Numerical Simulation of the Oil Spilling Impact on Water Environment

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Abstract. Taking Ganyu Port project (Phase I) as background, based on hydrodynamic and Euler-Lagrangian theory, a 2-D tidal current and oil spill numerical model are established and verified by measured data. According to different meteorological conditions, select representative scenes, the oil film sweep range and diffusion distance are predicted, and the oil spilling impact on surrounding water environment is analyzed. The results show that: the oil sweep range and drift track are closely related to the oil spilling time and wind direction. Under no wind condition, the farthest distance from the oil film edge to the oil spilling point is about 30 km in 72 hours, which will influence the present aquaculture area, but had no effect on the protected area. Under N and WNW adverse wind direction, the farthest distance are respectively 32km and 67km from the oil film edge to the oil spilling point, which will both influence aquaculture area and some individual protected area.

1. Introduction

With the development of offshore oil and the increasing of sea transportation in recent years, oil is a typical marine pollutant, it brings great economic benefits and also increases the hidden dangers of marine oil pollution. Once oil spills occur, the leaking oil will drift and spread with the movement of water flow. It will cause deterioration of marine environment and pollution of water quality, which will endanger marine life and destroy marine ecosystem.

In view of the frequency and severity of oil spill events, since 1960s, foreign scholars have begun to study the numerical simulation of oil spill transportation and diffusion. Reed etc. [1] reviewed the research and development of oil spill model during 20th century, the oil spill model research can be divided into three simulation categories: Fay model, based on Euler's viewpoint to solve the convection-diffusion equation and the "oil particle" model based on Lagrange's viewpoint. After 21th century, some scholars proposed to complement advantages of different simulation methods [2]. At the same time, the oil spill business prediction system is gradually consummated, the relatively high recognition abroad includes the OILMAP system and GNOME system of the United States, and the OSIS system of the United Kingdom, Norway's OILPILL/STAT system and OSCAR commercial software. The oil spill model in China began in early 1980s. In recent years, domestic scholars have carried out numerical simulation of oil spill diffusion for offshore, open sea and pipeline oil spills. Li Yan, Li Huan and Zhang have summarized the progress of numerical simulation of oil spill [3-5]; Lin and Li [6-7] has carried out model research on oil spill diffusion of submarine pipeline, Guo and Yu [8-9] have carried out model research around the near shore and offshore oil film drift diffusion.

In this paper, taking Ganyu Port project (Phase I) as background, based on hydrodynamic and Euler-Lagrangian theory, a 2-D tidal current and oil spill numerical model are established and verified by
measured data. According to different meteorological conditions, select representative scenes, the oil film sweep range and diffusion distance are predicted, and the oil spilling impact on surrounding water environment is analyzed. Results can provide reference for relevant environmental assessment work.

2. Model Theory

2.1. Hydrodynamic Model

\[
\frac{\partial h}{\partial t} + \frac{\partial hu}{\partial x} + \frac{\partial hv}{\partial y} = hS
\]

\[
\frac{\partial hu}{\partial t} + \frac{\partial hu^2}{\partial x} + \frac{\partial huv}{\partial y} = \rho f\bar{h} - gh\frac{\partial \eta}{\partial x} + \frac{gh^2}{2\rho_0} \frac{\partial \rho}{\partial x} \frac{\tau_x}{\rho_0} + \frac{\partial}{\partial x} (hT_{x}) + \frac{\partial}{\partial y} (hT_{y}) + huS
\]

\[
\frac{\partial hv}{\partial t} + \frac{\partial hv^2}{\partial x} + \frac{\partial hvu}{\partial y} = -\rho f\bar{h} - gh\frac{\partial \eta}{\partial y} + \frac{gh^2}{2\rho_0} \frac{\partial \rho}{\partial y} \frac{\tau_y}{\rho_0} + \frac{\partial}{\partial x} (hT_{y}) + \frac{\partial}{\partial y} (hT_{y}) + hvS
\]

Where: \( h = \zeta + d \) is the total water depth; \( \zeta \) is the elevation of water surface; \( d \) is water depth; \( x \) and \( y \) represent the coordinates of the horizontal axis and the longitudinal axis respectively; \( t \) is time; \( g \) is the acceleration of gravity; \( u \) and \( v \) are the average velocity of depth along the axis of \( x \) and \( y \) respectively; \( f \) is Coriolis force coefficient; \( \rho \) is water density; \( \rho_0 \) is the reference density; \( (\tau_x, \tau_y) \) and \( (\tau_u, \tau_v) \) are the wind stress and the bottom shear stress along the axis of \( x \) and \( y \), respectively. \( S \) is source discharge, \( u_s \) and \( v_s \) are the velocity component along the axis of \( x \) and \( y \). \( T_{ij} \) is a stress term, including viscous stress, turbulent stress and convection etc., calculated according to the average velocity gradient of water depth.

In this study, nesting calculation of large and small model is adopted. The large model range includes the whole Haizhou Bay, and the small model includes main port area of Rizhao and Lianyungang, China (see figure 1). The open boundary is provided by ChinaTide offshore tidal prediction program, which developed by the Ocean University of China [10]. Unstructured triangular mesh are used in the computational domain (see figure 2).

The hydrodynamic numerical model is verified by the hydrographic data measured in 2013. The results show that the tidal level, current velocity and direction are in good agreement with the measured values, which meet the requirements of relevant specification [11]. Therefore, this model can be used in the numerical simulation of oil spill diffusion. In order to save space, the verification is shown in the reference [12].

![Figure 1. Location of the Project](image1.png)

![Figure 2. Mesh generation of local model](image2.png)
2.2. Oil Spill Model

MIKE21 SA module is used to predict the oil spill diffusion, which is developed by the Danish Water Environment Research Institute (DHI). Based on the Euler-Lagrangian theory, the variation of the properties of oil particles at each time is calculated in this paper, and the transport process and weathering process are considered in the calculation.

2.2.1. Transport Process

The transport of oil particles includes the processes of expansion, drift, diffusion and so on. These processes are the main reasons for the change of oil particles’ position, but the components of oil particles do not change in these processes.

(1) Extended motion

Based on modified Fay Theory, oil film expansion is calculated using gravity and viscosity Formula.

\[
\frac{dA_{oil}}{dt} = K_a \cdot \frac{1}{A_{oil}} \left( \frac{V_{oil}}{A_{oil}} \right)^{2/3} \tag{4}
\]

Where: \( A_{oil} \) is oil film area, \( A_{oil} = \pi R_{oil}^2 \), \( R_{oil} \) is oil film radius; \( K_a \) is coefficient (0.6 in this research); \( t \) is time; \( V_{oil} \) is oil film volume; \( h_i \) is initial oil film thickness.

\[ V_{oil} = R_{oil}^2 \cdot \pi \cdot h_i \tag{5} \]

(2) Drift motion

Drift force of oil particle include water flow and wind drag. The total drift velocity of oil particle is calculated by the following weight formula.

\[ U_{oil} = c_w(z) \cdot U_w + U_i \tag{6} \]

Where: \( U_w \) is wind speed; \( U_i \) is surface current speed; \( c_w \) is wind stress coefficient.

2.2.2. Weathering Process

The weathering of oil particles includes evaporation, dissolution and formation of emulsifying substances. During these processes, the composition of oil particles has changed, but its horizontal position has not changed.

(1) Evaporation

Oil film evaporation is affected by oil content, temperature, oil spill area, wind speed, solar radiation and oil film thickness. Assuming that the diffusion inside the oil film is not limited (when the temperature is higher than 0 degrees and the oil film thickness is less than 10 cm), the oil film is completely mixed. The partial pressure of the oil component in the atmosphere is negligible compared with the vapor pressure.

The evaporation rate can be represented by the following formula:

\[ N_{ei}^t = k_{ei} \cdot \frac{P_{sat}^i}{RT} \cdot \frac{M_i}{\rho_i} \cdot X_i \tag{7} \]

Where: \( N_{ei} \) is evaporation rate; \( k_{ei} \) is mass transport coefficient; \( P_{sat} \) is vapor pressure; \( R \) is gas constant; \( T \) is temperature; \( M_i \) is molecular weight; \( \rho_i \) is the density of the oil component; \( X_i \) is mole fraction; \( i \) represents various oil components. \( k_{ei} \) can be estimated from the following formula:

\[ k_{ei} = k \cdot A_{oil}^{0.045} \cdot S_{ei}^{2/3} \cdot U_w^{0.78} \tag{8} \]

Where: \( k \) is evaporation coefficient (0.029 in this research); \( S_{ei} \) is the vapor Schmidts number of component \( i \).

(2) Dissolution

Assuming that the hydrocarbon concentration is negligible compared with the solubility, then the solubility of oil in water is expressed as follows:
\[
\frac{dV_{\text{oil}}}{dt} = K_i \cdot C_{\text{sat}} \cdot X_{\text{mol,i}} \cdot \frac{M_i}{\rho_i} \cdot \lambda_{\text{oil}}
\]

Where: \(C_{\text{sat}}\) is solubility of component i, \(X_{\text{mol,i}}\) is mole fraction of component i, \(M_i\) is molar mass of component i; \(K_i\) is transfer coefficient of dissolution.

### Emulsification

Emulsification is the function of a liquid uniformly dispersed in another liquid that is insoluble in small droplets. The movement of oil into water includes diffusion, dissolution and precipitation. The amount of oil loss from the diffusion of oil film to water body D is:

\[
D = D_s \cdot D_h
\]

\[
D_s = \frac{0.11(1 + U_y)^3}{3600}
\]

\[
D_h = \frac{1}{1 + 5 \mu_{\text{oil}} h \gamma_{\text{on}}}
\]

Where: \(D_s\) is the component that enters the water body; \(D_h\) is the component that does not return after entering the water body; \(\mu_{\text{oil}}\) is oil viscosity; \(\gamma_{\text{on}}\) is the oil-water interfacial tension.

The return rate of oil droplets is as follows:

\[
\frac{dV_{\text{oil}}}{dt} = D_s \cdot (1 - D_h)
\]

The variation of water content in oil can be expressed by the following equation:

\[
\frac{dy_{\text{w}}}{dt} = R_i - R_z
\]

\[
R_i = K_1 \frac{(1 + U_y)^3}{\mu_x} (y_{\text{wax}} - y_{\text{w}})
\]

\[
R_z = K_2 \frac{1}{A_s \cdot \text{Wax} \cdot \mu_x} y_{\text{w}}
\]

Where: \(y_{\text{w}}\) is actual moisture content; \(R_i\) and \(R_z\) are water absorption rate and release rate, respectively; \(A_s\) is Asphalt content in oil; \(W_{\text{wax}}\) is Paraffin content in oil; \(K_1, K_2\) are absorption coefficient and release coefficient.

### Hydrodynamic Simulation Results

Using the validated numerical model, large tidal current field during spring tide is shown in figure 3, and the analysis is as follows:

In the Haizhou Bay, where Ganyu Port is located, tidal current movement shows reciprocating feature in the direction of NE~SW. Tidal current in Lianyungang and its south sea area is mainly rotating counterclockwise. In the vicinity of Gaogongdao and Xiaoding Harbor, the tidal current presents reciprocating flow along the coast. The velocity distribution shows the trend of north strong and south weak, and the velocity during flood tide is a little larger than ebb tide. The current velocity of most natural sea areas is between 0.4m/s and 0.7m/s, due to the construction of Ganyu Port, the velocity near the buildings is relatively large.

### Oil Spill Simulation Results

On the basis of hydrodynamic simulation, a 2-D oil spill model in Ganyu Port area was established by using MIKE21 SA module. The oil leakage source is 100 tons and the source is instantaneous. The oil spilling point is located at the front of wood wharf. Oil spilling moment includes high water level(HWL), low water level(LWL), flooding and ebbing (see table 1). According to the surrounding environment sensitive target, a total of 4 protected areas are close to the project, and a large number of aquaculture areas are existed around the project. In this research, N wind and WNW wind are selected as adverse wind to predict the oil spill, and the wind speed is the maximum of 5 class wind, which is about 10.7 m/s. Through analysis, some conclusions are made as follows:

1. After the oil spill accident, the oil film drifts and diffuses under the movement of current. Under no wind condition (see figure 4 and figure 5), when oil spill occurs at the HWL moment, the oil film...
drifts to the open seas under the ebbing flow, thus the influence area is relatively large, when oil spill occurs at the LWL moment, the oil film drifts to the coastal area under the flooding flow, thus the influence area is relatively small. The oil spilling point is located at the front of the wood wharf, the current velocity is generally low, so the oil film sweep area is small in the initial stage of oil spill. The farthest distance is about 30 km from the oil film edge to the oil spilling point in 72h, and the oil spill diffusion have no direct effect on the protected area in 72h. However, due to the existence of a large number of aquaculture in Ganyu Port area, oil spill will inevitably influence the aquaculture areas.

(2) According to the above simulation results, the oil film sweep range is only calculated at HWL moment under adverse wind condition (see figure 6). After 72h of oil spill accident, under adverse wind condition of N, the farthest distance from the oil film edge to the oil spilling point is about 32 km. Under the adverse wind condition of WNW, the farthest distance from the oil film edge to the oil spilling point is about 67km (see table 2). In terms of the impact on adjacent sensitive areas, it can be seen that under the adverse wind condition, oil spill diffusion will have a direct impact on the surrounding protected areas and aquaculture areas. Therefore, in order to protect the marine environment and the surrounding water quality, oil spills should be avoided as far as possible. When the oil spill accident occurs, the emergency response measures should be taken quickly, and combined with the shortest time that the oil spill reach the environmental area, measures such as intercept, clean up, and recover the oil spill should be taken to minimize the serious losses to the sea environment and ecosystem, and to prevent the possible adverse effects of leakage accident on the surrounding water environment.

| Case | Oil spilling point | Wind condition | Oil leakage moment |
|------|-------------------|----------------|-------------------|
| 1    | Wood wharf apron  | No wind        | Flood             |
| 2    | Wood wharf apron  | No wind        | Ebbing            |
| 3    | Wood wharf apron  | No wind        | HWL               |
| 4    | Wood wharf apron  | No wind        | LWL               |
| 5    | Wood wharf apron  | N              | HWL               |
| 6    | Wood wharf apron  | WNW            | HWL               |

Table 1. Oil spill prediction condition

| Case | Wind condition | Oil leakage moment | 1-72h sweeping area (km²) | 1-72h furthest diffusion distance (km) | Impact on environmental protected area |
|------|----------------|-------------------|--------------------------|--------------------------------------|---------------------------------------|
| 1    | No wind        | Flood             | 390.5                    | 28.2                                 | No effect on protected areas, but influence the aquaculture areas. |
| 2    | No wind        | Ebb               | 307.9                    | 26.0                                 | The same as above                     |
| 3    | No wind        | HWL               | 415.5                    | 29.1                                 | The same as above                     |
| 4    | No wind        | LWL               | 102.1                    | 17.2                                 | The same as above                     |
| 5    | N              | HWL               | 295.5                    | 32.5                                 | Directly influence both protected areas and aquaculture areas. |
| 6    | WNW            | HWL               | 749.0                    | 66.9                                 | The same as above                     |
Figure 3. Large tidal current filed (Left: flood; Right: ebb)

Figure 4. Influence range of oil spill 1-72 hours under no wind condition (Left: flood; Right: ebb)
5. Conclusions

In this paper, taking Ganyu Port project (Phase I) as background, based on hydrodynamic and Euler-Lagrangian theory, a 2-D tidal current and oil spill numerical model are established and verified by measured data. According to different meteorological conditions, select representative scenes, the oil film sweep range and diffusion distance are predicted, and the oil spilling impact on surrounding water environment is analyzed. The results show that:

(1) After the oil spill accident, the oil sweep range and drift track are closely related to the oil spilling time and wind direction. Under no wind condition, the farthest distance is about 30 km from the oil film edge to the oil spilling point after 72h, and the oil spill diffusion have no direct effect on the protected area in 72h. However, due to the existence of a large number of aquaculture in Ganyu Port area, oil spill will inevitably influence the aquaculture areas. Under adverse wind condition of N, the farthest distance from the oil film edge to the oil spilling point is about 32 km. Under the adverse wind condition of WNW, the farthest distance from the oil film edge to the oil spilling point is about 67km.

(2) In order to protect the marine environment and the surrounding water quality, oil spills should be avoided as far as possible. When the oil spill accident occurs, the emergency response measures should be taken quickly, and combined with the shortest time that the oil spill reach the environmental area, measures such as intercept, clean up, and recover the oil spill should be taken to minimize the
serious losses to the sea environment and ecosystem, and to prevent the possible adverse effects of leakage accident on the surrounding water environment.

6. References
[1] Reed M, Johansen Ø, Brandvik P J, et al 1999 Oil spill modeling towards the close of the 20th century: overview of the state of the art (England: Spill Science & Technology Bulletin) Vol. 5(1) pp 3-16
[2] Guo W J, Wang Y X 2009 A numerical oil spill model based on a hybrid method (England: Marine Pollution Bulletin) Vol. 58(5) pp 726-734
[3] LI Y, YANG Y Q, PAN Q Q 2017 Review on the oil spill numerical forecasting technology (Beijing: Marine forecasts) 34(5) pp 89-96
[4] LI H, SHAO W Z, LI C 2017 Research on numerical prediction technology of oil spill spreading, drift and diffusion (Beijing: Marine forecasts) Vol. 36(5) pp 379-384
[5] ZHAGN A, ZHOU J, LI Y, et al 2017 Review of numerical model research on oil spill (Dalian: Marine Environmental Science) Vol. 36(2) pp 313-320
[6] LIN M H, HE G X, LI Y S, et al 2017 A numerical simulation on the spilled oil diffusion of submarine pipelines (Beijing: Beijing Institute of Petrochemical Technology) Vol. 25(4) pp 83-90
[7] LI X J 2012 Numerical Simulation of the Spread-Diffusion Process of Oil Spilled from Submarine Pipeline (Qingdao: Ocean University of China)
[8] Guo J 2017 The Risk Simulation and Environment Sensitive area Nearby Effects of Oil Spill in Binhai Offshore (Shanghai: Shanghai Ocean University)
[9] YU M R, WEI C L, JIANG S C, et al 2017 A comparison among different oil spill simulation methods. Transactions of oceanology and limnology (Tianjin: Transactions of oceanology and limnology) Vol. 5 pp 58-62
[10] LI M G, ZHENG J Y 2007 The application of Chinatide, a tidal prediction software in Chinese waters (Tianjin: Journal of Waterway and Harbor) Vol. 1 pp 65-68
[11] JTS/T 231-2-2010 Technical specification for tidal current and sediment simulation in coastal and estuary areas
[12] ZHANG N, YAO S S 2013 Numerical study on the environmental impact of Ganyu Port Project (Phase I) (Tianjin: Technical Report of Tianjin Research Institute for Water Transport Engineering, M.O.T., China)

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