Application of marine oil spill model based on Monte Carlo method in Laoshan Bay

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Abstract. The Monte Carlo method is used to simulate the random motion of oil particles, and it is more and more widely used in the oil spill model. The marine oil spill model established in this paper focuses on the two most important processes in the oil spill process: one process is to simulate the diffusion process of oil spill, whose main method is the Monte Carlo method; the other is to simulate the oil film drifting on the sea, which mainly considers the marine hydrological conditions during the oil spill, especially the transport of the wind field and the surface flow field to the oil film. After using this model to simulate an oil spill accident, in order to verify the accuracy, the mature simulation software Mike21 OS module is used to simulate the oil spill under the same conditions, and finally the two results will be compared and analyzed. In this paper, the improvement and innovation of the model design and calculation method are made. When considering the influence of the flow field on the oil film motion, the flow field at the corresponding moment of the oil particle is accurately calculated by the differential method, and the accuracy of the simulation is improved. The Euler-Lagrangian particle tracking method is used to determine the drift process of the oil film. The Monte Carlo method is used to simulate the diffusion process of the oil film and to establish the marine oil spill model. In the calculation, mainly by dividing the simulation process into a certain number of time periods, the motion of the oil particles under the influence of wind speed and flow velocity and the free diffusion motion are superimposed in each time period to obtain the motion distance of this time period.

1. Introduction

Due to the serious impact of oil spills on the ecological environment, research on marine oil spills has increasingly attracted the attention of experts in the marine field. The construction of the oil spill model is the key to the study of oil spills. The Fay (1969, 1971) oil spill model fully considers the influence of various forces on oil spill, and proposes a three-stage theory of classical oil film expansion [1]. In the subsequent development, the model is constantly revised, and the most influential one is the oil particle model proposed by Johansen and Anduson. The theory of this model is to discretize the oil spill film into a large number of oil particles, and each oil particle represents a certain amount of oil. The specific oil content of each oil particle depends on the amount of oil spilled and the number of oil particles [2]. At present, the "oil spill impact model application system" widely used in the United States, Australia and other countries. The Monte Carlo method is used for particle tracking, and the simulation effect is better in the two-dimensional direction of the sea surface. In recent years, domestic scholars have also made great achievements in oil spill research. By using the method of random particle to simulate the
turbulent diffusion of oil spill, Lou Angang and Xi Pangen obtain a good result in the diffusion simulation. The three-dimensional oil spill simulation was also constructed by the two researchers\cite{3}. Yang Hong and Wang Wei use the "two-stage method" to improve the accuracy in the calculation of the oil film diffusion area. They find that when the amount of oil spill is the same, the oil particles with different characteristic volumes had significant effects on the oil spill area \cite{4}. Guo Weijun et al. find that the fBm model has more advantages than the traditional Brownian motion method in the simulation of actual oil spill accidents, and its simulation results are closer to satellite prediction results \cite{5}.

The main function of the oil spill model is to predict the extent of oil film diffusion, sea sweeping area and the evaporation of oil spills after oil spill occurs. These simulation results can provide a scientific basis for emergency measures to reduce effect of oil pollution after the occurrence of oil spills. In the process of simulating the diffusion and drifting of oil spill on the sea, it can be assumed that the oil film on the sea surface is composed of many oil particles. The scattered area of the particles on the sea surface represents the area of oil film covering the sea surface. On the one hand, the oil film spreads around by gravity, inertial force, surface tension and sea surface turbulence. On the other hand, it is transported in a certain direction under the action of sea surface wind and surface current \cite{6}. Through such a model, a more accurate simulation of oil spills at sea can be performed.

2. Control equation of hydrodynamic model

The reliability and accuracy of hydrodynamic condition calculation is the premise of the subsequent oil spill calculation. For water bodies such as nearshore bays and lakes, the horizontal scale is generally on the order of 103–105m, while the scale in the vertical direction is generally on the order of 101–102m, and the relative water depth is obviously smaller, which leads to the flow change of the hydraulic element in the vertical direction is much smaller than the change in the horizontal direction. Therefore, the movement of such water bodies can be regarded as shallow water movement \cite{7}.

Basic equations

(1) Continuity equation
\[
\frac{\partial \xi}{\partial t} + \frac{\partial p}{\partial x} + \frac{\partial q}{\partial y} = \frac{\partial \eta}{\partial t} \tag{1}
\]

(2) Momentum conservation equation in the x direction
\[
\frac{\partial p}{\partial t} + \frac{\partial}{\partial x} \left( \frac{p^2}{h} \right) + \frac{\partial}{\partial y} \left( \frac{pq}{h} \right) + gh \frac{\partial \xi}{\partial x} + \frac{gq \sqrt{p^2 + q^2}}{c^2 h^2} - \frac{1}{\rho_w} \left[ \frac{\partial}{\partial x} (h \tau_{xx}) + \frac{\partial}{\partial y} (h \tau_{xy}) \right] - \Omega_p - fVV_y + \frac{h \frac{\partial}{\partial y} (p_a)}{\rho_w} = 0; \tag{2}
\]

(3) Momentum conservation equation in the y direction
\[
\frac{\partial q}{\partial t} + \frac{\partial}{\partial x} \left( \frac{pq}{h} \right) + \frac{\partial}{\partial y} \left( \frac{q^2}{h} \right) + gh \frac{\partial \xi}{\partial y} + \frac{gq \sqrt{p^2 + q^2}}{c^2 h^2} - \frac{1}{\rho_w} \left[ \frac{\partial}{\partial x} (h \tau_{xy}) + \frac{\partial}{\partial y} (h \tau_{yy}) \right] - \Omega_p - fVV_x + \frac{h \frac{\partial}{\partial x} (p_a)}{\rho_w} = 0; \tag{3}
\]

Where \(h(x, y, t)\) is the static water depth; \(C(x, y)\) is the Chézy coefficient; \(f(V)\) is the wind friction factor; \(\Omega(x, y)\) is the Coriolis parameter.

Through the above basic equations and open boundary tidal conditions, the surface flow field at each moment during the oil spill can be calculated for the establishment of the subsequent oil spill model.

In order to verify the accuracy of the above results, we can select a point to compare the calculated results with the actual tide level. The verification results are shown in Figure 1. The dotted line is the calculated tide level value, and the point is the actual observation value at each moment. The coordinates of the tidal observation point are 120°43’E, 36°19’N, and the time is from 0:00 to 24:00 on January 9, 2018. The comparison shows that the amplitude and phase of the actual tide level at this site are basically consistent with the calculated values.
3. Oil spill model based on Monte Carlo method

After the oil spill accident at sea, on the one hand the oil film drifts by the wind field and the surface flow field, and on the other hand, it spreads to the surrounding itself, which can be simulated by the Monte Carlo method\(^8\). For the diffusion process, the Monte Carlo method is used to study the oil spill, and the motion of the oil particle is regarded as a simulation of a Wiener process in mathematics\(^9\). The time step can be set as \(\Delta t > 0\),

\[
X_n = X_{n-1} + \sigma \sqrt{\Delta t} W_n (\sigma > 0)
\]

where \(\{W_n\}\) is an independent \(N(0,1)\) random number\(^{10}\). The increment \(X_n - X_{n-k}\) depends only on the \(k\) variables (\(W_{n-k+1},...,W_n\)) corresponding to \((n-k,n)\), \((k<n)\), so that \(X_n - X_{n-k}\) has \(N(0, \sigma \sqrt{\Delta t})\) distribution.

For the drift process of the oil film, the position of each particle at different time can be calculated according to the following formula. The envelope of these particles is used to show the shape, drift trajectory and influence range of oil film diffusion after oil spill\(^{11}\).

\[
X = X_0 + (U + aW_{10} \cos A + r \cos B) \Delta t
\]
\[
Y = Y_0 + (V + aW_{10} \sin A + r \sin B) \Delta t
\]

Where \(\alpha\) is the correction coefficient; \(r\) is the random diffusion term, \(r=RE\), \(R\) is a random number between 0 and 1, \(E\) is the diffusion coefficient; \(B\) is the random diffusion direction, \(B=2\pi R\).

4. Oil spill simulation

According to the theoretical method mentioned above, in this oil spill accident, 100 tons of diesel oil is simulated to leak at a uniform speed within one hour. The oil leakage point is located at 36.40°N, 120.78°E, and 0.5 m below sea level. The oil spill point is located in Laoshan Bay. The simulated wind direction was constant at 330 degrees within 48 hours after the oil spill, and the wind speed was constant at 7 m/s. In this oil spill accident, the number of simulated particles is 1000, and the simulating time is 48 hours.

In order to meet the convenience the distance calculation, the maps in Laoshan Bay and its adjacent sea areas in latitude and longitude coordinates are converted into maps under the Mercator projection, which is maps in UTM coordinates.

After the oil spill occurs, the oil film on the sea surface drifts under the joint action of the surface flow field and the wind field. Since the wind field is constant, the wind direction and wind speed do not change over time. The flow field is constantly changing with time, so the oil particles are constantly changing under the influence of the flow field at different times. By subdividing the time, and then accumulating the time and direction of the oil film in each tiny time period, the changes accumulate and finally the position of the oil film at different times is obtained. Figure 3-8 shows the position and diffusion range of the oil film on the sea at 1h, 3h, 9h, 18h, 24h and 48h after oil spill occurred.
Fig 2 The place of the spilling point

Fig 3 The place of slick after 1h

Fig 4 The place of slick after 3h

Fig 5 The place of slick after 9h

Fig 6 The place of slick after 5h

Fig 7 The place of slick after 6h
After simulating the drift trajectory of the center of the oil film and the position at which the oil film finally arrives, we superimpose the position of the oil film at different times to obtain the sea-sweeping area of the oil film, as shown in Fig. 10. From this, we can clearly see the sea area polluted by the oil within 48 hours after the oil spill, so that combined with the functional zones of each sea area, it can be determined which area has a greater impact, and which area less affected. It is also possible to take measures to promote the decomposition of the oil film in the area where the oil film is to be reached, so that the oil film can disappear sooner and reduce the impact on the marine ecological environment.
Fig 11 The trajectory of slick center Mike21 simulation.

The simulation results of the above oil spill model are compared with the results of the simulation of Mike21. By comparing the simulation results of the two numerical simulation methods, it can be seen that the oil film center finally arrives at the same position in the same time, and the overall trend of drift is the same, both toward the southeast direction, as shown in Fig. 11. In addition, the trajectories of the center of the oil film drawn by the two methods across the sea surface during the drift process are also basically the same, as shown in Fig. 12. This also proves that the method used in this paper is more reasonable and more accurate.

Fig 12 The final position of slick under Mike21 simulation

5. Conclusion

In this paper, the tidal currents in the Laoshan Bay waters during the oil spill are simulated by the shallow water equation and the boundary tidal conditions. Then the Euler-Lagrangian particle tracking method and particle random diffusion theory are applied to simulate the oil spill, and finally the Monte Carlo method based marine oil spill model is established.

Based on the above theory, the oil spill analysis model of the Laoshan Bay sea area was established, and the simulation results of the model were compared with those of the Mike21 oil spill module under the same environmental factors. The comparison shows that the results obtained by the two simulations are basically consistent, which proves the accuracy and reliability of the model built in this paper.
In the process of calculating the oil film motion according to the tidal current field, the flow velocity at any point can be calculated from the flow velocity at a finite point by the differential method, and the accuracy of the motion path calculation is improved. Compared with the previous Monte Carlo particle tracking method, this paper abandons the method of using equal concentration lines to represent the oil spill diffusion range, but uses a more accurate triangulation method to represent the diffusion area.

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