Development and Application of Oil Spill Model for Singapore Coastal Waters

Xiaobo Chao[1]; N. Jothi Shankar, M.ASCE[2]; and Sam S. Y. Wang, F.ASCE[3]

Abstract: This paper presents the development and application of a three-dimensional oil spill model for predicting the movement and fate of an oil slick in the coastal waters of Singapore. In the model, the oil slick is divided into a number of small elements or grids for simulating of the oil processes of spreading, advection, turbulent diffusion, evaporation, dissolution, vertical dispersion, shoreline deposition and adsorption by sediment. This model is capable of predicting the horizontal movement of surface oil slick, the mass balance of oil spill and the oil particle concentration distribution in water body. Satellite images and field observations of oil slicks on the surface in the Singapore Straits, and measurements of the vertical concentration of oil particles in flume are used to validate the newly developed model. Compared with the observations, the numerical results of the oil spill model show good conformity.

DOI: 10.1061/(ASCE)0733-9429(2003)129:7(495)

CE Database subject headings: Oil spills; Three-dimensional models; Singapore; Coastal environment.

Introduction

With the increasing contamination of water bodies adjacent to shoreline areas by oil spills, oil pollution in coastal waters has received particular attention over past years by researchers and governmental officials. It is important to take effective clean-up measures quickly after each accident. Therefore, it is important also to have a computational model for forecasting the oil spill in real time. This will support environmental engineers and planners in designing and carrying out effective clean-up operations.

In recent decades, many researchers have studied the transport and fate processes of oil spills based on the trajectory method and mass balance approach (Huang 1983; Delvigne 1994; Yapa et al. 1994, 2002; Fingas 1994; Spaulding 1995; ASCE Task Committee 1996; Reed et al. 1999). Some well-established models, such as OILMAP [Applied Science Associations (ASA) 1997], SINTEF (Reed et al. 2000), and GNOME [National Oceanic and Atmospheric Administration (NOAA) 2001], are used currently to predict oil movement and distribution in a water body. Among these oil spill models, many focus on the surface movement of oil spills, and the oil slick is assumed to consist of a large number of particles. But the initial distribution and amount of particles are difficult to prescribe. There has been little published research on oil concentration distribution and fate processes beneath the surface. For shoreline deposition and adsorption of oil by sediment, only a few research publications were found (Humphrey et al. 1993; Kobayashi and Yapa 1995; Cheng et al. 2000), and many other models did not consider these processes. In view of the limited understanding of oil spill processes, the accuracy of simulations using the aforementioned models has room for improvement.

Singapore is a major oil refinery center with frequent movement of oil tankers in its coastal waterways. The risk of oil spills in the Straits of Singapore has caused serious concern. A recent example is a massive spill of 28,500 tons of heavy bunker fuel oil on 15 October 1997 from the tanker Evoikos. In order to minimize environmental damage and recover the oil, an important part of the contingency plan was developed using a computational model to predict the location and distribution of the oil spill. In recent years, a few two-dimensional numerical models based on some simple oil transport processes have been applied to simulate the oil movement on the water surface in Singapore coastal waters (Shankar et al. 1998; Cheong et al. 1999). This paper reports a newly developed three-dimensional (3D) oil spill model for simulating the movement of oil slicks on the water surface and oil particle concentration distribution in water body. Using Singapore coastal waters as a test bed, the numerical simulations are carried out and the results are compared to observed data and satellite images.

Development of Three-Dimensional Oil Spill Model

During the early stages of an oil spill, the transport of spilled oil is governed mainly by: Spreading due to gravity, inertia, viscous and surface tension forces, advection and horizontal turbulent diffusion due to current and wind, evaporation and dissolution due to weathering processes, and vertical dispersion due to breaking waves and upper layer turbulence. If oil slicks move toward the islands or shoreline, shoreline deposition and re-entrainment should be considered.

After some time, due to the spreading, advection, evaporation, dissolution, vertical dispersion, etc., the oil slick becomes thinner. Under the actions of breaking wave and upper layer turbulence,

[1]Research Associate, National Center for Computational Hydroscience and Engineering, Univ. of Mississippi, Carrier Hall 102, University, MS 38677 (corresponding author). E-mail: chao@ncche.olemiss.edu.

[2]Professor, Dept. of Civil Engineering, National Univ. of Singapore, Singapore 117576.

[3]Professor and Director, National Center for Computational Hydroscience and Engineering, Univ. of Mississippi, Carrier Hall 102, University, MS 38677.

Note. Discussion open until December 1, 2003. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on November 19, 2001; approved on January 14, 2003. This paper is part of the ***Journal of Hydraulic Engineering***, Vol. 129, No. 7, July 1, 2003. ©ASCE, ISSN 0733-9429/2003/7-495–503/$18.00.

the thinner oil slick may break up into small particles, which advect and diffuse in water. Some of the particles resurface from the water column, while some others form water-in-oil or oil-in-water emulsions. The specific gravity of the resulting oil–water emulsion can be close to that of the water (ASCE Task Committee 1996). They can stay in the water column for a long time, and pollute the water to a non-negligible depth below the free surface. The oil particles can also be adsorbed by various suspended substances in the water.

To take into account some of these important processes, a 3D oil spill model is developed to predict the surface movement of oil slick and the oil particle concentration distribution in water body.

Fate and Trajectory Processes in Model

Spreading

Fay's formula (1971) is widely used to simulate surface spreading of oil slicks. Due to the omission of the influence of wind and associated turbulence, horizontal oil spreading predicted by Fay's formula has been found to be less than that observed by field measurements. Lehr et al. (1984) proposed a revised model to account for the observed nonsymmetrical spreading of oil slicks. Based on the assumption that the oil slick is to spread in the shape of an ellipse with the major axis in the direction of the wind, the Lehr's spread equations can be written as

$$L_{\min}=53.76\left(\frac{\Delta\rho}{\rho_o}\right)^{1/3}V_{\text{oil}}^{1/3}t^{1/4} \tag{1}$$

$$L_{\max}=L_{\min}+0.95W_{\text{wind}}^{4/3}t^{3/4} \tag{2}$$

$$A=(\pi/4)L_{\min}L_{\max}=2{,}270\left(\frac{\Delta\rho}{\rho_o}\right)^{2/3}V_{\text{oil}}^{2/3}t^{1/2}+40\left(\frac{\Delta\rho}{\rho_o}\right)^{1/3}V_{\text{oil}}^{1/3}W_{\text{wind}}^{4/3}t \tag{3}$$

where $L_{\min}$ and $L_{\max}$=length of the minor and major axes, respectively (m); A=area of oil slick (m^2); $\Delta\rho=\rho_w-\rho_o$, ρ_w, and ρ_o =density of water and oil, respectively; V_{oil}=total volume of the spilled oil in barrels; W_{wind}=wind speed in knots; and t=time in minutes.

Advection and Horizontal Turbulent Diffusion

In many oil spill models, the oil slick is assumed to be a group of a large number of particles and the initial amount and distribution of particles have to be selected by the model user. In this study, based on the amount of the oil spill and initial spreading area, the oil slick is divided into a large 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.

The advective velocity of an oil slick $\mathbf{U}_d$ is given as (ASCE Task Committee 1996)

$$\mathbf{U}_d=K_t\mathbf{U}_t+K_w\mathbf{U}_w \tag{4}$$

$\mathbf{U}_t$=surface water current velocity; $\mathbf{U}_w$=wind velocity at a height of 10 m above the water surface, its deflection angles vary between 0° and 25° to the right- or left-hand side respective to the wind direction; K_t=current factor; and K_w=wind drift factor.

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's study (1989), the distance that an element (ΔS) travels by horizontal diffusion is

$$\Delta S=[R_s]_0^1\sqrt{12D_h\Delta t} \tag{5}$$

where $[R_s]_0^1$=random number in the interval 0 to 1; and D_h=horizontal diffusion coefficient. The displacement of the oil slick due to advection and horizontal turbulent diffusion can be computed as

$$L_x(\Delta t)=U_{dx}\Delta t+\Delta S\cos\theta \tag{6}$$

$$L_y(\Delta t)=U_{dy}\Delta t+\Delta S\sin\theta \tag{7}$$

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

$$\theta=2\pi[R_\theta]_0^1 \tag{8}$$

where $[R_\theta]_0^1$=random number in the interval 0 to 1.

Vertical Dispersion

A main objective of vertical dispersion study is to estimate the rate of oil entrainment in the water column. Delvigne et al. (1989, 1994) conducted a series of laboratory investigations to determine the relationships between oil entrainment rate, particle size, and intrusion depth of oil particles. They obtained the entrainment rateas a function of the oil type, breaking-wave energy, and temperature using the empirical relation

$$Q(d)=K_{\text{en}}D_{ba}^{0.57}S_{\text{cov}}F_{wc}d^{0.7}\Delta d \tag{9}$$

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

$$D_{ba}=0.0034\rho_w gH_{\text{rms}}^2 \tag{10}$$

$$F_{wc}=0.032(U_{\text{wind}}-U_i)/T_w \tag{11}$$

in which ρ_w=density of water (kg/m^3); g=acceleration due to gravity (m/s^2); H_{rms}=root-mean-square (rms) wave height (m); U_{wind}=wind speed (m/s); U_i=threshold wind speed for a wave breaking (≈5 m/s); and T_w=breaking wave period (s).

Based on Eq. (9), the rate of vertical dispersion (S_{vd}) can be obtained by an integration over all particle sizes, given by

$$S_{\text{vd}}=\int_{d_{\min}}^{d_{\max}}Q(d)\Delta d \tag{12}$$

Maximum and minimum particle sizes are calculated as follows (Raj 1979)

$$d_{\max}=\left[\frac{12\sigma}{g(\rho_w-\rho_o)}\right]^{1/2} \tag{13}$$

$$d_{\min}=\frac{0.12\sigma^{3/5}\omega_f^{2/5}}{\rho_w^{3/5}g^{4/5}} \tag{14}$$

where σ=interfacial tension; ρ_w and ρ_o=density of water and oil, respectively, and ω_f=wave frequency.

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

$$Z_i \approx 1.5 H_b \tag{15}$$

where H_b = height of the breaking wave.

Evaporation and Dissolution

Evaporation and dissolution occur immediately after the spill. Mackay (1981) developed a multicomponent theory to compute the rate of oil evaporation and dissolution. In this theory, the evaporative amount of a given component of oil was given by

$$M_i = K_e A t X_i P_i^s/(RT) \tag{16}$$

in which M_i = amount of component i lost by evaporation (mole); K_e = mass transfer coefficient of evaporation (m/s); A = area of the oil slick (m^2); t = time (s); R = gas constant (atm m^3/mol K); T = the air temperature above the slick (K); $X_i P_i^s$ represents the partial vapor pressure of component i; P_i^s = vapor pressure of component i; and X_i = component mole fraction defined as $X_i = M_i/\Sigma M_i$. Then, the rates of evaporation can be calculated as

$$S_e = \sum M_i/t = \sum K_e A X_i P_i^s/(RT) \tag{17}$$

Some of the oil components, which are subjected to evaporation, can also dissolve into the water column from a surface slick. The amount of component i lost by dissolution can be calculated by

$$M_{\mathrm{di}} = K_d A t X_i S_i \tag{18}$$

in which M_{di} = amount of component i lost by dissolution (mol); K_d = dissolution mass transfer coefficient; X_i = component mole fraction; A = area of the oil slick (m^2); t = time (s); and S_i = solubility. The rates of dissolution are then calculated as

$$S_d = \sum M_{\mathrm{di}}/t = \sum K_d A X_i S_i \tag{19}$$

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 oil-holding capacity is reached, oil will be exposed to longshore transport processes. Based on Humphrey's study (1993), the maximum beach capacity for oil can be expressed as

$$Q_{\max} = L_s W_s D_s \eta_{\mathrm{eff}} \tag{20}$$

where $Q_{\max}$ = maximum capacity of a beach for oil (m^3); L_s, W_s, and D_s = length, width, and depth of sediments on the beach, respectively (m); and η_{eff} = effective porosity of the sediments on the beach (0.12–0.46).

Adsorption of Oil by Sediment

Due to the actions of breaking waves and water turbulence, the thinner oil slick may break into small particles. These particles advect and diffuse in the water, and can be easily adsorbed by various suspended and bed substances, such as sediment, small coals, and dust, etc. The author has studied the adsorption properties of oil by sediment using the experimental method (Chao 1995; Zhao et al. 1998). The theoretical analysis and experimental study indicate that both the surface and pores of sediment can adsorb molecular oil. So the adsorption of oil by sediment can be classified as two kinds: Surface adsorption due to active ions on the sediment surface and capillary adsorption due to pores. Based on the experimental results, the capacity of surface adsorption can be described by the well known Langmuir adsorption equation (Langmuir 1916), while the capacity of capillary adsorption is mainly related to the diameter of sediment particles. So the equilibrium adsorption capacity (Q_s) can then be expressed as the sum of the capacities of surface adsorption (Q_{s1}) and capillary adsorption (Q_{s2}):

$$Q_s = Q_{s1} + Q_{s2} = \frac{bkC_{oe}}{1 + kC_{oe}} + k_p d_s^m \tag{21}$$

where C_{oe} = oil concentration of the mixture liquid after the adsorption reaches equilibrium; d_s = sediment diameter; and b, k, k_p, and m = adsorption parameters that, based on the experimental results (Chao 1995), can be given as $b = 1.96 \times 10^{-4} d_s^{-0.62}$, $k = -68.31 d_s + 112.21$, $k_p = 8.14 \times 10^{-6}$, and $m = -0.78$.

It is assumed that the volume of the oil/water/sediment mixture solution = V_0, which is a constant before and after adsorption. C_0 = initial oil concentration in the solution and C_s = sediment concentration. Since the initial amount of oil in the solution is same as when the adsorption reaches equilibrium, it can be expressed as

$$C_0 V_0 = C_{oe} V_0 + C_s V_0 Q_s \quad \text{or} \quad C_{oe} = C_0 - C_s Q_s \tag{22}$$

By substituting Eq. (19) into Eq. (18) and simplifying, it can be shown that

$$Q_s = \frac{1}{2}\left[\left(\frac{C_0}{C_s} + \frac{1}{kC_s} + b + k_p d_s^m\right) - \sqrt{\left(-\frac{C_0}{C_s} - \frac{1}{kC_s} + b + k_p d_s^m\right)^2 + \frac{4b}{kC_s}}\right] \tag{23}$$

Eq. (20) expresses the relationships between the equilibrium adsorption capacity of oil by the sediment, the initial oil concentration, sediment concentration, and the sediment diameter.

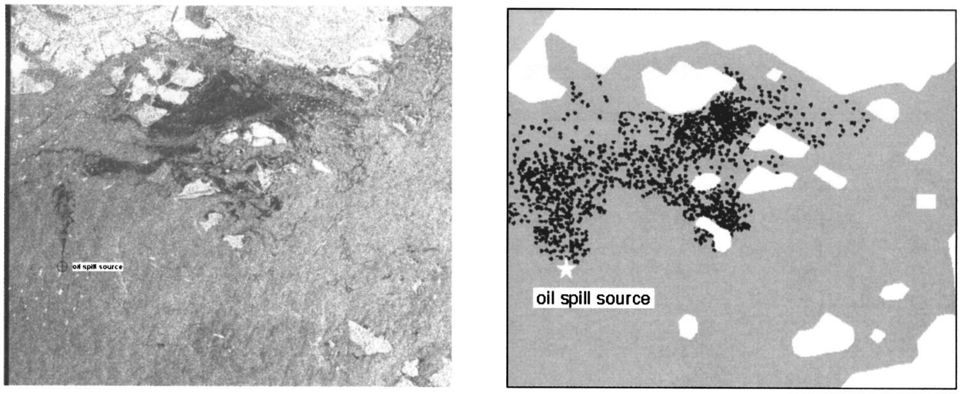
Oil Spill Modeling

Simulation of Surface Oil Slick

Based on the initial quantity and area, an oil spill can be divided into a number of small grids or elements, to which a set of plane local coordinates are assigned. At every time step, after incorporation of the evaporation, dissolution and vertical dispersion properties of oil spills, the volume remaining on the surface can be obtained. Using Eq. (3), the spreading area of the oil slick can be estimated. During the same time step, because of advection and horizontal turbulent diffusion, the oil slick will move to a new location and its displacement can be determined using Eqs. (6) and (7). 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 toward the island or shoreline, it may get deposited along the shoreline, and later re-entrained into the water. The maximum oil-holding capacity of a beach is given by Eq. (20). Using the oil spill model, the movement of oil slicks as well as the mass balance of oil spills can be simulated.

Simulation of Oil Particle Concentration Distribution

As the fate and transport processes of oil spills in the water are very complex, there has been little published research on oil con-



(a) Satellite image of oil slick plume (©ESA 1996)   (b) Numerical results of oil spill model

Fig. 1. Comparison between numerical model and observed results by satellite (time: 0:00 hrs, 08/14/1996; areas: Latitudes 1°4′N to 1°20′N and longitudes 103°37′E to 103°54′E): (a) satellite image of oil slick plume and (b) numerical results of oil spill model.

centration beneath the water surface. In this study, a three-dimensional oil spill model is developed to simulate the oil particle concentration distribution by using the mass transport equation. In the model, the oil particles are classified into a few groups depending on the range of diameters estimated using Eqs. (13) and (14). In each group (ith size class), the rate of vertical dispersion of the oil slick can be obtained using Delvigne's formula [Eq. (9)], and the concentration distribution of oil particles in water column can be described by

$$\frac{\partial C_i}{\partial t}+\frac{\partial(UC_i)}{\partial x}+\frac{\partial(VC_i)}{\partial y}+\frac{\partial(WC_i)}{\partial z}=\frac{\partial}{\partial x}\left(D_x\frac{\partial C_i}{\partial x}\right)+\frac{\partial}{\partial y}\left(D_y\frac{\partial C_i}{\partial y}\right)+\frac{\partial}{\partial z}\left(D_z\frac{\partial C_i}{\partial z}\right)+\frac{\partial}{\partial z}(\omega C_i)+\sum S_m \tag{24}$$

in which U, V, and W = water velocity components in longitudinal (x), lateral (y), and vertical (z) directions, respectively, and they can be obtained from the 3D hydrodynamic model (Chao et al. 1999); C_i = oil particle concentration of the ith size class before the oil adsorbed by sediment; D_x, D_y, and D_z = mixing coefficients in x, y, and z directions, respectively; ΣS_m = effective source term, which includes the evaporation, dissolution, vertical dispersion, as well as the shoreline and bed deposition (Yapa 1994); and ω = buoyant velocity of the oil particle. For the small size ($d \leqslant 1$ mm), it can be written as

$$\omega=\frac{\mathsf{R}\mu}{\rho_w d} \tag{25}$$

where R = Reynolds number, it should be modified using Clift's formula (Clift et al. 1978); ρ_w = mass densities of water; μ = dynamic viscosity of water; and d = size of the oil particle. For the other size ranges (1 mm $< d \leqslant 15$ mm or $d > 15$ mm), the buoyant velocities can be computed using the newly developed formulas (Zheng and Yapa 2000).

The horizontal mixing coefficients are given as (Davies et al. 1997)

$$D_x=D_y=C_{sa}\Delta x\Delta y\left[\left(\frac{\partial U}{\partial x}\right)^2+0.5\left(\frac{\partial V}{\partial x}+\frac{\partial U}{\partial y}\right)^2+\left(\frac{\partial V}{\partial y}\right)^2\right]^{1/2} \tag{26}$$

where C_{sa} = arbitrary constant of order 0.5 and Δx and Δy are the grid lengths in the x and y directions. The vertical mixing coefficient D_z can be expressed in terms of turbulent eddy viscosity and the mixing length turbulent closure (Chao et al. 1999). As the oil density is less than the water, the influence of buoyancy on the mixing length and turbulent Schmidt number need to be considered according to the Munk–Anderson formula (Patankar 1980).

This oil concentration model couples with a 3D hydrodynamic model. Also, the grid systems and the numerical solution are similar to the hydrodynamic model (Chao et al. 1999). A stagger grid system is used to solve the Eq. (24). The concentration is placed at the center of the grid, while velocity components U, V, and W are placed at the midpoints of the east interface, south interface, and lower interface, respectively. A second-order implicit finite difference scheme is used to obtain a numerical solution of the governing Eq. (24), which is a sparse matrix equation. By solving this sparse matrix, the concentration of oil particles for one size class can be obtained. By integrating over all size classes, the oil concentration distribution before adsorbed by sediment can be obtained.

Based on the aforementioned solved oil particle concentration, and the sediment concentration and diameter, the equilibrium adsorption capacity of oil by sediment can be obtained using Eq. (23). Then the final oil concentration distribution in the water can be calculated using Eq. (22).

Model Validation

Before applying the oil spill model to the Singapore Straits, the model is first applied to some cases for validation purposes. The first simulation is about the surface movement of oil slick on the water surface and the results are compared with a satellite image. The second simulation presents the oil particle concentration distribution and the results are compared with experimental measurements.

Comparison of Oil Spill Movement on Surface with Satellite Image

An interesting oil spill that was used as a test benchmark for validating the oil spill model is the case of oil spilling from one of several ships located in the open waters southwest of the Singapore Straits. Fig. 1(a) shows a satellite image of the oil slick plume emanating from the ship. The satellite picture was fur-

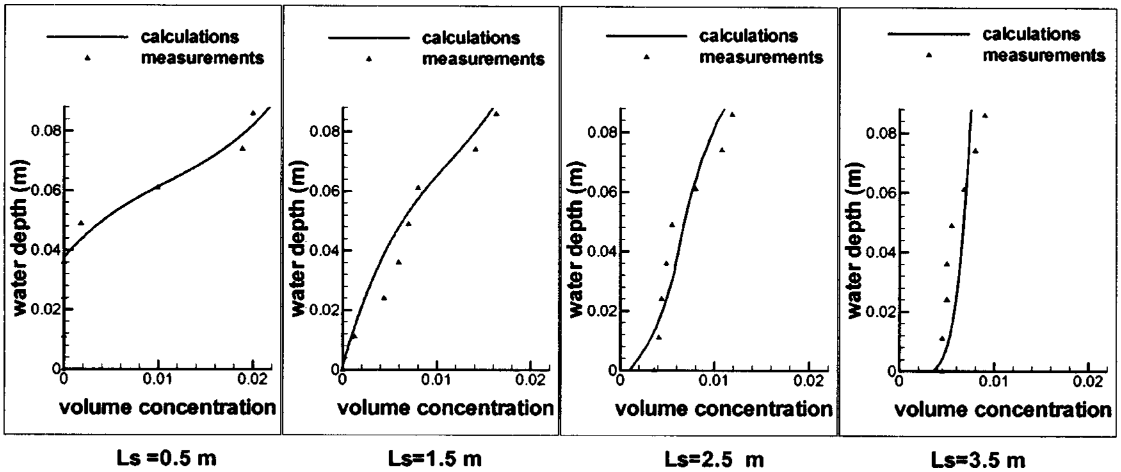


Fig. 2. Vertical oil particle concentration distribution along flume

nished by the Center for Remote Imaging, Sensing, and Processing (CRISP), National University of Singapore. This picture covers an area enclosed by latitudes 1°4′N to 1°20′N and longitudes 103°37′E to 103°54′E. Personnel from the Maritime and Port Authority of Singapore (MPA) also observed oil patches outside the west coast of Singapore.

Based on the location of the source of the oil spill provided by CRISP, simulations were conducted for tracking the oil slick. The following conditions were considered in the oil spill simulation:

- Type of oil: 1,000 tons multicomponent crude oil,
- Simulation period: 22:00 hrs, Aug. 11, 1996 to 0:00 hrs, Aug. 14, 1996,
- Wind: Using the field measurements data provided by MPA,
- Current pattern: Based on the 3D hydrodynamics model (Chao et al. 1999), and using the four-points interpolation, the surface flow fields of the simulation area can be obtained, and
- Oil processes: Based on the studies described in the previous section.

Fig. 1(b) shows the distribution of oil patches after 50 h of simulation from the discharge of the ship. A comparison between the satellite image of the oil slick plume and the results of the simulation shows that the distribution of oil parcels correlates well with the observation.

Comparison of Vertical Oil Particle Concentration with Experimental Data

It is very difficult to obtain the oil particle size and concentration distribution in the water body. Chao (1995) did a simple experiment to study the diffusion properties of oil in the water. The experiment was done in an indoor glass flume, which was 20 m long, 20 cm wide, and 20 cm high. The bottom slope of the flume was 2.84×10^{-3}. The oil particle samples used in the experiment were made by pumping mixtures of kerosene and water, and discharged onto the water surface uniformly along the traverse direction. The flow fields were measured by laser Doppler velocimeter, and the oil distributions under the water were recorded by a video camera. After processing the recorded image of the oil particles using the digital image processing technique, the vertical concentration distribution of oil particles along the flume can be obtained. In this experiment, complicated oil processes, such as evaporation, dissolution, deposition, adsorption, etc., were not considered. Based on the experimental conditions, the proposed oil spill model is used to simulate the oil particle concentration distribution in the water column.

In this simulation, the flow discharge was 8.86 L/s; the water temperature was 7°C; the average oil particle size was 3 μm; and the oil density was 0.918 g/cm^3. Using the proposed oil spill model, the vertical oil concentration distribution along the flume was obtained. Compared with the experimental data, the numerical results of the oil spill model shows good conformity (Fig. 2).

Application to Singapore Coastal Waters

Study Area

Fig. 3 shows the computational domain. It covers an area of 110 km by 72 km bounded by latitudes 0°59′N to 1°44′N and longitudes 103°18′E to 104°20′E. There are four open boundaries in the west, east, southwest, and southeast of the domain, respectively. The seabed topography, shown in Fig. 3, is very complex. The water depth ranges from 1 m to 115 m. There are many islands in the Singapore Straits and the middle section is very narrow.

The flow fields are simulated using a 3D multilevel hydrodynamic model, and the water surface elevations as well as the tidal currents are generally well predicted (Chao et al. 1999).

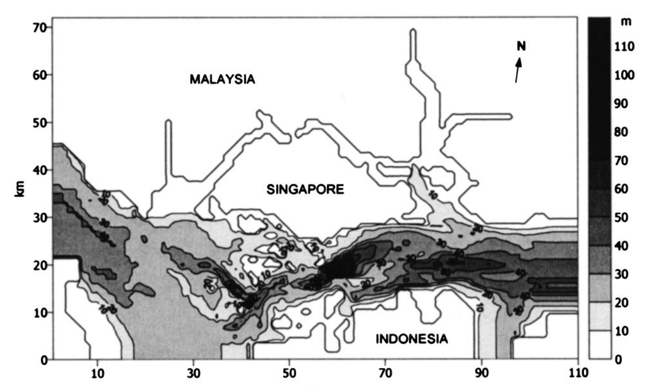


Fig. 3. Computational domain of Singapore Coastal waters

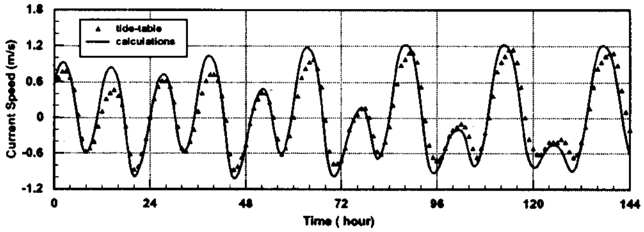


Fig. 4. Time history of current speeds at Station (50,17) (10/15/97–10/20/97)

Simulation of Evoikos Oil Spill Accident

On October 15, 1997 around 9:00 pm, the crude oil tanker "Orapin Global" collided with the oil tanker "Evoikos" at latitude 1°10′52″N, longitude 103°48′30″E. Oil spilled out immediately from the Evoikos tanker which was broken by the collision, and around 28,500 t (or 30,000 m^3) of heavy bunker fuel oil spread into the Singapore Straits. After the accident, the MPA conducted extensive monitoring and an emergency operation to contain and clean up the oil spill. Based on some observed data provided by the MPA, the authors used the proposed oil spill model to simulate the movements of the surface oil slick and the oil particle concentration distribution.

The simulation period was chosen from 0:00 hrs on October 15 to 24:00 hrs on October 20, 1997. Using the 3D hydrodynamic model, the flow fields in this period were obtained. Fig. 4 shows the water currents from the numerical model are in good agreement with the tide table data published by MPA (1997). The wind data in the computational domain were obtained from field measurements (Fig. 5). The oil data were obtained from some measurements and oil property databases. The parameters used in the oil spill model are presented in Table 1.

Surface Movement and Mass Balance

Using the oil spill model, the fate and transport of the oil slick on the water surface can be obtained. Fig. 6 shows the average thickness of the oil slick as a function of time. It can be observed that the oil slick thickness decreases rapidly during the first 6 h. This means that the first stage of spreading occurs within a short time. After the initial phase involving gravity, inertia, and viscous forces, the surface tension phase of spreading takes over and lasts for a longer time until the oil slick becomes unstable and breaks up. Fig. 7 shows the mass balance of oil spills. It can be observed that evaporation mainly happens in the first one to two days with an evaporation ratio on the order of 36%. Due to dissolution and dispersion, the oil is dispersed and mixed in the water column. About 5.2% of the oil was dissolved and dispersed in the water column within a few days. As there are many islands in the Singapore Straits, the shoreline deposition is the other major oil process. It can be observed that the shoreline deposition increases gradually after the oil moves to the shoreline. Once the shoreline oil-holding capacity is reached, the oil deposited on the bed and re-entrained into water reaches quasiequilibrium.

Table 1. Oil Properties and Some Parameters Used in Oil Spill Model

Properties of oil	Parameters
Oil type	heavy bunker fuel oil
Oil quantity	28,500 t
Oil density	965 kg/m^3
Oil viscosity	3,180 cP
Oil/water interfacial tension	39.8 dyre/cm
Temperature	28°C
Minimum thickness	0.1 mm
Current factor K_t	1.0
Wind drift factor K_w	0.03
Horizontal diffusion coefficient D_h	10 m^2/s
Initial grid number of oil slick	5,000
Sediment concentration	0.2 kg/m^3
Sediment diameter	0.043 mm

One of the most important applications of the oil spill model is to simulate the surface movements of oil slicks. Normally the movement of a surface oil slick is mainly dependent on its advection velocity, which can be obtained based on the water surface velocity and wind speed. Previous studies (Chao et al. 1999; Zhang and Gin 2000) have indicated that the residual flow is not very strong in the Singapore Straits, especially in the offshore area. So the influence of wind on the advective velocity of an oil slick is relatively more important. In this case, field measured wind speeds (Fig. 5) and calculated surface flow velocities are used to determine the advective velocities of the oil slicks.

Fig. 8 shows the comparison of the movement of the oil slick on the water surface obtained numerically and observed by the MPA. It can be seen that the major movement direction and the polluted area of the oil slick are generally in agreement with the observed results. Based on the numerical results and observed data, it can be concluded that northwest of the Singapore Straits is the major pollution area of the Evoikos oil spill accident. It can also be seen that the oil slick moved on the water surface without disintegration during the first day. After 2 or 3 days, as the oil slick became progressively thinner, with the influence of

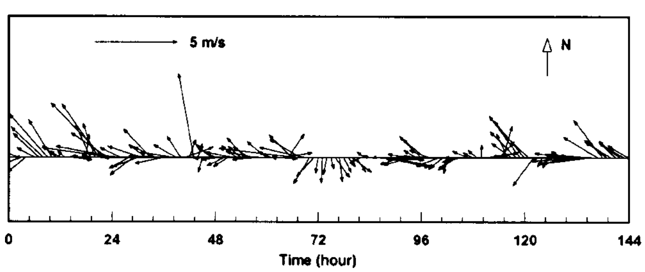


Fig. 5. Time history of wind speed (meters/seconds) (10/15/97–10/20/97)

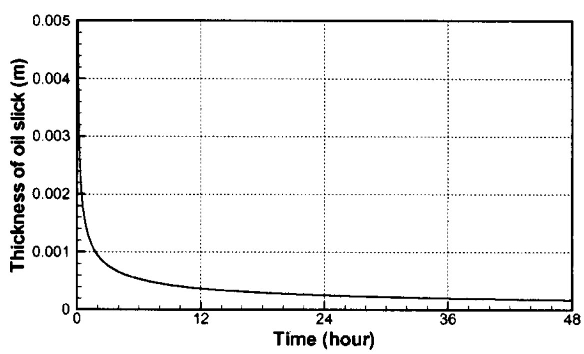


Fig. 6. Averaged thickness of oil slick

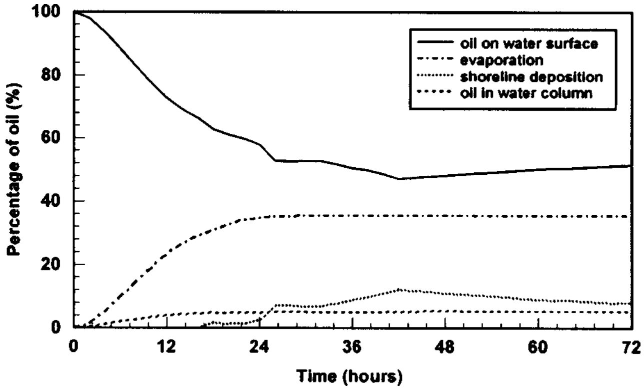


Fig. 7. Mass balance of oil spill

wave, turbulence, and horizontal gradients of velocities, some slicks broke into smaller oil patches, and moved on the water surface.

Oil Particle Concentration Distribution

The concentration distribution of the oil particles can be obtained by solving Eq. (24). Eq. (24) describes the transport properties of the oil particles of one size class in the water column. After solving Eq. (24) and integrating the oil particle concentration of each size class, the oil concentration distribution before being adsorbed by sediment can be obtained.

Based on the processes of vertical dispersion and dissolution, the amount of oil particles at each time step can be obtained. This newly developed model can be used to simulate the concentration distribution for nonuniform oil particle sizes beneath the water surface. Since measurements under the water surface are very difficult to obtain, the authors do not have enough data for further studies, and only present a simple case study here. In this application, only one class of oil particle size ($d = 10\ \mu m$) is simulated. The averaged size and concentration of sediment in the Singapore Straits were assumed to be 0.043 mm and 0.2 kg/m^3, respectively, depending on field measurements [Port of Singapore Authority (PSA 1989)]. In the 3D oil spill model, the effective source terms include the effects of evaporation, dissolution, vertical dispersion, as well as the shoreline and bed deposition terms. The effects of oil adsorption by sediment on the oil concentration are also considered in the model. After obtaining the water elevation, current pattern, and the equilibrium adsorption capacity of oil by sediment, the concentration distribution of oil particles under the water surface can be solved using the proposed oil spill model.

Fig. 9 shows the oil particle concentration distribution at the surface, middle, and bottom layers, respectively. It can be seen

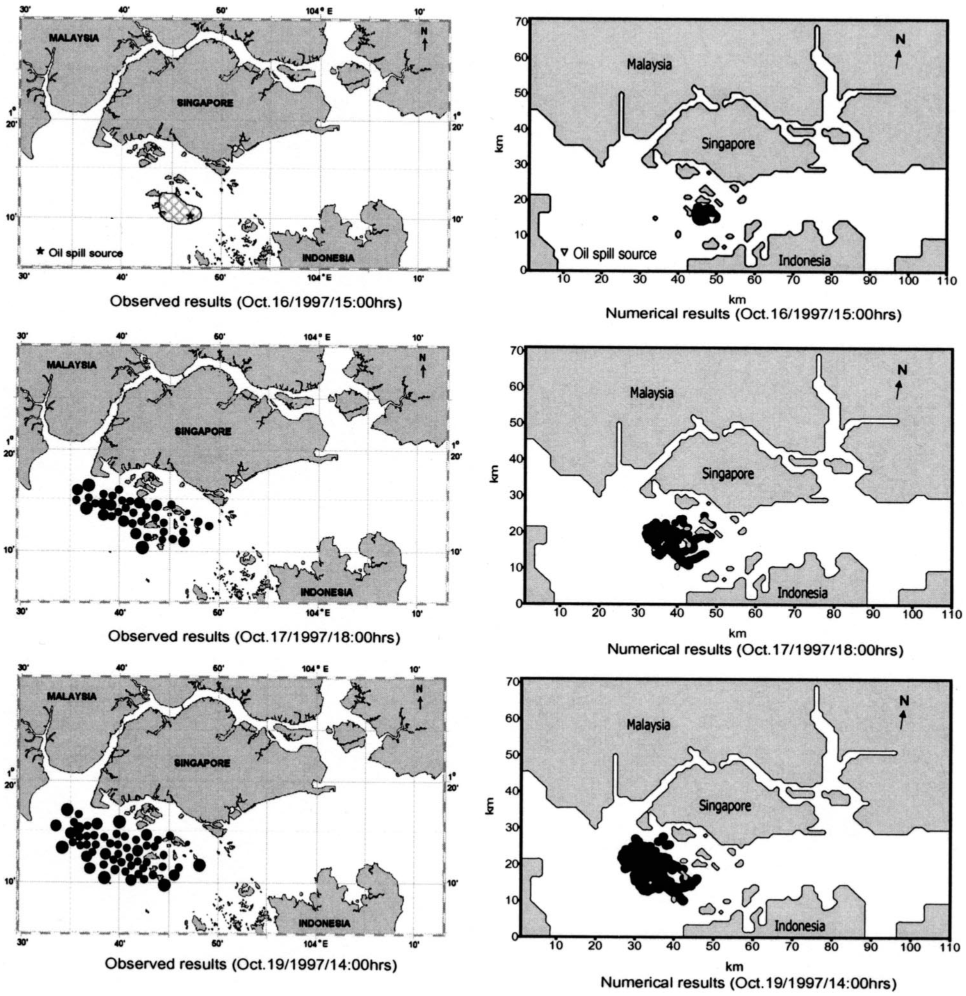


Fig. 8. Comparison of oil movements on water surface

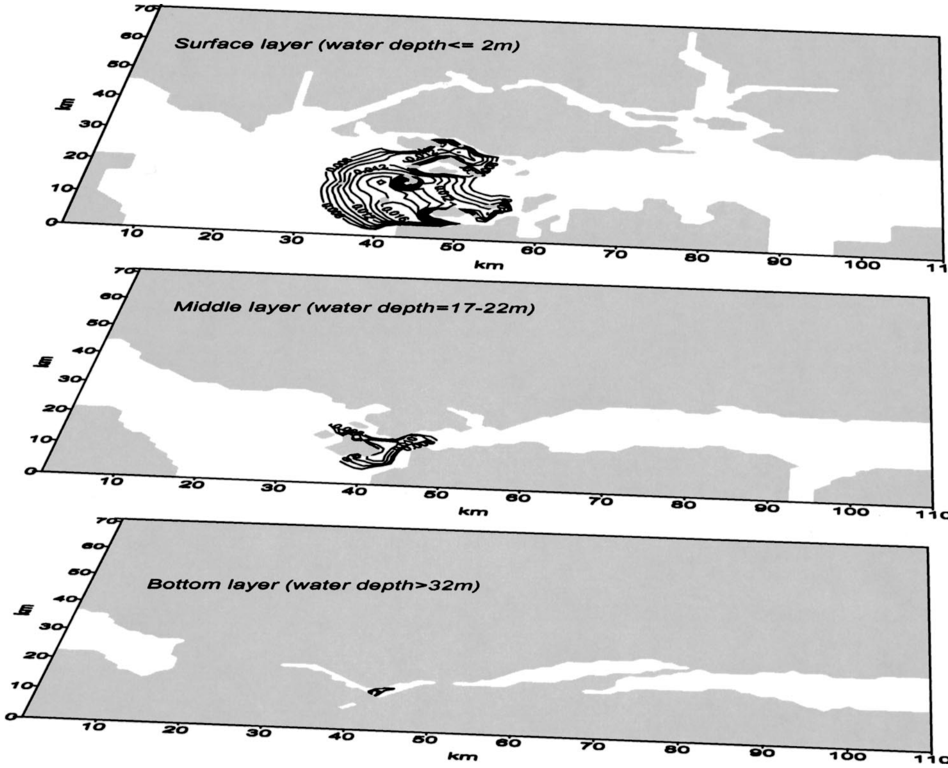


Fig. 9. Concentration distribution of oil particle (18:00 hrs, 10/20/1997, parts per million)

that the oil concentration becomes smaller and smaller with the increase of water depth, and the upper layers are the major polluted areas during the first 1 week after the oil spill accident. Since this is a hypothetical case study, the writers only show the capabilities of the proposed oil spill model. The writers hope to get some more measured oil spill data beneath the water surface for further studies.

Conclusions

A three-dimensional oil spill model has been developed to simulate the movement or trajectory of surface oil slicks, the mass balance of oil spill, and the oil particle concentration distribution. Compared with satellite images, field observations, and experimental data, the results of the numerical model are generally in good agreement with the observations.

This proposed oil spill model includes several improvements. Some examples are described next. By assuming that the oil slick can be discretized into small elements (or grids), a time-dependent scheme can be applied to predict the movements of oil elements, which allows the prediction of the trajectory and spreading of the oil slick as well as other mixing processes at each time step. By adopting the formula developed by Lehr (1984), the nonsymmetric spreading of an oil slick can be estimated. Based on the 3D mass transport equation, the concentration distribution of nonuniform oil particles in the water column can be obtained. The oil particles adsorbed by the suspended sediments are considered to modeling the oil particle concentration. The oil deposition on the beach along the shoreline as well as its re-entrainment into the water has also been included.

The field data obtained from the oil spill incident in the Singapore coastal water was used to perform a validation test of the proposed model. The direction of the oil slick movement and the pollution area simulated with the oil spill model compare well with satellite images and field observed data. Furthermore, this model is also capable of predicting oil particle concentration in water. Compared with a simple laboratory experiment, numerical results show good agreement with measurements. A hypothetical case study for the Singapore Straits was also presented to show this capability.

One of the main problems in the oil spill modeling study is the difficulty in obtaining sufficient field data, especially below the water surface, for calibration and validation. This causes some limitations when predicting oil concentration distributions in the water body. For further refinement of the model, the writers will collect more field measurements and focus on the oil spill process and transport under the water surface.

Acknowledgments

The writers wish to acknowledge the National University of Singapore and the financial and technical support by the MPA. The suggestions and advice provided by Professor P. D. Yapa of the Clarkson University and Dr. T. C. Song of the MPA in the project are highly appreciated.

References

Al-Rabeh, A. H., Cekirge, H. M., and Gunay, N. (1989). ‘‘A stochastic simulation model of oil spill fate and transport.’’ *Appl. Math. Model.*, 13, 322–329.

Applied Science Associates (ASA). (1997). *OILMAP for Windows technical manual*, ASA Inc., Narragansett, R.I.

ASCE, Task Committee. (1996). ‘‘State-of-the-art review of modeling transport and fate of oil spills.’’ *J. Hydraul. Eng.*, 122(11), 594–609.

Chao, X. B. (1995). ‘‘Study on the characteristics of oil diffusion and transport in the sediment-loden water flow.’’ PhD thesis, Sichuan Univ., Sichuan.
Chao, X. B., Shankar, N. J., and Cheong, H. F. (1999). ‘‘A three-dimensional multilevel turbulence model for tidal motion.’’ *Ocean Eng.*, 26, 1023–1038.
Cheng, N. S., Law, W. K., and Findikakis, A. N. (2000). ‘‘Oil transport in surf zone.’’ *J. Hydraul. Eng.*, 126(11), 803–809.
Cheong, H. F., Shankar, N. J., Chao, X. B., and Ng, P. H. (1999). ‘‘An oil spill fate modeling system for Singapore coastal waters.’’ *Proc., 9th KKNN Joint Seminar on Environmental Engineering*, National Univ. of Singapore, Singapore.
Clift, R., Grace, J. R., and Weber, M. E. (1978). *Bubbles, drops, and particles*, Academic, New York.
Davies, A. M., Jones, J. E., and Xing, J. (1997). ‘‘Review of recent developments in tidal hydrodynamic modeling. I: Spectral models.’’ *J. Hydraul. Eng.*, 123(4), 278–292.
Delvigne, G. A. L. (1994). ‘‘Natural and chemical dispersion of oil.’’ *J. Adv. Marine Technol. Conf. Japan*, 11, 23–40.
Delvigne, G. A. L., and Sweeney, C. E. (1989). ‘‘Natural dispersion of oil.’’ *Oil Chem. Pollution*, 4, 281–310.
Fay, J. A. (1971). ‘‘Physical processes in the spreading of oil on a water surface.’’ *Proc., Joint Conf. on Prevention and Control of Oil Spills*, American Petroleum Inst., Washington, D. C., 463–467.
Fingas, M. (1994). ‘‘Chemical processes related to oil spills.’’ *J. Adv. Marine Technol. Conf., Japan*, 11, 41–64.
Huang, J. C. (1983). ‘‘A review of the state-of-the-art of oil spill fate/behavior models.’’ *Proc., 1983 Oil Spill Conf.*, Washington, D.C., 313–322.
Humphrey, B., et al. (1993). ‘‘Development of a stranded oil in coarse sediment model.’’ *Proc., 1993 Oil Spill Conf.*, American Petroleum Inst., Washington, D.C., 573–582.
Kobayashi, T., and Yapa, P. D. (1995). ‘‘Modeling oil deposition on shorelines and re-entrainment.’’ *Proc., Int. Conf. on Hydraulic and Water Resources Eng.*, ASCE, New York, 653–657.
Langmuir, I. (1916). ‘‘The constitution and fundamental properties of solids and liquids.’’ *J. Am. Chem. Soc.*, 38, 2221–2295.
Lehr, W. J., et al. (1984). ‘‘A new technique to estimate initial spill size using a modified Fay-type spreading formula.’’ *Mar. Pollution Bull.*, 15, 326–329.
Mackay, D. (1981). ‘‘Physical-chemical weathering of petroleum hydrocarbons from the Ixtoc I Blow Out-chemical measurements and a weathering model.’’ *Proc., 1981 Oil Spill Conf.*, American Petroleum Inst., Washington, D.C., 453–460.
Maritime and Port Authority of Singapore (MPA). (1997). ‘‘1997 Singapore tide tables and port information.’’ Maritime and Port Authority of Singapore.
National Oceanic and Atmospheric Administration (NOAA). (2000). *GNOME user's manual*, NOAA, Washington, D.C. ⟨http://response.restoration.noaa.gov/⟩ (July 10, 2001).
Patankar, S. V. (1980). *Numerical heat transfer and fluid flow*, Hemisphere and McGraw–Hill, New York.
Port of Singapore Authority (PSA). (1989). ‘‘Report on tidal motion and sedimentation in Singapore Coastal Waters: Field measurements.’’ *Rep. No. 04/89*, Port of Singapore Authority, Singapore.
Raj, P. P. K., Park, A., and Griffiths, R. A. (1979). ‘‘The survival of oil slicks on the ocean as a function of sea state limit.’’ *Proc., 1979 Oil Spill Conf.*, American Petroleum Inst., Washington, D.C., 719–724.
Reed, M., et al. (1999). ‘‘Oil spill modeling towards the close of the 20th century: Overview of the state of the art.’’ *Spill Sci. Technol. Bull.*, 5(1), 3–16.
Reed, M., et al. (2000). ‘‘A multicomponent 3D oil spill contingency and response model.’’ *Proc., 23rd Arctic and Marine Oilspill Programme (AMOP) Technical Seminar, Ottawa, Canada*, 663–680.
Shankar, N. J., Ng, W. J., Yang, H., and Toh, A. C. (1998). ‘‘Application of oil spill fate model in the Singapore Straits.’’ *Singapore Maritime & Port J.*, 1, 84–96.
Spaulding, M. L. (1995). ‘‘Oil spill trajectory and fate modeling: State-of-the-art review.’’ *Proc., 2nd Int. Oil Spill Research and Development Forum*, International Maritime Organization, London.
Yapa, P. D., Shen, H. T., and Angammana, K. (1994). ‘‘Modeling oil spills in a river-lake system.’’ *J. Mar. Syst.*, 4, 453–471.
Yapa, P. D., and Xie, H. (2002). ‘‘Modeling underwater oil/gas jets and plumes: Comparison with field data.’’ *J. Hydraul. Eng.*, 128(9), 855–860.
Zhang, Q. Y., and Gin, K. Y. H. (2000). ‘‘Three-dimensional numerical simulation for tidal motion in Singapore's coastal waters.’’ *Coastal Eng.*, 39, 71–92.
Zhao, W. Q., Chao, X. B., and Huang, Q. S. (1998). ‘‘Mathematic model and experimental study on adsorbing oil by sediment.’’ *Int. J. Sediment Res.*, 13(3), 1–9.
Zheng, L., and Yapa, P. D. (2000). ‘‘Buoyant velocity of spherical and nonspherical bubbles/droplets.’’ *J. Hydraul. Eng.*, 126(11), 852–854.