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Oil Spill Model Operational Application in Damage Assessment and Case Study of Validation

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Abstract

Oil spill modeling is an important technical measure to evaluate the impact of oil spills scientifically. Because of the great uncertainty in its early development, simulation results have not been used as the basis of judgments for environmental compensation cases. Despite this, scientific research institutes in many countries, including China, are still devoted to the research and development of oil spill models and their applications in environmental damage assessment, which makes it possible to apply them in the judicial arbitration of damages claims. The relevant regulations on the Chinese compensation fund for oil pollution damage from ships and the judicial authentication of environmental damage have also accredited such kind of modeling applications. In order to enhance the applicability of oil spill model further, it is necessary to expand its damage assessment function, and to test, calibrate and verify the accuracy of the evaluation. To this end, the author adopts the self-developed 3-dimentionaloil spill model—CWCM to simulate the "Tasman Sea" oil spill accident. By comparing the simulation results of tidal current field, wind field, oil spill trajectory with those observed, the model coding and parameter selection are corrected, and it is realized that the simulation being basically consistent with the measured results. In addition, the results of the scale reduced simulation test of oil spill weathering are applied verifying and perfecting the weathering model of CWCM. The technical requirements and process for operational application of oil spill model in judicial arbitration are also put forward. In view of the rapid simulation function, the operational updating program for oil spill weathering model, coupled current model and dynamic update wind field diagnostic model are put forward in order to further improve the operational evaluation function and evaluation efficiency of oil spill model.

Keywords

Oil Spill Model, Ecological Environmental Damage, Identification and Evaluation, Verification, Case Study

1. Introduction

Oil spill modeling is a technical method using the principles of environmental science, and applying mathematical models to analyze and quantify drift and diffusion patterns of oil spills. Examining the scope and extent of environmental fate of oils spills may be completed by including oil spill weathering, environmental impact analysis, and the coupled hydrodynamic, wind field and database models. In recent years, oil spill model technology has made great progress internationally. It has been widely used in oil spill risk assessment, prediction and early warning, as well as emergency response decision-making support amongst other applications.

Currently, oil spill modeling is applied in emergency response system and intelligent information system [1] [2], as well as in-depth studies on marine ecosystem impact assessment and risk prevention, such as [3]. The fast prediction model of oil spills is applied to the backwater variation zone of the Three Gorges Reservoir Area [6] to advance existing, GIS-based research on oil spill drift diffusion forecasting modeling [4], and to further research currently supported by special funds for scientific and technological work on the theory of oil spill models [5].

Oil spill modeling is widely considered an important technical means for scientific assessment of the environmental impact of oil spills. Nevertheless, the "International Convention on Civil Liability for Oil Pollution Damage" (CLC) and the "International Fund for Compensation for Oil Pollution Damage Compensation Convention" (FUND) have been regarding the modeling in its preliminary stage since the previous century. The international maritime jurisdiction does not consider modeling technology as mature enough. Calculated results based on the discussed models show great uncertainty. Therefore, the simulation results are not deemed fit as a base for compensation rulings and damage calculations continue to be determined using the traditional empirical methods instead.

Despite the oil spill model technology having matured considerably, no advancements have been made in deciding whether it can be applied in the maritime jurisdiction to date. Taking into consideration related laws and international experience, this paper analyzes data from oil spill models for ecological environment damage assessments to determine whether operational applications are feasible. Additionally, a case study of the oil spill model is validated as a starting point for the authors to outline technical requirements to verify the accuracy of applying the operational process model, as well as the fast simulation function. Furthermore, suggestions for continuous improvements are made regarding the operational program of oil spill weathering model, coupling current model, and the dynamic update wind field diagnosis model, in order to further development of the oil spill model evaluating function and operational efficiency.

2. Feasibility Analysis of Operational Application of Oil Spill Model in Ecological Damage Assessment

2.1. Application Dispute and Fund Compensation Limited Analysis

The application of oil spill modeling in the field of pollution damage compensation has been limited because of a long-standing controversy. The International Maritime Commission (CMI) was founded in 1897 and undertook CLC and FUND preparation work in 1994. They adopted the guidelines on oil pollution damage to determine the scope of economic compensation claims [7]. The eleventh clause of these guidelines states: "The compensation for environmental damage shall be limited to the actual measures taken or will be taken for reasonable restoration measures. The claim of damages calculated by the theoretical model on the basis of abstract quantification is not compensable."

Despite these expressed restrictions, the guidelines also emphasize the importance to carry out special research to determine the severity and scope. The fifth article states: "Pure economic loss caused by oil pollution can be compensated, but is usually limited to the following: the loss must be caused by the pollution itself. It is not enough to merely prove causation between oil spill loss and the oil discharge accident ship." Additionally, article 12.2 states: "In order to identify or verify oil pollution damage, it is necessary to determine whether the rehabilitation measures are practical, and whether speeding up the natural recovery of the environment is required. If such research is in reasonable proportion to the actual damage and provides or may provide the required data, reasonable fees for such research may be compensated."

After comprehensive analysis of the above terms, it is clear that the guidelines state the need for special study of the quantification of damage in addition to providing evidence of causation. However, it is regrettable that the quantitative calculation of the oil spill model is not taken as a basis for claims. Nevertheless, the US EPA and NOAA, as well as the China Waterborne Research Institute among others, have developed an oil spill environmental damage model, and its application for damage claims in business cases remains promising.

2.2. Application Opportunity and Requirement Analysis of Fund Compensation

In May 2012, with the approval of the State Council, China began to levy a compensation fund for oil pollution damage caused by ships. The specific compensation or compensation scope and order include: 1) emergency disposal costs; 2) measures to control or eliminate pollution costs; 3) the direct economic loss of fisheries, tourism etc.; 4) the cost of recovery of marine ecology and natural fishery resources; 5) China ship oil pollution damage compensation fund management committee (hereinafter referred to as the "management committee") and its secretariat by themselves or entrusting the relevant units or agencies to implement the monitoring costs incurred, such as the management committee and its secretariat by themselves or entrusting the relevant units to collect accident image, the oil pollutant character image, damage image of biological resources, carry out the oil spill trajectory simulation, the use of oil spill surveillance satellite navigation, the expenses paid by the remote sensing technology for the dynamic monitoring of oil pollution; 6) other fees approved by the state council [8]. Claims document audit requirements include: The assessment of damage caused by oil spill pollution in the Marine Oil Spill Pollution Ecological Damage Assessment Report (MOSPEDAR) provided by the claimant is appropriate, and ecological restoration measures proposed are feasible in technology.

The above terms indicate that the management committee and the secretariat may own or entrust the relevant units to carry out the monitoring work to determine the compensation or compensation for marine ecological restoration and natural fishery resources measures and other expenses. The monitoring work also includes "oil spill drift trajectory simulation", and is responsible for examining whether the damage evaluation in the MOSPEDAR provided by the claimant is appropriate. On this basis, the claim is likely to get China ship source oil pollution damage compensation funding. Therefore, it is deducted that the oil spill model is feasible in the funding claims and business claims applications alike.

2.3. Application and Requirement Analysis of Environmental Damage Judicial Expertise

According to Chinese relevant regulations, forensic identification of environmental damage refers to appraiser applying environmental science and technology or expertise, and use of techniques and methods of monitoring, testing, field investigation, experimental simulation or comprehensive analysis etc. within environmental litigation to identify and judge the environmental pollution or ecological damage. The judicial authorities should prevent excessive registration and examination of qualifying institutions, which leads to vicious competition and decline in quality of identification. Authorities should encourage and support the establishment of high-quality institutions with high-quality resources, while ensuring neutrality of the judicial appraisal organizations and the third party status [9].

The above provision provides opportunities for application of oil spill model in environmental damage forensic identification. The regulations also provide high qualification, high level, third party for organizations concerned with the activities of appraisal and evaluation activities. Therefore, it is necessary that the applying institutions strengthen their oil spill damage assessment model function and verifying the accuracy, and enhance its applicability in judicial expertise. On the other hand, it is suggest to relevant administrative departments to establish matching management system, as well as standardizing operational processes for applications.

3. Oil Spill Model Validation Case Study

3.1. Case Analysis of Oil Spill Incident Simulation Verification

3.1.1. Jiaozhou Bay "Oriental Ambassador" and Pearl River Estuary "3.24" Oil Spill Cases

The author developed the CWCM oil spill model [10] coupled with finite element simulation results of TIDE2D tidal current model [11], using Monte Carlo random walk and dissolution model for conducting 3D simulation of the oil spill trajectory and environmental fate after inputting oil spill and meteorological information. By inputting the relevant data of oil spill incidents of Jiaozhou Bay "Eastern Ambassador" in 1986 and Pearl River Estuary "3.24" in 1999 into CWCM, the temporal and spatial distribution simulation results of the oil spill trajectory and fate were in good agreement with actual oil spill records [1].

In the simulation process of the above two oil spill accidents, the authors first carried out the verification of the tidal current model within the accident areas. After the tidal current model was in good agreement, the oil spill information and meteorological conditions were inputted to CWCM to perform simulation calculations. However, it was not until after collecting and inputting the actual measured meteorological data in the accident area, that the simulation results were consistent with the oil spill incident record. This highlights that up to date and accurate meteorological data is crucial to the accuracy of the oil spill model simulation results.

3.1.2. "Tasman Sea" Accident Case

"Tasman Sea" oil spill accident happened in November 2002 in Caofeidian sea area. Considering the obvious changes of the coastline in the accident period and the flow measurement period, the finite element triangular meshes of the tidal current models were made for different time periods separately. The triangular grid and its open boundary node of the accident period were shown in **Figure 1**.

The quantity of tidal components and the amplitude and delay angle of tidal components of the boundary nodes in the numerical simulation are determined by using different literatures, respectively M2, S2, K1, O1 of four constituents [12] and M2, S2, K1, O1, 2N2, J1, K2, L2, M1, MU2, N2, NU2, OO1, P1, Q1, T2 of sixteen constituents [13], the latter ones are used to calculate the east and north components of currents according to Equation 1and Equation 2 with parameters in **Table 1** [14].

$$u = u_0 + \sum_{i=1}^{16}\left[F_i \times \left[UR_i \times \cos\left(\omega_i t + E_i\right) + UI_i \times \sin\left(\omega_i t + E_i\right)\right]\right] \quad (1)$$

$$v = v_0 + \sum_{i=1}^{16}\left[F_i \times \left[VR_i \times \cos\left(\omega_i t + E_i\right) + VI_i \times \sin\left(\omega_i t + E_i\right)\right]\right] \quad (2)$$

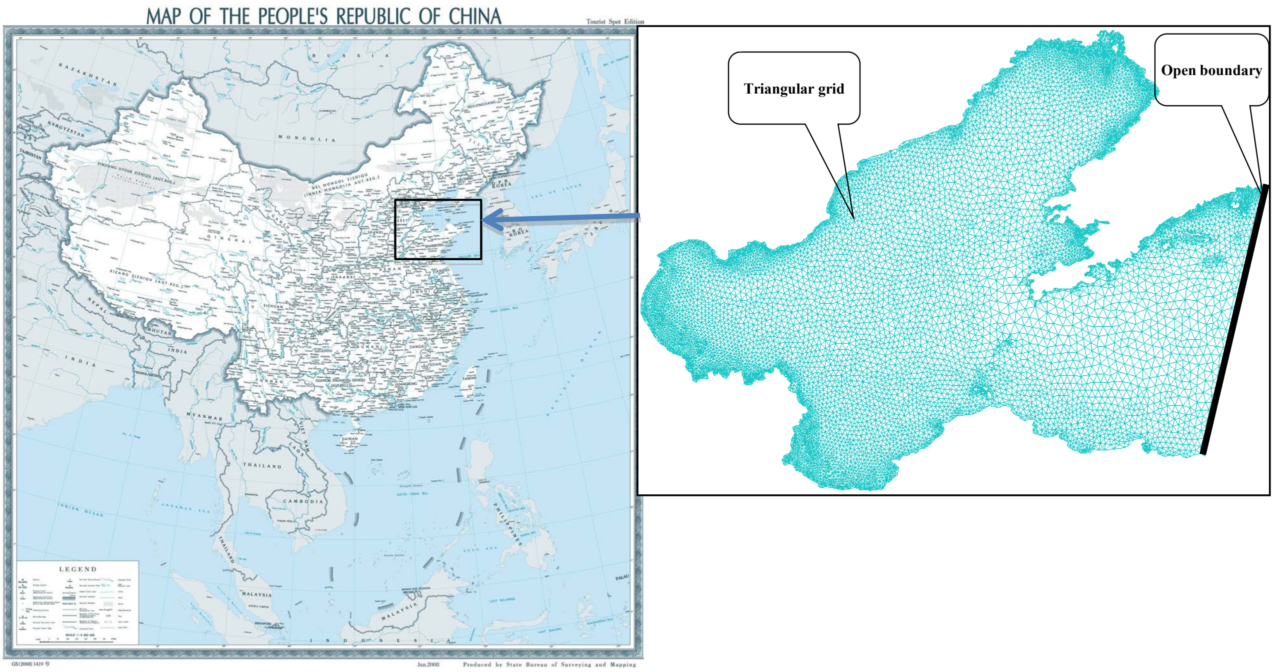


Figure 1. The triangular grid and its open boundary node of "Tasman Sea" accident period.

Table 1. Value of correction factor in harmonic analysis of tidal current model verification test.

Tidal component		M2	S2	K1	O1	2N2	J1	K2	L2
Correction factor	Amplitude	0.96658	1	1.10485	1.17005	0.96658	1.15453	1.28867	1.26946
	Delayed angle	134.52	0	69.57	66.25	171.97	49.53	318.77	306.42
Tidal component		M1	MU2	N2	NU2	OO1	P1	Q1	T2
Correction factor	Amplitude	1.28566	0.96658	0.96658	0.96658	1.70969	1	1.17005	1
	Delayed angle	104.55	269.94	153.24	251.22	250.27	287.15	84.98	300.18

In Equation (1) and Equation (2), u, v: the tidal current velocity component in the east and north direction; u_0; v_0: the tidal residual flow velocity component in the east and north direction; F_i, E_i: the i^{th} tidal component's amplitude and delayed angle correction factors for harmonic analysis; UR_i, UI_i: the harmonic constants of real and imaginary value of the i^{th} tidal component's flow velocity in the east direction; VR_i, VI_i: *t* the harmonic constants of real and imaginary value of the i^{th} tidal component's flow velocity in the north direction; ω_i: angular velocity constant of the i^{th} tidal component, *t*: GMT begun to count since 0 hour March 1, 2004.

The validation and comparison results show that the flow direction simulation results are closer to the measured values when harmonic analysis of sixteen tidal currents is carried out with correction of factors (Figure 2(b)), but the simulated value of tidal current are lower than the measured value indicating there are still some deviations (Figure 2(a)). The reason may be related to the uncertainty of coastline and water depth during the period of measurement. At the same time,

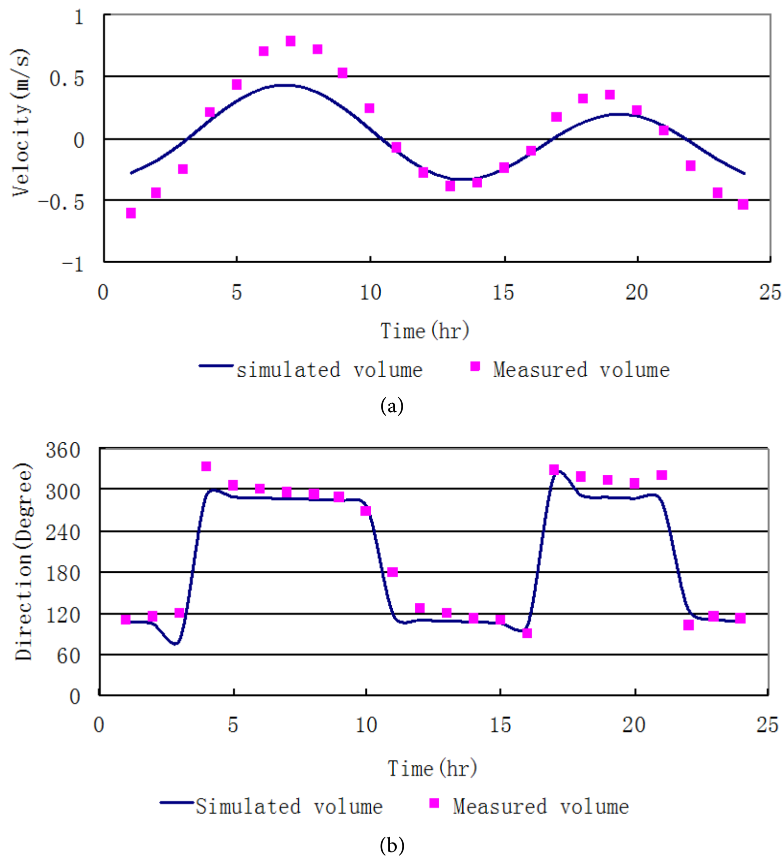


Figure 2. Comparison of simulated and measured flow velocity and direction during measuring period (samples).

it shows that the tidal current model still needs further refinement and improvement.

Figure 3 shows the dialog box of CWCM input with the related information of "Tasman Sea" oil spill incident, in which the mean value of meteorological data measured in Qinhuangdao and Tanggu terrestrial weather stations surrounding the accident area (Figure 4). The wind field data, after diagnostic analysis [15], are adopted separately as the sea surface wind field data in the first and second verification test stages and the tidal current model, with topographic condition during the period of flow measurement, is adopted. When superimposed comparing the simulating result 12 hours after the accident happened with the related record [16], shown in Figure 5(a), it can be found that there is an obvious deviation of the simulated oil spill drift direction. After carefully checking the model code and correcting the error in the drift direction, the deviation is eliminated, shown in Figure 5(b). The oil spill model is coupled separately with the tidal current models adopted topographic conditions during the flow measurement period and the period of the accident, to simulate 12 hours oil spill drift. The results showed that the simulated oil spill drift coupled tidal current model of the accident period and the inputted second stage wind field data is in close agreement with the actual observation, as shown in the master

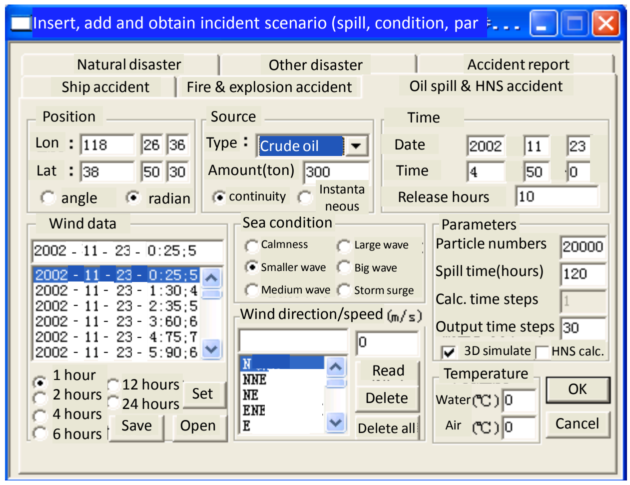
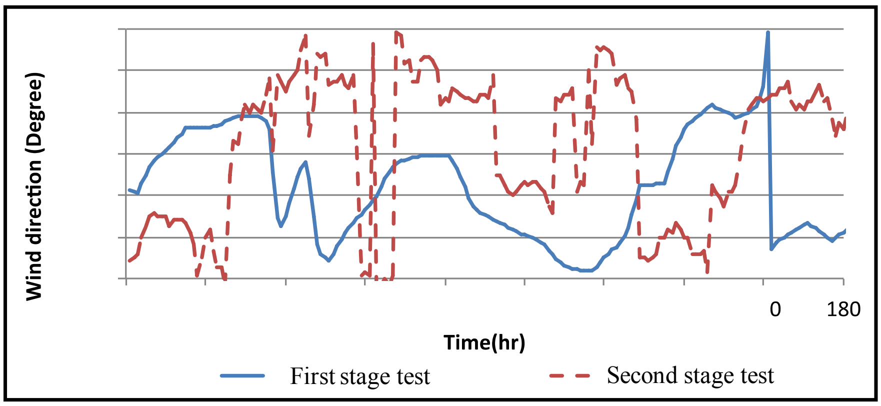
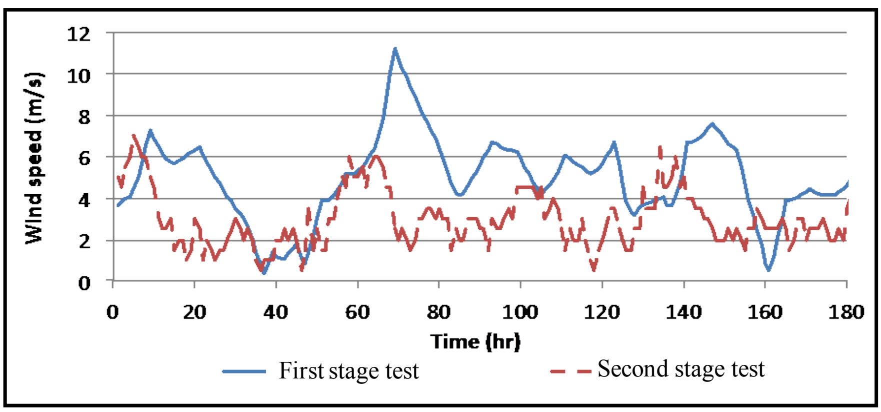


Figure 3. Dialog box of CWCM inputting the related information of "Tasman Sea" oil spill incident.



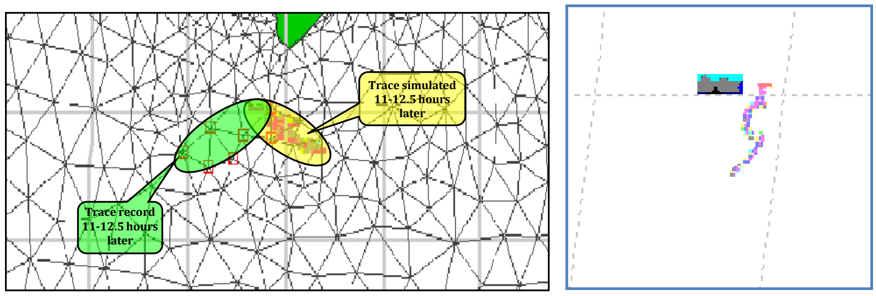
(a)



(b)

Figure 4. Wind direction (a) and speed (b) adopted in validation test of "Tasman Sea" oil spill accident case.

diagram in Figure 6. However, the simulation results coupled with tidal current model of the flow measurement period and the input of the first stage wind field data is also reliable, as shown in the chart built in Figure 6.



(a) (b)

Figure 5. (a) Comparison between record and simulated oil traces before coding correction of CWCM program; (b) Simulated oil trace after the correction.

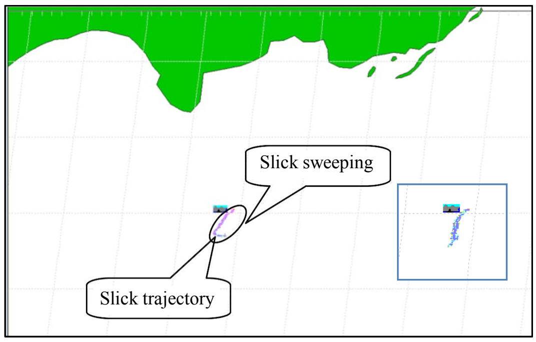


Figure 6. Main plot: simulation result using second stage wind data; Chart built: simulation result using tidal current model in current measurement period.

106 hours simulation was carried out using the first, second stage wind data separately, and the result compared overlayed with the interpretation results of related satellite images [16] shows that most of the location and range of the oil spill trajectory simulated using the first stage wind data can be located in the oil contaminated zone interpreted by the satellite, but the oil slick range is smaller than that of the satellite interpretation (**Figure 7**). However, the simulation results using the second stage wind data cannot match the satellite image interpretation results. It is shown that although the wind field diagnostic model can reproduce the wind condition better in the first 12 hours, the long term diagnostic simulation needs to update the initial data dynamically to improve the accuracy.

3.2. Calibration Analysis of Reduced Scale Oil Spill Weathering Simulation Test

Reduced scale simulation experiments of oil spill weathering of four oil types in winter and summer were carried out in Shenzhen using self-made marine oil spill weathering simulator [17] [18] [19] [20]. Test oil types are respectively: diesel oil and heavy oil in winter (temperature 11˚C - 23˚C), Oman and Wen-Chang crude oils in summer (temperature 27˚C - 34˚C). The size of simulation test device is 5.0 m long × 3.0 m wide × 1.0 m water deep. There are two permeable pushing water plates with a distance of about 1.4 m placed in the tank

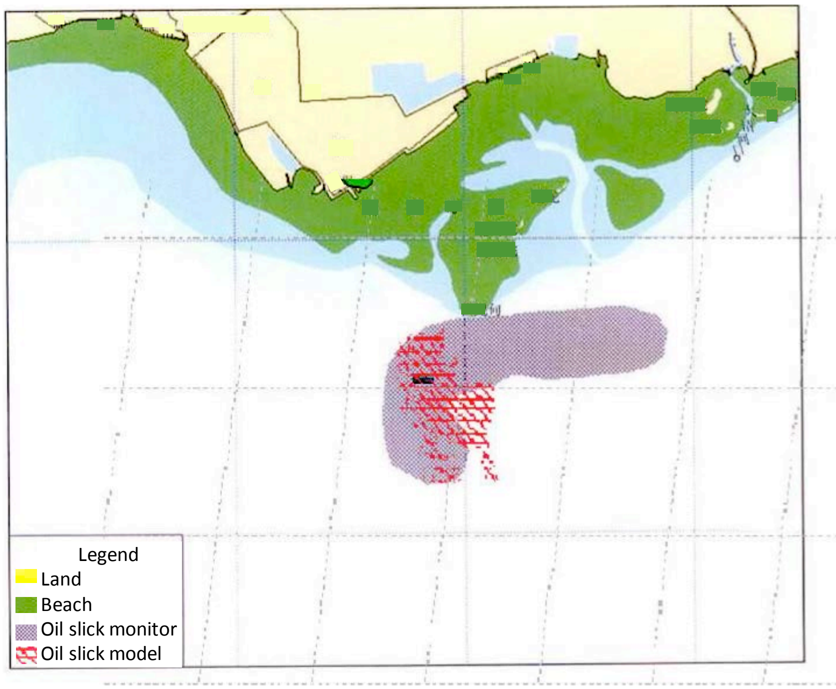


Figure 7. The 106th hour simulation result using first stage wind data overlaid with satellite interpretation map.

moving back and forth according to the cycle of 1 min. The speed of motion is about 0.3 m/s, and the weathering test time is 1 month per period.

3.2.1. Weathering Model of Oil Spill Source Term

Weathering test results (see Table 2 and Figure 8 and Figure 9) show that the different oil types and different environmental temperature and light conditions will affect the weathering speed. Weathering is faster in summer than that in winter, and significantly faster when oil viscosity is lower (kinematic viscosity of diesel at 20˚C 4.584 mm^2/s; Oman crude oil at 50˚C 3.38 mm^2/s) than when oil viscosity is higher (kinematic viscosity of Wen-Chang crude oil at 50˚C 4.955 mm^2/s; fuel oil at 100˚C 35.57 mm^2/s). The viscosity if oil types with more complicated components (crude oil, fuel oil), increases rapidly associated with the weathering process (Figure 8). Water apparently encapsulated in the fuel oil as its moisture content reached 70% at 100 hours of weathering (Figure 9).

It can be seen from Table 2, that C10 - C14 in four kinds of oils are all weathered completely at 10 to 20 days in summer and more than 30 days in winter; weathering of C15 - C20 in winter is not obviously, weathering of C15 - C17 in summer is partially, weathering of C18 - C20 in summer is not obviously, and C21 - C24 of all oils are basically non weathering in winter and summer. The ratio of GCMS peak area of C10 to C24 components before weathering and weathering for 1 month are shown in Figure 10 and Figure 11, from which it can be analyzed that the proportion of hydrocarbon weathering components are about 41.1% in Oman crude oil, 32.9% in Wen-Chang crude oil, 26.9% in diesel oil and 10.4% in fuel oil.

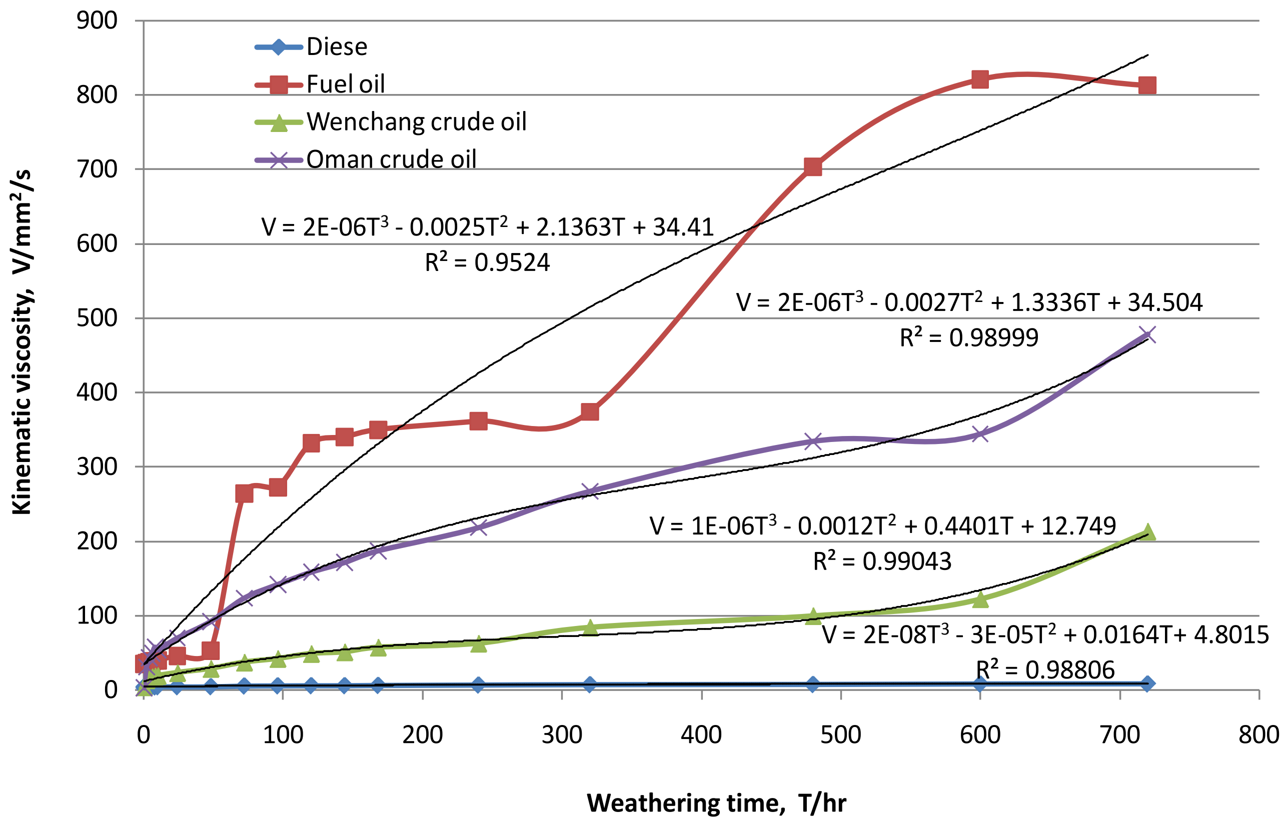


Figure 8. Dynamic changes and statistical regression curves of viscosity.

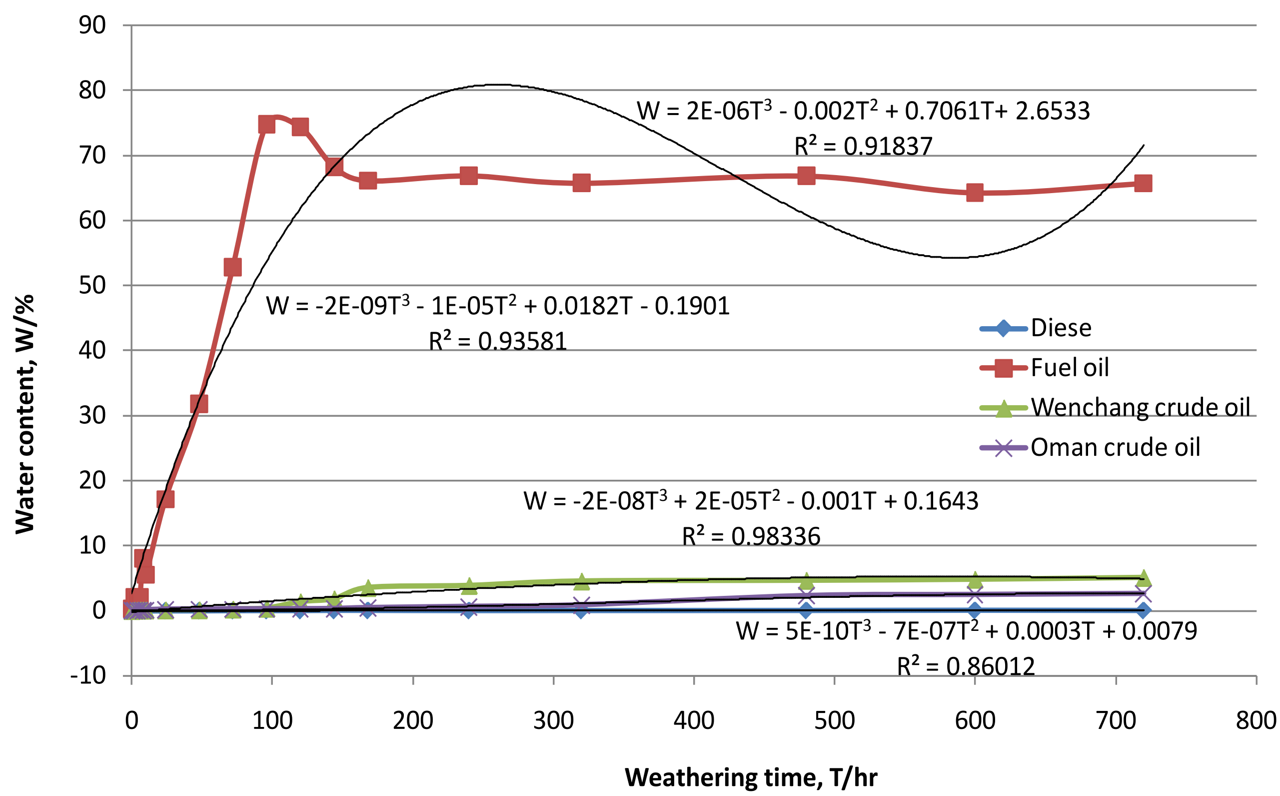


Figure 9. Water content in four types oil spill weathering tests.

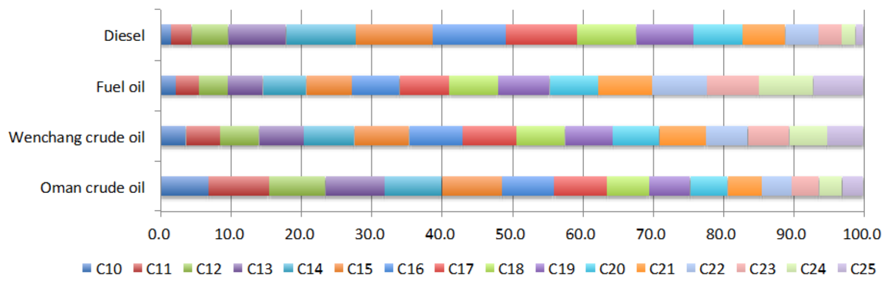


Figure 10. The ratio of GCMS peak area of C10 to C24 components before weathering.

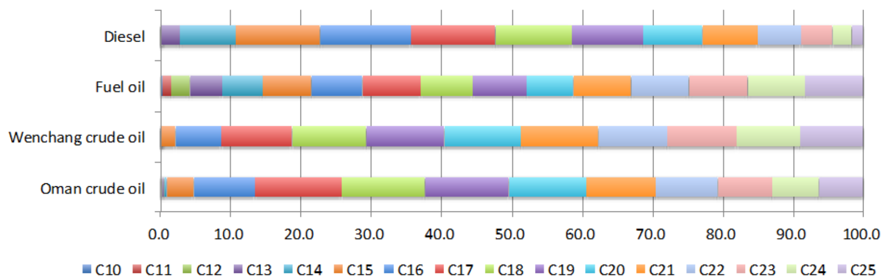


Figure 11. The ratio of GCMS peak area of C10 to C24 components weathering for 1 month.

Table 2. Table type styles (Table caption is indispensable).

Oil type	C10 - C11	C12	C13 - C14	C15 - C17	C18 - C20	C21 - C24
Diesel	120 h Weathering finished	Obvious weathering		Weathering is not obvious		Basically non weathering
Fuel oil	240 h Weathering finished					
Oman crude oil	96h Weathering finished		240 h Weathering finished	Partial weathering	Weathering is not obvious	
Wenchang crude oil			480 h Weathering finished			

3.2.2. Influence Model of Oil Spill Weathering on Water Quality

The results of water quality comparison of similar diesel oil in oil spill weathering tests were compared. Because the oil spill slick of "Tasman Sea" accident was thinner similar to that of diesel oil in weathering test, actual monitored water quality [16] was compared with the simulated test [19] to calibrating the simulation model based on reduced scale oil spill weathering test. When DO, COD, and oil concentration adjustment factors were taken (205, 8, 1) and reduced scale simulation ratios(1:2, 1:48, 1:368) concentration of water quality calculated by model were similar with the actual monitored ones in the same oil spill weathering time period.

Actual monitored water quality of Dalian "7.16" accident [21], where the oil spill slick was thicker and similar to that of crude oil, was compared with reduced scale weathering test results of crude oil [19]. When DO, COD, BOD5 and oil concentration adjustment factor taken (5, 8, 4, 1) and reduced scale simulation ratios (1:16 - 1:145, 1:26 - 1:232, 1:13 - 1:116, 1:3 - 1:29) used the calculated water quality index at the same spill time is 0.9 - 4.6, and ratios oil content exceeding the standard are 2.4 - 17.2, which are in good agreement with the real monitoring results of the spill.

4. Conclusions and Recommendations

1) As important means of damage monitoring analysis and judgment, application of oil spill model in judicial identification of environment damage and damage fund claims business has been recognized in China. Therefore, it is necessary to extend damage evaluation function of oil spill model, and to test, to calibrate and to verify the evaluation accuracy of the model to enhance its applicability.

2) The simulation accuracy of oil spill model depends on the scientific merit of the model theory and parameter selection, the correctness of software coding, and the authenticity of oil spill source item and of meteorological and hydrological data. CWCM oil spill model developed by the author is verified and compared by using environmental monitoring information and the oil spill accident case data. Its short-term oil drift and diffusion simulation results are consistent with the real spill data. However, in order to further improve the evaluation function and accuracy of oil spill model, the oil spill weathering model and water quality impact assessment model still need to be improved according to the late oil spill weathering reduced scale simulation test and calibration results. Additionally there is a need to enhance the accuracy of 3-D current model coupled by supplying dynamic updates of diagnostic wind field and other functions.

3) It is recommended that competent departments are established to improve record supervision of the damage assessment model of appraisal institutions, including, the requirement of R & D and applying units of oil spill models to provide complete and detailed explanation on the ecological environmental damage simulation function and scientific principle at the time of filing, and to submit audit documents issued by authorized inspection and testing organizations, to standardize supporting operational application programs and processes, etc.

To further improve the operational evaluation function and evaluation efficiency of oil spill model, it is recommended to improve the coupled current model, wind field model, oil spill weathering model, water quality impact model, ecological impact model, and to carry out the oil spill case verification. The updating scheme of oil spill model for operational application is shown in Figure 12.

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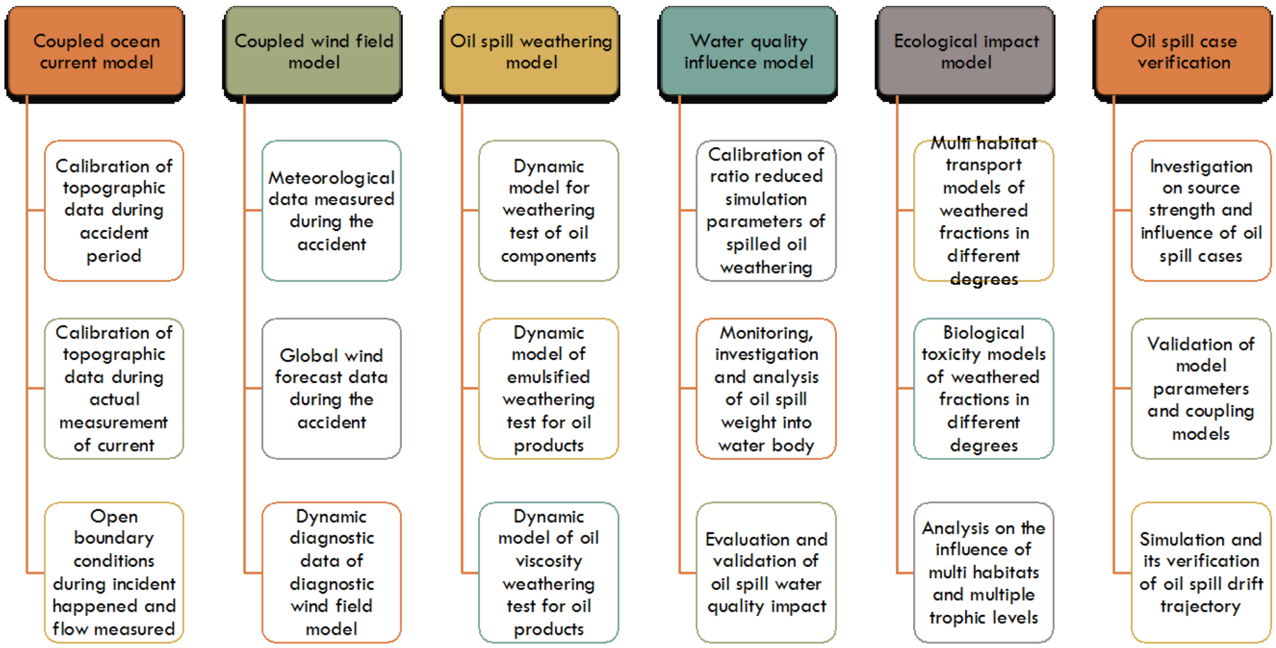

Figure 12. Update scheme of oil spill model for operational application.

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