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Oil Spill Models: A State of the Art of the Grid Map as a Function of Wind, Current and Oil Parameters

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ABSTRACT: An integrated model, which contains flow and transport-fate modules, will be presented for simulating transport and fate of oil spills at seas. The flow module uses different kinds of meshes that provide great flexibility for modeling the flow in complex geometries of currents and barriers. The refined grid resolution in regions of interest is important. Horizontal diffusion is simulated using random walk techniques in a Monte Carlo framework, whereas the vertical diffusion process can be solved on the basis of the Langeven equation. The model contains the most significant processes which affect the motion of oil particles. For a better fit to the curvature of the coastline there are used unstructured non overlapping rectangular or triangle grid cells. Special attention must be paid to choose the horizontal and vertical resolution in simulating the oil trajectory in the coastal area.

1 OIL SPILL MODEL IN THE LITERATURE

1.1 *Types of oil spill models*

Oil weathering models predict the changes in oil characteristics – evaporate, emulsify and disperse into the water column. The changes may occur over time under the influence of environmental conditions like water temperature, wind speed, wave heights, sea state, salinity, sediment concentration. The appropriate environmental conditions and oil type are selected from the model's database.

Trajectory or deterministic models allow to predict not only weathering profiles but also potential migration of an oil slick over time, slick volume, oil properties like viscosity or flash point and other details such as potential beaching sites or the lengths of coastline impacted.

Stochastic models (probability models) are built on the basis of historical wind records. The frequency of wind speed and direction is allowed to estimate the probability of where an oil spill might travel in defined time periods. The results indicate waters and shorelines which are most at risk during various seasons.

Hind-cast models (backtrack models) are allowed to estimate the spill origin. These models run contrary to the trajectory models.

Three dimensional models (3D) estimate oil spill trajectories, weathering profiles, oil component concentrations and make simulations of dispersion into the water column. These models required complex current data and a sophisticated oil characterization. These are the only models which consider the oil migration at depth.

Details of these models are described in the Technical Paper (ITAC).

1.2 *Input data of oil spill model*

The quality of the data used has a huge influence on the effectiveness of the model results. The data require by most oil spill models relate hydrodynamic data, wind data and oil type.

The most important parameter is hydrodynamic data. Gathering a database of currents is costly and time consuming but currents have the greatest influence on oil migration. Technological advance, the development of models and simulation allow to forecast currents but it is not useful in extreme environments such as storms or high runoff. Advective currents in oil spill simulations may be derived from current atlases or other static approximations. Wind data are much easier to acquire. Weather forecasting services provide general information on wind direction and magnitude. The oil types are available from database of modeling systems. Oil database contains essential oil properties.

1.3 *Oil weathering model*

The Figure 1 presents the general layout of weathering model. Under the influence of hydro-meteorological condition and oil type there are occured physical and chemical processes, which are direct or indirect linked. Reed in the paper (Reed et al. 1999) investigates an overview of different approaches applied in numerical models of the behavior of oil spill in the marine environment. Early oil spill models were typically two-dimensional models, present study use three-dimensional processes. The oil moves in the marine environment not only horizontally but also vertically, on and in the sea. Oil is transported horizontally under force of the wind, current, wave and vertically in the water column as droplets of various sizes. In light winds without breaking waves, 3.5% of the wind speed in the direction of the wind gives a good simulation of oil slick drift in offshore areas. As wind speed increases, oil will be dispersed into the water column, and current shears become more important.

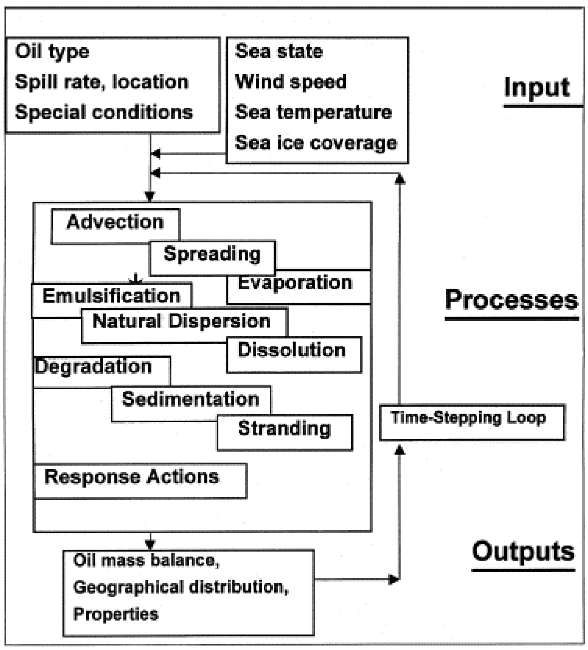

Figure 1. General layout of oil weathering (Reed et al. 1999)

All physical and chemical processes related oil spill have a huge impact on the oil composition and properties with time. Estimates of slick area and film thickness are used in the computation of evaporation. Estimates of evaporative losses are required in order to assess the lifetime of the spill. In addition, these estimates are required for evaluation of the potential efficiency of different oil spill combat methods, and for assessments of environmental impacts.

1.4 *Oil spill simulation*

Numerical prediction models have been generally used to solve the movement and diffusion of water-borne pollutants. To simulate oil transported on the sea surface there is used the advection–diffusion equation, (Choi et al. 2010). It is the general Eulerian equation, common mathematical model defined as:

$$\frac{\partial C}{\partial t} + U\nabla C = \nabla(D\nabla C) + S \quad (1)$$

where C is the density of oil, U is the velocity vector, D is the diffusivity coefficient, and S is external fluxes. Equation 1 is calculated from Lagrangian formula as follows:

$$L=(U_{current}+\alpha U_{wind})\Delta t+L_{random} \quad (2)$$

where L is the moving distance of each particle during Δt, α is the wind drift factor (usually taken as 0.03), $U_{current}$ is the ocean current velocity at the sea surface, and U_{wind} is the wind velocity at 10 m above the water surface, respectively. The advection due to turbulent diffusion L_{random} is computed by the random walk method for Gaussian "spillets" as

$$L_{random} = R\sqrt{6D/\Delta t} \quad (3)$$

where R is the random number between −1 and 1. The empirical diffusivity coefficient D is taken as 10 m^2/s. The oil spill model, Equation 2, calculates the oil transportation.

Choi in the article (Choi et al. 2010) constructed of the high resolution oil spill forecast simulation system. This model was built for the whole routes between Japan and Middle East, so to verify of the performance and accuracy of the simulation system there was used the accident of the Russian tanker "Nakhodka" in the East/Japan Sea, in January 1997. Simulation experiment of this accident was conducted and the simulation results were compared with the observation and the previous study.

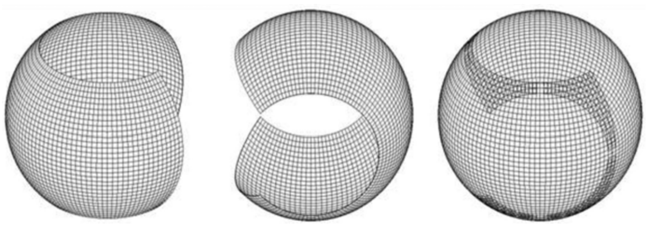

Figure 2.The Yang grid (on the left), the Yin grid (in the middle), their composition – the Yin-Yang grid (on the right)(Choi et al. 2010)

In presented model there is used global grid system, named "Yin-Yang grid". This grid consists of two grid components that have exactly the same shape and size, as shown in Figure 2. The adoption of nesting grid system for neighboring Japanese Islands and the global ocean model by means of Yin–Yang grid enables us to realize the quick and accurate response for emergency countermeasures. The movements of spilled oil are defined by the surface wind drift and ocean currents which are obtained from the general circulation model.

In the model described in the article (Morita et al. 1997) the experiment was used to estimate the degree of oil weathering on the sea surface and to determine parameter values of surfacing, sinking, and resurfacing speed for the forecasting model.

The Figure 3 presents the laboratory setup. The wave generator was made with an electric motor and an acrylic board. Five liters of fresh crude oil was added to the water surface in a 60 liter tank.

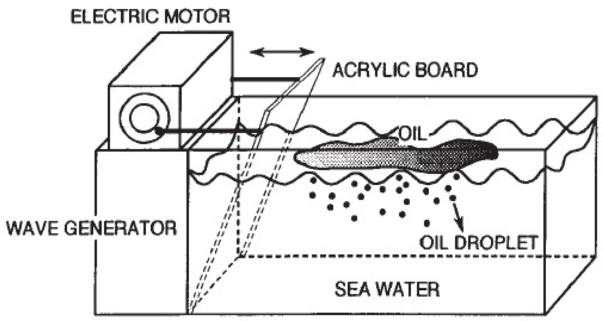

Figure 3. A sketch of the weathering experiment setup (Morita et al. 1997)

At the beginning of the experiment, after 3, 6, 12 hours and after 1, 2, 4, 8, 12 days the surface oil was sampled. The research has shown that the specific gravity of the oil increased logarithmically with time and the viscosity of surface oil increased exponentially with time. The oil droplets were patchy. The surfacing, sinking and resurfacing speed of emulsion, which was estimated with a video and photographic camera, increased with droplet diameter.

2 OIL SPILL MODEL WITH DECISION MAKING

2.1 *Oil spill model*

The model widely described in (Mazurek & Smolarek 2012) consists of the model of oil spill on the grid graph, the stochastic model of action time of spill surrounding and the stochastic model of oil slick drift. Water area is described by a grid, where an every vertex of grid corresponds to rectangular area of the sea and an every edge of grid represents contact between two areas. The size and the dimensions of area of the sea related to one vertex depends on hydro-meteorological condition and type of substance spill. We consider three grids: the Cartesian grid, the triangular grid and the strong grid, Figures 4-6.

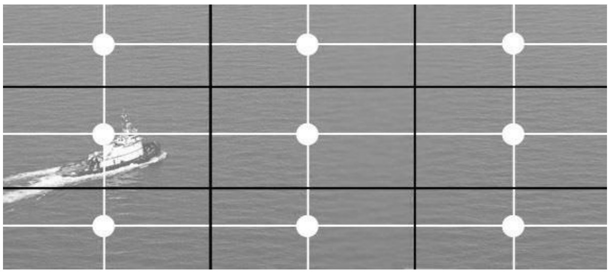

Figure 4.The Cartesian grid model.

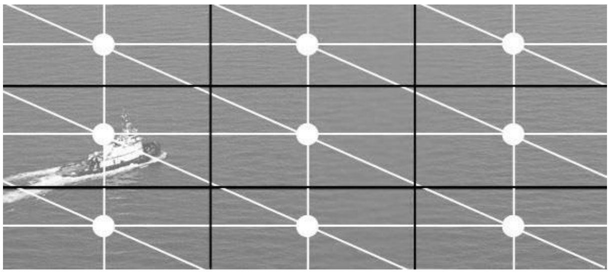

Figure 5.The triangular grid model.

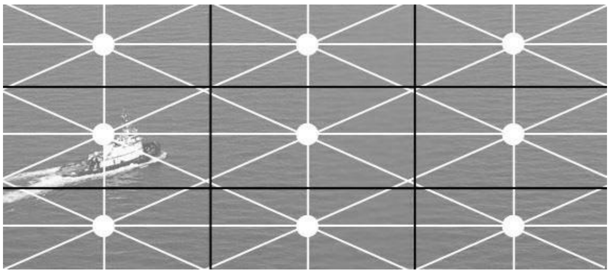

Figure 6.The strong grid model.

The choice of grid allows to take into account the prevailing conditions at the sea, in particular the speed of the spill spreading. In model there is applied the algorithm of a spill surrounding, known as "firefighter algorithm", (Fogarty 2003). This algorithm shows how to use available forces and resources to bound a spill. The methodology that was used allows to estimate the time of action preparation, the time of action of a spill surrounding, the size of the spillage and the amount of resources used.

In real situation incompleteness and uncertainty of the data do not enable to establish when start the rescue operation. In the stochastic model we assume that the time since oil spill occurs to starting the action is composed of two stages. The first stage is related to information about the spillage and the second stage depends on the time of share preparation: collect forces and resources, locate and get to the spill space by the rescue units. We use the triangular distribution to describe the time of these stages, because we usually know the shortest time, the longest time and the most probable time of these stages.

The time of the first stage is defined by parameters a_1, m_1, b_1, denoting minimum time, most probable time and maximum time, respectively. The time of the second stage is described by parameters a_2, m_2, b_2. We assume that the time of share preparation is a random variable described by a sum of two triangular random variables, (Mridula et al. 2009). The following formula presents the probability density function of this variable in case $a_1 \le x \le m_1$, $a_2 \le x \le m_2$

$$f(x) = k_1 \left[\frac{x^3}{6} - \frac{x^2}{2}(a_1 + a_2) + \right.$$
$$- x\left(\frac{m_1^2}{2} + \frac{m_2^2}{2} - a_1 m_1 - a_2 m_2 - a_1 a_2 \right) +$$
$$- \frac{m_1^2}{2}(a_1 - a_2) + \frac{m_2^2}{2}(a_1 - a_2) +$$
$$- a_1 a_2 (m_1 + m_2) + \frac{m_1^3}{3} + \frac{m_2^3}{3} \tag{4}$$

where

$$k_1 = \frac{4}{(b_1 - a_1)(b_2 - a_2)(m_1 - a_1)(m_2 - a_2)}$$

for $x \ge m_1 + m_2$.

The stochastic model of oil slick drift takes into account speed and direction of the wind and currents. This model is needed to research the horizontal movement of oil slick.

2.2 *The decision making process in oil spill model*

Models described in the first paragraph dissect all physical and chemical processes occurring at oil spills. The model proposed in the second section was built to analyze the rescue action for the management on the tactical and strategic level. The main feature of the model is the decision making process.

Decision making is the process of recognizing a problem and finding a solution to it. Many of these decisions are relatively simple and routine, they are known as programmed decisions. However, there are nonprogrammed decisions where neither the appropriate solution nor the potential outcome is known. Decision making process has a six-steps, (French, 1998):

- identify the problem, the decision maker must be sure he or she has an accurate grasp of the situation,
- gather relevant information, all the facts gives the decision maker much better chance of making the appropriate decision,
- develop many alternatives ,
- evaluate alternatives to decide which is the best,
- decide on and implement the best alternative,
- follow-up the decision.

Most significant are two first steps because it is important to pinpoint the actual cause of the situation, which may not always be obviously apparent. When an uninformed decision is made, it is important to know all the facts before proceeding. People at different levels in a company have different types of decision-making responsibilities.

Strategic decisions, which affect the long-term direction of the entire company, are typically made by top managers, (French, 1998). Examples of strategic decisions might be to focus efforts on a new ships or methods of oil spill fighting. These types of decisions are complex and uncertain, because available information is often limited.

Tactical decisions, which focus on more intermediate-term issues, are typically made by middle managers, (French, 1998). The purpose of decisions made at this level is to help move the company closer to reaching the strategic goal. Examples of tactical decisions might be to select the location, deployment of resources to be put into action.

Decision makers managing rescue services at the tactical and strategic level take decisions which have a major influence on the ecological effects of spill. The use the presented model to support decision-makers work enables a thorough analysis of the rescue operation. Parameters of the model are as follows:

- the time of preparation rescue operation,
- the time of rescue operation,
- the size of the contaminated area,
- forces and resources used in action,

and they define the main criteria for evaluating decisions. The proposed criteria enable to determine the set of admissible decision and the set of optimal decisions. An analysis of all possible strategies and their evaluation allow for a rational and logical identification of an emergency situation.

3 CONCLUSIONS

The model described in this paper is a model for decision-makers on the strategic or tactical level; it is not addressed to a head of a rescue operation. In the construction of the model there are taken into account the dynamic parameters, e.g. the velocity of the spread of the oil spill, the hydro-meteorological conditions that affect the direction and the velocity of the surface oil slick. Models presented in section 1 will be used to determine the size of the mesh graph because they include not only physical and chemical properties of the spilled substance but also physics phenomena related to the spill, such as evaporation, sedimentation, etc.

The main objective is to create a tool that allows the decision maker to evaluate the extent to which available forces and resources will be need. Moreover their location influence effects of maritime oil spill disasters at the sea. The model is currently under construction and will be eventually supplemented by a simulation program for the analysis and visualization of the development and effects of the rescue operation.

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