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ON THE SIMPLIFIED MATHEMATICAL MODELS FOR OIL SPILL SIMULATIONS

(INVITED SESSION PAPER)

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ABSTRACT

The most principal issues today are the environment, green energy and food. One branch is also Blue Seas, the protection of the marine environment. UL-FPP is linked to the Blue for Seas (B4S) project, which deals with oil pollution in the oceans and where we are looking at all possible aspects to protect the marine environment. One of the topics is also oil pollution simulations. This article presents some models that can quickly calculate oil spills' dynamics. If simulation needs to be fast, preferably in real-time, you need a simplified model. How much to simplify the model is an open dilemma. Most important is the ability of the model to predict the motion almost correctly under basic parameters. The word "almost correct" here means a balance between speed and accuracy. The simplest model is the diffusion equation solution for the source type with simple advection coupling. In addition to describing the simplified models, some examples of source diffusion models with simplified advection are also presented.

Keywords: Oil pollution, Numerical simulations, Advection-diffusion equations, Model approximations, B4S

1. INTRODUCTION

A severe accident could have catastrophic effects on the fragile environment, the natural resources of the enclosed seas, and their important uses, such as for tourism and local fisheries. Environmental hazards in the marine environment can arise from a variety of natural and anthropogenic sources. One of the biggest sources of danger, which has been a problem for decades, is oil. As oil pollution can have multiple environmental and socio-economic impacts, the risk of oil pollution from human activities needs to be minimised. The main sources of oil pollution in marine waters are natural seepage, industrial and urban runoff from land, offshore extraction and shipping. On average, 1,250,000 tonnes of oil from the sea enter the marine environment annually GESAMP, 2007. Another source of oil pollution is leaking shipwrecks. The number of shipwrecks (non-tankers of at least 400 GRT and tankers of at least 150 GRT) in global marine waters is estimated at > 8600, and some of these wrecks still contain significant amounts of oil. However, many other sources of low-level pollution are of concern, including leakage from wrecks, fishing activities, operational discharges, and low-level leaks of lubricants (like damaged stern tube seal). The amount of petroleum products in the wrecks is estimated at 2.5-20.4 million tonnes [1,2]. On the other hand, operational pollution from seagoing vessels includes various types of discharges of oil and oily mixtures, including chemicals, resulting from routine daily operations. A calculated amount of illegally discharged oil in the Adriatic Sea per year would be about 3,000 m^3 annually [3].

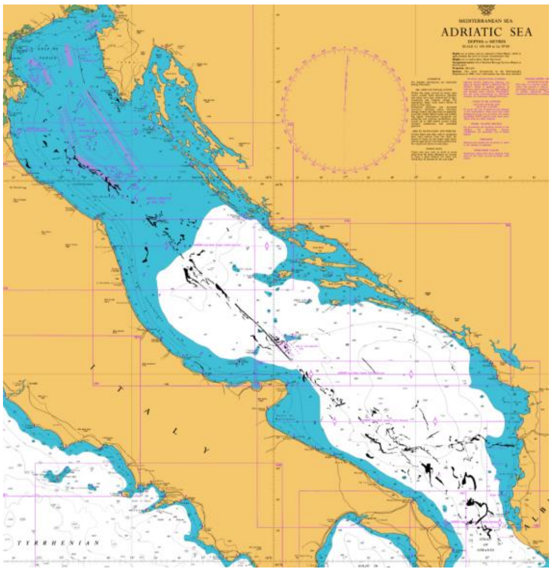

Figure 1: Probable oil spills in the Adriatic Sea [3]

In general, oil spills can be divided into large (macro) and small (micro) spills. Large oil spills from marine disasters and offshore oil drilling affect biota differently than small but frequent discharges from shipping and urban/industrial runoff. Impacts can range from acutely toxic to sublethal. Large oil spills, for example, can cause narcotic effects, oxygen depletion, obstruction of the transmission of sunlight to the water and hypothermia of seabirds. In addition to acute effects, they can also have long-term consequences for marine ecosystems. Unlike large oil spills, small oil spills usually only lead to chronic and long-term impacts. Therefore, both large and small oil spills can be of ecological importance [2].

Risk is usually defined as a combination of the probability of a negative event, its consequences and the uncertainty associated with both. In the context of oil spill risk assessment, it can be expressed as a combination of the probability of a particular pollution event occurring and the magnitude of the consequences of that pollution. Both the probability and the consequences of an oil spill are subject to a degree of uncertainty, which leads to uncertainty in the final risk value of an oil spill.

The probability of an oil spill scenario is usually estimated from historical data and/or expert surveys. In the case of a sunken vessel, the oil spill is assumed to be caused by activities that may damage the wreck. The wreck and the site-specific conditions have an influence on the degree of impact of the hazardous activities. In addition, the wreck must still contain oil. Taking these uncertain factors into account, a PDF can be derived to describe the uncertainty of the probability of an oil spill. The uncertainty of the consequences/impacts of oil spills can be quantified through simulations. Trajectory models can be used to predict the behavior of oil in the environment and the relative spatial and temporal extent of the potential consequences.

The circumstances of an oil spill, such as the source, the cause, the type of oil, the amount and speed of the spill, the location of the spill, and the time of year in which the spill occurs are examples of factors that influence the impact of an oil spill. To account for the uncertainties of these factors, the calculation of impacts should be based on trajectory modeling of the expected total of a wide range of accident scenarios [2].

The research presented in the current discussion deals with the comparison between a professional oil spill simulation tool PISCES II (Potential Incident Simulation, Control and Evaluation System) [4], and a simple advection-diffusion model.

As we will see, one of the main effects is hidden in the diffusion and advection of the oil spill. The comparison shows that the advection in the simple model is exaggerated because it does not consider the shear force exerted on the oil slick by the forced flow of the surrounding fluid.

2. MODEL

A fully developed oil model should consider changes that occur to oil as it spends time in the environment. Main weathering processes are spreading, evaporation, dispersion, emulsification, viscosity variations, combustion, and shore interactions. Additional factors such as shoreline description, current field representation, water temperature, wind speed, and directions, and finally oil properties should be considered in the modeling.

The PISCES model uses a Lagrangian approach to describe the oil slick, i.e., the oil is represented by an ensemble of particles moving independently under the influence of wind and current. The trajectories of the oil particles are two-dimensional and are calculated by a two-dimensional flow field.

It is assumed that the particles have the same properties and do not interact with each other. The water parameters and weather conditions are the same for the entire oil spill. These parameters are used to simulate the weathering processes.

The flow field is determined using constant basis vectors with a specific rate of change over time. The flow velocity at a given point is calculated by interpolating the basis vectors and considering the sliding resistance of the shoreline. Delaunay triangulation is used for the above procedure.

At the beginning, one should determine the information about the source of the oil slick: Time, location, quantity and type of oil slick such as:

- Point source – with given mass and position of the oil slick
- Area source – with specified mass, position and area of the oil spill
- Source of the oil spill – where the amount of spilled oil depending on the position and time is specified.

In this part, we focus only on the comparison of oil dispersion between the models PISCES and FE. The theoretical background of the advection-diffusion problem in oil spill modeling is based on the solution of a one-dimensional advection-diffusion equation in a plane

$$\frac{\partial u}{\partial t} + \boldsymbol{v} \cdot \nabla u = \frac{1}{Pe} \Delta u, \quad \text{in } \Omega \tag{1}$$

where u is the height of the oil spill, $\boldsymbol{v}$ is the velocity vector field in the plane, Pe is a dimensionless number and Ω is a computational domain in our case $\mathbb{R}^2 \times \mathbb{R}^+$ To solve (1) we need to specify the initial and boundary conditions

$$\begin{aligned} u &= u_0, \quad \text{in } \Omega \\ u &= u_D, \quad \text{on } \partial\Omega \end{aligned} \tag{2}$$

Initial condition in (2) is defined with a bump function

$$\Psi(x) = \begin{cases} exp\left(-\dfrac{1}{a^2 - x\cdot x}\right), & x \in [-a, a]^2 \\ 0, & \text{otherwise} \end{cases} \quad (3)$$

The characteristic of the bump function is that its value is positive inside the region bounded by the radius *a*, and zero otherwise. Boundary condition is of Dirichlet type and is initially set to zero.

System (1)-(2) is solved with FE (Finite Element) method, where the stabilization of advection nature of Eq. (1) is stabilized by SUPG method [5]. Implementation of the problem was realized in Fenics/Dolfin FEM environment [6].

The results of the solution FEM are compared with the software Spill Management Simulator PISCES II This software was originally developed by Transas Marine as an exercise management tool for the U.S. Coast Guard. Today, PISCES II is used to train students and professionals on how to respond to major oil spills and minimize the impact on the environment and local economies.

It's also used to test and/or develop appropriate response plans and improve teamwork and decision-making.

3. RESULTS

Using a PISCES II software we have first simulated a point-source spill (at 45° 31'N latitude and 013° 32'E longitude) of 100 m^3 of fuel oil (IFO 180) with a viscosity of 180 cSt, the surface tension of 30.7 dyn/cm (mN/m), and a density of 967.9 kg/m^3 (14.7 API). The oil pour point is -10 °C and the oil flashpoint is 91 °C.

The sea temperature was 15 °C and the air temperature 20 °C, without waves, the density of the sea was 1027 kg/m^3 and 5 tenths of clouds.

Two scenarios were analyzed and compared. In the first case, only the wind is used for the movement of the oil slick, and in the second case, only the current is used for the movement of the oil slick.

Wind external force

The wind blows from the direction 315°, with a speed of 10 m/s. Fig. 1 and 2 show the results from PISCES and FEM for a time interval of 1 hour.

The first difference when comparing the results in Fig. 2 and Fig. 3 is the length of the overflow path, which is related to the advection term in (1). In the case of PISCES, it's about 4700 m and in the case of FEM, it's 33500 m. It's obvious that the solution of FEM doesn't take into account the stress and friction forces between the oil slick and the air/water surface. The introduction of an empirical shear force friction coefficient or some kind of transport coefficient would improve the results of FEM.

The comparison of the final shapes shows some differences, which are probably also due to the different stress/friction coefficients.

The diffusion in (1) is associated with the Peclet number *Pe*. In all simulation cases it was set to 100. The results of PISCES and FEM for the diffusion are shown in Figs. 2 and 4.

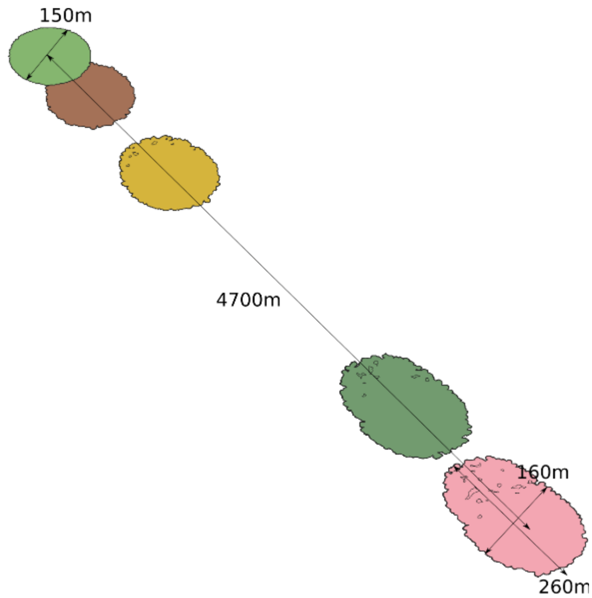

Figure 2: PISCES solution of wind forced oil spill motion

The differences in the size of the oil slick also show the effect of non-constant diffusion in the model PISCES. A constant diffusion coefficient as in the model FE (1) clearly doesn't do justice to the real conditions.

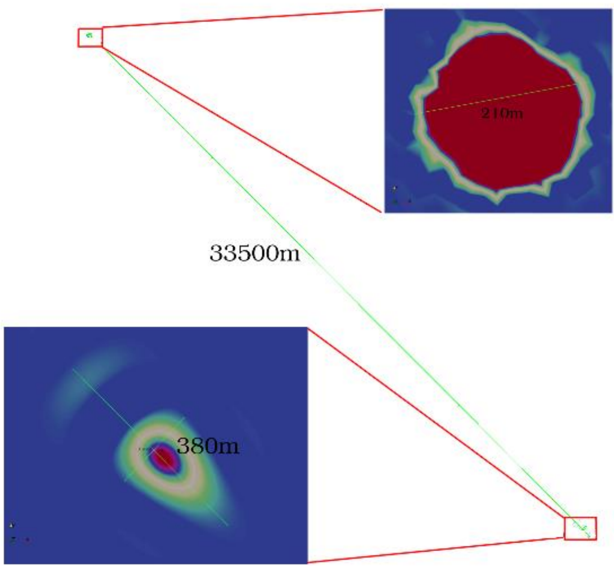

Figure 3: FEMS solution of wind forced oil spill motion

Current external force

The current flow acts in direction 135° with a speed of 0.2 m/s in a time window of 3 hours. The results are similar to the wind-driven situation.

In this case, the diffusion is very isotropic, probably due to the small advection velocity term. Nevertheless, the growth of the silk area can be observed well.

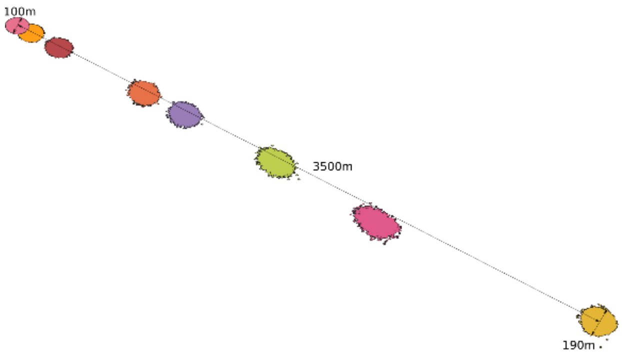

Figure 4: PISCES solution of current-driven oil spill motion.

The spread of the slick in conjunction with the change in thickness of the stain over time is shown in the figure below (Fig. 5). Note that other processes such as dissolution of the slick in the water column, emulsification, and even evaporation are virtually absent during the first few hours. When viscous fuel is spilled, it evaporates barely 0.1 percent of its mass in three hours.

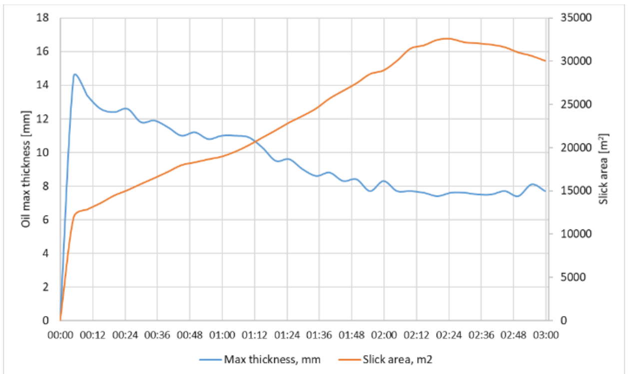

Figure 5: PISCES solution of current-driven oil spill motion

4. DISCUSSION AND CONCLUSIONS

This paper compares the movement of the oil spill between two different mathematical models. In the first model of the linear advection-diffusion model, the solution is calculated using the FEM approach. It clearly shows all the basic motion phenomena, but lacks the complexity of the coupling between the external force, friction and the oil slick, which is probably introduced by the transport coefficient. Also the diffusion doesn't seem to be constant, probably a non-linear relationship, when comparing the results of FEM and PISCES. PISCES is known as a good simulation tool for oil spills and the comparison between these two models shows the main differences between the very simple model and a model that includes many oil spill motion effects.

The results show that the simple linear advection-diffusion model cannot predict the movement of the oil spill, but with some basic extensions such as the introduction of a transport coefficient and a non-constant diffusion coefficient, the results could be improved.

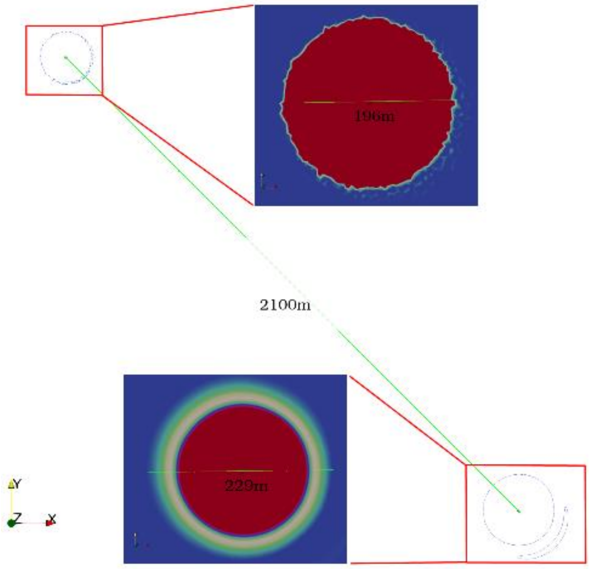

Figure 6: FEM solution of current-driven oil spill motion.

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