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Modelling of the behavior of marine oil spills: applications based on random walk techniques

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Abstract: A numerical model has been developed to simulate the transport and fate of oil spilled at sea. The model combines the transport and fate processes of spilled oil with the random walk technique. Oil movement under the influence of tidal currents, wind-driven currents, and turbulent eddies is simulated by the PLUME-RW dispersion model developed by HR Wallingford. The weathering processes in the model represent physical and chemical changes of soil slicks with time, and comprise mechanical spreading, dispersion, evaporation and emulsification. Shoreline stranding is determined approximately using a capacity method for different shoreline types. This paper presents details of the model, and describe the results of various sensitivity tests. The model is suitable for oil spill contingency planning.

Key words: oil spill; modelling; random walk technique

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Introduction

The frequency of accidental oil spills, and the associated aquatic pollution, are growing concerns. There is a need for model system that can be used in both rapid spill response and contingency planning. Many oil spill models have been constructed to represent oil transport and fate processes (Mackay, 1980; Spaulding, 1992; Humphery, 1993; ASCE Task Committee, 1996). These models include transport calculations which determine the oil movement in space and time, and fate models which estimate oil partition between various environmental compartments and changes of oil properties. Most models use a mass balance approach to track the amount of oil in compartments, which include the sea surface, the atmosphere, the water column, the shoreline, the sea bed, biodegraded and so on.

For some years, random walk models have been used as planning tools for assessing the probable impacts of waste discharges on the marine environment. This paper describes an extension of this modelling method to simulate the behavior of oil spilt at sea. The concepts upon which the new model, OIL-RW, is based form the basis of other oil spill models, but the intention here is to focus on the combination of these concepts with the random walk technique.

1 Model formulation

In OIL-RW, spilled oil is assumed to consist of a large number of model particles, with each particle representing a defined quantity of oil. Effectively, model particles are treated as "mass points", with their transport determined by tidal currents, wind-driven current, turbulent eddies (represented using the random walk method), gravitational spreading and buoyancy. Each particle on the water surface is treated as an individual oil slick when simulating weathering, so that its volume and properties change with time. Dispersion and initial oil distributions are determined using stochastic methods. Model particles generally move in the horizontal plane on the water surface, but some move in three dimensions within the water column after entrainment by breaking waves.

1.1 Random walk method

Vertical structure of tidal and wind-driven currents: In order to compute the movement of oil droplets in the sea, the oil spill model fits an analytic current profile to tidal currents computed by two-dimensional, depth-averaged flow models, and superimposes a wind-driven current profile. The profiles are based on the equations (Mead, 1991):

$$u(z) = (u_0)_T / k_0 \ln(30.1z/k_s), \tag{1}$$

$$U_w(z) = U_s(3(1 - z/d)^2 - 4(1 - z/d) + 1), \tag{2}$$

where u is the tidal current speed(m/s), $(u_0)_T$ is the tidal current friction velocity(m/s), k_0 is von Karman's constant, z is the height above the sea bed(m), k_s is the roughness length(m), U_w is the wind-driven current speed(m/s) and U_s is the surface wind-driven current speed(m/s) and d is water depth(m). Usually, U_s is 3—3.5 percent of the wind speed at a height of 10 m above the sea surface (ASCE Task Committee, 1996).

Turbulent diffusion: Horizontal and vertical diffusive displacements are used to simulate the effects of turbulent eddies on oil slick movement, and these are added to the ordered movements that represent advection by mean currents. The eddy diffusivity is a specified constant for horizontal diffusion, but is determined from the following equation for vertical diffusion:

$$D = 0.16z^2(1 - z/d)\left|\frac{U_*}{k_0 z}\right|, \tag{3}$$

where D is the eddy diffusivity(m^2/s), and U_* is the total friction velocity due to wind-driven and tidal currents(m/s). The directions of the displacements are random.

1.2 Oil weathering

Evaporation: Evaporative loss of oil from the sea surface is determined by a mass-transfer equation derived by Stiver and Mackay (Stiver, 1984):

$$\frac{\mathrm{d}F}{\mathrm{d}t} = \frac{K_E}{h}\exp[k_1 + k_2(C_1 + C_2F)], \tag{4}$$

where F is the fraction of oil evaporated, and k_1 and k_2 specify the temperature dependence of the vapor pressure: $k_1 = 48.5 - 0.1147T_0$, $k_2 = 4.5 \times 10^{-4}\, T_0 - 0.1921$ (T_0 is the ambient temperature (K)). K_E is a mass transfer coefficient for evaporation (m/s), $K_E = 2.5 \times 10^{-3} U_{10}^{0.78}$, h is oil slick thickness (m), and C_1 and C_2 are constants derived from crude oil distillation data (Leech, 1992).

Emulsification: Emulsification is modelled using the algorithm of Mackay *et al*. (Mackay, 1980). The rate of water incorporation into oil slicks is given by:

$$\frac{\mathrm{d}Y_w}{\mathrm{d}t} = K_A(1 + U_{10})^2(1 - K_B Y_w), \tag{5}$$

where Y_w is the fractional water content of the oil, K_A is a water incorporation rate constant for emulsifying oils ($\sim 2 \times 10^{-6}$) and K_B is an oil dependent constant, 0.7 for crude oils and heavy fuel oil.

Weathering: The weathering of oil can be estimated from the equations of Mackay *et al*. (Mackay, 1980):

$$\mu = \mu_0 \exp(C_4F) \cdot \exp\left(\frac{2.5Y_w}{1 - C_3Y_w}\right), \tag{6}$$

$$\rho = Y_w\rho_w + (1 - Y_w)(\rho_{\text{crude}} + C_{\text{dn}}F), \tag{7}$$

where μ is the emulsion viscosity (mPa. S) and μ_0 is the crude oil viscosity (mPa. s), C_4 is an oil dependent constant (1 for gasoline, light diesel; 10 for crude soil), C_3 is the mousse viscosity constant, ~0.65, ρ is the density of emulsified oil (kg/m^3), ρ_{crude} is the density of crude oil(kg/m^3), ρ_w is the density of seawater(kg/m^3), and C_{dn} is a constant based on density-composition data.

1.3 Oil transfer

Spreading: In OIL-RW, oil spreading on the sea surface is represented by enhancing the horizontal diffusion for the surface particles. A spreading diffusivity is derived on the basis of the thick slick formulation of Mackay *et al*. (Mackay, 1980). Each model particle undergoes additional random walk diffusion given by:

$$D_{\text{sp}} = \frac{K_1 A^{0.33}}{8\pi}\left(\frac{V}{A}\right)^{1.33}, \tag{8}$$

where D_{sp} is the spreading diffusivity (m^2/s), A is the surface area of the oil slick (m^2), V is the volume of the oil slick(m^3), and K_1 is a constant with a default value of 150/s (Mackay, 1980). This specification of particle displacements causes patches of model particles to simulate the gravitional spreading of oil slicks.

Dispersion: The dispersion of oil from the sea surface into the water column is calculated using the method of Delvigne and Sweeney (Delvigne, 1988). The dispersion rate is expressed as:

$$Q_{\text{d}} = C_0 \cdot D_{\text{d}}^{0.57} S_{\text{cov}} \cdot F_{\text{wc}} \cdot d_0^{0.7} \Delta d, \tag{9}$$

where Q_{d} is the dispersion rate of oil droplets with diameters in the range Δd centered on d_0[kg/(m^2·s)], C_0 is an empirical dispersion coefficient dependent on the oil type and weathered state, D_{d} is the dissipated breaking wave energy per unit surface area (J/m^2). $D_{\text{d}} = 0.0034\rho_w \cdot g \cdot H_{\text{rms}}^2$ here, H_{rms} is the rms wave height, (m), ρ_w is the density of water (kg/m^3), g is the acceleration due to gravity (m/s^2), S_{cov} is the fraction of the sea surface covered by oil ($0 < S_{\text{cov}} < 1$), F_{wc} is the fraction of the sea surface hit by breaking waves per unit time(s^{-1}). $F_{\text{wc}} = 0.032(U_{10} - U_{\text{T}})/T_{\text{w}}$($U_{\text{T}}$ is the threshold wind speed for wave breaking (5 m/s), T_{w} is the breaking wave period (s)), and d_0 is the oil droplet diameter(m; the oil droplet size range is typically 10—500 μm). Marine observations indicate that breaking wave events rapidly distribute the oil in near-surface zone, typically restricted to a depth: $Z_{\text{m}} = (1.5 \pm 0.35)H_{\text{b}}$($H_{\text{b}}$ is the breaking wave height (m)). OIL-RW assigns each model particle a droplet diameter in the range 10—500 μm at random. The probability of a model particle dispersing from the sea surface into the water column is calculated using Equation (9) and the process is applied stochastically. The dispersion coefficient C_0 is calculated in OIL-RW using formulae based on the experimental data for Delvigne and Hulsen (Delvigne, 1994): when μ is less than 100 cP, $C_0 = 1500$; whilst when $\mu \geqslant 100$ cP, $C_0 = 1500 \times 100/\mu$.

Buoyancy: Vertical particle movements result from buoyancy effects, as well as random turbulence caused by tidal flow and wind-driven currents. Buoyancy is a function of oil droplet diameter and density. The vertical buoyant velocity is given by Stoke's Law.

Stranding: When oil spills occur during onshore winds, oil may impinge on nearby shorelines. However, field observations of large spills indicate that the capability of beaches to hold oil is limited. Once the shoreline is reached, oil will be exposed to longshore transport processes. According to Humphery *et al*. (Humphery, 1993), the maximum capacity of a beach for oil can be expressed as:

$$C_{\max} = L \cdot W \cdot D \cdot \eta_{\text{eff}}, \tag{10}$$

where $C_{\max}$ is the maximum capacity of a beach for stranding (m^3), L, W and D 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).

2 Results and discussion

2.1 Sensitivity studies

As the oil properties summarized in section 1 determine the distribution of oil between different phases, it is necessary to validate the model parameters using experimental data. Buchanan and Hurford (Buchanan, 1987) have reported measurements of an experimental spill of 20 tons of crude oil (mainly Forties Crude) at 52°10′N, 2°23′E in the North Sea between 14 and 17 July 1987. Measurements of the wind conditions and oil evaporative loss, viscosity, water content and density were performed over a 75-hour period. Fig. 1 shows that effects of changes in the value of the model's emulsification constant on the evaporation rate, water content and viscosity of spilled oil, together with comparison with the experimental data. The figure demonstrates that the value of the emulsification constant, K_A, has little effect on the evaporation rate of oil, but has significant effects on the water content and viscosity. A value of 1×10^{-6} was selected for use in the model, as this gave optimum agreement between the model results and the observations.

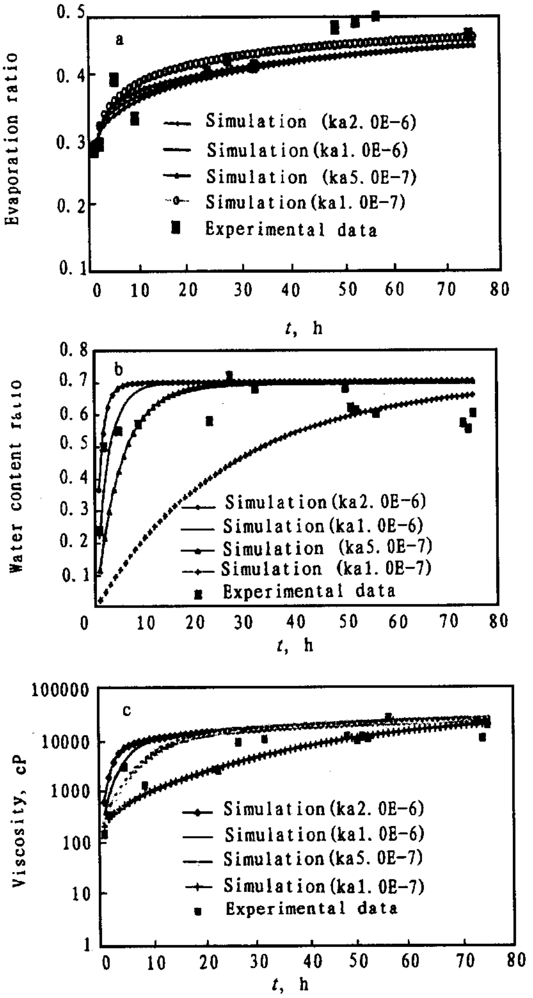

Fig. 1 Comparison of weathering process of model simulation with expermental data

(a) effect of emulsification on evaporation ratio; (b) effect of emulsification on water content; (3) effect of emulsification on oil viscosity

Fig. 2 shows the effect of viscosity on the dispersion coefficient. It can be seen that the dispersion coefficient, C_0, can be regarded as constant when the oil viscosity is less than 100 cP, but decreases rapidly when the viscosity exceeds 100 cP. This indicates that weathering tends to reduce dispersion rates. The algorithm used to calculate C_0 agrees well with the experimental data.

The effects of the oil-dependant constant, C_4, on viscosity are shown in Fig. 3, which demonstrates that oil type has significant effects on weathering processes. Viscosity changes with time are larger for crude oils with high C_4 values than for lighter oils.

2.2 Overall mass balance

A model test run was carried out to examine the overall mass balance of a hypothetical oil spill 6 km off the coast of south east Dorset, United Kingdom. In the test, 43270 m^3 of Arabian Heavy Crude were released over a 48-hour period. The wind was constant at 7 m/s from 120°N. Oil release began at high water.

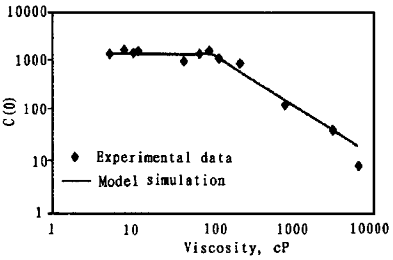

Fig.2 The effect of viscosity on dispersion coefficient

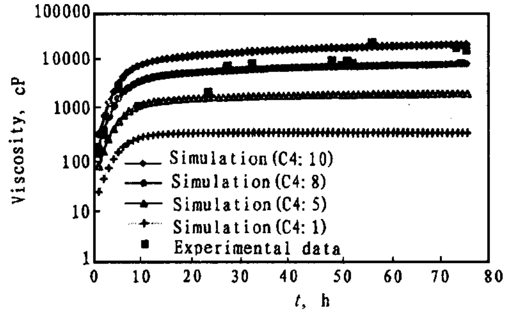

Fig.3 The effect of evaporation coefficient on viscosity

The mass balance as a function of time is shown in Fig.4. About 20% of the oil evaporates rapidly, on first exposure to the ambient water. At the same time, the percentage of entrained oil also increases relatively quickly, but tends to decrease subsequently, due to the increase in viscosity associated with emulsification. The fluctuations in the quantity of oil entrained occur because resurfacing is affected by vertical diffusion, which varies with the changing tidal current speeds. Around 21 hours after the start of the spill, part of the oil reaches the shoreline and becomes stranded. The quantity of stranded oil increases with time until the shoreline becomes saturated.

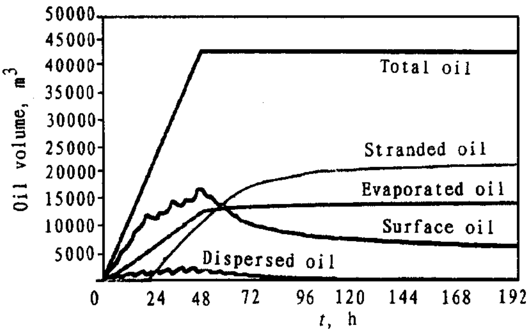

Fig.4 Mass balance vs. time at South West Dorset

The simulated slick locations at intervals over a two-day period are shown in Fig.5. Initially, the size of the slick increases, and it moves periodically with the tidal current. After the cessation of the spill at 48 hours, the proportions of surface and entrained oil decrease as increasing quantities

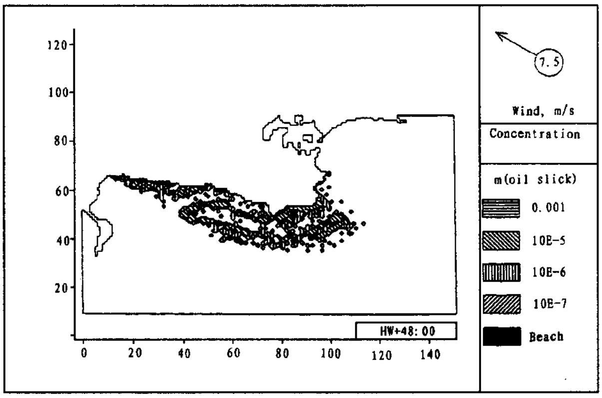

Fig.5 Trajectories of spilled oil of two days after spilling

of oil become stranded on the shoreline north west of the source under the influence of the imposed wind.

3 Conclusion

A comprehensive oil spill model has been developed, primarily for use in contingency planning. The model combines oil spill trajectory computations, based on the random walk technique, with weathering calculations. As well as simulating surface oil movement, it includes vertical exchanges and partitions between various phases.

The oil spill model has been validated by comparison with observational data. Evaporation, emulsification and weathering are simulated well. A functional form was selected for the dispersion coefficient, which resulted in good agreement between the model and experimental data.

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