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NUMERICAL SIMULATION STUDY OF OIL SPILL DIFFUSION IN THE QUANZHOU BAY AREA BASED ON AN OIL PARTICLE MODEL

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NUMERICAL SIMULATION STUDY OF OIL SPILL DIFFUSION IN THE QUANZHOU BAY AREA BASED ON AN OIL PARTICLE MODEL

Xiao-Feng Guo, Chu-Han Chen, Jun-Jian Tang, and Zhou-Hua Guo

Key words: Quanzhou Bay, oil particle model, oil spill, numerical simulation.

ABSTRACT

Based on a two-dimensional tidal current mathematical model, this study used the oil particle method to establish an oil spill model in the Quanzhou Bay area to simulate the oil film drift path and degree of impact after the oil spill under various tidal conditions, i.e., the maximum flood, spring tide, maximum ebb and low tide in a tidal cycle under conditions of calm wind, the prevailing northeasterly wind in winter and the prevailing southwesterly wind in summer. The simulation results indicate that the drift trajectory of oil film in the Quanzhou Bay area was primarily influenced by the position of the oil spill point, wind conditions and tide when the oil spill occurred: marine areas of approximately 40-117 km^2, 18-117 km^2, and 51-159 km^2 were affected by the oil film in 12 hours in a NE wind-driven current in winter, a SW wind-driven current in summer, and calm wind conditions, respectively. This study provides the scope and degree of influence of possible oil spill accidents in the Quanzhou Bay area and the time intervals between when an oil spill occurs and when sensitive targets become affected. This work offers scientific support for decision making and environmental damage assessment for oil spill emergencies, as well as useful exploration criteria for the accurate simulation of oil spill diffusion at sea.

I. INTRODUCTION

With the fast-paced economic development around the world, marine oil spill accidents have become increasingly frequent (Wang et al., 2014) in recent years. Oil spill diffusion at sea is a highly complex process subject to the physical and chemical properties of oil, the weather conditions at the accident site, and the hydrodynamic characteristics. Because of these combined effects, the oil in water will experience a series of processes, such as spreading, drifting, diffusion, evaporation and dissolution (Zhu, 2012). The early oil spill model of the 1970s was mainly based on a "three-phase spread model of oil slicks" in a calm sea or constant current environment (Fay, 1969). Numerous improved models taking into consideration the impacts of actual marine environmental dynamics have been proposed by numerous scholars (Lou et al., 2000; Yang and Yin, 2000; Lehr et al., 2002;Yang et al., 2007; Zang, 2011; Huang et al., 2013). At present, the oil spill calculation model fully considers various factors, including the oil properties, the settling process and other factors related to ocean currents, wind and spilled oil weathering. Currently, scholars at home and abroad primarily adopt the Mike 21/3SA, DELFT 3D and OIL MAP models to simulate and predict the spatial and temporal distribution and trace the travel distance of oil slicks after oil spill diffusion (Huang et al., 2011; Pan et al., 2011; Qi et al., 2015). To date, to meet the increasingly stringent requirements for the accuracy of oil spill prediction, the "oil particle" model, which combines the spreading of oil slicks caused by their own properties and the dispersion due to environmental dynamics (Liu et al., 2005), was forwarded. This oil particle model is built on the concept that the spilled oil can be divided into innumerable oil particles and each particle represents a certain amount of oil (Cai, 2010). The spatial position of each oil particle at specific moment is observed by tracking the particle trajectory in the flow field, and the spatial distribution of the oil spill at specific moment is obtained based on the statistics of the oil particle positions (Chen, 2008). Therefore, this model can provide an accurate simulation of the actual condition, and the calculation accuracy is significantly improved compared to other models.

Quanzhou Bay is located off the center of the southeastern coast of Fujian Province in China (Fig. 1). It is surrounded by Huian County to the northeast, Quanzhou City to the northwest, and Jinjiang City and Shishi City to the southwest, and adjoining the Taiwan Strait on the east. Quanzhou Bay has a wide mouth and winding shorelines. The bay mouth opens to the southeast, with Dazhui and Xiaozhui islands located in middle of the entrance. Quanzhou Bay is an open bay. The Quanzhou Bay artificial island port district is on the Xiesha Shallow at the center of the bay mouth, running from east to west and being primarily parallel to the tidal current. Several 50,000-ton multifunctional berths were planned along the southern coastline (Guo 2011;

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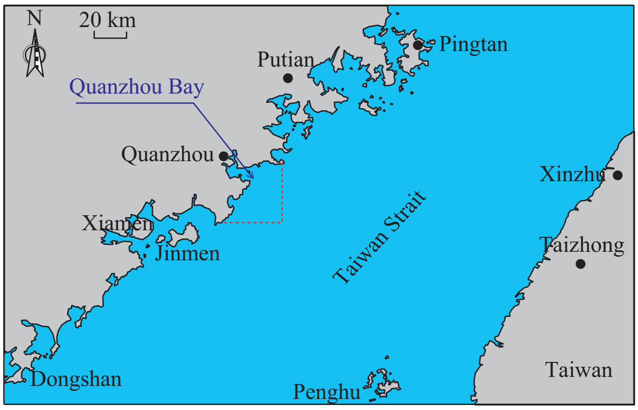

Fig. 1. Geographical location of Quanzhou Bay.

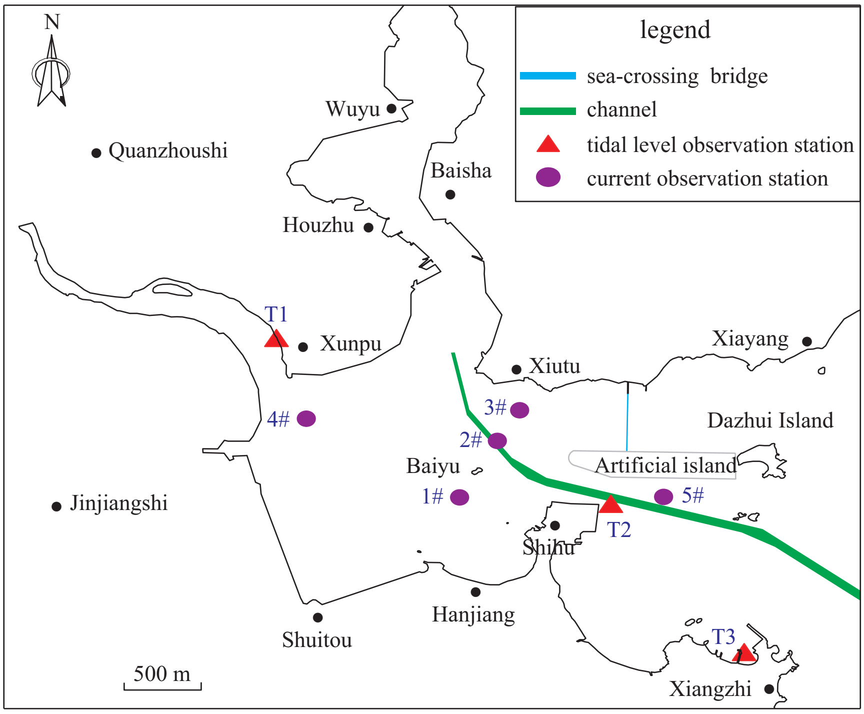

Fig. 2. Locations of the Quanzhou Bay artificial island and hydrometric stations.

Fig. 2). An oil spill accident will have a severe impact on the marine ecological environment because the artificial island port area is in the bay mouth, and ecologically sensitive districts, such as the Quanzhou Bay Estuarine Wetland Provincial Natural Conservation Area, are also located in Quanzhou Bay. This study used an oil particle model based on the two-dimensional tidal current field to study the drift and diffusion of oil slicks caused by possible oil spill accidents in the Quanzhou Bay artificial island port area. The proposed model has great practical significance and is valuable for accurate simulation of oil spill diffusion at sea.

II. NUMERICAL TIDAL CURRENT MODEL

1. Model Control Equations

The following two-dimensional shallow water equations in plane rectangular coordinates were used to simulate the tidal current field:

$$\frac{\partial \eta}{\partial t} + \frac{\partial}{\partial x}(Hu) + \frac{\partial}{\partial y}(Hv) = 0 \quad (1)$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -g\frac{\partial \eta}{\partial x} + fv - ru + A_x\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) \quad (2)$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -g\frac{\partial \eta}{\partial y} - fu - rv + A_y\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) \quad (3)$$

where x and y are plane rectangular coordinates; t is the time; H is the water depth ($H = d + \eta$); d is the water depth beneath the mean water level; η is the water level; u and v are the directional components in the x and y directions respectively; $u = (1/H)\int_{-h}^{\eta} u'dz$ and $v = (1/H)\int_{-h}^{\eta} v'dz$ are the average flow velocities at water depth; g is the gravitational acceleration; f is the Coriolis parameter; r is the bottom friction coefficient; c_n is the Chézy coefficient, which equals to $c_n = H^{1/6}/n$ in $r = g\sqrt{u^2+v^2}/c_n^2 H$; n is the roughness coefficient of the seabed; and Ax and Ay are the viscosity coefficients of horizontal movement in the x- and y-directions respectively. Eqs. (1)-(3) were solved by the semi-implicit finite difference method proposed by Cassulli and Chen (1992) and others (Casulli and Cheng, 1992; Casulli and Cattani, 1994; Oliveira and Baptista, 1995; Casulli and Zanolli, 1998; Zhang et al., 2004; Tang and Wen, 2006; Tang et al., 2011).

2. Boundary and Definite Conditions

The coastal line is a solid boundary. The flow velocity in the normal direction is zero. The tidal flat is represented by a variable boundary. The water level of the open boundary of the tidal current field is controlled by the tide level of the tidal current field in the Taiwan Strait.

3. Computational Domain and Associated Identification

Fig. 3 shows the computational scope of the extended marine area and non-structural mesh schematics for Quanzhou Bay in the simulation, which includes the marine area to the east of Weitou and south of Chongwu and the entire Quanzhou Bay. The meshes were refined for the marine area near the Quanzhou Bay construction site. The maximum and minimum mesh sides were approximately 1,000 m and 5 m respectively. The overall mesh nodal was approximately 20,000, with approximately 40,000 meshes. The coastline is a solid boundary. The flow velocity in the normal direction is zero. There are two cross sections in the fluid open boundary of the open sea: one control point is secured as the SE point at the southeastern corner of the computational marine area; the southern side of the open boundary section is defined by the connecting line of Weitou and the SE point; and the the eastern side, the connecting line of the SE point and Chongwu. The water depth of the open boundary is controlled by the tide level of the tidal current field of the Taiwan Strait.

Simulation data ofthe tidal level and current were taken from the flow measure of spring tide and real testing data of the synchronization tidal level in 2009. The locations of the hydrological observation stations are shown in Fig. 2. Tidal level stations were located at Xunfu, Shihu and Xiangzhi. There were five tidal current observation stations. Stations 1 through 3 were located at both sides of the artificial island, station 4 was located at the Jinjiang River estuary and station 5 was located at the edge of the main navigation channel.

Fig. 4 shows the computational and observed data of the tidal level during flow measurements of the spring tide at the Xunfu, Shihu and Xiangzhi temporary tidal level stations in February 2009. The tidal curve obtained in the model corresponds well with that based on the observed values. Fig. 5 shows the identification curve diagram between the simulated and observed values at tidal current stations No. 1 through 5 in February 2009. The computational values of slow velocity and direction generally accorded with the observed values. Thus, the results

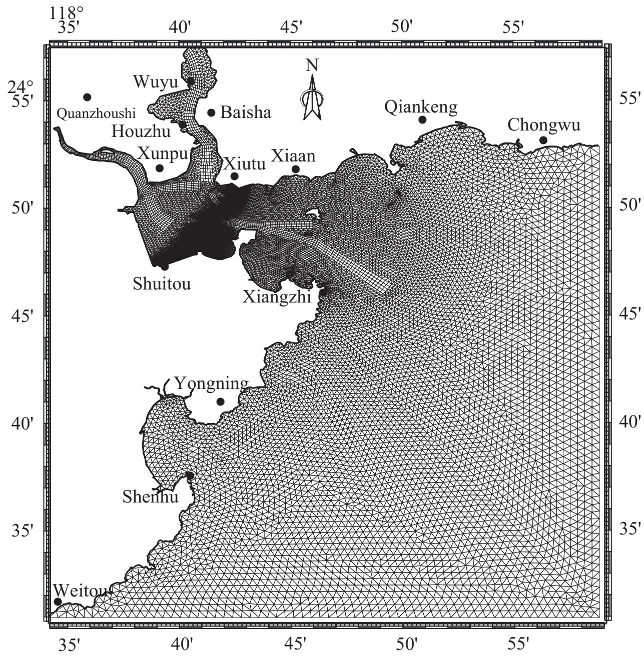

Fig. 3. Non-structural grid in the sea areas adjoining Quanzhou Bay.

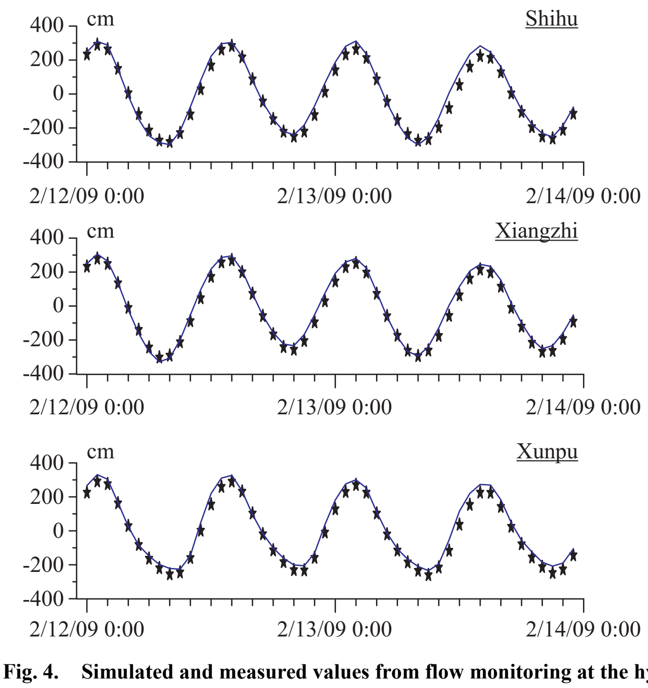

Fig. 4. Simulated and measured values from flow monitoring at the hydrometric stations.

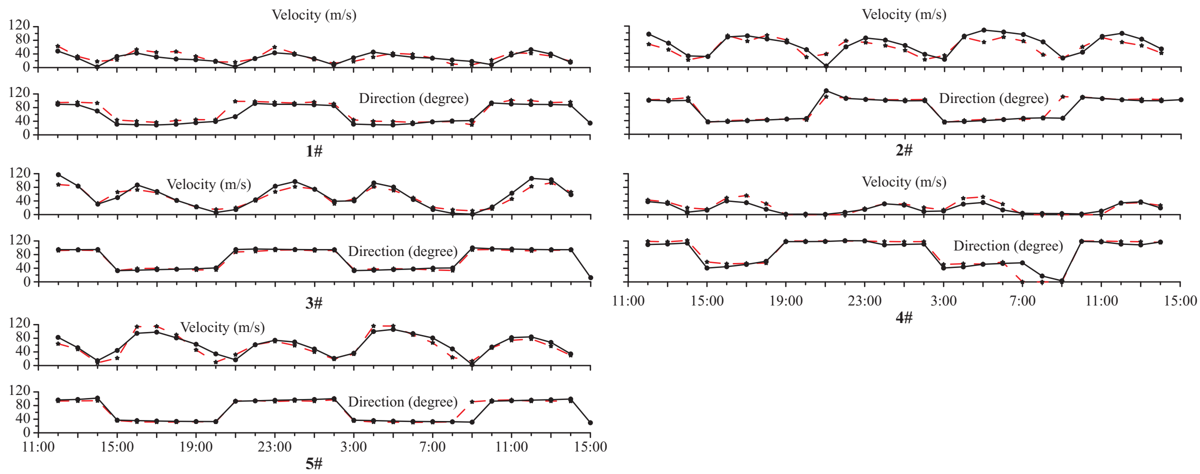

Fig. 5. Simulated and measured verification curves collected at the hydrometric stations.

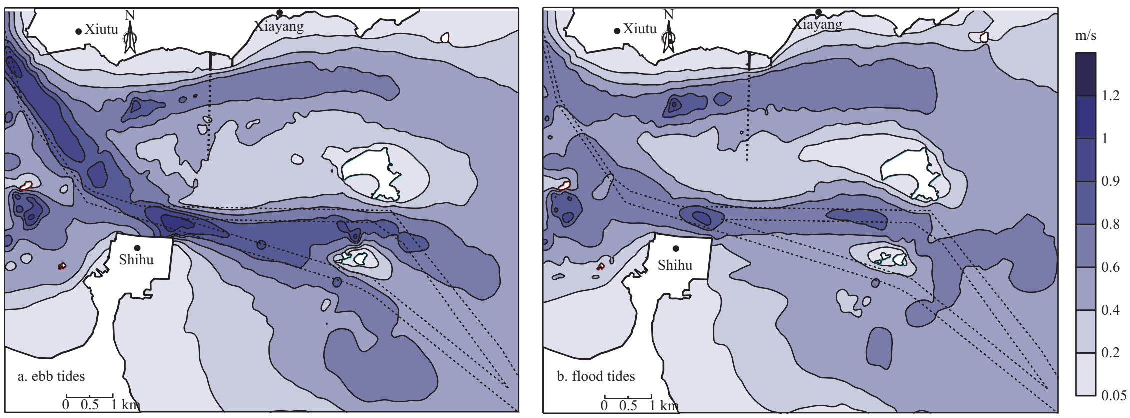

Fig. 6. Average flow velocity distribution of the spring tide in the marine area of the Quanzhou Bay mouth.

from the numerical simulation proved that the simulation model satisfactorily reflects the tidal movement in Quanzhou Bay and can be used as the hydrodynamics basis for oil spill impact prediction.

4. Tidal Current Field Simulation Results

Fig. 6 shows the isogram distribution of the average flow velocity during tide rise and fall in the marine area of the Quanzhou Bay mouth. Fig. 6 illustrates that the flow velocity in the Quanzhou Bay was high at the southern and northern channels and low at in the shallow area (Fig. 6). At ebb tide, the flow velocity of the channel to the north of Xiesha was approximately 0.4-0.8 m/s; the average flow velocity at the deep trough of the Shihu frontier was approximately 0.8-1.0 m/s; and the flow velocity at the deep trough to the south of Dazhui Island was approximately 0.6-0.8 m/s. The flow velocity of the flood currents in the channel to the north of Xiesha was slightly higher at rising tide than at ebb tide; however, for other areas, the average flow velocity of the flood currents was lower than that of the ebb currents. The tidal currents at the southwestern frontier of Dazhui Island were reciprocating tidal currents, where the currents flowed from northwest from the southern side of the Dazhui Island to the Xiesha Shallow at the flood tide; and at ebb tide, it flowed southeast from the Xiesha Shallow to converge with the mainstream of the ebb tide at the southern side of Dazhui Island, where the current flow is relatively tranquil.

III. PREDICTION AND SIMULATION OF AN OIL SPILL

1. Oil Particle Model

When spilled crude oil enters the water, its film is extremely thick and spreads rapidly in all directions; the oil layer becomes increasingly thin under the combined effects of tidal currents, wind and waves and breaks down into fragments; these fragments drift and spread with tidal currents and are subject to weathering processes, such as evaporation, dissolution and emulsification. By coupling the tidal current field with the wind field on the sea surface, the oil particle model traces the particle trajectories using the Lagrange particle tracking method, simulates the turbulent diffusion field of the oil particles of the spilled oil (Jiang, 2007) using the stochastic model, and simulates the turbulent diffusion of oil particles using the random walk method (Danish Hydraulic Institute, 2012), which computes the movement of the oil particles under various environmental conditions (primarily the flow field), so as to improve the accuracy of oil spill prediction (National Marine Environmental Monitoring Center, 1995; Zhang and Dou, 1997)

Setting aside the turbulent diffusion, the particle drifting process was traced by the Lagrange method based on the mathematical simulation of the flow field (Eulerian field) and the particle trajectories in tidal current (including wind-driven current) were derived. The velocity of the wind-driven current (2% of the wind velocity at 10 m above the sea surface) was obtained from the empirical equation.

$\overline{P_1P_2}$, the water particle trajectory rom moment n to n + 1, is a streamline; assuming that $x(t)$ is the position of the water particle at moment n and $x(t+\Delta t)$ is its position at moment n + 1, then

$$\frac{dx}{dt} = \vec{u}_3(t) \tag{4}$$

where $\vec{u}_3(t)$ is the particle's speed at moment *t*; integration of this equation yields

$$x(t+\Delta t) = x(t) + \int_t^{t+\Delta t} \vec{u}_3(t)dt \tag{5}$$

The water particle displacement of time span Δ*t*, which is $\overline{P_1P_2}$, can be obtained from the this equation (Zhang et al., 2004).

The random walk method was adopted to simulate the turbulent diffusion of the oil particles: the oil film was regarded as a particle cloud composed of numerous oil particles; the scale of the particle cloud increased with time as a result of the random walk of oil particles; and the variance of the random walk of the particle cloud equaled to the that of the particle cloud variance:

$$\langle \gamma'^2 \rangle = \sigma^2(t+\Delta t) - \sigma^2(t) \tag{6}$$

Thus,

$$\langle \gamma'^2 \rangle \approx \frac{d\sigma^2}{dt}\Delta t \tag{7}$$

where operator <> is used to average all oil particles and $\sigma(t)$ is the standard deviation of the particle cloud at moment *t*. The variance rate oil particle cloud is defined as the diffusion coefficient *K*:

$$K = \frac{1}{2}\frac{d\sigma^2}{dt} \tag{8}$$

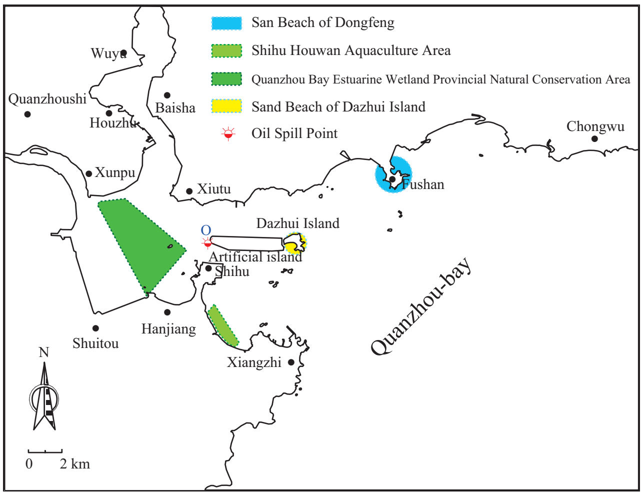

Fig. 7. Locations of environmentally sensitive targets and the oil spill.

The relationship between the random walk variance and turbulent diffusion coefficient *K* is

$$\langle x'^2 \rangle = 2K\Delta t \tag{9}$$

From this equation, the random walk distance is derived as

$$\Delta\alpha = \eta\sqrt{2K\Delta t} \tag{10}$$

where $\Delta\alpha$ is the distance of oil particle diffusion caused by turbulent motion along the α (*x* or *y*) direction in time step Δt, and η is a random number from the Gaussian distribution when the mean value is 0, the standard deviation is 1, and $K = 5.0$ m^2/s.

L is the migration distance of the oil particle under the combined effects of the sea surface wind field, tidal current field and turbulent diffusion:

$$L = P_1P_2 + \alpha\ . \tag{11}$$

The trajectory of each oil particle during the tidal cycle can be computed using this integral equation.

Oil particles drift to the seashore will stick to the shore; however, some oil particles may be brought back to the water due to the impact of the water flow; the amount of particles reentering the water is related to the water flow velocity, concentration gradient and natural conditions of the shore. The following equation is proposed by Torgrimson (1980) to calculate the amount of oil dA_b going back into the water during time period Δ*t*:

$$\frac{dA_b}{A_b} = 1 - 0.5^{\Delta t/\lambda} \tag{12}$$

where A_b is the total amount of oil adhering to the shore and λ is the half-life period, which is 1 h at an open, flat shore.

Table 1. Simulated Working Conditions of the Oil Spill Accident Risk.

Working Condition #	Oil Spill Point	Wind Condition	Spilled Amount
I	O (on the western end of the artificial island)	NE (5.6 m/s)	500 t
II		SW (4.7 m/s)	500 t
III		C (calm wind)	500 t

Table 2. Areas Affected by the Spilled Oil during Various Tides under Working Condition I.

Oil film thickness (μm)	Oil spilled at spring tide (km^2)	Oil spilled at maximum ebb (km^2)	Oil spilled at low tide (km^2)	Oil spilled at maximum flood (km^2)
	12 hours	12 hours	12 hours	12 hours
0.02	37.91	57.11	31.39	14.01
0.1	29.6	47.25	24.68	12.52
0.3	22.32	39.85	19.87	11.1
1	13.4	28.44	13.93	9.4
5	6.63	14.8	7.36	7.21
15	4.22	7.39	4.57	4.34
20	3.6	5.49	4.13	3.71
100	1.39	0.86	1.15	1.33
1000	0.02	0.01	0.08	0.05
Sweeping area (km^2)	117.01	110.37	64.61	39.78

Table 3. Areas Affected by the Spilled Oil during Various Tides under Working Condition II.

Oil film thickness (μm)	Oil spilled at spring tide (km^2)	Oil spilled at maximum ebb (km^2)	Oil spilled at low tide (km^2)	Oil spilled at maximum flood (km^2)
	12 hours	12 hours	12 hours	12 hours
0.02	34.82	16.62	5.9	3.29
0.1	27.97	13.05	4.76	2.69
0.3	22.24	11.21	3.9	2.3
1	17.45	8.67	2.86	2
5	10.74	4.37	2.1	1.52
15	5.89	1.38	1.57	1.18
20	4.5	1.12	1.47	1.12
100	0.39	0.51	0.51	0.39
1000	0.07	0.12	0.08	0.09
Sweeping area (km^2)	117.43	58.62	18.46	18.07

2. Computable Working Conditions

The oil particle model proposed in this paper primarily simulates the scope and level of contamination caused by oil spill drift, spread and random diffusion during a tidal cycle (12 h). The wind in Quanzhou Bay is primarily oriented in the NE direction in winter and in the SW direction in summer. The oil spill point is located on the western end of the artificial island and in the Quanzhou Bay mouth. The impact of spilled oil diffusion at point O under 3 types of wind conditions are simulated assuming a spill amount of 500 t. Fig. 7 shows the location of the oil spill. Table 1 shows the computable working conditions. The spilled oil is heavy oil with a density of 950 kg/m^3. The spilled oil was divided into quantities of oil particles in the simulation. Assuming that an “oil film” formed by 1 t of oil includes 4×10^4 oil particles, then 500 t of oil is consisted of 2×10^7 oil particles; all oil particles were discharged within 30 min. The position of each oil particle is computed after 12 h’s drift in the tidal current, wind-driven current, and random diffusion under various tidal conditions to obtain the number of oil particles in each mesh. The volume of oil particles were converted into the thickness of the oil film. The isogram distribution of the oil film thickness was plotted to describe the path and scope of the oil film contamination and the level of contamination in the corresponding marine area.

3. Spilled Oil Diffusion Simulation Results

The simulation results of spilled oil diffusion are shown in

Table 4. Areas Affected by the Spilled Oil during Various Tides under Working Condition III.

Oil film thickness (μm)	Oil spilled at spring tide (km^2)	Oil spilled at maximum ebb (km^2)	Oil spilled at low tide (km^2)	Oil spilled at maximum flood (km^2)
	12 hours	12 hours	12 hours	12 hours
0.02	41.48	77.25	24.77	31.9
0.1	30.72	65.75	20.19	27.09
0.3	19.91	56.01	17.03	23.16
1	9.65	42.33	13.5	18.51
5	6.31	22.77	9.56	10.32
15	4.5	8.11	7.15	6.84
20	3.98	5.02	6.58	5.83
100	1.58	0.12	1.34	1.22
1000	0	0.05	0	0.03
Sweeping area (km^2)	158.6	131.53	51.29	60.45

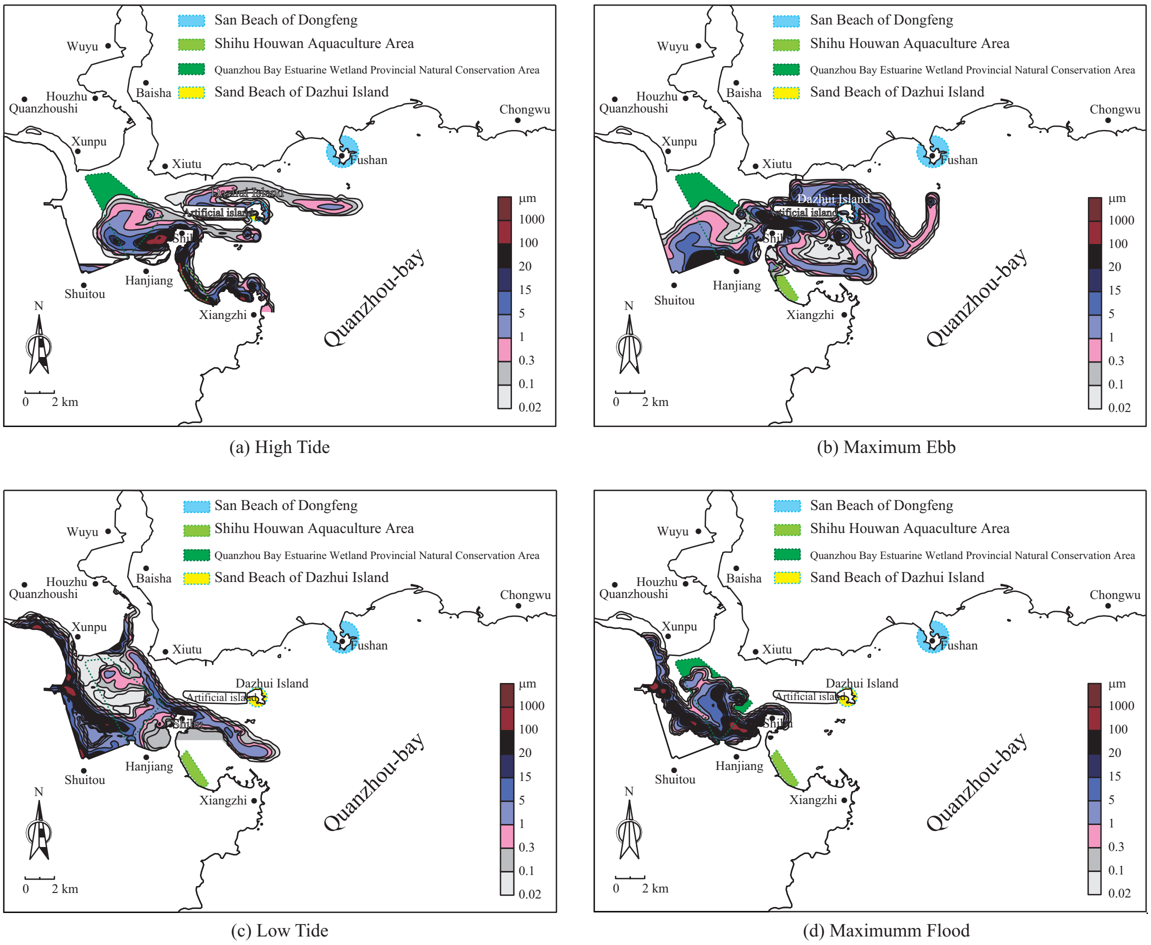

Fig. 8. Distribution of the oil film 12 hours after the oil spill under working condition I.

Figs. 8-10 and Tables 2-4. The following observations were made:

Working condition I (NE, 5.6 m/s): The oil spill occurred at four typical tides under the effects of NE wind-driven current, and the oil film drifted and diffused with rising and ebb tides. A marine area of approximately 40-117 km^2 was affected by the oil film 12 h after the oil spill. The oil film primarily drifted and diffused in the marine area of the Quanzhou Bay mouth, around the artificial island at the shallow to the south of Baiyu and in the Jinjiang River estuary, and was relatively concentrated in the mid-west area of Quanzhou Bay.

Working condition II (SW, 4.7 m/s): The oil spill occurred at four typical tides; a marine area of approximately 18-117 km^2 was affected by the oil film 12 h after the oil spill. The oil film

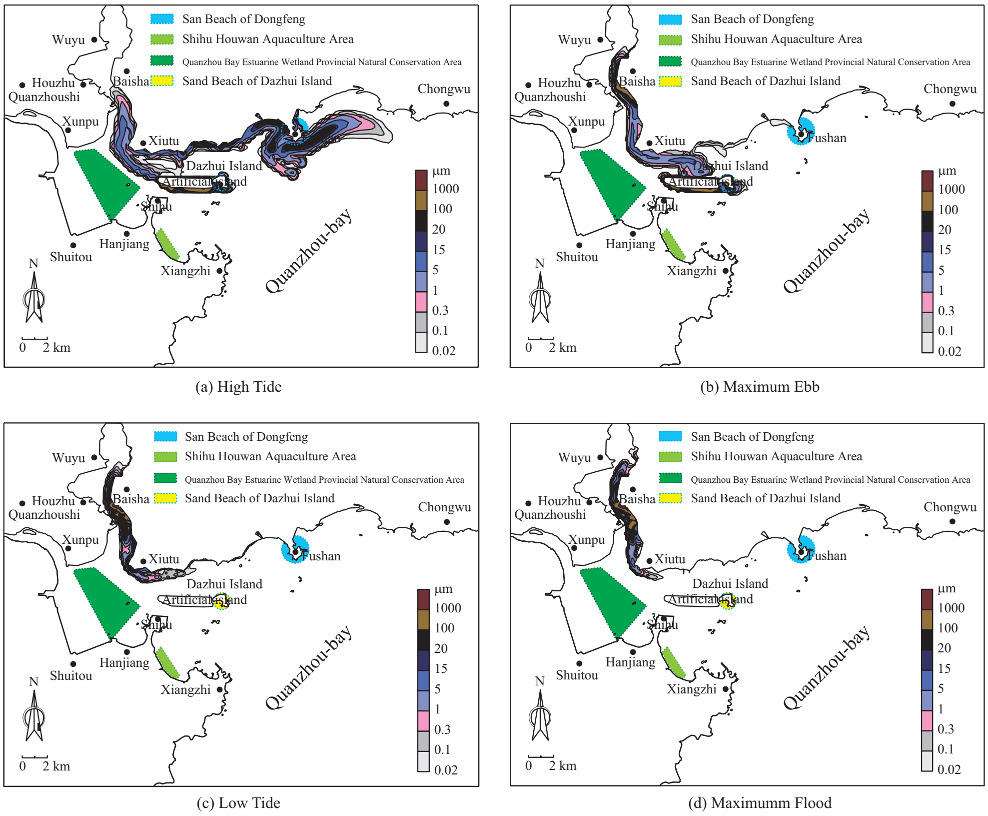

Fig. 9. Distribution of the oil film 12 hours after the oil spill under working condition II.

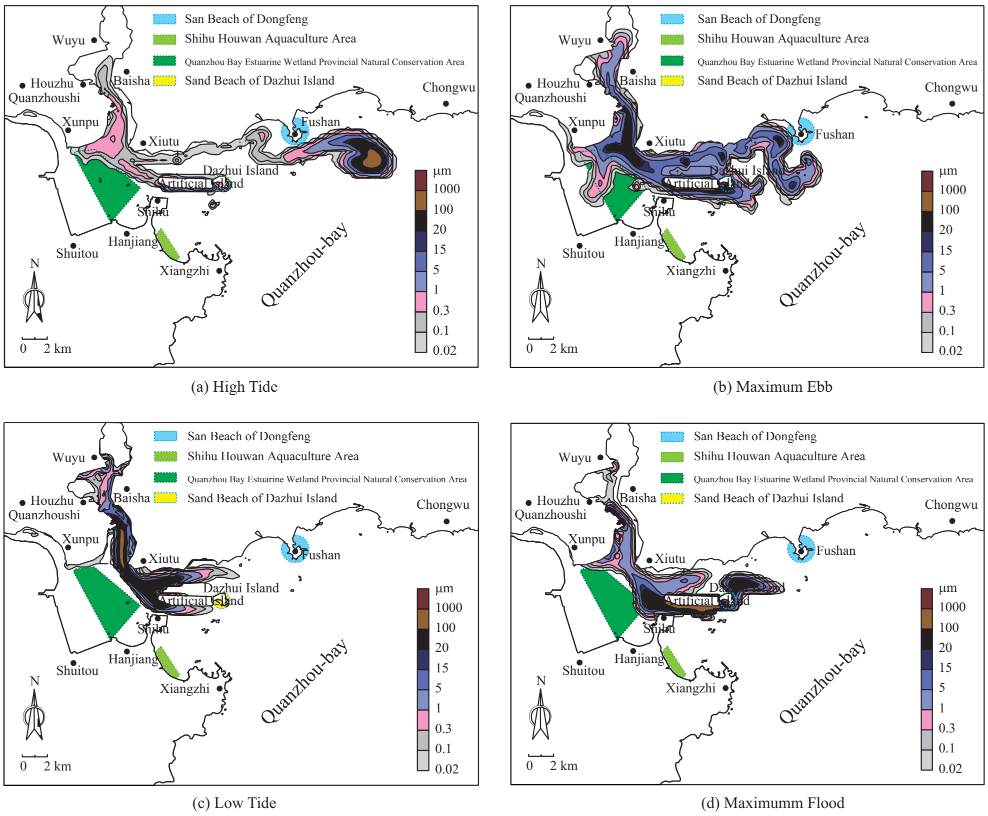

Fig. 10. Distribution of the oil film 12 hours after the oil spill under working condition III.

Table 5. Time (h) for the oil film to reach the environmentally sensitive targets under each working condition.

Working condition	Time of the Oil Spill Accident	Quanzhou Bay Estuarine Wetland Provincial Natural Conservation Area	Shihu Houwan Aquaculture Area	Sand Beach of Dazhui Island	Sand Beach of Dongfeng
Working condition I	At spring tide	10.5	0.5	7	×
	At maximum ebb	7	2	0.5	×
	At low tide	0.5	9	×	×
	At maximum flood	0.5	12	×	×
Working condition II	At spring tide	×	×	0	7
	At maximum ebb	×	×	0	6
	At low tide	×	×	×	×
	At maximum flood	×	×	×	×
Working condition III	At spring tide	12	×	0	9
	At maximum ebb	7	×	0	5
	At low tide	6	×	12	×
	At maximum flood	3	×	8	×

Note: "X" means that the oil film did not arrive.

started at spring tide and maximum ebb primarily drifted and diffused in the marine area around the artificial island and near the northern shore of the Quanzhou Bay (from Fushan to Houzhu) under the impact of SW wind-driven current; whereas the oil film started at low tide and maximum flood entered the Houzhu marine area and was distributed along the shore from Houzhu to Xiutu.

Working condition III (calm wind): The oil film drifted and diffused with flood and ebb currents, and mainly drifted in the marine area to the north of Quanzhou Bay, around the artificial island and from Xiutu to Houzhu. The area of the oil film diffusion was relatively large under calm wind conditions, and a marine area of approximately 51-159 km^2 was affected by the oil film 12 h after the oil spill.

4. Time for the Spilled Oil Film to Reach Environmentally Sensitive Targets

An oil spill has a substantial impact on environmentally sensitive targets in a marine area. Predicting the time at which important environmentally sensitive targets will be affected can provide technical support for establishing contingency plans, inproving emergency response capacities and taking risk prevention measures. Table 5 shows the shortest time for the oil film to reach the environmentally sensitive targets in Quanzhou Bay under each working condition. The oil film drifted to the northeast with the tidal currents under the effects of prevailing NE wind in winter and arrived at the Quanzhou Bay Estuarine Wetland Provincial Natural Conservation Area, Shihu Houwan aquaculture area and the sand beach of Dazhui Island within 0.5 h in the earliest case. With the prevailing SW wind in summer, the oil film arrived at the sand beach of Dazhui Island immediately and at the sand beach of Dongfeng in 6 h. Under calm wind conditions, the oil film arrived at the sand beach of Dazhui Island instantaneously, at the Quanzhou Bay Estuarine Wetland Provincial Natural Conservation Area within 3 h, and at the sand beach of Dongfeng within 5 h.

5. Analysis and Discussion

The marine area of Quanzhou Bay is divided by the Xiangzhi-Fushan section. reciprocating currents are the predominant tidal currents in the bay mouth, and rotary currents are dominant outside it.The drifting trajectory of the spilled oil film in the marine area of Quanzhou Bay is primarily affected by the location of the oil spill, the wind conditions and the tidal current when the oil spill occurs. When an oil spill occurs at typical tides under the three working conditions, the oil film covers a smalle area and has a large thickness in the first 3 h and then gradually spreads and becomes larger and thinner.

Without the impact of wind-driven currents under calm wind conditions, the tidal currents play a dominant role in oil film migration, which can reach as far eastward as the eastern marine area of Chongwu and as far westward as the Houzhu marine area. In the NE oriented wind, the oil film is lifted and pushed by wind and swings back and forth in the sea area between the Quanzhou Bay mouth and the Jinjiang River estuary, resulting in a large contamination area at spring tide and maximum ebb. In the SW oriented wind, the oil film moves close to the marine area to the north of Quanzhou Bay and gradually sticks to the seashore, resulting in a less significant contamination.

IV. CONCLUSIONS

This paper established the tidal current field using two-dimensional shallow water equations in plane rectangular coordinates and used the oil particle model to simulate the drift path and degree of influence of spilled oil in Quanzhou Bay under the conditions of calm wind and prevailing winds in winter and summer respectively. This study can provide technical support for decision-making and environmental damage assessment in unexpected oil spill accidents in Quanzhou Bay. Moreover, useful exploration was performed to accurately simulate the oil spill diffusion at sea.

Fuel oil was used in this study to simulate the oil film drift path and the degree of influence 12 h after a 500 t oil spill accident. The simulation results indicated that the drift motion of the spilled oil film was primarily affected by the tidal current field and wind conditions: when the oil spill occurred at typical tides, the oil film featured a smalle area and a large thickness during the first 3 h and then gradually spread and became larger and thinner. The area of oil film diffusion was relatively large under calm wind; a marine area of approximately 51-159 km^2 was affected 12 h after oil spill; at any given moment, the oil film can drift to the Jinjiang River Estuary. The simulation results differ from the model results to certain extent, because the model used in this paper is based on the long-term meteorological records and lacks the data of real oil spill diffusion for verification. A regional meteorological model will be considered in future studies to provide real-time wind field drive, and actual oil spill diffusion data will be used for the model verification to improve the accuracy of prediction. Such efforts will be useful for minimizing the impact of oil spill accidents on the environment, as well as promoting the comprehensive management of marine environment risks and emergency response capabilities.

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