Numerical simulation of the environmental impact of oil spill in the Liuheng Island of Zhoushan City

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Abstract. At present, numerical models of 2D tidal current and oil spill have been widely used in simulating the diffusion and spread of spilled oil. Thus, this paper adopts the MIKE21_FM hydrodynamic model, and establishes a 2D tidal current dynamic model based on unstructured meshes in the Liuheng Island of Zhoushan city. After verification by the measured data, it can be found that this model can reflect the hydrodynamic characteristics perfectly, and provide sufficient hydrodynamic conditions for the simulation of oil spill. Based on that, the MIKE21/3 OS model is applied for predicting the risk of oil spill. Accordingly, 8 working conditions are simulated to track the spread and sweeping area of spilled oil. The results show that both oil spill time, tidal current and wind direction can affect oil diffusion, while wind direction is the most dominant factor. Moreover, the sweeping area increases gradually with time, and the maximum area reaches 2018.95 km² after 72 hours at ebb tide under the wind direction of WNW.

1. Introduction

With the rapid development of economy, China has built many large coastal ports along its coast. During the construction and operation of these ports, oil spill accidents may occur and have a huge negative impact on the surrounding marine environment, aquaculture industry, nearshore environmental sensitive area (e.g. natural reserves, wetland ecosystems, etc.). Oil spill is a complicated process, which can be affected by both climatic conditions such as temperature, visibility and wind, and the physical and chemical properties of oil[1]. In order to minimize its impact on marine environment, various numerical models have been proposed to study the drift, diffusion, behaviour and fate of oil spill.

To simulate the physical expansion process of oil, some scholars deduce formulas to calculate the expansion diameter from mass conservation relationship of oil[2]. Such method assumes that oil expands on a free plane, and considers the influence of oil gravity and volume. It can reflect the inertial expansion but ignore the surface tension and viscous force. Based on that, Fay fully considers the above factors, and believes that the expansion stages can be divided into three stages: gravity-inertial force stage, gravity-viscous force stage and surface tension-viscous force stage[3-4]. He
assumes that the sea surface is calm, and the nature of oil remains unchanged during expansion. Thus, a large-volume of spilled oil expands as a circle, and its expansion range can be measured by diameter. As a ground-breaking result, various improvements have been made on Fay’s theory by many scholars. For instance, Mackay and Matsugu develop Fay’s theory, and establish an empirical formula for evaporation considering both wind speed and oil volume [5]. A significant development of oil spill researches is the oil particle model proposed by Johansen [6] and Elliot [7]. The basic idea of this model is to regard the spilled oil as a massive number of small-volume discrete particles, and uses the particle motion to approximately simulate oil drift and diffusion process, where the particle motion is tracked by Lagrange method. In this model, each particle represents a certain amount of oil, and the mass loss can reflect oil evaporation, emulsification, and dissipation. Moreover, the total mass of oil is conserved, and the calculation principle is to track the path of the particles, so the oil particle model can simulate the actual diffusion phenomena directly. At present, several oil spill dynamic models have been developed considering oil drifting trajectory and its weathering process, such as Navy, OSCAR, MIKE21/3 OS, etc. [8-9]. This paper adopts MIKE21_FM model to establish a tidal flow mathematical model in the sea area around Liuheng Island, and validates the simulating results by measured data. Additionally, MIKE21/3 OS model is used to establish an oil spill model. It can simulate the oil expansion numerically, analyse the potential impacts on surrounding sea area, and provide effective references for the emergency response of the oil spill in this region.

2. Hydrodynamic numerical model

2.1. Hydrodynamic control equation

MIKE21_FM is a numerical model which can be applied in estuaries, bays and offshore tide current. It has been widely used in the simulation of two-dimensional flow field, and is adopted to simulate the hydrodynamics of the high-pilled wharf in the north area of Liuheng Island. Afterwards, the validated tidal data are input in oil spill module as the driving factor of hydrodynamic field. The continuity equation and momentum conservation equation are governing equations of hydrodynamic model used to describe flow field and tidal fluctuation, which can be given as follow:

\[ \frac{\partial \zeta}{\partial t} + \frac{\partial}{\partial x} [(h + \zeta)u] + \frac{\partial}{\partial y} [(h + \zeta)v] = 0 \]  
\[ \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} - fu = -g \frac{\partial \zeta}{\partial x} + \frac{\partial}{\partial x} (N_x \frac{\partial u}{\partial x} + N_y \frac{\partial u}{\partial y}) - f_b \frac{\sqrt{u^2 + v^2}}{h + \zeta}u \]  
\[ \frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + fu = -g \frac{\partial \zeta}{\partial y} + \frac{\partial}{\partial x} (N_x \frac{\partial v}{\partial x} + N_y \frac{\partial v}{\partial y}) - f_b \frac{\sqrt{u^2 + v^2}}{h + \zeta}v \]

Where \( x, y \) are two axes of the coordinate system; \( t \) is time; \( \zeta \) is water level relative to the datum plane; \( h \) is water depth relative to the datum plane; \( u, v \) are average vertical velocities in \( x, y \) directions, respectively; \( N_x, N_y \) are eddy viscosity coefficients of flow turbulence in \( x, y \) directions, respectively; \( f \) is Coriolis force coefficient, where \( f = 2\omega \sin \phi \), \( \phi \) is latitude, \( \omega \) is earth rotation speed; \( f_b = g/C^2 \) is bottom friction factor, \( C \) is Chezy coefficient; \( g \) is acceleration of gravity.

2.2. Calculation region and mesh generation

Liuheng Island is located in the southern Zhoushan sea area, which is 7.5 km west of Beilun, Ningbo, and 24.8 km north of Shenjiamen. Considering the selection of boundary conditions, the calculation region is larger than Liuheng Island, which is connected to Yangtze estuary in the north, Jiushan Island in the south, Shengshan Island in the east. The calculation model adopts unstructured triangle meshes, and the northwest harbour area of Liuheng Island is partially dense with a minimum mesh size as 20 meters. Thus, the entire region contains 34112 mesh nodes, 65111 mesh units, 2 tidal stations and 4 current stations (Figure 1). In addition, we apply a wetting-drying method to solve the
moving boundary problem, and an equivalent roughness method to generalize the piers of surrounding high-pile wharfs.

![Figure 1. Topographic map and meshes of the region (left); hydrometric stations (right)](image)

2.3. Validation of the model

In this study, the model is validated by using measured data (tide level and current data) in May 2020. The results show that the simulation fits well with field measurements, and the error of each station is less than 10%. Due to the limitation of space, the verification results of two stations (T1 and C2, which are close to the oil spill point) are given in Figure 2 and Figure 3. From these two figures, the proposed numerical model can reflect the actual situation perfectly and provide sufficient hydrodynamic conditions for simulating the oil spill.

![Figure 2. Model and measured water level data of observations at station T1 and T2](image)

![Figure 3. Verification of tidal current during spring tide at C2 station](image)

Surface flow field is the driving force for oil drifting on the sea surface. From the hydrodynamic calculation results, it can be seen that the spring current from the East China Sea rises to the calculation area from south. Being subjected to surrounding islands, the current flows through Liuheng, Xiazhi, Taohua and Zhujiajian islands successively, and the direction changes from N to SE. When the
current arrives Zhitouyang area (northwest of Liuheng Island), the flow direction changes from WSW to SE until it enters the Hangzhou Bay. The flow direction of ebb current is opposite to the spring current, but the route is basically the same as spring current.

3. Risk forecast model for the oil spill
The simulation of oil spill motion predicts the behaviour and fate of oil spill during drifting process, which provides the basis for emergency decision and evaluation. The behaviour and fate of oil can be affected by multiple factors, such as water current, wind, location and volume of oil spill, physical and chemical properties of oil, etc. The transportation and weathering of spilled oil is accompanied by heat migration of three phase (water, oil and atmosphere), and the properties of oil, such as viscosity and surface tension, also change continuously during the variation of oil composition and temperature. MIKE21/3 OS is a stable and efficient model which utilizes Lagrange method to track oil particles. It can simulate the drift trajectory, sweeping region and affected area of oil spill by simulating its expansion, transmission, turbulent diffusion, dispersion, evaporation, emulsification, and melting.

3.1. Behaviour and fate of the oil spill
The behaviour and fate of oil spill includes processes of spread, transport and weathering. Each process can be accompanied by the change of location and composition.

• Spreading process
The spreading process can be expressed by the following equation:
\[
\frac{dA_o}{dt} = K_s \cdot A_o^{1/3} \cdot (V_o / A_o)^{1/3}
\]
(4)
Where \(A_o\) is the area of oil; \(t\) is time; \(K_s\) is diffusion coefficient; \(V_o\) is the volume of oil.

• Transport process
Oil transport includes drift and turbulent diffusion, while oil drift is mainly driven by wind and current. The velocity can be calculated as follows:
\[
U_t = C_w \cdot U_w + U_s
\]
(5)
Where \(U_t\) is total velocity of oil particles; \(U_w\) is wind speed (10m above the sea surface); \(C_w\) is wind drift coefficient, generally takes 0.03–0.04; \(U_s\) is surface velocity.
Turbulent diffusion is an isotropic diffusion process at sea level, and its random moving equation is:
\[
S_a = [R]^{1/2} \cdot \sqrt{6D_a \Delta t}
\]
(6)
Where \(S_a\) is random moving distance within a time step in direction \(a\); \([R]^{1/2}\) are random numbers from -1 to 1; \(D_a\) is diffusion coefficient in direction \(a\); \(\Delta t\) is time interval of diffusion.

• Weathering process
Weathering process refers to the compositional change of oil residues due to physical and biological interactions over time. It mainly includes evaporation, emulsification and melting, etc. Evaporation process converts the light weight oil to a gaseous state, which can be expressed as:
\[
\frac{dQ}{dt} = (K_2 \cdot PA_o / RT) \cdot f_e \cdot M
\]
(7)
Where \(dQ/dt\) is evaporation rate; \(K_2\) is transmission coefficient of light weight oil \((K_2 = k \cdot A_o^{0.045} \cdot S_c^{2/3} \cdot U_w^{0.78}\); \(k\) is evaporation coefficient, \(S_c\) is Schmidt number; \(P\) is steam pressure; \(R\) is gas constant; \(T\) is temperature; \(f_e\) is evaporation fraction of oil; \(M\) is molecular weight.
Under strong wind or wave breaking conditions, emulsification can occur a few hours after the oil spill. The equilibrium process contains two stages in this model, which are water-in-oil and oil-in-water. The water content can be expressed by the following equation:
\[
Y_w = K_d \cdot (1 - e^{-K_a \cdot (1 + U_s)^2}) / K_B
\]
(8)
Where $Y_w$ is water content of emulsion; $K_d=4.5\times10^{-6}$, $K_b=1/Y_f$, $Y_f$ is final water content.

3.2. Calculation conditions for the oil spill

Ships can be damaged by a series of terrible accidents, such as collision, stranding, etc. These accidents can trigger oil spills and affect the marine environment. To simulate the oil spill, this paper assumes that 1000 tons of oil spilled from a 300,000 tons tanker, and the leakage point is located in the channel. The oil spill location and environmental sensitive points are shown in Figure 4. Moreover, the spilled oil simulated in this paper is fuel oil with the density of 970 kg/m$^3$. It can be further divided as volatile oil, heavy oil, wax and asphaltene, and the last two categories are non-degradable, non-evaporable, and insoluble in water.

![Figure 4. Oil spill source and sensitive points](image)

According to the long term meteorological data from the neighbouring Meishan Station, dominant wind directions in this region throughout the year are northerly wind (N~NE) and southerly wind (S~SSW), and the frequency of north wind is 18.6% with an average speed as 4.7 m/s. After further consideration of the relative location between oil spill point and sensitive points, three unfavourable wind directions (E, SW and WNW), are considered in this simulation. While the wind speed is selected as level 6 (10.8~13.8 m/s), which is the maximum speed during ship operations. Furthermore, different flow directions at spring tide and ebb tide can change the oil diffusion significantly. Such difference should be considered for the simulation of oil spill. Considering the above factors, we simulate oil spill under 8 working conditions. It can be explained as four wind conditions multiplied by two tidal conditions (spring tide and ebb tide), while the four wind conditions include one dominant wind direction, and three unfavourable wind directions. The working conditions are listed as: condition 1, spring tide, north wind (N), 4.7 m/s; condition 2, ebb tide, N, 4.7 m/s; condition 3, spring tide, east wind (E), 10.8 m/s; condition 4, ebb tide, E, 10.8 m/s; condition 5, spring tide, southwest wind (SW), 10.8 m/s; condition 6, ebb tide, SW, 10.8 m/s; condition 7, spring tide, west-northwest wind (WNW), 10.8 m/s; condition 8, ebb tide, WNW, 10.8 m/s.

4. Analysis of prediction results of the oil spill

This paper simulates oil diffusion process after an oil spill accident under 8 working conditions. The sweeping area of oil spill after 24h, 48h, and 72h are listed in Table 1, and the arrival times of oil particles under 8 working conditions from 0 to 72 hours are visualized in Figure 5.
Table 1. Sweeping area of oil spill.

| Condition | Wind | Tide time | Statistical time period |
|-----------|------|-----------|-------------------------|
|           |      |           | 24h | 48h | 72h |
| 1         | N    | Spring    | 261.95 | 916.1 | 1465.86 |
| 2         | N    | Ebb       | 407.87 | 1070.82 | 1665.85 |
| 3         | E    | Spring    | 205.65 | 603.99 | 772.60 |
| 4         | E    | Ebb       | 316.69 | 544.77 | 628.02 |
| 5         | SW   | Spring    | 176.24 | 708.23 | 1346.59 |
| 6         | SW   | Ebb       | 349.34 | 1158.39 | 1877.04 |
| 7         | WNW  | Spring    | 184.92 | 941.85 | 1891.51 |
| 8         | WNW  | Ebb       | 277.57 | 927.23 | 2018.95 |

- When oil spill occurs at spring tide under north wind, the oil spill first drifts to NE direction, and then moves to the south sea of Fodu Island. Under long-term effects of wind and tide, the oil spill reaches point MG1 after 22 hours, point MG3 after 29 hours, and region A after 35 hours. Under this condition, the sweeping area after 72 hours is 1465.86 km². When oil spill occurs during ebb tide under north wind, it spreads faster at the beginning, but become slower gradually. Thus, the oil reaches region B six hours earlier, and 1–9 hours later to the other five sensitive points than spring tide. The sweeping area during ebb tide is 1665.85 km², which is larger than that during spring tide.

- When oil spill occurs under east wind, the diffusion process is faster at ebb tide during the early stage, but spreads a broader range at spring tide after 72 hours. Moreover, when the oil spills at spring tide, it can affect the following sensitive points, which are MG1, MG3, MG4, MG5, and B; when it spills at ebb tide, it only affects point MG3. Furthermore, the strong east wind blows oil to the coast of Beilun. Since the coast can block and adsorb oil, less impact is made on marine environment, so the sweeping area after 72 hours is 772.60 km² at spring tide, and 628.02 km² at ebb tide.

- When oil spill occurs under southwest wind, the drifting path of oil spill at spring tide is basically consistent with that at ebb tide. The strong southwest wind blows spilled oil to the northeast sea around Liuheng Island at the beginning, and then spreads wider at ebb tide, drifting northward to the south of Zhoushan Island and east of Jintang Island. Additionally, all sensitive points or regions are affected by oil spill under this condition. Compared with ebb tide, the arrival time of spilled oil to MG3 is earlier at spring tide, by 6–18 hours later to the rest points. The sweeping area after 72 hours is 1346.59 km² at spring tide, and 1787.04 km² at ebb tide.

- When oil spill occurs under west-northwest wind, the oil slick mainly drifts to the southeast of Liuheng Island. Since this region is connected to the open East China Sea, few obstacles can block the fully spread of oil. For the impacts of spilled oil on each sensitive point, MG2 and MG3 are less affected under this condition, and the rest points are influenced within 14–40 hours. Similarly, the sweeping area after 72 hours is 1891.51 km² at spring tide, and 2018.95 km² at ebb tide.
Figure 5. Arrival time of oil particles during 0-72h period for 8 conditions

5. Conclusion
This paper uses MIKE21_FM model to establish a hydrodynamic model of the sea area near Liuheng Island, and simulates the characteristics of current field successfully. On this basis, a simulation of oil spill accidents is conducted on the north pier of Liuheng Island, and the impact of oil spill on surrounding waters is analysed. To simulate the drifting path and sweeping area of spilled oil accurately, 8 different working conditions are selected in this research. The results show that the drifting process is related to the occurring time of oil spill, characteristics of flow field and direction of wind. Among which, the direction of wind has greatest influence on oil drifting. Moreover, the spread
of oil can be affected by tidal currents. At the preliminary stage of oil spill, it spreads faster and further at ebb tide. Additionally, since wind direction is an important factor, the diffusion of oil under different wind directions is researched. Due to the obstruction and absorption of coastlines, the sweeping area under east wind is the smallest. On the contrary, west-northwest wind blows oil to the open sea at the southeast area of Liuhe Island, so the sweeping area is the largest after 72 hours, which reaches 2018.95 km².

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