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Oil spill model development and application for emergency response system

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Abstract: The paper introduces systematically the developing principle of CWCM 1.0 oil spill model based on Lagrange system and oil spill fate processes in environment, reviews two oil spill incidents of "East Ambassador" in Jiaozhou Bay and "Min Fuel 2" in the mouth of Pearl River, and designs the predictable system simulating oil spill applied in contingency plans. It is indicated that CWCM 1.0 has met preliminarily the demands for functions of precision simulating and predicting oil spill, and can plan an important role to support oil spill response.

Key words: oil spill model; emergency response; simulating and predicting system; Jiaozhou Bay; mouth of Pearl River

Introduction

Oil is a kind of necessary energy and resource in present human production and daily life. But as soon as oil spilling at the sea, it will become a disaster source polluting environment and destroying ecology. Related to many oil spill fate processes, oil spill model is a kind of comprehensive model to simulate the trajectory, fate and environmental impact of oil spill based on the principles of environmental science, which can fast simulate and dynamically show the oil slick trajectories in different time and different thickness.

Oil spill models play a very important technical supporting role in oil spill emergency response system, mainly including: (1) to simulate and assess oil spill risk and environmental impact; (2) to assist decision making and response actions; (3) to assist the post impact assessment of oil spill incident. This paper introduces systematically the developing principle of CWCM 1.0 oil spill model based on Lagrange system and oil spill fate processes in environment, reviews two oil spill incidents of "East Ambassador" in Jiaozhou Bay and "Min Fuel 2" in the mouth of Pearl River, and designs the predict system simulating oil spill applied in contingency plants.

1 Basic principals of oil spill model

Because the significant difference of mathematical and physical methods in natural science describing the motion of material according to the Euler or Lagrange system, there is a significant difference of numerical simulation methods in environmental science to describe pollutant trajectories. In the development and application of CWCM 1.0, the tidal predict models of Jiaozhou Bay and the mouth of Pearl River have applied numerical methods basing on the Euler system, three dimensional trajectory and fate model have applied total motive forces and environmental fate models basing on the Lagrange system.

1.1 Model of total motive forces

Hypothesis 1: Oil spill source is composed of many small motive particles, each of which moves in the nature under certain effects of motive forces. The space moving distance of particle p in time interval $t_1 - t_2$ is $\boldsymbol{x}_p$.

Hypothesis 2: Motive forces include mainly (1) tidal, density and river mouth currents, speed $\boldsymbol{U}_C$; (2) turbulence current, speed $\boldsymbol{U}_T$ (Stronach, 1993); (3) gravity subside, speed U_G; (4) wind generated current, speed $U_{W'} \times f$, f is the wind effect parameter, normally adopting 3% – 5%, $\boldsymbol{U}_{W'}$ indicates that the current direction turn right of the wind direction, normally about 10 – 15°.

Hypothesis 3: The space moving distance of particle p in a short time interval, $\mathrm{d}t$, under the effect of total motive forces is $\Delta \boldsymbol{x}_p = (\boldsymbol{U}_C + \boldsymbol{U}_T + \boldsymbol{U}_{W'} \times \mathrm{f} + U_G)\mathrm{d}t$; $\boldsymbol{x}_p = \int_{t_1}^{t_2} (\boldsymbol{U}_C + \boldsymbol{U}_T + \boldsymbol{U}_W \times f + U_G)\mathrm{d}t$.

Hypothesis 4: Natural space is divided into equal volume (V) cubes (Fig.1). The number of oil particles in the (i, j, k)th grid at t time is $N(i, j, k, t)$. The weight of each particle is W_p. The oil concentration in the grid at t time is $C(i, j, k, t) = N(i, j, k, t) \times W_p / V$.

Hypothesis 5: The oil at the surface grid may be in different states, e.g. dissolved, absorbed or oil slick. The particle number in slick state at t time are $N_s(i, j, 0, t)$. The oil density is ρ. The surface area of each grid is A. The thickness of oil slick is $H(i, j, 0, t) = N_s(i, j, 0, t) \times W_p / (\rho \times A)$.

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1.2 Models of oil spill environmental fate

1.2.1 Gravity spreading model of oil slick

It is assumed, according to the experimental model of Toronto University (Hodgins, 1992), that oil slick is composed of thick and thin slicks, and that the area of thin slick is 4 times of the thick slick. The dynamic formulas calculating the slick spreading area caused by gravity are listed in Eq. (1) and (2).

$$dA_n/dt = C_1 A_n^{1/3}\exp[-C_3/(h_n + h_c)], \quad (1)$$

$$d(A_c + V_n/h_c)/dt = C_2 A_c^{1/3} h_c^{4/3}, \quad (2)$$

where, A_n, A_c are the areas of thin and thick slicks; h_n, h_c are the thickness of thin and thick slicks; V_n is the volume of thin slick; C_1, C_2, C_3 are the experimental constants.

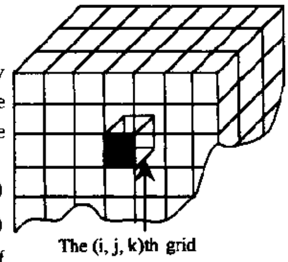

Fig. 1 Grids of an oil spill model

1.2.2 Oil evaporating model

According to the experimental model of Toronto University (Hodgins, 1991), the dynamic formulas calculating the slick evaporating are listed in Eq. (3) and (4).

$$dV_c/df_c = -V_c/(1 - f_c), \quad (3)$$

$$dV_n/(f_{max} - f_n) = -V_n/(1 - f_n), \quad (4)$$

where V_n, V_c are volumes of thin and thick slicks; f_n, f_c the fractions of evaporated amount of thin and thick slicks in total slick amount; f_{max} the maximum evaporating friction; $df_c = Hd\theta, H = PM_v/RT$, $P = P_0\exp(-Cf_c)$, in which M_v is the mole volume of evaporated state, R is the gas constants, T is the temperature, $d\theta - K_e dt/h_c$, K_e is the mass transport coefficient, C is the experimental constant, h_c is the thickness of thick slicks.

1.2.3 Shoreline absorb model

For different types of shoreline(m), the model defines related maximum absorb capacities, $A_{m,max}$, and velocity absorb oil, V_m. The dynamic formula shoreline absorbing oil is listed in Eq. (5).

$$dA_m/dt = V_m; A_m \le A_{m,max}, \quad (5)$$

where A_m is the absorb amount of m type shoreline.

1.2.4 Dissolving model in water column

The model calculating the largest dissolving concentrations of main dissolvable compositions of oil is build according to the dissolving principle (Qiao, 1998), listed in (6).

$$C_{n,max}(T, P) = S_n(T, P)K_{n,M}K_{n,E}K_{n,S}K_{n,D}, \quad (6)$$

where, $C_{n,max}(T, P)$ is the largest dissolving concentration of n composition at T temperature and P pressure; $S_n(T, P)$ is the dissolving degree of n composition at T temperature and P pressure; $K_{n,M}$ is the effect coefficient of other compositions, including surface active agent; $K_{n,E}$ is the effect coefficient of sea surface energy; $K_{n,S}$ is the effect coefficient of salt consent of sea; $K_{n,D}$ is the effect coefficient of water depth.

1.2.5 Depositing and re-suspending model

The depositing velocity is calculated with Eq. (7) according with the Stocks formula, and the depositing amount and re-suspending velocity are calculated with Eq. (8) and (9) (Jiang, 1998).

$$W_s = g(\rho - \rho_0)d^2/(18\mu), \quad (7)$$

$$Q_d = W_s C_b[1 \quad (V^*/V_{Cr,d})^2]; (V^* < V_{Cr,d}), \quad (8)$$

$$P_e = f_M(V^{*2} - V^2_{Cr,d}); \quad (V^* > V_{Cr,d}), \quad (9)$$

where W_s is the depositing velocity; g is the gravity accelerate; ρ is the density of oil; ρ_0 is the density of sea water; d is the oil particle diameter; μ is the viscosity coefficient of sea water; Q_d is the total depositing amount; C_b is the oil concentration in bottom grids; V^* is thefriction velocity of sea bottom; $V_{Cr,d}$ is the critical friction velocity of sea bottom; P_e is the velocity of re-suspending; f_M is the constant.

2 Application of oil spill model

2.1 Post assessment of spill incidents in Jiaozhou Bay and the mouth of Pearl River

2.1.1 Setting up and verifying tidal current predict models

The horizontal motion equations of shallow water are listed in Eq. (10) and (11), obtained by integrating vertical items of the Navier-Stohes equation when ignoring vertical force of free surface. Using finite element numerical simulating model can obtain the solution of motion equation for a certain area.

$$\partial \boldsymbol{u}/\partial t + \boldsymbol{u} \cdot \nabla \boldsymbol{u} + f \times \boldsymbol{u} + g\nabla\eta + \tau_b = 0, \quad (10)$$

$$\partial\eta/\partial t + \nabla \cdot [(H + \eta)\boldsymbol{u}] = 0, \quad (11)$$

where $\boldsymbol{u}$ is the two dimension horizontal current velocities; t is the time; f is the coefficient of Coriolis force; g is the gravity accelerate; η is the depth of mean sea level; τ_b is the friction force of sea bottom; H is the current height.

According to the distributions of coast lines and depth of Jiaozhou Bay and the mouth of Pearl River, the finite element grids of related areas, shown in Fig. 2, were built aided by certain tools (Foreman, 1990). Amplitudes and phases of main tidal constituents and current velocity of river mouth, summarized from observed data, were taken as boundary conditions in numerical simulation (Fang, 1998; Zhao, 1994). The harmonic constants at grid connecting points were simulated through many time iterative calculations, which form tidal current model for the specific marine areas, to predict tidal current direction and velocity in any given time and at any given site, and can be identified automatically by CWCM 1.0. It is verified, by comparing with the related public data (NICO, 1999), that the simulating results of model have good accuracy, which are shown in Fig. 2.

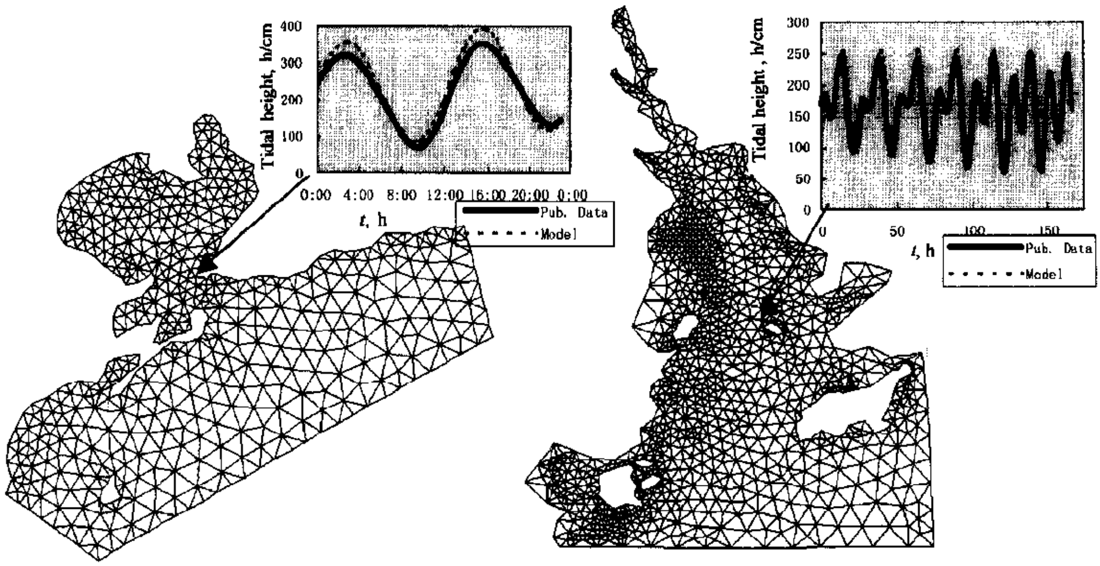

Fig. 2 Finite element grids and tidal model verify curves
(left: Jiaozhou Bay; right : Pearl River)

2.1.2 Incident reviews

At 17 o'clock on November 25, 1983, the oil tank of East Ambassador navigating in Chinese Jiaozhou Bay stroked a reef and resulted 3×10^3 tone crude oil spill during about 40 hours. The seawater and coastline of Qingdao had been seriously polluted. At 2 o'colok on March 24, 1999, a two tank striking incident happened in the mouth of Pearl River under heavy fog. One of the tanks, Min Fuel 2, released about 6×10^2 tone heavy fuel oil during 5 days and heavily polluted the marine area and coastline of Zhuhai.

According to the real records of two incidents, the dynamical simulating results of CWCM 1.0 (examples shown in Fig. 3), reflected basically the spatial and temporal variation tendency of oil spills. It is verified that CWCM has the capacity to simulate an predict accurate oil spill.

Based on certain environmental impact degrees, ten day simulating results varied with different impact types, degrees, and scopes are calculated (Fig. 4 for "3.24 Incident" in the mouth of Pearl River).

2.2 Scheme of simulating and predicting system

To design the scheme of simulating and predicting system has very special meaning for enhancing both the technical level of emergency response system and the practical function of the contingency plan to guide the actions against oil spill.

2.2.1 Structure of distributional net system

The theoretical structure and functions of national emergency response system put forward based on Saridis' intelligent control theory have three levels arranged from upper to lower (Qiao, 1997), i.e. national decision-making and organizing level, regional uniting and coordinating level, and local administrating and managing level. Although the practical system formed by combining the Chinese special situation has more complex structure, detailed example of southern Chinese sea area is shown in Fig. 5, it will aid to realize an organic connection of different levels and different regions in order to give full plays to the functions of the above three levels. Fig. 5 also shows or implies several regional command posts, sub-posts, and branch divisions of maritime affairs offices, all of which are needed to allocate software and hardware of oil spill models and related databases in order to support rapidly decision making and reaction for emergency responds, which can build a distributional net system.

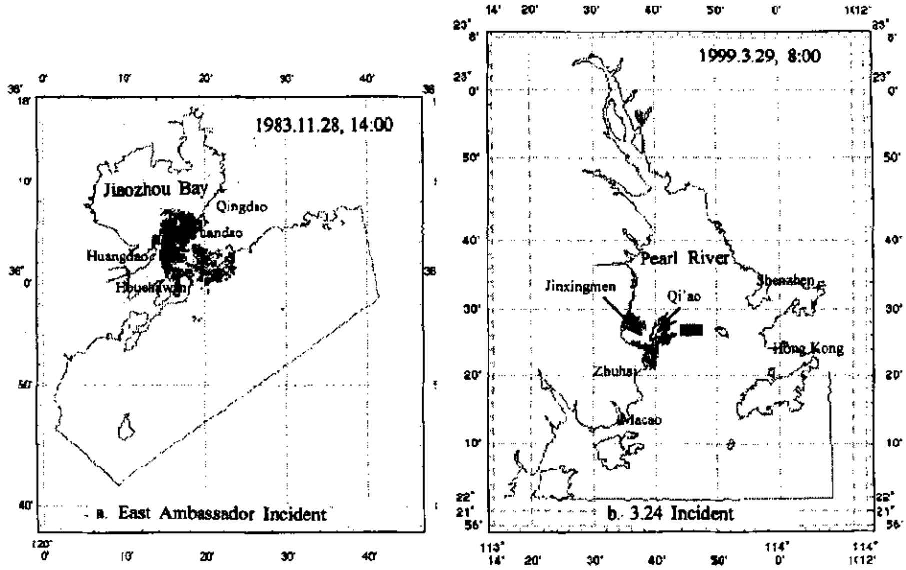

Fig.3 Examples of spill incident reviews

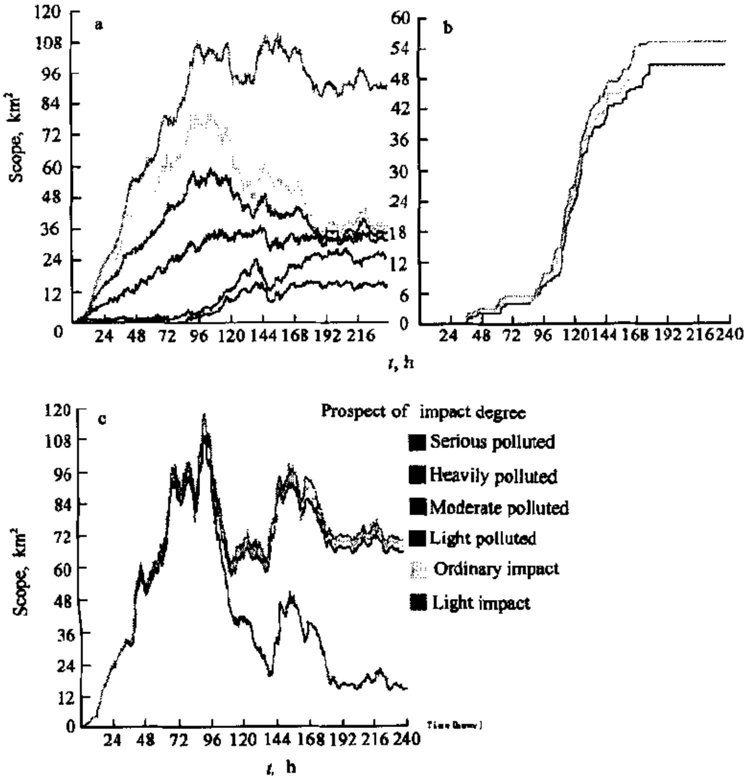

Fig.4 Scopes of different degrees of impacts for "3.24 incident" in the mouth of Pearl River
(a: sea surface; b: coastline; c: above water column)

2.2.2 Scheme connecting meteorological data

To get the accuracy of simulating and predicting results it is very important to obtain timely detailed and accurate

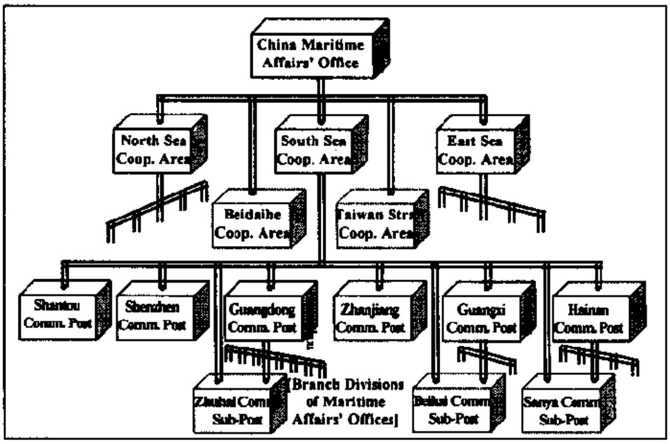

Fig. 5 Structure illustration of national response system

observed and predicted meteorological data as far as possible. Therefore, it is necessary to connect the oil spill predicting system with local metrological stations.

2.2.3 Quality control of the system building

Only the occupational qualified units can be competent for the job constructing the oil spill model system, because of high technical requirements. To enhance the quality control of the system building, the related management contents should be adopted into the contingency plans, for example, all of functions and necessary simulating results of the selected models must take verifying test and pass the experts' judgment. Only the models reaching satisfied accuracy and reliability can be used in the real response. Having preliminarily the necessary functions and accuracy, CWCM 1.0 is estimated to play important role of technical supporting in oil spill response.

2.2.4 Scheme of system applying, maintaining and management

Oil spill contingency plans should be helpful for implementing the daily operation, maintaining and management of emergency response system. The detailed suggestions include: (1) use special software and hardware; (2) take special technical training and obtain qualification for the operating personnel; (3) take system drill and response plan research periodically; (4) set up system archives and record all important information.

3 Conclusion

The paper researches and develops an oil spill model of CWCM 1.0, which is applied to review real incidents and achieves good simulating results. Based on experiment work of the review, a scheme of oil spill simulating and predicting system used for contingency planning is designed. It is indicated that CWCM 1.0 has met preliminarily the demands for functions of precision simulating and predicting oil spill, and can plan an important role supporting oil spill response.

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