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Abstract. With the construction of reservoirs in China, inland waterway conditions have been greatly improved. The number of ships and tankers navigated in the inland waterways significantly increased which may lead to an increased risk of oil spill accidents. Oil pollution is one of the major threats to economy and ecosystem. To date research on oil spill is mainly focus on marine environment, however it is very limited on inland river. The purpose of this study is to combine our previous liner experimental study of characteristic of spread and transport of oil spill to develop a coupled two-dimensional oil spill model. An oil trajectory model has been conducted and applied for water surface spread simulation in the Luoqi reach of Yangtze River. The results can provide a reference for the prediction of spread and transport of oil spill in inland waterway.

1. Introduction

Oil spills caused by accidents of oil tankers or marine vessels occurred frequently. It is reported that from 1977 to 2002, there were 63 oil spills of more than 50 tons in China's coastal ships and wharves [1]. Once the oil spill accident occurs, it will cause serious ecological damage and economic losses. In recent years, after a large number of reservoirs have been built, the transportation condition in inland waterway has been improved greatly, the number of ships has increased and the water accidents often occur which may lead the risk of oil pollution. After the impoundment of the Three Gorges Reservoir(TGR), the Yangtze River has become the golden waterway with the largest inland river freight volume in the world. According to statistics, from 2010 to 2017, only the Chaotianmen-Changshou reach of Chongqing had 22 average accidents. Ship collision and grounding may cause serious oil spillage, which has aroused widespread concern worldwide[2-4].

When oil spilled into the water, it undergoes a complex process, including physical, chemical and biological changes[5], such as diffusion, drift, evaporation, emulsification, dissolution, dispersion, sedimentation, shore adsorption, photo-oxidation and biodegradation[6]. The fate of spilled oil in the water depends upon factors such as quantity spilled, the oil's initial physical and chemical properties, the prevailing climatic and flow conditions and whether the oil remains at river or is washed ashore [7]. Compared with the marine environment, inland waterway has the characteristics of narrow river width, and prominent convection. More attention has been paid to the impact of oil spill and emergency measures in the short term, so the emphasis was focused on the effect of convection and wind. In order to respond quickly and effectively after an oil spill and determine impact risks from different potential pollution sources, an accurate numerical oil spill model is essentially required[8]. The previous oil spill simulations mainly focused on marine environment, so the research on oil spill in inland waterway is still needed.

In our present work, a coupled two-dimensional oil spill model considering the effects of convection and wind are presented, and our previous experimental data was adopted in verifying the model, simulation results of the oil trajectory maps were plotted and analyzed. The results gained through these efforts are hoped to provide reference for the prediction of spread and transport of oil spill in inland waterway.

2. Material and methods

2.1. Experimental results

Jiang et al[9] have carried out the experimental study on characteristic of spread and transport of oil spill in inland waterway. Firstly, the relationship between oil film color and average thickness is established. Secondly, the quantitative relationship between the average thickness, area and time of oil spill film is established. The average thickness of oil spill film is a power relationship with time, and the oil spill area is linearly related to time. The experimental oil types adopted in experiment were lubricating oil and petroleum ether, only the experimental analysis results of lubricating oil are shown here. The experimental results and analysis can provide a basis for the verification of oil spill model in inland waterway.

With the continuous diffusion of oil film, its shape will become more and more irregular, which makes it difficult to measure its area. However, if the gray value of oil film is known, the average thickness of oil film can be indirectly calculated by the formula as $h=0.0069x^2-2.6488x+229.28$.Where x is grayscale value, h is the average thickness of oil slick, 10^{-2}mm.According to the experiment results, after analysis and fitting, a power law relation was found between the average oil film thickness(h/h_0) and time(t/t_0), the formula is $S/S_0=\alpha(t/t_0)+\beta$, and the oil film area (S/S_0) is linearly correlated with time (t/t_0), the formula is $h/h_0=\xi(t/t_0)^{-\eta}$.

Where h is oil slick mean thickness (mm), h_0 is the initial film thickness(mm),t is the time(s), t_0 is the total time of oil spill diffusion (s). S, S_0 are oil film area and 17s final oil film area (m^2), respectively, ξ,η,α,β are parameters related to water flow velocity and oil mass. The value range of ξ is 0.0460-0.1704, the smaller the value, the faster the attenuation rate of oil film average thickness. When the value range of η is 0.634-1.478, the smaller the value, the faster the average oil film thickness attenuation rate[9].

2.2. Model development

In this paper, the oil model is established by combining the non-uniform flow model with the oil particle model, the flow model refers to the non-uniform flow model established by Tang et al[10]. Based on the Lagrangian theory of oil particle model, the oil film is discretized into many oil particles, the volume of the oil particle can be expressed as follows.

$$V_i=\frac{\pi}{6}(d_i)^3 \tag{1}$$

Where V_i , d_i are the volume and diameter of the i_{th} oil particles, The volume percentage(f_i) of the oil particles in the total volume of the whole oil film is as follows.

$$f_i=\frac{\frac{\pi}{6}(d_i)^3}{\sum_{k=1}^{n}\frac{\pi}{6}(d_k)^3} \tag{2}$$

Where n is the total number of oil particles. The characteristic volume of each oil particle is V_i, $V_i = f_i V_0$, V_0 is the initial volume of spilled oil.

When the oil enters the water, the oil film will quickly spread around under the influence of gravity, inertial force, viscous force and surface force. The modified Fay gravity-viscosity formula is adopted to calculate the related parameters of diffusion process of oil film.

$$\frac{dA}{dt} = K_0 A^{1/3} (\frac{V_0}{A})^{4/3} \tag{3}$$

In Eq.(3),*t* is time(s),*A* is the area of oil slick(m^2),K_0 is the coefficient, take150(s^{-1}) ,V_0 is the volume of oil , $V_0 = \pi R_0^2 h_0$.The drift of oil slick is the overall movement of many oil particles driven by external power. For the mountainous River, the main dynamic factors affecting the drift are water flow and wind. The transport velocity of oil particles can be calculated according to the following formula.

$$V_P = V_f + aV_w \tag{4}$$

Where V_p is the translation velocity of oil particles (m/s), V_f is the flow velocity (m/s), V_w is the wind speed at 10m above the water surface (m/s), *a* is the wind factor. In the model, the influence of wind on oil film is generally calculated as 3% ~ 4% of the wind speed[11]. Assuming that the diffusion of oil particles in water is isotropic, the drift distance of oil particles in horizontal direction in a time step can be expressed as follows.

$$S_0 = R\sqrt{6D_0 \Delta t} \tag{5}$$

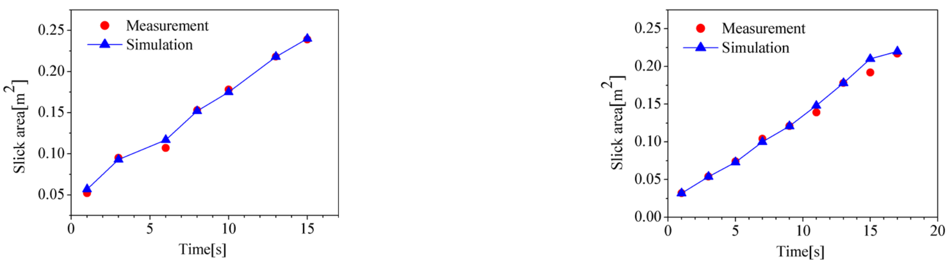
Where S_0 is the drift distance (m), *R* is a random number from -1 to 1; D_0 is the horizontal diffusion coefficient. The distance S_t of oil particles in each time step can be calculated by the following formula. The model is built by FORTRAN language.

$$S_t = V_p \Delta t + S_0 = (V_f + \alpha V_w)\Delta t + S_0 \tag{6}$$

2.3. Calibration and validation of the model

To calibrate and verify the horizontal diffusion coefficient D_0 of oil film in the model, two experimental scenarios were selected for simulation, the method is to change the size of D_0 and display the simulation results in AutoCAD software, then manually measure its area, and comparing repeatedly with the oil slick area measured by experiment until they are basically consistent.

Finally, the calibration result of diffusion coefficient of lubricating oil was D_0=3.0× 10^{-4},one case was selected to calibrated, the deviation is within 15%,another case was used for verification, the result of error analysis is 8%, which indicated that the oil model in current study can be adopted to simulate the diffusion of oil spill in inland rivers, and the comparison of oil spill test data and model calculation results are shown in Fig. 1.



(a)Calibration (v=0.20m/s, m=29.3g) (b) Verification (v=0.15m/s, m=41.7g)

Fig. 1. Comparison of numerical simulation and experimental results

3. Results and Discussion

3.1. Study area and wind data

The TGR is a super-large reservoir, the length of the perennial backwater area is about 400 km (from dam to Fuling) and the fluctuating backwater area is about 250 km (from Fuling to Jiangjin). The TGR covers Hubei Province and 21 counties and cities in Chongqing, with a total area of about 1084 km^2. When the water level reaches 175m, the reservoir capacity is about 22.1×10^8 m^3 [12]. The construction of the TGR has greatly promoted the economic development of the Yangtze River Basin. Since its operation in 2003, the TGR has played an important role in flood control, power generation and navigation. By the end of 2011[13], there are 50 domestic water intakes, one aquaculture farm, one Nature Reserve, 14 tourist attractions and 62 industrial water intakes in the TGR area from Chongqing to Wushan. The key point of the national strategy is to protect the environment of the TGR. At the same time, with the demand of economic development, the number and throughput of dangerous chemical terminals in the TGR area increased year by year [14] , leading to the risk of oil spill at the wharf; the increase of ship flow led to the increase of water traffic safety risks. Therefore, it is necessary to simulate and predict the oil spill trajectory in inland waterway.

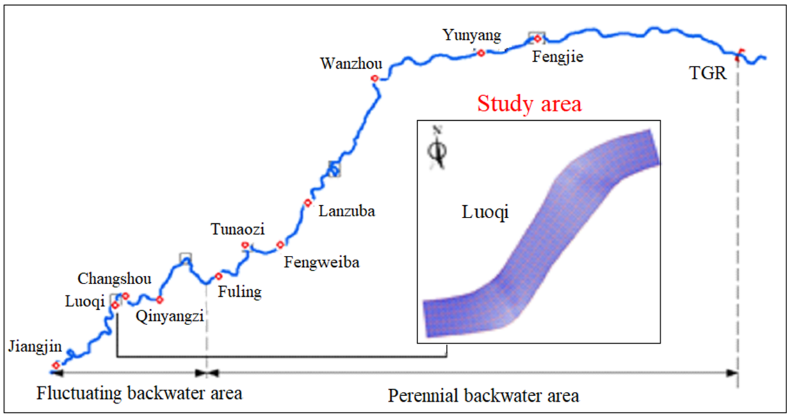


Fig. 2. Sketch map of the locations of the Yangtze River and the study area

A small reach (Luoqi reach) located in fluctuating backwater area is selected to simulate the trajectory of oil spill, the sketch map of the locations of the Yangtze River and the study area are shown in Fig.2. Luoqi reach is located about 50 km downstream of Chongqing, with a total length of about 8.6km. Because Luoqi reach is close to Chaotianmen port, there are many ships entering and leaving the port, which cause the heavy traffic, the risk of oil spill is increased. In in inland waterway, wind is another important factor of impact on the spread and drift of oil spill. The dominant wind direction in May,2018 is “W” and the frequency is 14.71%, the mean velocity in the corresponding direction is 0.63m/s.

3.2. Simulation results

According to the actual flow velocity distribution of the TGR area, the simulation of oil spill was carried out. The model simulation information was shown in Table 1. At May 28,2018, the discharge of Luoqi reach is 6180m^3/s, with 154.0m tail water level, the oil spill mass is 300kg, and the time interval is 20s. The simulation results are expressed in CAD form, as shown in Fig. 3.

When the oil spill touches the water, it diffuses itself in a short period of time, and then drifts simultaneously driven by the flow field. May 2018 is in flood season, with larger flow, lower water level and relatively higher flow velocity, ranging from 0.5~1.6m/s. After 10000s, the oil film has drifted out of the simulated reach.The drift trajectory of the oil spill film is roughly the same as that of the mainstream of the river, as shown in Fig.3(a). Because the oil film is greatly affected by the water flow in the shear diffusion process, the convection has a significant impact on the shape change of the oil film. When the flow velocity is lager, the shape of oil film becomes narrow and long, as shown in Fig.3(b). When the flow velocity shifted from fast to slow, the oil film diffused along the vertical direction of the velocity. The influence of wind on the drift direction of oil film is not obvious, as shown in Fig.3(c), the oil film shows an obvious trend of drift with the flow direction. When the flow velocity is large, the oil spill drifts fast and the distance is long, so it is difficult to conduct on-site containment. This requires appropriate emergency measures to be taken in a short period of time, to protect the sensitive waters such as the water intake and nature reserve as soon as possible. In addition, the oil spill should be intercepted in the lower reach of the accident site with relatively slow flow velocity, and the oil containment boom should be used to prevent the oil spill from escaping.

Table 1. Basic conditions of numerical simulation of oil spill model

River reach	Date	Tail water level(m)	Discharge(m^3/s)	Mass(kg)	Oil Type
Luoqi	May 28, 2015	154.0	6180	300	Lubricating oil

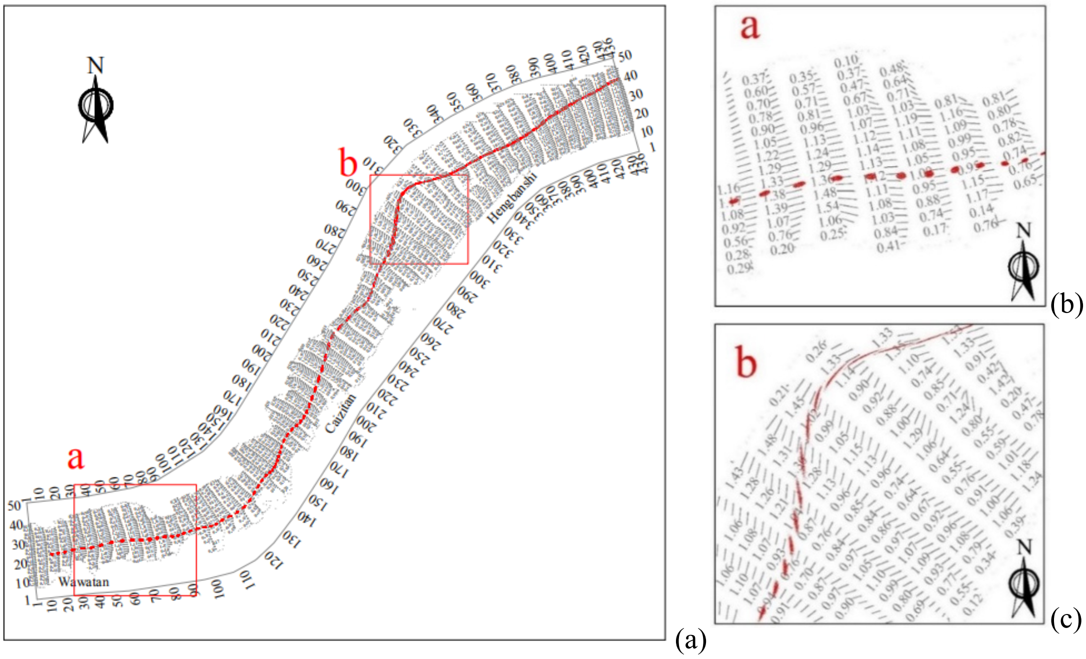


Fig. 3. Simulation results of oil spill drift trajectory

4. Conclusions

In this paper, combined with our previous experimental study, the diffusion coefficient in the oil model is calibrated and verified by comparing the calculated and measured oil film area. The results show that the deviation is less than 8%, which means that the model can be used for simulating the oil spill trajectory in inland waterway. Luoqi reach, where ship collision accidents occur frequently, is selected as a typical reach to study the application of oil spill in inland waterway. The simulation results show that the oil film drift distance and direction are mainly affected by the size and direction of flow velocity, and the influence of wind is not obvious. In addition, the convection has a significant impact on the shape change of the oil film, when the flow velocity is lager, the shape of oil film becomes narrow and long.

In the process of spread and drift of oil spill in the river channel of the reservoir area, the oil spill will be adsorbed to the beach land and concave bank boundary where the water flow exchange is slow, and the contaminants are difficult to self-purification. Therefore, the adsorption effect of the river bank on the oil spill is a prominent problem that needs to be considered in the diffusion of spilled oil in inland waterway. This model only focuses on the influence of flow on the diffusion and drift of oil spill, and the adsorption on boundary has not been considered. In future work, the study on the mechanism of oil film adsorption on shore is necessary. There are certain limitations to verifying the applicability of the oil model through experimental data. In addition to the basic research that requires to develop and refine existing physical model, every effort should be made during riverine oil spills to gather the leakage information that could be used to help validate the oil spill numerical models envisioned for the future.

In the follow-up study, oil spill in the vertical elevation also needs to be considered by carrying out the three-dimensional analysis. Hydrodynamic model, water quality model and GIS visualization technology need to be integrated to improve the presentation effect of the analysis results.

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