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Numerical simulation of the oil spilling diffusion in waterway engineering

S S Yao[1,3], P Zhang[2] and B Yan[1]

[1]Coastal & Estuarine Engineering Research Center, Tianjin Research Institute for Water Transport Engineering, Tianjin, China
[2]CCCC Tianjin Dredging Co. Ltd, Tianjin, China

E-mail: shanshan.hhu@163.com

Abstract. Taking Guangli waterway engineering of Dongying Port as background, based on hydrodynamic and Euler-Lagrange theory, a numerical model of two-dimensional tidal current and oil spill diffusion is established and verified by measured data. According to different meteorological conditions, choose representative scenes, the drift range of oil film after oil spill accident and its influence on the surrounding water environment are predicted. Results show that: the range and track of oil film are closely related to the oil spilling time and wind direction. Under no wind condition, the oil sweep area is between 45 km^2 and 65 km^2 in 24h; Under strong wind direction of NW, the furthest distance to the southeast can be up to 23 km, and the oil sweep area is between 70 km^2 and 135 km^2 in 24h. Oil spills will have different effects on adjacent reserves. It is suggested that emergency response measures should be taken quickly in case of oil spills to minimize the adverse effects on the surrounding marine environment.

1. Introduction

Dongying is located in the Yellow River Delta region in the north of Shandong Province. The city has abundant oil, natural gas and marine resources. The second major oil field Shengli Oilfield is located in Dongying city. This waterway project is located in the estuarine area of Guangli River in Dongying city. It is one of the key development areas in Dongying port. The project is surrounded by lots of environmental sensitive areas, such as Yellow River Delta National Nature Reserve in Shandong province, Solenidae Ecological National Marine Reserve of Laizhou Bay in Dongying city and Lobworm Ecological National Marine Reserve in Guangrao, Dongying city. Once an oil spill accident occurs, it will have a serious impact on the surrounding marine environment, so it is of great practical significance to predict the oil spilling diffusion after the waterway project. In recent years, domestic scholars have carried out numerical simulation of oil spill diffusion for offshore, open sea and pipeline oil spills. Zhang and Li have summarized the progress of numerical simulation of oil spill [1,2]; Yu and Guo [3,4] have carried out model research around the near shore and offshore oil film drift diffusion. Li and Lin [5,6] has carried out model research on oil spill diffusion of submarine pipeline.

In this paper, based on the MIKE 21 hydrodynamic module (HD) and oil spill analysis module (SA) [7], numerical study on the tidal current and oil spilling diffusion of Guangli waterway engineering is carried out, which will provide reference for engineering design and relevant environmental assessment work.

2. Model Theory

2.1. Hydrodynamic model

The governing equations of the hydrodynamics follow the depth-averaged shallow water equations derived from the original three-dimensional Reynolds form, see equation (1) to equation (3).

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

$$\frac{\partial hu}{\partial t}+\frac{\partial hu^2}{\partial x}+\frac{\partial hvu}{\partial y}=f\bar{v}h-gh\frac{\partial \eta}{\partial x}-\frac{gh^2}{2\rho_0}\frac{\partial \rho}{\partial x}+\frac{\tau_{sx}}{\rho_0}-\frac{\tau_{bx}}{\rho_0}+\frac{\partial}{\partial x}\left(hT_{xx}\right)+\frac{\partial}{\partial y}\left(hT_{xy}\right)+hu_sS \tag{2}$$

$$\frac{\partial hv}{\partial t}+\frac{\partial hvu}{\partial x}+\frac{\partial hv^2}{\partial y}=-f\bar{u}h-gh\frac{\partial \eta}{\partial y}-\frac{gh^2}{2\rho_0}\frac{\partial \rho}{\partial y}+\frac{\tau_{sy}}{\rho_0}-\frac{\tau_{by}}{\rho_0}+\frac{\partial}{\partial x}\left(hT_{xy}\right)+\frac{\partial}{\partial y}\left(hT_{yy}\right)+hv_sS \tag{3}$$

Where: $h=\zeta+d$ is the total water depth; ζ 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. f is Coriolis force coefficient; ρ is water density; ρ_0 is the reference density; (τ_{sx}, τ_{sy}) and (τ_{bx}, τ_{by}) 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, large and small model nesting form is used. The large model includes the Bohai Sea, and the small model includes Laizhou Bay, China (figure 1). The open boundary is provided by *China Tide* offshore tidal prediction program, which developed by the Ocean University of China [8]. Unstructured triangular mesh is generated in this calculation domain (figure 2).

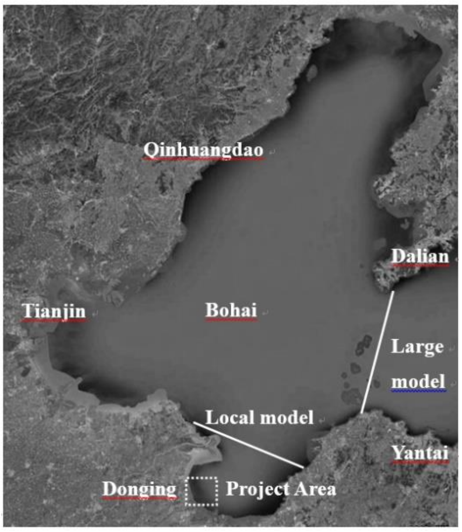


Figure 1. Location of the Project.

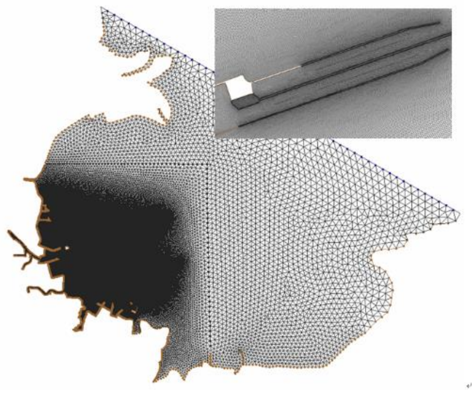


Figure 2. Mesh generation of local model.

The hydrodynamic numerical model is verified by the hydrographic measured data in 2008. Results show that the tidal level, current velocity and direction are in good agreement with the measured values, which meet the requirements of related specification [9]. Therefore, this numerical model can be used in the simulation of oil spilling diffusion. In order to save space, the verification is shown in reference [10].

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-Lagrange theory, the variation of the 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.

- Extended motion

Based on modified Fay Theory, oil film expansion is calculated using Gravity and viscosity Formula, see equation (4).

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

Where: A_{oil} is oil film area, $Aoil=\pi R_{oil}^2$, R_{oil} is oil film radius; K_α is coefficient (0.6 in this research); t is time; V_{oil} is oil film volume which can be calculated by equation (5); h_s is initial oil film thickness.

$$V_{oil} = R_{oil}^2 \cdot \pi \cdot h_s \tag{5}$$

- 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, see equation (6).

$$U_{tot} = c_w(z) \cdot U_w + U_s \tag{6}$$

Where: U_w is wind speed; U_s 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.

- 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 equation (7):

$$N_i^e = k_{ei} \cdot \frac{P_i^{SAT}}{RT} \cdot \frac{M_i}{\rho_i} \cdot X \tag{7}$$

Where: N_e is evaporation rate; k_{ei} is mass tranpoort coefficient; P^{sat} is vapor pressure; R is gas constant; T is temperature; M is molecular weight; ρ is the density of the oil component; X is mole fraction; i represents various oil components. k_{ei} can be estimated from the following formula equation (8)

$$k_{ei} = k \cdot A_{oil}^{0.045} \cdot Sc^{\frac{-2}{3}} \cdot U_w^{0.78} \tag{8}$$

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

- Dissolution

Assuming that the hydrocarbon concentration is negligible compared with the solubility, then the solubility of oil in water is expressed as follows in equation (9)

$$\frac{dV_{oil}}{dt} = K_{si} \cdot C_i^{SAT} \cdot X_{mol_i} \cdot \frac{M_i}{\rho_i} \cdot A_{oil} \quad (9)$$

Where: C_i^{SAT} is solubility of component i, X_{moli} is mole fraction of component i, M_i is molar mass of component i; K_{si} 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 can be calculated by equation (10):

$$D = D_\alpha \cdot D_b \quad (10)$$

$$D_a = \frac{0.11(1+U_w)^2}{3600} \quad (11)$$

$$D_b = \frac{1}{1+50\mu_{oil} h_s \gamma_{ow}} \quad (12)$$

Where: D_α is the component that enters the water body, see equation (11); D_b is the component that does not return after entering the water body, see equation (12); μ_{oil} is oil viscosity; γ_{ow} is the oil-water interfacial tension.

The return rate of oil droplets is shown in equation (13):

$$\frac{dV_{oil}}{dt} = D_\alpha \cdot (1 - D_b) \quad (13)$$

The variation of water content in oil can be expressed by the following equation equation (14):

$$\frac{dy_w}{dt} = R_1 - R_2 \quad (14)$$

$$R_1 = K_1 \frac{(1+U_w)^2}{\mu_{oil}} (y_w^{\max} - y_w) \quad (15)$$

$$R_2 = K_2 \frac{1}{As \cdot Wax \cdot \mu_{oil}} y_w \quad (16)$$

Where: y_w is the water content; R_1 and R_2 are water absorption rate and release rates respectively, which can be calculated by equations (15) to (16); A_s is Asphalt content in oil; W_{ax} is Paraffin content in oil; K_1, K_2 are absorption coefficient and release coefficient.

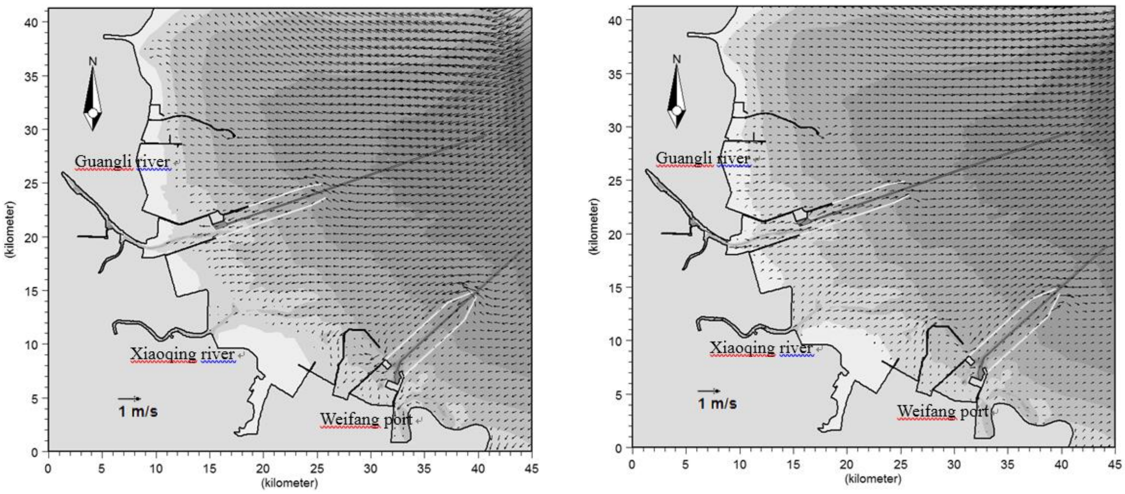
3. Hydrodynamic simulation results

Using the validated numerical model, large tidal current field during spring tide is shown in figure 3, the water depth in figures 3 to 5 is based on Theoretical Lowest Tide Level. The analysis is as follows: Tidal current in the project area shows reciprocating feature in the direction of W~E. After the construction of the waterway project, the current has a certain trend of returning to the channel due to dredging. The average velocity between the north and south dike is within 0.80 m/s, and the maximum velocity around the dike head is above 1.30 m/s. The average velocity in the harbor basin is between 0.10 m/s and 0.40 m/s, and the average velocity along the channel is between 0.30m/s and 0.60 m/s.

4. Oil spill simulation results

Based on hydrodynamic simulation, a 2-D oil spilling model of Guangli port was established by using MIKE21 SA module. The oil leakage source is 225 tons and it will be leaking over in 1 hour. The oil spilling point is located at the central line of the channel near the harbor entrance, oil spilling moment includes high water level (HWL) and low water level (LWL). According to the surrounding environment sensitive targets, we choose no wind condition, strong wind direction of NW and constant wind direction of SSE as the adverse direction to calculate the oil spilling diffusion range(figure 4~figure 6). The calculation cases are summarized in table 1, and the oil sweeping area is shown in table 2. Through analysis, some conclusions are made as follows:

- After the oil spill accident, the oil film sweep area and drift track are related to the oil leakage time. As time goes on, the oil film sweep area increases gradually. Under no wind condition, the sweep area of oil film is between 45 km^2 and 65 km^2 in 24h. The oil spill diffusion has a direct effect on the Solenidae Reserve, but has no effect on the other reserves around the project in 24h.
- Under wind condition, the oil film will drift significantly with different wind direction. The furthest distance under strong wind direction of NW is 23 km in 24h to the southeast, and the oil sweep area is between 70.0 km^2 and 135.0 km^2, the oil leakage has no influence on all the reserves. The furthest distance under normal wind direction of SSE is about 20 km to the north, and the oil spill sweep area is between 50.0 km^2 and 100.0 km^2, the oil leakage has direct effect on both Solenidae Reserve and Yellow River Reserve.
- Therefore, no matter under wind condition or not, the oil leakage will influence the adjacent reserves in different degrees. It is suggested that when the oil spill accident occurs, emergency response measures should be taken quickly, 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.



(a) (b)

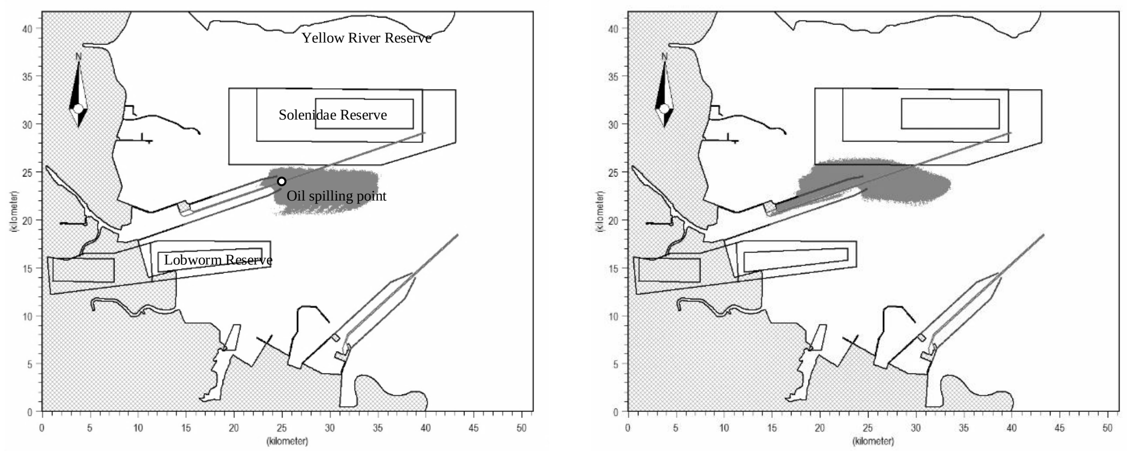
Figure 3. Large tidal current filed. (a) flood and (b) ebb.

Table 1. Oil spill prediction condition.

Case	Oil spilling point	Wind condition		Oil leakage moment
		Wind direction	Wind speed (m/s)	
1	Central line of the channel near the harbor entrance	No wind	-	HWL
2				LWL
3		NW	10.8	HWL
4				LWL
5		SSE		HWL
6				LWL

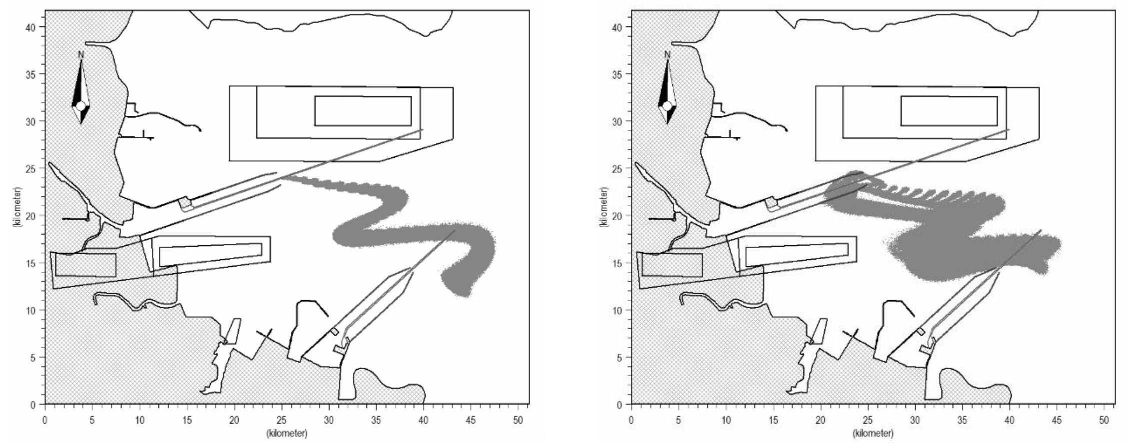
Table 2. Statistics on oil spill sweeping area and influence distance.

Case	Wind condition		Oil leakage moment	1-24h sweeping area (km^2)	Impact on environmental reserves
	Wind direction	Wind speed (m/s)			
1	No wind	-	HWL	45.5	Only influence Solenidae Reserve
2	No wind	-	LWL	56.9	The same as above
3	NW	-	HWL	69.1	No influence on all reserves
4	NW	-	LWL	133.1	No influence on all reserves
5	SSE	10.8	HWL	68.4	Influence both Solenidae Reserve and Yellow River Reserve
6	SSE	10.8	LWL	53.1	The same as above



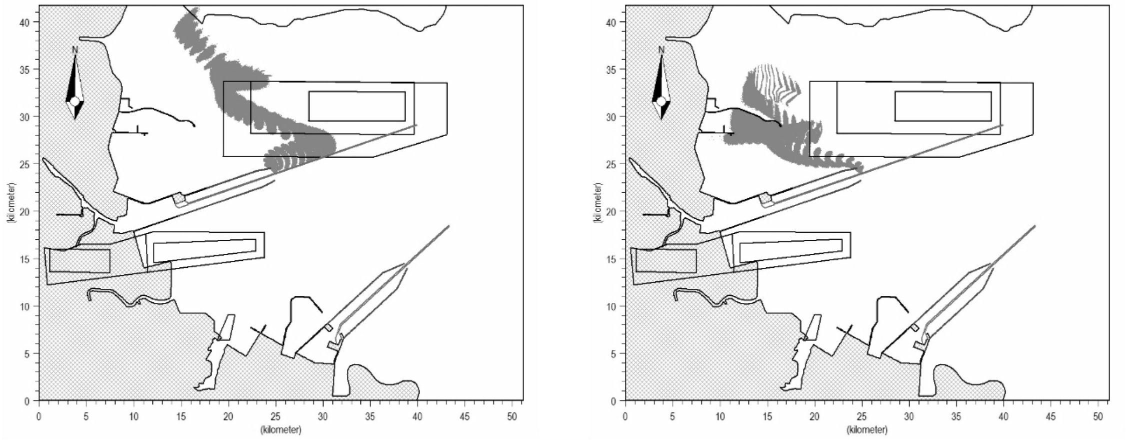
(a) (b)

Figure 4. Influence range of oil spill in 24h under no wind condition. (a) HWL and (b) LWL.



(a) (b)

Figure 5. Influence range of oil spill in 24h under NW wind condition. (a) HWL and (b) LWL.



(a) (b)

Figure 6. Influence range of oil spill in 24h under SSE wind condition. (a) HWL and (b) LWL.

5. Conclusions

In this paper, taking Guangli waterway engineering of Dongying Port as background, based on hydrodynamic and Euler-Lagrange theory, a numerical model of two-dimensional tidal current and oil spill diffusion is established and verified by measured data. According to different meteorological conditions, choose representative scenes, the drift range of oil film after oil spill accident and its influence on the surrounding water environment are predicted. The results show that:

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- It is suggested that when the oil spill accident occurs, emergency response measures should be taken quickly 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.

Acknowledgments

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