr>
</tbody>
</table>

The mouth of Xuwei harbour district is near the -5m isobath, and the mouth width is 1200m. The newly excavated 300 thousand tons channel is 17.6km long, the bottom elevation is -22m; the harbour direction is 196°-16°, as shown in Fig.1

**Fig.1 Sketch of Lianyungang waterway engineering**

**THE ESTABLISHMENT AND VERIFICATION OF FLOW-SEDIMENT MODEL**

**Establishment**

Under the Boussinesq approximation, the static pressure hypothesis and rigid-lid assumption, the depth-averaged horizontal 2D governing equations for tidal currents in the Cartesian coordinate can be written as:

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

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = -f \cdot v - g \frac{\partial \zeta}{\partial x} + \frac{\tau_{xx} - \tau_{hx}}{\rho (h + \zeta)} - \frac{1}{\rho (h + \zeta)} \left( \frac{\partial S_{xx}}{\partial x} + \frac{\partial S_{xy}}{\partial y} \right) + \varepsilon_x \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right)$$  \hspace{1cm} (2)

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} = -f \cdot u - g \frac{\partial \zeta}{\partial y} + \frac{\tau_{yy} - \tau_{hy}}{\rho (h + \zeta)} + \varepsilon_y \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right)$$  \hspace{1cm} (3)

where $\zeta$ is the tidal level; $h$ is the still water depth; $u$, $v$ are the components of the velocity vector in $x$, $y$ directions; $f$ is the Coriolis coefficient ($f = 2\omega \sin \varphi$, $\omega$ is the angular velocity of earth rotation, $\varphi$ is the local latitude); $g$ is the gravity acceleration; $\varepsilon_x$, $\varepsilon_y$ are the turbulent viscosities in $x$, $y$ directions respectively.

$$\left( \tau_{xx}, \tau_{xy} \right) = \rho_a u |W| W$$  \hspace{1cm} (4)
\[ \tau_{bx} = \frac{\rho g w}{C^2} \sqrt{u^2 + v^2 + \frac{\rho \pi}{8} f_w u_w \sqrt{u_w^2 + v_w^2}} + \frac{\rho B}{\pi C} \sqrt{2g w} \sqrt{u^2 + v^2} u_w \]  
\[ \tau_{by} = \frac{\rho g n^2 v}{C^2} \sqrt{u^2 + v^2 + \frac{\rho \pi}{8} f_w v_w \sqrt{u_w^2 + v_w^2}} + \frac{\rho B}{\pi C} \sqrt{2g w} \sqrt{u^2 + v^2} v_w \]  

where \( \rho_a \) is the air density; \( r_a \) is the wind drag coefficient; \( r_d = (0.80 + 0.065 \times |W|) \times 10^{-3} \); \( \rho \) is the water density; \( C \) is the Chezy coefficient; \( C = \frac{1}{n} (h + \zeta)^{1/6} \); \( n \) is the Manning coefficient; \( f_w \) is the Jonsson’s wave friction coefficient(Jonsson and Carlsen, 1976); \( f_w = 0.01 \sim 0.02 \); \( u_w, v_w \) are the two components of amplitude of bottom water particle speed in wave; \( U_{\text{wave}} = \frac{n H_w}{T_w \sinh kD} \), \( w_u = U_{\text{wave}} \cos \theta \), 
\( v_w = U_{\text{wave}} \sin \theta \), in which \( H_w, k, T_w \) are wave height, wave number and wave period, respectively; \( D \) is the water depth ( \( D = h + \zeta \) ); \( \theta \) is the angle between wave direction and x-axis; \( B \) is the wave-current interaction coefficient. According to the findings of Soulsby(Soulsby et al, 1993), if wave and current are in the same direction, \( B = 0.917 \); if they are perpendicular to each other, \( B = -0.198 \), and \( B = 0.359 \) in other cases. \( S_{xx}, S_{xy}, S_{yx}, S_{yy} \) are four components of the wave radiation stress tensor, and the expressions are:

\[ S_{xx} = E \left[ C_n \cos^2 \theta n \frac{1}{2} (2C_n - 1) \right] \]
\[ S_{xy} = S_{yx} = \frac{1}{2} EC_n \sin 2\theta \]
\[ S_{yy} = E \left[ C_n \sin^2 \theta n \frac{1}{2} (2C_n - 1) \right] \]  

in which, \( E = \frac{1}{8} \rho g H_w^2 \) is the average wave energy during one wave period in unit water column; \( C_n \) is the wave energy transport rate, \( C_n = \frac{1}{2} \left( 1 + \frac{2kD}{\sinh(2kD)} \right) \).

Suspended sediment transport equation:

\[ \frac{\partial}{\partial t} \left[ \frac{h + \zeta}{h} S \right] + \frac{\partial}{\partial x} \left[ (h + \zeta) u S \right] + \frac{\partial}{\partial y} \left[ (h + \zeta) v S \right] + F_S = \]  

The bed evolution equation(Dou et al, 1995):

\[ \gamma_0 \frac{\partial \eta}{\partial t} = \alpha \eta (S - S^*) \]  

where \( S \) is the depth-averaged sediment concentration; \( \gamma_0 \) is the dry density of bed sediment; \( \eta \) is the scour or siltation height; \( D_x, D_y \) are the sediment diffusion coefficients in the \( x, y \) directions; \( F_S \) is the scoursiltation function; \( \alpha \) is the settling probability; \( \omega \) is the settling velocity and \( S^* \) is the sediment carrying capacity under the wave-current interactions(Liu, 2009).

\[ S^* = 0.0273 \gamma_S \left( \frac{|V_1| + |V_2|}{gd} \right)^2 \]  

in which \( V_1 \) is the averaged velocity of tidal current; \( V_2 \) is the averaged horizontal velocity of the water body in wave; \( \gamma_S \) is the sediment density, \( \gamma_S = 2650 \text{kg/m}^3 ; d \) is the mean depth of the shoal.

The model scope in the longshore direction is 120km, and in the offshore direction is 82km, as shown in Fig.2. The non-uniform triangular mesh is adopted; the maximum mesh is 1500m, and the minimum mesh is 30m. The computation method is the triangular element law(The industry standard of the People's Republic of China, 2010).
Verification

In order to pander to the preliminary study of the waterway engineering, some measured data survey were implemented in site, including the tidal level and wave data from the Xuwei ocean station, a number of C1-C4 velocity and sediment concentration measured data, and the deposition height observational data of 50 thousands tons channel excavation. The excavated depth of 50 thousands tons channel is 11.5-12.5m, and the observation date is from Aug. 18th, 2011 to April 11th, 2012.

The tidal current field during the observation period in Xuwei 50 thousands tons channel is simulated through the model. The verification results are shown in Fig.3 to 7. From the tidal level series verification of Xuwei ocean station (Fig.3), the calculated result is in good agreement with the measured data. Moreover, the verifications of velocity and sediment concentration of C4 measuring point have shown better results as well (Fig.4 to Fig. 6). Moreover, present model can also predict reasonable deposition height of 50 thousands tons channel. Consequently, present model is capacity of simulating tidal current field and sediment transport in site (Fig. 7).

The measured deposition process has shown that, channel deposition intensity increases with shore depth, and appears nearly linear distribution. The channel deposition height is about 2.5m near the 3.0m isobath, which is only 1.0m at the 5.0m isobath. This deposition distribution indicates that, when the wave is active, the sediment dynamics near the 3.0m isobath is strong influenced by wave, and sediment concentration increases obviously what induces the formulation of high-intensity siltation. Accordingly, the breakwater construction is imperative for this channel section protection.

Fig.2 Computation mesh

Fig.3 Tidal level series verification of Xuwei ocean station (June 13th-20th, 2010)
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Fig. 8 shows the tidal current field of Xuwei harbour district at the peak time of flood and ebb. The flood and ebb peak current fit well with the outer channel. At the peak time of flood, flow at the mouth of inner harbour is strong, and the recirculations exit symmetrically at both side of the inner harbour channel. The west side recirculation is relative strong, and its influence area is well broad; the east recirculation appears in the harbour layout of 30 thousands crude terminal. The bottom flow is relative weak in the harbour layout. At the peak time of ebb, flow at the outer side of mouth is stronger, and the recirculation appears at the outer side of west breakwater.

The current in the inner harbour channel is smooth, and is in better accordance with channel. The crosscurrent both in the inner mouth and outer channel are weak. The maximum crosscurrent near the mouth is 0.30-0.36 m/s, as shown in Fig. 9.

Fig. 7 The siltation process verification in 50 thousands tons channel (during 269 days)

**TIDAL CURRENT FIELD SIMULATION**

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CHANNEL SILTATION CALCULATION

Annual deposition intensity distribution of 300 thousand tons channel of Xuwei harbour district is shown in Table 6-2. The maximum deposition intensity of outer channel is about 2.10-2.20 m/a. The maximum siltation region locates at the section of Outer-2, and the siltation obviously weakens outward. The deposition is not obvious near the mouth owing to the influence of in-out flow as shown in Fig.10.

![Fig.10 The prediction of annual channel siltation distribution](image)

CONCLUSIONS

Through the analysis on the flow dynamics, sediment transport and beach evolution of Lianyungang seas, and on the basis of analyzing the measured data from numbers of hydrological surveys and channel siltation, the tidal current field variation and deposition height after the project of 300 thousand tons channel of Lianyungang and Xuwei harbour district are simulated by using flow-sediment mathematical model in the Lianyungang seas.

When the wave is active, the sediment dynamics near the 3.0 m isobath is strong influenced by wave, and sediment concentration increases obviously what induces the formulation of high-intensity siltation. Accordingly, the breakwater construction is imperative for this channel section protection. The results show that, the mouth location of harbour layout should be at the -5.0 m isobath.

REFERENCES


