SOTECH Vol.1; No.2, pp 41~49

Journal of
Ship&Ocean
Technology

"Green Sea Ranger", an Oil-Spill Model for Korean Coastal Waters

Keyyong Hong[1], Museok Song[2]

[1]Korea Research Institute of Ships and Ocean Engineering, Taejon, Korea
[2]Dept. Naval Architecture & Ocean Eng., Hong Ik University, Chochiwon, Korea

Abstract

We reviewed various oil-spill models and condensed the integrated information into a prediction model, "Green Sea Ranger" which is applicable to Korean coastal area. The developed software consists of pre- and post-modules for environment setup and display of results and main module for the prediction of oil's fate. In the pre-module target areas can be selected from the included geographic information system and various environmental and optional numerical data for the prediction can be input through easy GUI or imported from the database we established. For the fate of the spilt oil we included effects of spreading, advection, evaporation, and emulsification. Preliminary numerical experiment has proved that the developed oil-spill prediction system can be easily utilized in on-site oil recovery operations which usually require a quick and reasonable prediction.

Keywords : oil-spill model, spreading, advection, evaporation, emulsification

1 Introduction

As the oil-based product consumption increases relocation of huge amount of crude or processed oil by marine transportation is also steadily increasing. As a result accidental oil spill events occur more frequently these days and some of the accidents are even catastrophic to the marine environment. Nevertheless because of the efficiency of the marine transportation the increasing oil transportation through the ocean seems to be unavoidable, hence well being prepared for the accidental oil spills may be one of the best ways we might have to pursue.

Under a given environmental condition, what we eventually want to know is how the spilt oil will evolve on the ocean. This information could be crucial for the cleanup operation to become more efficient and effective over all and, eventually, damages associated with the spill might become minimal. There have been numerous experimental and analytical investigations aiming at further understanding of the fundamental interaction mechanism between the contaminants and the environment, however, even up-to-date information we have is rather far behind what we need in order to fully understand it (see [Lee et al., 1990]). Nevertheless, we still need to have prediction tools to cope with the frequently occurring oil spill accidents.

In this context, we developed a prediction system of the spilt oil's fate which can be applicable to Korean coastal area and briefly report related studies here. We reviewed previous investigator's fate models and selectively included some of them which we believe important in the prediction

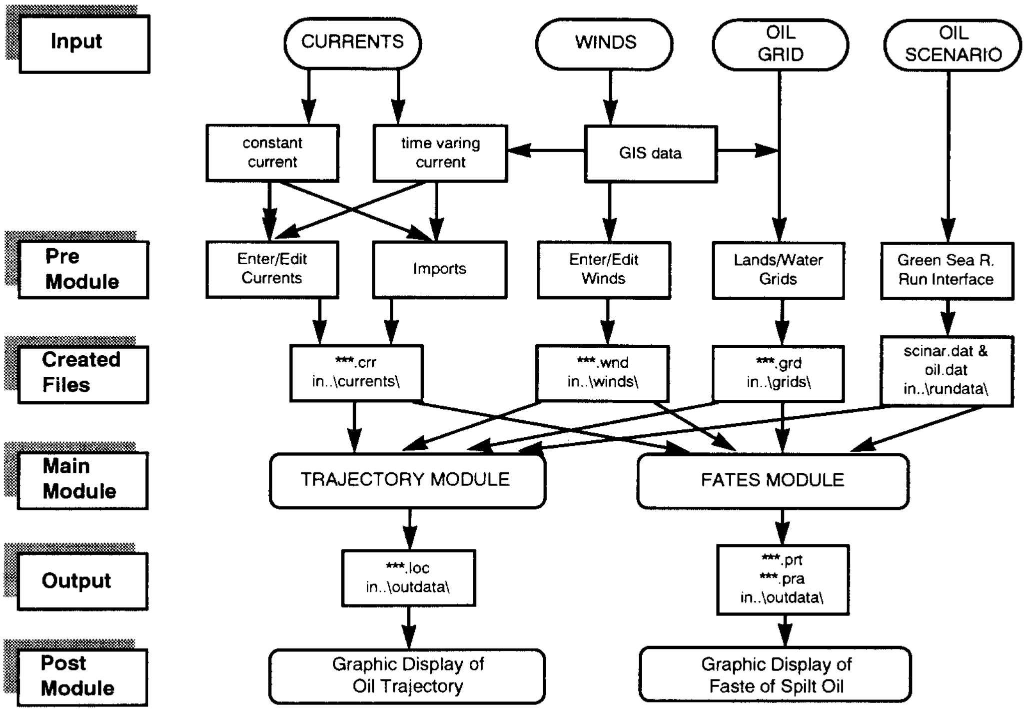

Figure 1. Structure of "Green Sea Ranger"

model. A friendly GUI for pre- and post-process is also developed and the whole system, named "Green Sea Ranger (Poo-Reun-Bah-Dah in Korean name)", has been proved useful from the preliminary experiments. A very preliminary version of the model which utilizes an existing pre/post module [Spaulding, 1993] was reported in [Song et al., 1995].

2 Structure of Green Sea Ranger

In order to make future upgrades easier we divided the program mainly into two parts which are pre/post and main modules and are linked each other by GUI (Figure 1). In the pre-module various required environmental and numerical informations are gathered and prepared as standardized formats for main module calculations. The main module is the part all the weathering models are integrated which will be discussed in the next section.

The working site is first to be chosen from the map of regional selections and then can be resized through zooming function. Once the working area is decided the grid distribution and the land/water classification is performed automatically. All the environmental data such as wind and current on the working area can be newly generated (or modified) easily and also can be imported from database. Wind can vary in time but is to be uniform over the working area for now. Current can be spatially uniform or variant and can be a sum of various harmonics.

For the accurate prediction of oil's fate, especially oil's trajectory, reliable wind/current information is essential but unfortunately existing such information is not usually fine or accurate enough. So numerical approaches to obtain the current information in a reasonably short time are usually employed but still there are practical problems such as boundary conditions to be resolved in order to be incorporated in the prediction models (see [Rho et al., 1995] and [Kim et al., 1996] for examples). It is more disappointing in wind data and one might utilize the results from large scale simulations or stochastic data if available.

Most of the important material properties required can be selected from the provided lists prepared based on [Whiticar et al., 1989] and can also be modified like all other input data at users' knowledge. Once a simulation with a certain combination of input data is completed various predicted variables such as trajectory and location of spills, area of polluted surface and oil's properties are displayed in graphics in post-module.

3 Fate Modeling

The fate of spilt oil can be understood as a process in which two different but closely related mechanisms are interacting each other; one is rather simple process which includes spreading and advection of oil while the other is more complicated physical, chemical and biological process which enhances the change of material properties of oil. This later process is often called weathering and it includes evaporation, diffusion, dissolution, emulsion, tar-lump formation, photochemical reaction, degradation, sedimentation and plankton ingestion and so on. But frequently we use the terminology, weathering, as covering the spreading and advection also. Each weathering process depends on different environmental parameter or parameters - material properties of oil and water, current, wind, sea state, temperature and so on - and people include some of the aforementioned weathering processes depending on their specific objectives.

As previously mentioned, there have been quite plenty of related studies on this interaction problem. Here, we selected a few fundamental elements which are believed crucially important and also for which relatively reliable evolution equations are provided with bearing in mind this is our first trial model. We briefly explain each of the process included in our model in the following.

3.1 Spreading

Spreading is generally treated as a process with three consecutive stages in which different driving/resisting parameters play important roles. First two of them are gravity/inertia and inertia/viscosity stages ([Fay, 1969]). The third one is interfacial-tension/viscosity stage but this is less important in the context of a quick cleanup operation compared to the other two. Followings are the equations used to determine the spreading at the very beginning according to [Fay, 1969].

$$R(t) = 1.14\nabla^{1/3}\left[\frac{g(\rho_w - \rho)}{\rho\nabla^{1/3}}\right]^{1/4} t^{1/2} \tag{1}$$

$$R(t) = 0.98\nabla^{1/3}\left[\frac{g\rho(\rho_w - \rho)}{\rho\mu^{1/2}}\right]^{1/6} t^{1/4} \tag{2}$$

where R = radius of oil slick (m),
t = time (s),
∇ = oil volume (m^3),

g = acceleration of gravity,
ρ = density,
Subscript w = water.

The above equations can be understood easily from the dimensional reasoning and the coefficients are determined semi-empirically. First we start with eq. (1) and once the slick thickness becomes $5mm$ we switch to eq. (2) until the slick becomes $1mm$ of thickness. This criteria was not unique but selected based on other experimental results. After then we use, following [Mackay, 1980], thick slick model since in the early stage of cleanup process slick area estimated with including very thin (a few micrometers) oil layer is meaningless.

$$\frac{dA}{dt} = K_1 A^{1/3} h^{4/3} \tag{3}$$

where A = slick area (m^2),
K_1 = empirical spreading constant, $150/s$ in general,
h = slick thickness (m).

3.2 Advection

Oil's advection is mostly due to the surface current and the wind while other effects, such as wave drift, can be important in special cases (see [Kang et al., 1996] for example). In addition we include the effect of turbulent diffusion and write the spillet's transport velocity, $\mathbf{V_s}$ as follows.

$$\mathbf{V_s} = \mathbf{V_c} + \mathbf{V_w} + \mathbf{V_t} \tag{4}$$

where $\mathbf{V_c}$ = due to current(m/s),
$\mathbf{V_w}$ = due to wind (m/s),
$\mathbf{V_t}$ = due to turbulent diffusion (m/s).

The transport velocity associated with current is taken from the value of surface current itself. The transport velocity associated with wind is generally taken as 3.5 percent of the wind velocity with a righting drift angle varying from 0 to 20° [Reed, 1989], [Galt, 1994], which includes both wave drift and wind shear. Here we adopted the suggestion by [Youssef et al., 1993] in which the drift factor (F) and the drift angle (θ) are given as follows.

$$F = 3.19 - 0.0318U. \tag{5}$$

$$\theta = 23.627 - 7.97 \log U. \tag{6}$$

where U = wind speed (m/s).

According to [Ellegaard et al., 1992] the turbulent diffusion is included by using the random walk concept and the expression is

$$\mathbf{V_t} = R\sqrt{\frac{6D_t}{\Delta t}} \tag{7}$$

where R = random number between -1 and 1,
D_t = diffusion coefficient (m^2/s),
Δt = size of time step (s).

In the real calculation the above velocity is determined by following two scalar expressions which are for latitudinal (x-direction) and longitudinal (y-direction) components, respectively.

$$V_x = R_x \sqrt{\frac{6D_x}{\Delta t}} \frac{u}{V}, \tag{8}$$

$$V_y = R_y \sqrt{\frac{6D_y}{\Delta t}} \frac{v}{V} \tag{9}$$

where R_x, R_y = random number,
D_x = latitudinal diffusion coefficient,
D_y = longitudinal diffusion coefficient,
u, v = latit. and longi. current speed,
$V = \sqrt{(u^2 + v^2)}$.

For the random number a random number (P) between 0 and 1 is generated first then $2(P - 0.5)$ is selected. The diffusion coefficients used are determined as $D_x = l^2 \partial u / \partial x$, for example, based on the mixing length concept where l is selected as 0.09 times of the grid size used. However, usually, grid size used for the prediction is relatively big, so dealing turbulent diffusion as the above can be meaningless. For this reason the turbulent diffusion is optionally modeled as a certain amount of the combined transport speed due to the current and wind with a directional randomness.

3.3 Evaporation

Once an oil spill occurs the most dominant weathering phenomenon is the evaporation during the first several days [Butler et al., 1976]. Consequently a significant amount of oil mass is transported into the atmosphere and the remaining oil's property is gradually changed. The most reliable evaporation formulas have been developed by [Stiver and Mackay, 1984] in which they analytically calculate the evaporation by using oil distillation data. The fraction evaporated is given as

$$F_v = \ln\left\{1 + B(\frac{T_G}{T})\Theta \exp(\alpha - \beta\frac{T_o}{T})\right\}\left(\frac{T}{BT_G}\right) \tag{10}$$

where T = ambient temperature (K),
T_o = initial boiling point of the modified distillation curve (K),
T_G = gradient of the modified distillation curve,
α, β = constants ($\alpha = 6.3$, $\beta = 10.3$ in general).

The evaporative exposure required in eq. (10) is given as

$$\Theta = \frac{K_m A t}{V_o} \tag{11}$$

where K_m = mass transfer coefficient (m/hr),
A = slick area (m^2),
t = time (hr),
V_o = volume of oil slick (m^3).

And the mass transfer coefficient used is

$$K_m = 0.0292 U^{0.78} D^{-0.11} Sc^{-0.67} \tag{12}$$

where U = wind speed (m/hr),
D = slick diameter (m),
Sc = oil vapor Schmidt number, 2.7 is typical.

As mentioned previously, the consequent change in oil's viscosity is determined using the evaporation fraction as

$$\mu = \mu_0 \exp(C_3 F_v) \tag{13}$$

where μ_0 = initial oil viscosity (cP),
C_3 = 1 for light oils, 10 for heavy oils.

3.4 Emulsification

The water-in-oil emulsification also affects the oil's property such as density and viscosity. If these property changes are not taken into account, cleanup operations may become harder than expected so we need to predict these effect carefully. [Mackay, 1980] model is believed reliable in general and we use his formula.

$$\frac{dW}{dt} = K_a(U+1)^2(1 - K_b\,W) \tag{14}$$

where W = fractional water content,
$K_a = 2 \times 10^{-6}$ for most emulsifying oils, 0 for non-emulsifying oils,
U = wind speed (m/s)
K_b = constant, 1.33.

The change of viscosity associated with the emulsification is also taken into account, according to [Mooney, 1951], as

$$\mu = \mu_o \exp\left(\frac{2.5W}{1 - K_c W}\right) \tag{15}$$

where K_c is a constant between 0.62 and 0.65.

4 Numerical Experiments and Discussions

The developed prediction system is applied to an oil spill event. We selected the "Sea Prince" incident in July of 1995 and tried to compare the prediction with observations reported. We took the working region roughly 150 km big in both latitudinal and longitudinal directions around So-Ree-Doh, Korea and 100 grids were used in both directions. We assumed 700 tons of oil is discharged at the accident site for 20 hours. The current is modeled to start from a flow condition with a typical speed, 50 cm/s. The simulated wind spped is based on observed data which is varying 10 m/s - 30 m/s during the period. Time step used for the simple Euler integration is 1 hr but it is variant during the simulation for the stability. For the shoreline interaction, we simply modeled that once slicks reach shores they stick to the shores.

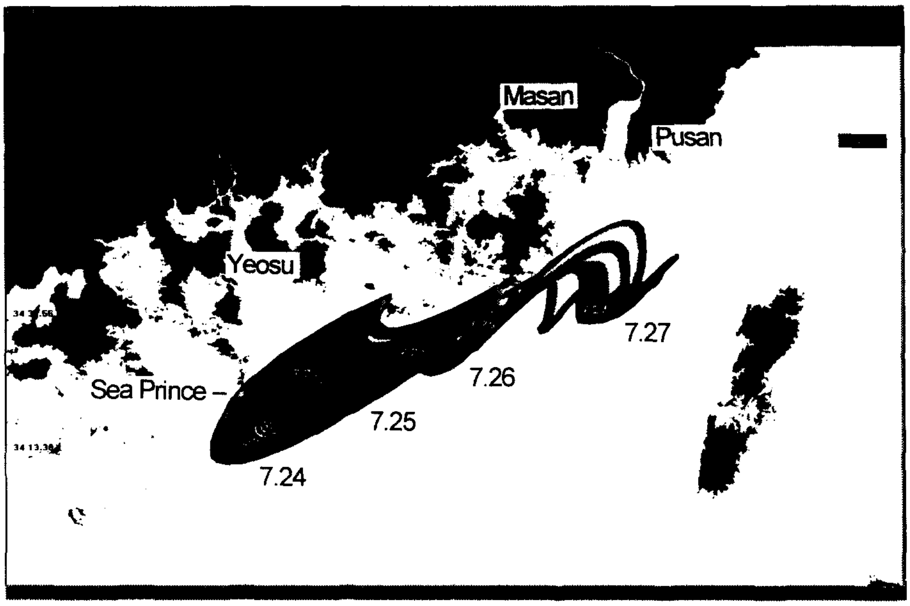

Figure 2. Simulated trajectory of spilt oil during the Sea Prince incident

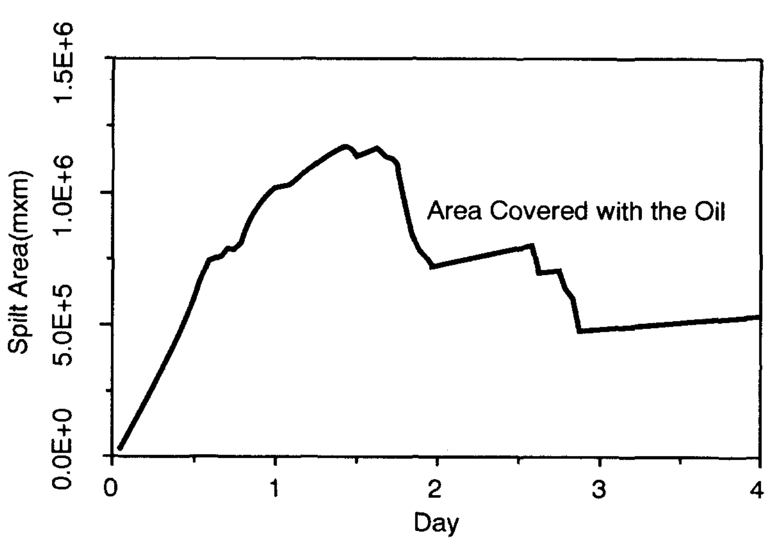

Figure 3. Simulated area covered with spilt oil as a function of time

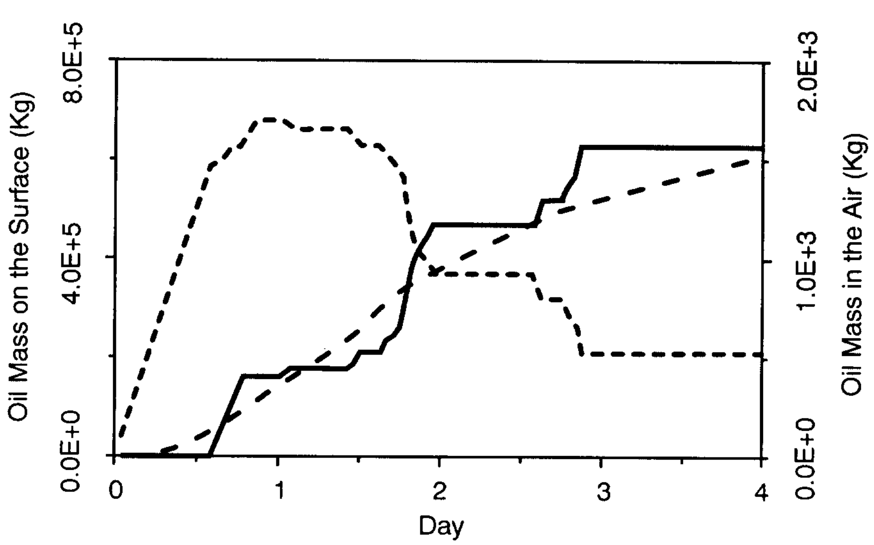

Figure 4. Oil mass distribution during the simulation

Spill location is marked as closed contours at four different times in Figure 2 along with small dots representing 100 oil spillets' trajectories which make the sequential oil evolution visible. As we can see, 4 days after the spill the front of spilt oil has nearly reached Busan and Tsushima of Japan, which are approximately 120 *km* apart from the accident location. A large scale periodic evolution due to the tide is clearly visible but the advection due to the strong wind played dominant role in this case.

Following Figures 3 and Figure 4 summarize the event. Figure 3 shows the water surface area covered with the spilt oil as a function of time. Initially it increases due to the continuous discharge and spreading but the stranding of spillets causes reduction of the area. In Figure 4 mass distribution of the spilt oil is shown as a function of time. The line steeply increasing from the beginning is for the mass on the ocean. Since the oil is discharged continuously it increases first but once some of the spillets reach the shore the mass decreases. At the same time the mass on the shore is increasing as shown as the stepwise increasing line. The smoothly increasing line is for the mass in the air and it shows continuous evaporation of the mass.

5 Conclusions

We developed a prediction system of the spilt oil's fate which is applicable to Korean coastal area. Most of the important weathering models such as spreading, advection, evaporation, emulsification and shoreline interaction are included based on the previous investigators' results, and friendly GUI is incorporated to maximize the efficiency of on-site operation.

Preliminary numerical experiment has demonstrated a possibility that the developed oil-spill prediction system could be easily utilized in on-site oil recovery operations which usually require a quick and reasonable prediction. The prediction system developed so far is equipped with more or less primitive fate models and limited environmental database. We believe that further improvement on the physical modeling and the database on ocean environments relevant to Korean cosatal waters should be made based on results from more rigorous field experiments and observations.

References

1. Butler, J. M. et al., 1976, The fate of petroleum in the open ocean, Sources effects and sinks of hydrocarbons in aquatic environment, The American Institute of Biological Sciences
2. Ellegaard, A. C., 1992, A PC modeling system for the simulation of transport and fate of solutes and suspended substances, Proc. 2nd International Conf. (ASCE), Tampa, FL
3. Fay, J., 1969, The spread of oil slicks on a calm sea, MIT, Cambridge, Massachusetts
4. Galt, J., 1994, Trajectory analysis for oil spills, J. Advanced Marine Technology Conference, Vol.11
5. Kang, K. H. and Lee, C. M., 1996, Prediction of drift in a free surface, Ocean Engng, Vol23, No.3
6. Kim, S.-Y., Song, M. and Han, S., 1996, An implicit numerical method for two-dimensional tidal computation, Proc. SNAK Spring Meeting
7. Lee, H.W. et al., 1990, Review on oil spills and their effects Center for applied coastal research, Department of civil engineering, Univ. Delaware
8. Mackay, D, Paterson, S. and Trudel, K., 1980, A mathematical model of oil spill behavior ",Department of Chemical Engineering, Univ. Toronto, Ontario
9. Mooney, M., 1951, The Viscosity of a Concentrated Suspension od Spherical Particles, J. Colloidal Sci., Vol.6
10. Reed, M., 1989, Field tests of satellite-tracked surface drifting buoys for simulating the movement of oil on the sea surfac, ASCE conf. on coastal and ocean modeling, Newport, Rhode Island
11. Rho, J. H. and Yoon, B. S., 1995, Numerical computation of near shore surface flow due to tide and wind, Trans. SNAK, Vol.32, No.2
12. Song, M., Kim, S.-Y., Hong, K. and Hyun, B.-S., 1995, A development of oil-spill model for Korean coastal waters, Proc. MARIENV'95, Tokyo, Japan
13. Spaulding, M., 1993, User's manual for OILMAP, ASA Inc.
14. Stiver, W. and Mackay, D., 1984, Evaporation Rate of Spills of Hydrocarbons and Petroleum Mixtures, Environ. Sci. Technol., Vol.18
15. Whiticar, S. et al., 1989, A catalogue of crude oil and products properties (1989 Version), Environment Canada. Report EE-114
16. Youssef, M. and Spaulding, M., 1993, Drift Currents under the Action of Wind and Waves, Proc. 16th Arctic and Marine Oilspill Program Tech. Seminar