Numerical modelling of oil spills in coastal zones. A case study

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Abstract

A computational structure has been developed to forecast the time-space evolution of oil spills in marine environments. This structure was developed taking into account widely used mathematical formulations for oil spreading and weathering processes. A Eulerian transport model, that uses hydrodynamic results obtained with a two-dimensional and a quasi three-dimensional hydrodynamic model, was used to predict the oil slick transport and spread. This paper presents the general characteristics of the computational structure and the results of its application to a real case study: the Cercal accident in October 1994.

1 Introduction

Petroleum products that enter the marine environment have distinct effects, according to their composition, concentration and the elements in the environment that are considered. Petroleum pollution modifies the environmental conditions and can be translated into: transformations of the chemical composition of the environment and alterations in its physical properties; destruction of the marine biomass nutritional capital; danger to human health; and changes in the environmental biological equilibrium.

In order to combat the permanent danger of marine pollution caused by hydrocarbon spills efficiently, it is extremely important, once a spill has been detected, to be able to predict both its location and the corresponding transformations as quickly and as precisely as possible. Under favourable conditions, tele-detection can be used to monitor the affected zones and the extent of the spills. However, numerical models are intrinsically capable of predicting the evolution and behaviour of the oil spill at sea, regardless of the
atmospheric conditions, hence their vast interest. In preventive terms, these models could even represent the unique method that can be used to plan the implementation of sea combating pollution facilities. Predictions provided by the numerical models should, in the meantime and whenever possible, be accompanied by direct observations. Among the various works developed in this field, it is important to highlight Borthwick et al. [1], Song et al. [2], Costa [3], Costa & Antunes do Carmo [4] and Sebastião [5].

2 Mathematical models

Numerical models are based on mathematical formulations that translate the processes of hydrocarbon spreading and weathering. Essentially, this computational structure uses the hydrodynamic data required for the Eulerian transport approach and describes the spreading and the weathering processes of the spilt oil. The hydrodynamic data is obtained with the Saint-Venant or shallow-water equations, using either a two-dimensional (2DH) or a quasi-three-dimensional (quasi-3D) form of the equations.

Most oil spill transport models have adopted a Lagrangian description. However, it is likely that Eulerian models will be used more frequently in the future, because they need to be coupled with (Eulerian) hydrodynamic models and (Eulerian) meteorological models of the lower atmospheric boundary layer.

2.1 Hydrodynamic models

A 2DH hydrodynamic model is implemented using a programme based on the finite element method (WES-HL [6]), and a quasi-3D hydrodynamic model is developed using a finite difference hydrodynamic model, which corresponds to a modified version of the Princeton Ocean Model (Mellor [7]; Pinho [8]). The 2DH model is used in situations where the water flow does not exhibit a significant vertical variation, and the quasi-3D hydrodynamic model is used to calculate the surface water currents when a significant vertical variation is associated with the water flow pattern.

2.2 Transport model

The surface transport of the pollutant oil mass is obtained with,

\[ \vec{U} = \vec{U}_w + C_v \vec{U}_v \]

where \( \vec{U} = (U, V) \) are the final velocity components found from the known flow velocities \( \vec{U}_w = (U_w, V_w) \) and the wind velocity component \( \vec{U}_v = (U_v, V_v) \); \( C_v \) is an empirically-based drift factor.

The Eulerian surface oil slick transport equation is a mass conservation equation for the surface oil layer:
\[
\frac{\partial C}{\partial t} + \frac{\partial}{\partial x} \left( UC \right) + \frac{\partial}{\partial y} \left( VC \right) - \frac{\partial}{\partial x} \left( E_x \frac{\partial C}{\partial x} \right) - \frac{\partial}{\partial y} \left( E_y \frac{\partial C}{\partial y} \right) + k_c C = 0
\]

(2)

where, \( C = \rho \delta \) is the local concentration of surface oil, \( t \) is time, \( \rho \) is the local mass density of oil, \( \delta \) is the local thickness of the oil layer, \( E_x \) and \( E_y \) are the local dispersion coefficients in the \( x \) and \( y \) direction, respectively, and \( k_c \) is the local mass transfer rate from source/sink processes. This equation is solved numerically using a modified version of the RMA4 programme (Pinho [8]).

2.3 Oil spill characteristics model

The evaporative loss fraction \( (F_e) \) of a given hydrocarbon is described by the following equation (Buchanan & Hurford [9]):

\[
\frac{dF_e}{dt} = \frac{K A_o}{V_o} \exp \left[ A - \frac{B}{T} (T_o + T_o F_e) \right]
\]

(3)

where \( K = 2.5 \times 10^3 U_v^{0.78} \); \( T = \) product temperature (°K); \( T_o = \) initial temperature (when \( F_e = 0 \)); \( A = 6.3 \); \( B = 10.3 \); \( T_o = \) distillation curve gradient (°K); \( \mu = \) dynamic viscosity (cP); \( A_o = \) oil slick area (m²); and \( V_o = \) oil volume (m³).

Vertical dispersion losses are modelled considering the rate proposed by Mackay et al. [10]):

\[
\gamma_d = \frac{0.11 \left( U_v + 1 \right)^2}{1 + 5 \mu \delta \gamma_{ow}}
\]

(4)

where \( \mu = \) dynamic viscosity (cP); \( \delta = \) pollutant slick thickness (cm); and \( \gamma_{ow} = \) oil-water surface stress (dyne/cm).

Taking the previous formulations for the oil losses, the volume variation can be expressed by (considering \( V_{o0} = \) initial oil volume):

\[
\frac{dV_o}{dt} = -V_{o0} \frac{dF_e}{dt} - \gamma_d V_o
\]

(5)

The area rate growth is modelled considering the following expression (Mackay et al., [10]),

\[
\frac{dA_o}{dt} = K_i A_o^{4/3} \left[ \frac{V_o}{A_o} \right]^{4/3}
\]

(6)

Emulsification is modelled by means of the expression (where \( Y \) is the water in oil fraction),

\[
\frac{dY}{dt} = 2.0 \times 10^{-4} \left( U_v + 1 \right) \left( 1 - \frac{Y}{Y^*} \right)
\]

(7)

where \( Y^* = 0.70 \) (crude oils, heavy oils) to 0.25 (light fractions).
Changes in dynamic viscosity and density are modelled by the following expressions:

\[ \frac{d\mu}{dt} = C_\mu \mu_o \frac{dF_\mu}{dt} + \frac{2.5 \mu_o}{1 - YF_o} \frac{dY}{dt} \]  
\[ \rho_e = \rho_o + (1 - Y)\left(\rho_o + YF_o\right) \]  

where \( \mu_o \) = initial viscosity (cP) and \( C_\mu \) is the mechanical oil rate recovery time. \( C_\mu = 1 \) (gasoline) to 15 (heavy crude oils). A numerical tool based on the Runge-Kutta method was developed to solve these equations.

3 Cereal accident modelling

3.1 Accident characterization

On the 2nd October 1994 the Panamanian oil tanker Cereal struck a rock while entering the harbour of Leixões (the Porto harbour), releasing about 2500 tonnes of crude oil (Arabian Light) into the sea. Figure 1 is a satellite-acquired image two days after the accident. The spill can be seen floating along the coast and out into the sea. The coastal city of Porto, lying near the centre of the oil spill, appears as a cluster of white dots. The rainy and foggy weather that prevailed in that region of Portugal on the date of the accident made it very difficult to evaluate the spill from an aircraft. However, thanks to the all-weather capabilities of the satellite instrument it was possible to acquire this very useful scene through the cloud cover. The Portuguese authorities monitored the accident and some laboratory work was carried out to evaluate the physical properties of the crude oil. Data on the oil slick position, its area and volume, and the mean daily wind velocity and direction are presented in Table 1.

Figure 1: Satellite-acquired image two days after the Cereal accident at the Leixões harbour (the Porto harbour).
Table 1: Changes in the position, volume and geometry of the pollutant slick from the Cereal accident, and wind characteristics.

<table>
<thead>
<tr>
<th>Position</th>
<th>Date Oct 1994</th>
<th>Geographical coordinates</th>
<th>Area (km²)</th>
<th>Volume (m³)</th>
<th>Wind Velocity (m/s)</th>
<th>Wind Direction (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>41°06'N-08°55'W</td>
<td>16</td>
<td>2400</td>
<td>4.12</td>
<td>320</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>41°13'N-09°01'W</td>
<td>39</td>
<td>1900</td>
<td>5.23</td>
<td>350</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>41°17'N-09°02'W</td>
<td>70</td>
<td>1530</td>
<td>7.71</td>
<td>30</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>41°23'N-08°57'W</td>
<td>100</td>
<td>1450</td>
<td>15.43</td>
<td>140</td>
</tr>
<tr>
<td>5</td>
<td>7</td>
<td>41°16'N-08°54'W</td>
<td>136</td>
<td>1400</td>
<td>5.14</td>
<td>300</td>
</tr>
<tr>
<td>6</td>
<td>8</td>
<td>41°18'N-08°58'W</td>
<td>178</td>
<td>1350</td>
<td>7.71</td>
<td>330</td>
</tr>
<tr>
<td>7</td>
<td>9</td>
<td>41°25'N-09°03'W</td>
<td>220</td>
<td>1290</td>
<td>5.14</td>
<td>300</td>
</tr>
<tr>
<td>8</td>
<td>10</td>
<td>41°28'N-09°06'W</td>
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<td>210</td>
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<td>41°22'N-09°11'W</td>
<td>315</td>
<td>1200</td>
<td>6.17</td>
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<td>1170</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.2 Modelling evolution of oil spill properties

A first attempt to model the oil spill was carried out using eqns (3) to (9) using a Runge-Kutta based integration tool and assuming the following crude oil parameters: \( \rho = 857 \text{ kg m}^{-3} \), \( \nu (\text{at 25 °C}) = 6.30 \text{ cSt} \), \( \gamma = 65\% \), \( T_0 = 292 \text{ °K} \), \( T_G = 624 \text{ °K} \) and \( \gamma_{ow} (\text{at 20 °C}) = 0.0309 \text{ Nm}^{-1} \) (Figure 2).

Figure 2: Oil spill characteristics evolution results obtained using eqns (3) to (9).

First results, presented in Figure 2, show that the volume and area of the oil cloud were not accurately estimated. Moreover, using eqn (3) to model the evaporated fraction leads to an overestimation of this quantity since, as laboratory experiments demonstrated, the fraction of evaporated oil is 48.9%. With the above mathematical formulation for the oil slick characteristics it is not possible to improve the model results, even if some of the equation coefficients are modified (as confirmed by sensitivity analysis to other coefficients, not presented in this paper). Thus, some modifications were made to the initial
evolution equations for the oil characteristics presented: (1) the maximum oil evaporation fraction was set at the laboratory-determined value (eqn (3) is used during the initial period, and when the maximum value for $F_e$ is reached it is kept constant in time); (2) the oil volume time variation was modelled using a first order decay equation; and (3) the oil slick area was estimated using an exponential equation. The volume time variation was modelled by means of the following equation:

$$\frac{dV}{dt} = -K_v V$$

(10)

with, $K_v = 8.223 \times 10^{-2}$ day$^{-1}$. Area growth was modelled with the following equation:

$$\frac{dA}{dt} = -K_A t^{(b-1)}$$

(11)

where $K_A = 2.893$ and $b = 1.363$.

Figure 3 presents the results obtained for the evolution of the oil characteristics over time, considering the modifications to the mathematical formulation described above. The mathematical formulation used to model the evaporation loss (eqn (3)) usually overestimates it (Sebastião [5]). However, since the major fraction of evaporation loss occurs in the first 24 to 48 hours (for this oil type), and the total simulation period modelled is 240 hours, the results are considered reasonable. This is because, for most of the simulation period, the evaporation loss can be disregarded (after the maximum evaporation fraction is reached). Eqns (10) and (11) had to be used with care for forecasting purposes since they were not validated with different data sets.

3.3 Hydrodynamic modelling

Water currents at the accident site can play an important role in the oil transport process. To quantify the water currents’ velocity at the northern Iberian Peninsula coastal zone during the accident, a 2DH hydrodynamic model was used. Figure 4 shows the geographical extent, the finite element mesh (with 5294 quadratic triangular elements) and the bottom topography. It must be emphasized that this model is still in the implementation phase, and, since there is no data available for model calibration and validation purposes, the parameters for it were established taking values used in similar studies.
Figure 3: Oil slick characteristics. Evolution results obtained using eqns (10) and (11) as an alternative to eqns (5) and (6).

Figure 4: 2DH hydrodynamic model: a) finite element mesh, b) bottom topography.

A hydrodynamic simulation was carried out imposing predicted tidewater surface elevations (JPL [11]) at the open ocean boundary (Figure 5). Figure 6 displays the instantaneous maximum tide current velocities (during ebb and flood) at the accident area.
Figure 5: Predicted tide water surface elevations at 43° N - 10° 2' 50" W from 1 to 13 October, 1994.

Figure 6: Instantaneous maximum tide currents velocities for: a) ebb, b) flood.

The hydrodynamic model results were used to calculate the daily residual tide current velocities during the accident period. Figure 7 presents the results for each day of the accident period.

As that Figure shows, the daily residual tide current velocities at the oil slick positions are lower than 2 cm s⁻¹ (the results were similar for days that are not shown in Figure 7). The wind therefore appears to have most influence on the oil transport process (compared with other types of current).
3.4 Transport modelling

In order to quantify the velocities to be used in the Eulerian transport model, the $C_v$ coefficient value must be established. According to the positions observed for the oil slick, the daily $C_v$ value varies between 0.01 and 0.02 (ignoring water flow current velocities, which is close to the real situation, if tide currents are assumed to be the most important flow currents).

To show the general capabilities of the transport model, a simulation was carried out taking the values calculated for $C_v$. Figure 8 presents the calculated oil slick thickness at different oil slick positions.
Several simulations were carried out considering different $C_v$ values during the simulation period. The results obtained have shown a high sensitivity to this parameter. An additional corroboration of the Eulerian model results was carried out, calculating the volume of oil within the spatial integration domain (Figure 9).

Figure 8: Eulerian transport model results: oil slick thickness at different observed positions.

Figure 9: Comparison between the observed oil volumes and the calculated volumes (using eqn (5) and the Eulerian model).
4 Conclusions

The performance of the computational structure described here, which is based on a Eulerian transport model, proved to be satisfactory for modelling an oil spill accident. Some widely applied expressions for oil spill characteristics (evaporation loss, volume and area) showed its suitability for modeling the Cereal oil spill. For forecasting purposes, special care must be taken in the prediction of the C, coefficient. Furthermore, wind characteristics (velocity and direction) must be properly recorded (or anticipated).

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References