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Two- and three-dimensional oil spill model for coastal waters

Xiaobo Chao *, N. Jothi Shankar, Hin Fatt Cheong

Department of Civil Engineering, National University of Singapore, Engineering Drive 2, Singapore 117576

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Abstract

This paper presents the development and application of two-dimensional and three-dimensional oil trajectory and fate models for coastal waters. In the two-dimensional model, the oil slick is divided into a number of small grids and the properties of each grid due to spreading, advection, turbulent diffusion, evaporation and dissolution are studied. This model can predict the movement of the oil slick on the water surface. In order to simulate the distribution of oil particles in the water column, a three-dimensional oil fate model is developed based on the mass transport equation and the concentration distribution of oil particles can be solved. A comparison of numerical results with the observed data shows good conformity.

Keywords: Oil spills; Oil trajectory model; Concentration of oil particle; Coastal waters

1. Introduction

In recent years there has been a growing concern over the increasing contamination of water bodies and adjacent shoreline areas by oil spills. Some processes, such as industrial discharge, oil exploration and transport, oil storage facilities, etc., have increased the risk of oil spill accidents. The oil spill accident is very harmful to the ocean environment and the health of mankind. A major oil spill can contaminate the shoreline, cause long-term damage to the aquatic environment for fishery and wildlife. Oil spills may also foul the harbour facilities and vessels. To prepare for such

* Corresponding author. Fax: +65-8724067.
E-mail address: tmscxb@nus.edu.sg (X. Chao).

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accidents, many government agencies have prepared oil spill contingency plans. An important component of these plans is the use of mathematical models to predict the oil slick motion and distribution of oil particle concentrations in the coastal waters.

Generally, the transport and fate of spilled oil can be affected by the physical, chemical and biological processes. These include spreading, advection, evaporation, dissolution, emulsification, photo-oxidation, sedimentation, and biodegradation. The chemical and biological processes generally occur a long time after the oil spill. Under the actions of the breaking wave and upper layer turbulence, the oil slick will break up and become small particles, then advect and diffuse in the water column. Some of the particles will resurface, while some will form water-in-oil or oil-in-water emulsions. The specific gravity of the resulting emulsion oil is close to the water (ASCE Task Committee, 1996). The oil particles can stay in the water column for a long time, and pollute the deeper water environment. In the last two to three decades, many researchers have studied the transport and fate processes of oil spills based on the trajectory method and mass balance approach, and various oil spill models have been developed (Mackay et al., 1980; Huang, 1983; Yapa et al., 1994; Spaulding, 1995; ASCE Task Committee, 1996; Li and Mead, 1999). Some commercial oil spill models, such as COZOIL (Reed et al., 1989), NOAA (Galt et al., 1991), OILMAP (Howlett et al., 1993), WOSM (Kolluru et al., 1994), are currently used to determine the oil movement and distribution in the water body. In view of the limited understanding of the oil spill processes, the accuracy of the simulations must be viewed with some reservation. Among these oil spill models, many of them focus on the surface movement of oil spills. There has been little published research on oil spill fate processes and concentration distribution in the water column.

In this study, a two-dimensional (2-D) trajectory and fate model is developed to simulate the processes of spreading, advection, turbulent diffusion, evaporation and dissolution of an oil slick on the water surface. Based on the mass-transport equations, a three-dimensional (3-D) oil fate model is established to simulate the distribution of oil particle concentration in the water column.

2. Oil spill processes

2.1. Spreading on the water surface

Spreading is the horizontal expansion of an oil slick due to gravity, inertia, viscous and surface tension forces. Fay (1971) considered an oil slick to pass through three phases and the axi-symmetrical spreading diameter in each of the phases can be defined. However, due to non-consideration of the influence of wind and associated turbulence, the prediction of oil spreading using Fay's formula has been found to be underestimating the horizontal spreading compared to that observed from field measurements. Lehr et al. (1984) formulated a modified Fay-type spreading equation considering the influence of wind:

$$A=2270\left(\frac{\Delta\rho}{\rho_o}\right)^{2/3}V^{2/3}t^{1/2}+40\left(\frac{\Delta\rho}{\rho_o}\right)^{1/3}V^{1/3}U_{\mathrm{wind}}^{4/3}t \quad (1)$$

where A is the area of the oil slick (m^2); $\Delta\rho=\rho_w-\rho_o$; V is the total volume of the spilled oil in barrels; U_{wind} is the wind speed in knots; and t is the time in minutes.

Based on the Lehr formula, the area of the oil slick due to spreading at every time step can be obtained.

2.2. Advection and turbulent diffusion on the water surface

2.2.1. Grid generation for oil slick

The shape and track of the oil slick are very important for predicting the oil movement. In this 2-D oil spill model, the initial oil slick area is divided into a number of small grids, and a set of plane coordinates are assigned to each grid. It is assumed that these grids advect with the surrounding water body and diffuse as a result of random processes. Based on the flow fields on the water surface and the wind velocity, the advection and diffusion properties of each grid point can be computed. Then the velocity and displacement of each grid can be solved. After calculating the grid coordinates at every time step, the shape and track of the oil slick can be decided.

2.2.2. Advection velocity

The advective velocity of each grid point $\vec{U}_d$ can be computed as:

$$\vec{U}_d=K_t\vec{U}_t+K_w\vec{U}_w \tag{2}$$

$\vec{U}_t$ is the surface water current velocity, it can be obtained from the 3-D turbulence tidal model (Chao et al., 1999); $\vec{U}_w$ is the wind velocity at 10 m above the water surface; K_t is the current factor and as the current velocity is the surface velocity, K_t is selected as 1.0; K_w is the wind drift factor, usually adopted as 0.03.

2.2.3. Horizontal turbulent diffusion

The turbulent diffusive transport is normally calculated by a random walk procedure. The diffusive velocity component can be modeled by a homogeneous random walk model. Based on Al-Rabeh et al.'s study (1989), the distance that any element (grid) travels by horizontal diffusion is:

$$\Delta S=[R]_0^1\sqrt{12D_h\Delta t} \tag{3}$$

where $[R]_0^1$ is the random number in the interval 0–1; D_h is the horizontal diffusion coefficient and in the present study we select D_h as 7 m^2/s.

2.2.4. Displacement of every grid point

The advective displacement of each grid point at every time step can be computed as:

$$L_x(\Delta t)=U_{dx}\Delta t+\Delta S\cos\theta \tag{4}$$

$$L_y(\Delta t)=U_{dy}\Delta t+\Delta S\sin\theta \tag{5}$$

where $L_x(\Delta t)$ and $L_y(\Delta t)$ are the displacements of each point in the x and y directions, respectively; U_{dx} and U_{dy} are the advective velocities in the x and y directions, respectively; and

$$\theta=2\pi[R]_0^1 \tag{6}$$

Then the x and y coordinates of each point on the oil slick at every time step can be obtained, and the shape and track of the oil slick at every time step can be obtained.

2.3. Evaporation

Evaporation occurs immediately after the spill. Mackay (1981) developed a multi-component theory to compute the rate of oil evaporation. In this theory the evaporative amount of a given component of oil was given by the following equation:

$$M_i=K_eAtX_iP_i^s/(RT) \tag{7}$$

in which M_i is the amount of component i lost by evaporation (mole); K_e is the mass transfer coefficient of evaporation (m/s); A is the area of the oil slick (m^2); t is the time (s); R is the gas constant (atm-m^3/mol K); and T is the air temperature above the slick (K). In the equation, $X_iP_i^s$ represents the partial vapor pressure of component i; P_i^s is the vapor pressure of component i; X_i is defined as following:

$$X_i=M_i/\sum M_i \tag{8}$$

Mackay and Matsugu (1973) proposed the following formulation to compute the mass transfer coefficient of evaporation K_e based on laboratory experiment results:

$$K_e=0.0292U_{\mathrm{wind}}^{0.78}D^{-0.11}S_c^{-0.67} \tag{9}$$

where K_e is the mass transfer coefficient (m/h); U_{wind} is the wind speed (m/h); D is the oil slick diameter (m); and S_c is the Schmidt number which represents the surface roughness and it is taken as 2.7 in this study.

Then the rates of evaporation can be calculated as:

$$S_e=\sum M_i/t=\sum K_eAX_iP_i^s/(RT) \tag{10}$$

Based on Eq. (10), the evaporative amount of oil at every time step can be calculated.

2.4. Dissolution

Some of the oil components, which are subjected to evaporation, can also dissolve into the water column from a surface slick. Mackay (1981) developed a multi-component theory to compute the rate of oil dissolution. The amount of component i lost by dissolution can be calculated by the following equation:

$$M_{di}=K_dAtX_iS_i \tag{11}$$

in which M_{di} is the amount of component i lost by dissolution (mole); K_d is the dissolution mass transfer coefficient (3.0×10^{-6} m/s was chosen); X_i is the component mole fraction; A is the area of the oil slick (m^2); t is the time (s); and S_i is the solubility.

The rates of dissolution were then calculated as:

$$S_d=\sum M_{di}/t=\sum K_d A X_i S_i \tag{12}$$

2.5. Vertical dispersion

The oil slick on the ocean is also subject to the action of waves, especially breaking waves and upper layer turbulence. Under their actions, the coherent oil slick will break up and become small particles, then advect and diffuse in the water column. These processes are defined as vertical dispersion. The main objective of vertical dispersion study is to estimate the oil entrainment rate and distribution of oil particles. Delvigne and Sweeney (1989) and Delvigne (1994) conducted a series of laboratory investigations to detect the oil entrainment rate, particle size and intrusion depth of oil particles. They described the entrainment rate as a function of the oil type, breaking-wave energy and temperature using an empirical relation given as:

$$Q(d)=K_{en}D_{ba}^{0.57}S_{cov}F_{wc}d^{0.7}\Delta d \tag{13}$$

in which d is the particle size (m); Δd is the particle size interval (m); $Q(d)$ is the entrainment rate of oil particles with particle sizes in the interval Δd around d (kg/m^2 s); K_{en} is an empirical constant dependent on the oil type and weathered state; D_{ba} is energy dissipation of the breaking wave per unit surface area (J/m^2); S_{cov} is the fraction of surface area covered by oil ($0\leq S_{cov}\leq1$) and F_{wc} is the fraction of sea surface hit by breaking waves per unit time. D_{ba} and F_{wc} are given by the following semi-empirical formulas:

$$D_{ba}=0.0034\rho_w g H_{rms}^2 \tag{14}$$

$$F_{wc}=0.032(U_{wind}-U_i)/T_w \tag{15}$$

in which ρ_w is the density of water (kg/m^2); g is the acceleration due to gravity (m/s^2); H_{rms} is the rms wave height (m); U_{wind} is the wind speed (m/s); U_i is the threshold wind speed for wave breaking ($\approx$5 m/s); and T_w is the breaking wave period (s).

Based on Eq. (13), the rate of vertical dispersion can be obtained by integration over all particle sizes, given by:

$$s_{vd}=\int_{d_{min}}^{d_{max}} Q(d)\Delta d \tag{16}$$

The maximum and minimum particle sizes are calculated as follows (Raj, 1979):

$$d_{max}=\left[\frac{12\sigma}{g(\rho_w-\rho)}\right]^{1/2} \tag{17}$$

$$d_{\min}=\frac{0.12\sigma^{3/5}\omega^{2/5}}{\rho_{\mathrm{w}}^{3/5}g^{4/5}} \tag{18}$$

where σ is the interfacial tension; ρ_{w} and ρ_{o} is the density of water and oil respectively; and ω is the wave frequency.

The intrusion depth Z_i was found experimentally by Delvigne and Sweeney (1989):

$$Z_i \approx 1.5H_{\mathrm{b}} \tag{19}$$

where H_{b} is the height of the breaking wave.

2.6. Shoreline deposition

Oil may be brought to and deposited along the shoreline, and re-entrained into the water. Field observations of large spills indicate that the capability of beaches to hold oil is limited. Once the shoreline capacity is reached, oil will be exposed to longshore transport processes. Based on Humphrey et al.'s study (1993), the maximum capacity of beach for oil can be expressed as:

$$C_{\max}=L_{\mathrm{s}}W_{\mathrm{s}}D_{\mathrm{s}}\eta_{\mathrm{eff}} \tag{20}$$

where $C_{\max}$ is the maximum capacity of a beach for oil (m^3); L_{s}, W_{s}, D_{s} are the length, width, and depth of sediments on the beach, respectively (m); and η_{eff} is the effective porosity of the sediments on the beach (0.12~0.46).

3. Development of oil spill models

3.1. Two-dimensional oil spill model for surface oil slick

During the early stages after the oil spill has occurred, the transport of spilled oil is mainly governed by: the spreading due to the gravity, inertia, viscosity and surface tension forces; the advection and turbulent diffusion due to current and wind; evaporation, dissolution and vertical dispersion. If the oil slick moves towards the islands or shoreline, the shoreline deposition and re-entrainment will also be considered. The above processes of oil spills have been studied in Section 2. Based on these studies, a 2-D trajectory and fate model is developed to simulate the movement of the surface oil slick.

In this 2-D model, the oil spills are divided into a number of small grids based on the quantity and initial area. A set of plane coordinates are assigned to each grid. At every time step, after incorporation of the evaporation, dissolution and vertical dispersion properties of oil spills (see Sections 2.3, 2.4 and 2.5), the volume of oil spills remaining on the water surface can be obtained. According to Eq. (1), the spreading area of the oil slick can be estimated. During the same time step, because of the advection and turbulent diffusion, the oil slick will move to a new location and its displacement can be determined using Eqs. (4) and (5). The new grid coordinates of the oil slick due to the combined effect of spreading, advection and diffusion are then calculated. After obtaining the grid coordinates of the oil slick at every time step, the shape and track of the oil slick can be obtained. If the oil slick moves towards the island or shoreline, it may deposited along the shoreline, and later re-entrained into the water. The maximum capacity of beach for oil is given by Eq. (20). Using this 2-D oil spill model, the movement of the oil slick as well as the mass balance of oil spills can be predicted.

3.2. Three-dimensional fate model for oil particle concentration

Because of spreading, advection, horizontal diffusion, evaporation and dissolution, the oil slick becomes thinner and thinner. Under the action of turbulent shear and breaking waves, the oil slick will disperse and become small particles. Delvigne and Sweeney (1989) and Delvigne (1994) has studied the vertical dispersion of surface oil slicks based on experimental data, and the dispersion rate can be solved. The small oil particles can advect and diffuse in the water column because of the turbulent waters. Some of them float back to the water surface, while some of them form water-in-oil or oil-in-water emulsions. Since the density of emulsion oil is close to that of water, it can stay in the water column for a long time. In order to simulate the distribution of oil particles in the water column, a 3-D oil spill numerical model is necessary. As the fate and transport processes of oil spills in the water column are very complex, there has been little published research on the 3-D oil spill model.

In this paper, the authors have studied the distribution of oil particles in the water column. Based on Delvigne's studies (Section 2.5), the rate of vertical dispersion of the oil slick can be obtained. Considering the evaporation and dissolution of the surface oil slick, the total quantity of oil particles at every time step can be calculated and set as a source term. In order to simplify the 3-D numerical model, the oil particles are assumed to be of uniform diameter and single component. Based on the mass transport equation, a 3-D oil spill model can be developed to predict the concentration distribution of oil particles in the water column.

3.2.1. Governing equation

A 3-D multi-level tidal hydrodynamics model has been developed based on the 3-D Navier–Stokes equations (Chao et al., 1999). Based on the 3-D Reynolds-averaged equations, applying the Boussinesq approximation, the turbulent stress and turbulent mass flux are simulated by the turbulent viscosity and turbulent diffusion. The governing equations of 3-D tidal flows as well as oil concentration distribution in coastal waters are as follows:

Continuity equation:

$$\frac{\partial U}{\partial x}+\frac{\partial V}{\partial y}+\frac{\partial W}{\partial z}=0 \tag{21}$$

Momentum equations in the x and y directions:

$$\frac{\partial U}{\partial t}+U\frac{\partial U}{\partial x}+V\frac{\partial U}{\partial y}+W\frac{\partial U}{\partial z}=-\frac{1}{\rho}\frac{\partial P}{\partial x}+\frac{\partial}{\partial x}\left(\nu_{\mathrm{h}}\frac{\partial U}{\partial x}\right)+\frac{\partial}{\partial y}\left(\nu_{\mathrm{h}}\frac{\partial U}{\partial y}\right)+\frac{1}{\rho}\frac{\partial(\tau_x)}{\partial z})+\Omega V \quad (22)$$

$$\frac{\partial V}{\partial t}+U\frac{\partial V}{\partial x}+V\frac{\partial V}{\partial y}+W\frac{\partial V}{\partial z}=-\frac{1}{\rho}\frac{\partial P}{\partial y}+\frac{\partial}{\partial x}\left(\nu_{\mathrm{h}}\frac{\partial V}{\partial x}\right)+\frac{\partial}{\partial y}\left(\nu_{\mathrm{h}}\frac{\partial V}{\partial y}\right)+\frac{1}{\rho}\frac{\partial(\tau_x)}{\partial z})-\Omega U \quad (23)$$

Hydrostatic pressure equation:

$$\frac{\partial P}{\partial z}+\rho g=0 \quad (24)$$

Oil particle transport equation:

$$\frac{\partial C}{\partial t}+\frac{\partial(UC)}{\partial x}+\frac{\partial(VC)}{\partial y}+\frac{\partial(WC)}{\partial z}=\frac{\partial}{\partial x}\left(D_x\frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial y}\left(D_y\frac{\partial C}{\partial y}\right)+\frac{\partial}{\partial z}\left(D_z\frac{\partial C}{\partial z}\right) \quad (25)$$
$$+\frac{\partial(\omega C)}{\partial z}+\sum S$$

Here U, V, W are the time-averaged velocity components in the longitudinal (x), lateral (y) and vertical (z) directions, respectively; t is the time; ρ is the density of oil–water flow; P is the time-averaged pressure; g is the gravitational acceleration; ν_{h} is the coefficient of horizontal eddy viscosity; τ_x and τ_y are the horizontal shear stresses resulting from vertical turbulent momentum transport; Ω is the Coriolis parameter, $\Omega=2\omega\sin\phi$, where ω is the angular speed of the Earth's rotation and ϕ is the geographical latitude; C is the concentration of oil particles; D_x, D_y and D_z are the diffusion coefficients in the x, y and z directions, respectively; ΣS is the effective source term; ω is the buoyant velocity of the oil particles, where

$$\omega=\frac{1}{18}\frac{\rho_{\mathrm{w}}-\rho_{\mathrm{o}}}{\rho_{\mathrm{w}}}g\frac{d^2}{\nu_{\mathrm{w}}} \quad (26)$$

Here ρ_{w} and ρ_{o} are the mass densities of water and oil respectively; d is the averaged oil particle size; and ν_{w} is the kinematic viscosity of water.

3.2.2. Numerical solution

In the numerical model, the coastal waters are divided into a number of layers. In every layer, the velocities are integrated along the layer depth direction. A second-order, implicit finite difference scheme is used to obtain a numerical solution to the governing equations involving velocity field, water surface levels and oil particle concentration. The variables in the equations are defined at staggered locations on a rectangular mesh. The scalar variables are placed at the center of grid, while the velocity components U, V, W are placed at the midpoints of the east interface, south interface and lower interface, respectively.

In an individual computational cell, the density (ρ) and the viscosity (ν) are distinguished by the fraction of the oil in the oil–water mixture flow and they can be defined as:

$$\rho=F_{\mathrm{ow}}\rho_{\mathrm{o}}+(1-F_{\mathrm{ow}})\rho_{\mathrm{w}} \tag{27}$$

$$\nu=F_{\mathrm{ow}}\nu_{\mathrm{o}}+(1-F_{\mathrm{ow}})\nu_{\mathrm{w}} \tag{28}$$

where F_{ow} is the fraction of the oil in the mixture.

According to the Boussinesq approximation, the Reynolds stresses are expressed through the turbulent viscosity terms. As regards the horizontal eddy viscosity terms, the homogeneous assumption is applied. Previous studies by Shankar et al. (1997) have shown that ν_{h}=5~10 m^2/s adequately represents the circulation in Singapore coastal waters. For the vertical exchange terms, the mixing length turbulence model is used and the turbulent stresses (τ_x, τ_y) in Eqs. (22) and (23) can be expressed as:

$$\tau_x=\nu_{\mathrm{t}x}\frac{\partial U}{\partial z}=\rho l_{\mathrm{m0}}^2\left|\frac{\partial U}{\partial z}\right|\frac{\partial U}{\partial z} \tag{29}$$

$$\tau_y=\nu_{\mathrm{t}y}\frac{\partial V}{\partial z}=\rho l_{\mathrm{m0}}^2\left|\frac{\partial V}{\partial z}\right|\frac{\partial V}{\partial z} \tag{30}$$

where $\nu_{\mathrm{t}x}$ and $\nu_{\mathrm{t}y}$ are the coefficients of turbulent viscosity in the x and y directions, respectively; l_{m0} is the mixing length and it is simply a function of the relative depth (z/H):

$$l_{\mathrm{m0}}=0.7z(1-z/H)^{0.5} \tag{31}$$

In the concentration Eq. (25), the horizontal diffusion coefficients can be obtained by Eqs. (32) and (33) (HR, Wallingford, 1982). As for the vertical diffusion coefficient, it can be expressed as the function of turbulent eddy viscosity:

$$D_x=\frac{A_x}{A_{\mathrm{t}x}}(F_0+F_1Q_{\mathrm{T}})+\alpha Q_k\frac{\Delta x}{A_x} \tag{32}$$

$$D_y=\frac{A_y}{A_{\mathrm{t}y}}(F_0+F_1Q_{\mathrm{T}})+\alpha Q_k\frac{\Delta y}{A_y} \tag{33}$$

$$D_z=\frac{\nu_{\mathrm{e}}}{\sigma_{\varphi z}}=\frac{\nu}{\sigma_{\varphi z}}+\frac{\nu_{\mathrm{t}}}{\sigma_{\sigma z}} \tag{34}$$

in which A_x and A_y are the cross-sectional areas in the x and y directions, respectively; $A_{\mathrm{t}x}$ and $A_{\mathrm{t}y}$ are the total cross-sectional areas in the x and y directions; Q_{T} is the tidal discharge across the interface; Q_{k} is the total discharge; F_0, F_1 and α are the empirical factors; Δx and Δy are the distances between element centers in the x and y directions, respectively; ν , ν_{t} and ν_{e} are the kinematic molecular viscosity, kinematic turbulent viscosity and kinematic effective viscosity, respectively; $\sigma_{\varphi z}$ is the turbulent Schmidt number. Based on the mixing length turbulent model, the same as Eq. (29), the turbulent viscosity v_t can be expressed as:

$$v_t=\rho l_m^2\left|\frac{\partial U}{\partial Z}\right| \tag{35}$$

where l_m is mixing length in the oil–water flow. It can be defined as:

$$\frac{l_m}{l_{m0}}=(1+\beta R_i)^{-0.5} \tag{36}$$

where β=20; l_{m0} is the natural mixing length, which can be obtained from Eq. (31); R_i is Richardson number, which can be expressed as:

$$R_i=-\frac{g}{\rho}\frac{\partial\rho/\partial z}{(\partial U/\partial z)^2} \tag{37}$$

For the turbulent Schmidt number $\sigma_{\varphi z}$, the buoyancy influence needs to be considered, and this can be accounted for by the Munk–Anderson formula:

$$\frac{\sigma_{\varphi z}}{\sigma_{\varphi 0}}=\frac{(1+3.33R_i)^{1.5}}{(1+10R_i)^{0.5}} \tag{38}$$

where $\sigma_{\varphi 0}$=1.0. After obtaining v_t and $\sigma_{\varphi z}$, the vertical diffusion coefficient can be obtained.

In this model, the concentration field is solved by coupling with the flow field. The finite difference method involves a time step procedure. The method chosen uses forward difference for time derivative and central difference for space terms. Combining the implicit finite difference equations for all the elements, a sparse matrix equation can be obtained. After solving the matrix equation, the water elevation, currents as well as the oil concentration in the water body at every time step can be obtained.

4. Application to Singapore coastal waters

As Singapore is a major oil refinery centre, and the Straits of Singapore is a very important shipping route in the region, with the frequent movement of oil tankers, the risk of oil spills in the coastal waters has increased. The most recent example is the case of the massive spill of 28,500 tonnes of heavy fuel oil on 15 October 1997 from the tanker Evoikos. The heavy fuel oil was discharged into the Singapore Straits in a very short time. As shown in Fig. 1, point A is the location of the oil spill accident (x=52 km and y=15.5 km).

In this paper the 2-D oil spill model is used to simulate the surface oil slick, and the movement of the oil slick on the water surface can be obtained. After the oil spill accident occurred, the Port of Singapore Authority (PSA) quickly observed movement of the oil spill. Based on their observed data, the location and polluting

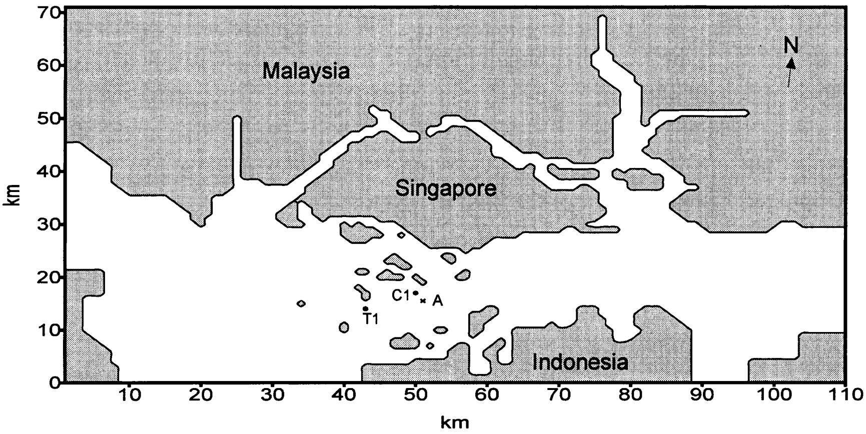

Fig. 1. Computational domain of Singapore coastal waters.

area could be obtained approximately and used to match the computed results (Fig. 6). As the range of oil pollution was very large, the observed results are not accurate. Only the approximative range of the oil slick distribution could be plotted on the map and used to compare with the numerical results. In order to study the longer-term environmental impact assessment of Singapore coastal waters by oil spills, the 3-D model is used to predict the oil particle concentration in the water column.

4.1. Simulation of 3-D tidal currents

Applying the 3-D multi-level turbulence tidal model (Chao et al., 1999), the flow fields in Singapore coastal waters can be simulated. At each time step the basic outputs, which include the water surface elevations and current speeds and directions in every layer, are obtained.

As shown in Fig. 1, the computational domain covers an area of 110×72 km. The water body is divided into eight layers. On the surface layer, there are 3188 active grids, including 86 open boundary grids. As for the eight layers, there are 15,496 active grids altogether, including 501 open boundary grids.

Figs. 2 and 3 show the comparisons between the time history records computed

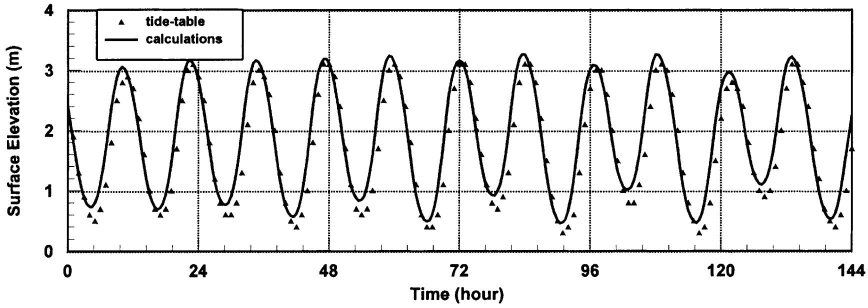

Fig. 2. Time history of surface elevations at T1 station (43, 14) (15–20 October 1997).

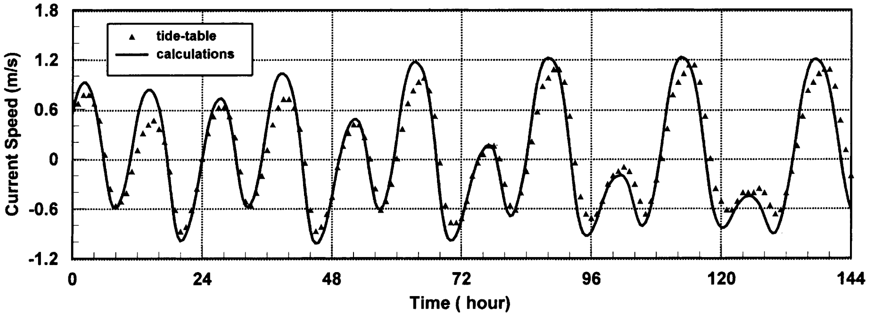

Fig. 3. Time history of surface layer currents at C1 station (50, 17) (15–20 October 1997).

from the multi-level model and the tide table data (MPA, 1997). It is observed that the water surface elevations and currents from the numerical model are in good agreement with the tide table data.

4.2. Simulation of the transport of the surface oil slick

Based on the 2-D trajectory and fate model, the convective and dispersive characteristics and weathering processes of the surface oil slick are obtained. Fig. 4 shows the thickness of the oil slick as a function of time. It can be observed that the oil slick thickness decreases rapidly during the initial 6 h. This means that the first stage of spreading occurs in a short time. After this initial phase involving gravity, inertia and viscous forces, the surface tension phase of spreading takes over and lasts for

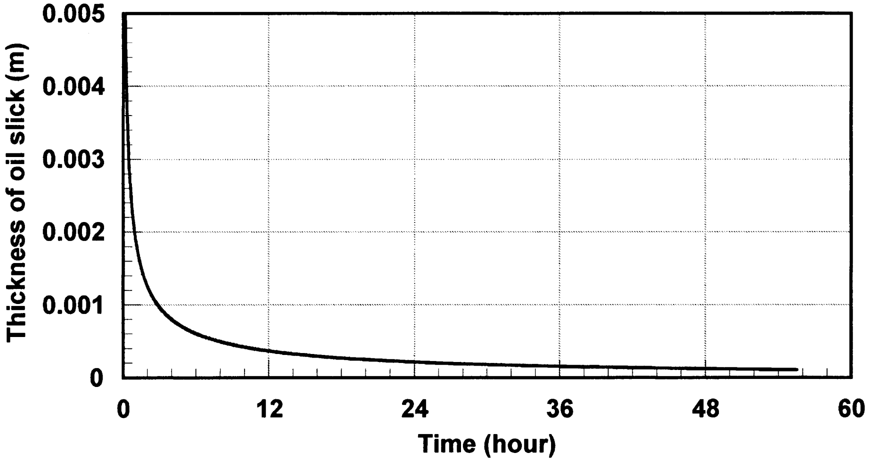

Fig. 4. Thickness of the oil slick versus time.

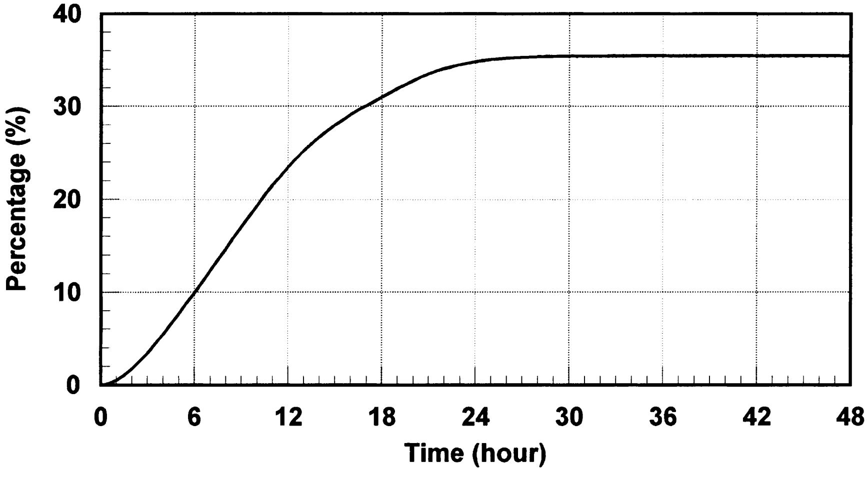

Fig. 5. Evaporation percentage of the oil slick versus time.

a longer time, until the oil slick becomes unstable and breaks up. Figs. 5 and 6 show the relations between the percentage of evaporation and dissolution versus time. It can be observed that the evaporation mainly happens in the first 1–2 days, when about 36% of the oil evaporates. In contrast, the amount of dissolution is very little, being only 0.029% of the total amount of spilled oil. Fig. 7 shows the movement of the oil slick on the water surface. It can be observed that the major movement direction and polluted area of the oil slick from the model are generally in agreement with the observed results by PSA. We can observe that the oil slick moves on the water surface without disintegration during the first day. After the oil moves to the shoreline, the shoreline deposition increases gradually. Once the shoreline capacity

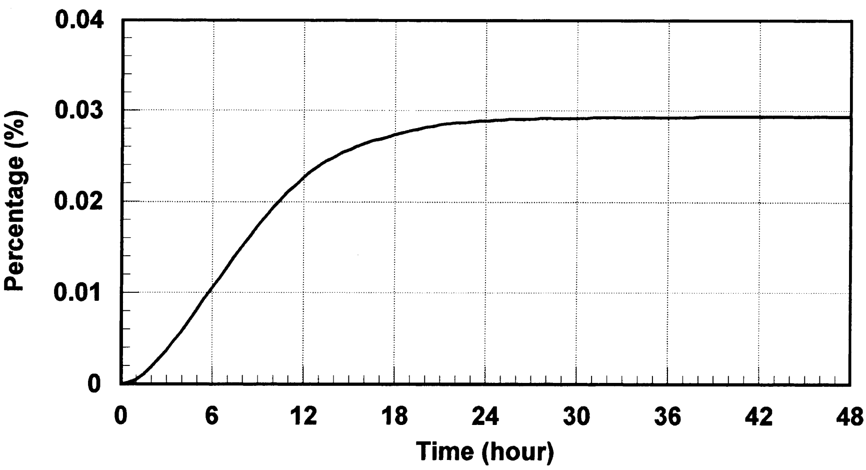

Fig. 6. Dissolution percentage of the oil slick versus time.

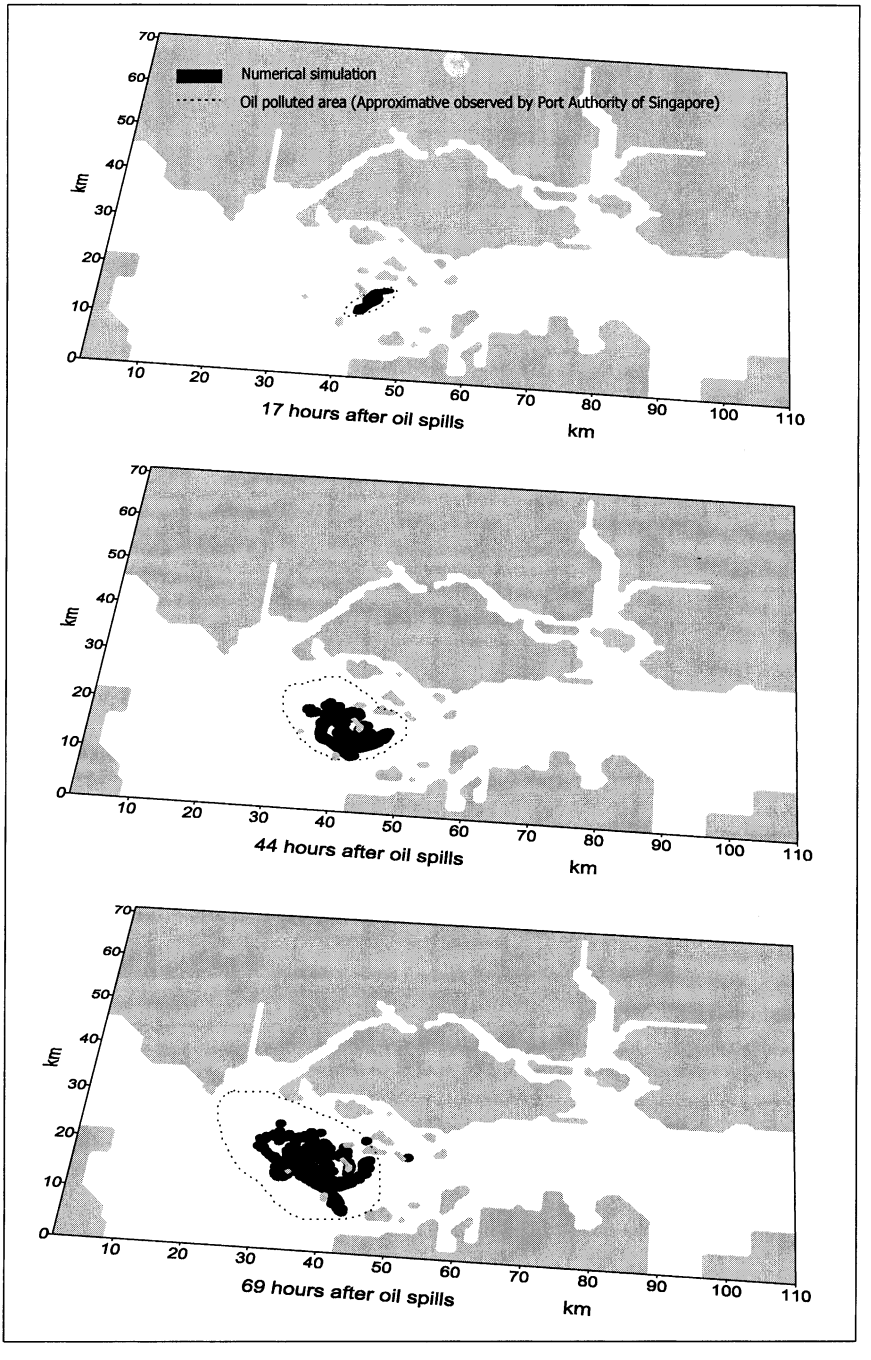

Fig. 7. Movement of the oil slick on the water surface.

of oil is reached, the deposited oil will be re-entrained into the water. After 2–3 days, the oil slick becomes progressively thinner. With the influence of turbulence and horizontal gradients of velocities, some slicks are broken up and become smaller oil patches, which move on the water surface.

4.3. Simulation of oil particle concentration distribution

Based on the study in Section 3.2, the oil particle concentration equation (25) can be solved by coupling with the flow field. Similar to the 3-D hydrodynamic model, the water body is divided into eight layers and the exchange of oil particles by turbulence and buoyancy between the neighboring two layers is calculated. Fig. 8 shows the concentration distribution at the surface, the middle and bottom layers, respectively, after the oil has dispersed into the water column. It can be observed that the oil concentration become smaller and smaller with the increase in water depth. More than 90% of oil particles stay in the upper layers (0~16 m under the water surface), which means that the upper water is the most polluted area after an oil spill accident.

5. Conclusions

2-D and 3-D oil trajectory and fate models have been developed to predict the movement of a surface oil slick and the concentration distribution of oil particles in the water column, respectively. After obtaining the surface currents from the model and measured wind speeds, the advection properties of the oil slick can be obtained. The simulation results from the 2-D model can show us the processes of the oil slick moving on the water surface. The major movement direction and polluted area of the surface oil slick are successfully predicted using this 2-D model. Because of the complex influencing factor, there is some difference between the numerical results and the observed data. Based on the 3-D oil spill model, the concentration transport equation (25) can be solved by coupling with the 3-D multi-level turbulence model, and the oil particle concentration in every layer is obtained. These two oil spill modules have proven to be useful to study the behaviour of oil spreading, advection, turbulent diffusion, evaporation and dissolution on the surface and the concentration distribution of oil particles in the water column.

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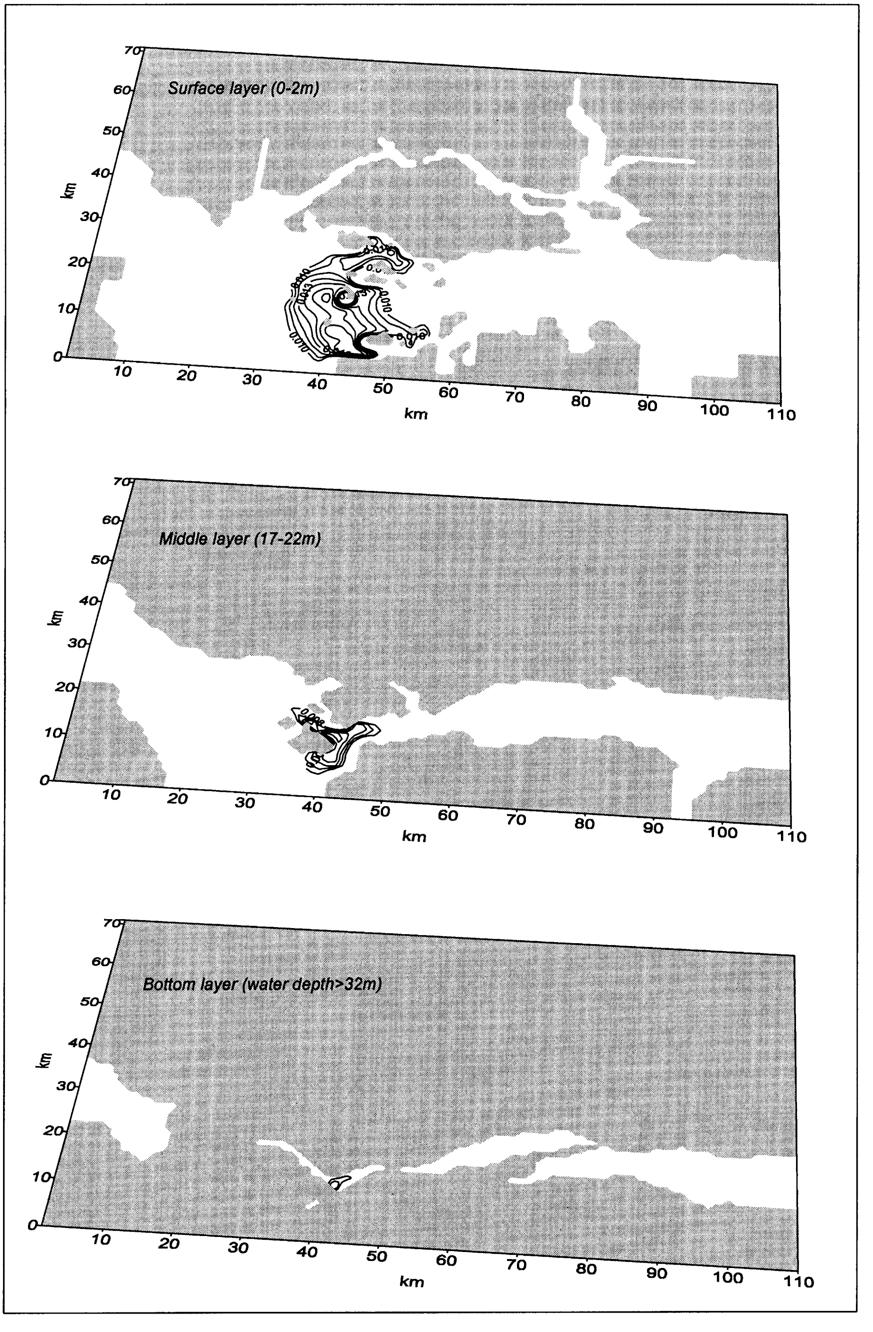

Fig. 8. Concentration distribution of oil particles (ppm).

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