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The influence of oil particle size distribution as an initial condition in oil spill random walk models

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Abstract

The transport of oil can be modeled either by solving the advection-diffusion equation on the nodes of a grid (Eulerian models), or by tracking particles which represents individual portions of the spill (Lagrangian models). Random walk (RW) models, which solve non-linear Langevin equation, belong to the later category. For the simplest case 2D horizontal RW models, initial conditions including the number of particles and time interval need to be specified. For RW spill models involving the vertical direction, oil particle size distribution must also be specified, since oil buoyancy influences oil spill movement and spreading. In this paper a random walk model was employed to study the influence of oil particle size distribution on horizontal spreading by a vertical shearing current.

1 Introduction

3D lagrangian modeling has been applied to simulate oil fate in the sea mostly using the approximation that considers several oil spillets, whose radious expression is given by different approximations [12]. Processes such as mechanical dispersion for breaking waves will introduce oil in the water column as particles of different sizes. These particles can resurface forming new spillets or being put back into the original ones [1]. Oil can also be considered as a set of particles, having to input both size range and distribution used, in the case of including vertical dimension. In this case, though position and spreading are

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easier to simulate, will depend on oil particle size ranges and distribution used [6], [9].

This paper will try to quantify the above dependence of horizontal oil spreading to size range and distribution. To do so, a random walk model is developed to study oil spreading in a shear current, where horizontal mixing will be augmentado by the shear dispersion. In this process, the basic result is that an effective longitudinal dispersion is produced by the combination of a transverse gradient of velocity with transverse turbulent mixing. Therefore, in the case of a vertical shearing current, the vertical gradient of velocity combined with vertical turbulent mixing leads to and effective diffusion in the horizontal direction. In this latter case, for non-passive solute shear dispersion will depend not only on the flow characteristics but also on the terminal velocity [2], [5], [3], [13], [14].

2 The oil spill model

In the lagrangian model, currents and turbulence will move each particle. The random step due to turbulence is

$$x' = \sqrt{2K_x \Delta t} \tag{1}$$

where K_x is the turbulent coefficient in that direction. The random step will be multiplied by a random number (between -1 and 1) taken from a uniform distribution [16]. Vertical advection is given uniquely by terminal velocity of oil particles, since vertical component of current velocity is considered to be zero.

Oil particles will follow three different size distributions named as distribution A, that is formed by the same amount of oil for every oil particle size interval, distribution B, that follows the relationship $n_d \approx d^{-2.3}$, where d is the particle diameter and n_d is the number of particles in the interval $d \pm \Delta d / 2$ (See [4]) and distribution C which is characterized for having equal number of particles at each size interval (figure 1).

In all cases, the same size range going from $100 \mu m$ to $1100 \mu m$ has been used and distributed in five intervals. A total amount of 8000 particles for each size interval has been used, since test results shown that the best simulations are given when the larger number of particles is used [7].

Reflectant and semiabsorbent condition at boundaries, surface and bottom, will be used. In the case of reflectant, particle will be put back into the water column reflectant having a position equal to the trajectory. Semiabsorbent condition is about oil particle getting the surface will stay there unless the resultant of the movement due to terminal velocity and turbulent component, takes the particle back to the water column. This same condition is also applied to bottom.

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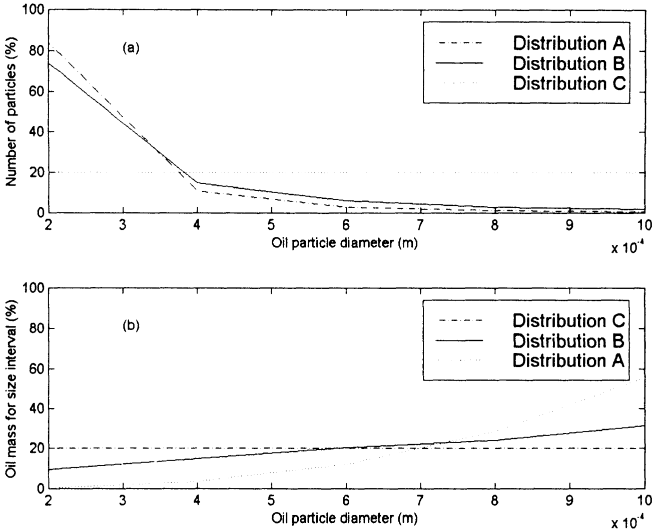

Figure 1: Number of particles and b) mass of oil vs. particle size.

3 Simulations

Spreading is studied by analyzing oil slick variance and its evolution with time. Horizontal variance is due to horizontal turbulent diffusion and shear spreading (see for example [2]).

$$\sigma_x = \sigma_{diffusion} + \sigma_{shear} \tag{2}$$

To study uniquely the oil spreading due to shear dispersion, simulations will be carried out in an infinitely wide channel of depth 10 m, without boundaries in longitudinal direction (x axis) and where horizontal turbulent diffusion has been assumed to be zero. Therefore, horizontal variance will be due uniquely to shear diffusion, $\sigma_x = \sigma_{shear}$.

In order to study shear diffusion, several velocity profiles will be set using the formulation,

$$u(z) = \frac{(q+1)}{q} z^{\frac{1}{q}} \tag{3}$$

where q is a constant that shows that velocity gradient diminishes for higher q values. Oil will be randomly placed from surface to bottom ($z = 0$ to $z = 10\ m$) at $x = 0$ and vertical turbulent diffusion will be given by a constant coefficient equals to $0.1\ m/s^2$.

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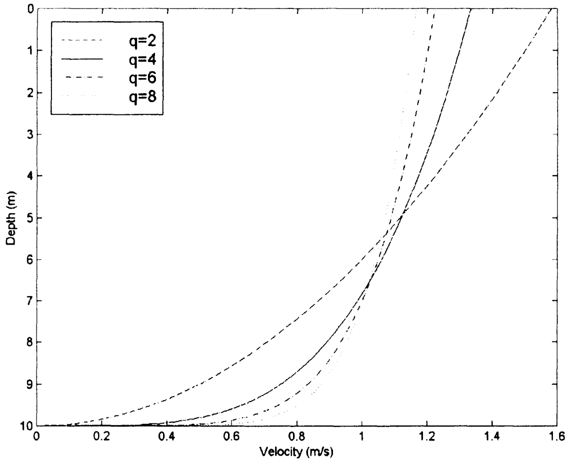

Figure 2: Velocity profiles for q=2,4,6,8.

Particle distributions are only considered in the x-direction (longitudinal dispersion) and characterized by moments about the mean.

A longitudinal dispersion coefficient K_x is defined, analogous to the diffusion coefficient

$$K_x = \frac{1}{2}\frac{d\sigma_x^2}{dt} \tag{4}$$

This coefficient will tend to a constant equilibrium value for large times. For a steady current this efficient shear dispersion coefficient is defined as (see for example, [8] and [17])

$$K_x = c_d T_z \bar{u}^2 \tag{5}$$

where c_d is a coefficient that depends on the velocity profile in a complicated way ([3], [8], [17]) and T_z is the mixing time, defined as:

$$T_z = \frac{1}{2}\frac{H^2}{K_z} \tag{6}$$

where H is the depth and K_z is the turbulent diffusion coefficient.

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4 Results

Simulations considering oil slicks formed by particles of the same size will show dependence of oil spreading to particle size, resulting larger elongation or horizontal variance higher for smaller oil particles and higher velocity gradients. Since variance grows almost linearly with time after an initial period of time, horizontal shear dispersion coefficient, K_x can be calculated from simulations (figure 3).

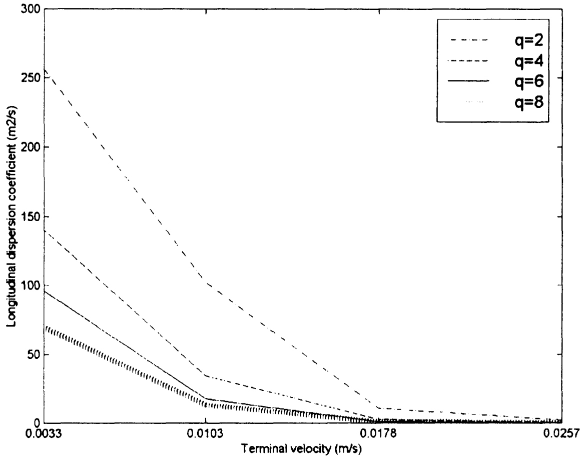

Figure 3: Horizontal dispersion coefficient calculated from simulations with semiabsorbent conditions at boundaries for size intervals and velocity profiles given.

To show the influence of buoyancy in shear dispersion, the efficient turbulent diffusion (eqn 4) can be rewritten as a function of oil particle sizes introducing the concept of maximum depth of oil particle penetration, that is the depth where oil downward flux by turbulent diffusion is balanced with upward flux due to oil buoyancy [10]

$$zi_{max} = \frac{K_z}{w_t} \tag{7}$$

where K_z is the vertical turbulent diffusion coefficient and w_t is the terminal velocity.

In that way, particles will be limited by its own intrusion depth more than depth channel. Substituting intrusion depth into the mixing time equation, $H = zi_{max}$ a new expression is obtained:

$$T_z = \frac{1}{2}\frac{zi^2{}_{max}}{K_z} = \frac{1}{2}\frac{K_z}{w_t^2} \tag{8}$$

being mixing time for smaller oil particles, which get higher intrusion depths. Therefore, the longitudinal dispersion coefficient can be rewritten for each particle size as

$$K_x = c_d \frac{K_z}{2w_t^2}\bar{u}^2 \tag{9}$$

To calculate the longitudinal dispersion coefficients as a function of terminal velocity, the coefficient c_d has been obtained from simulations made for passive particles using the same velocity profiles given and reflectant conditions at boundaries. Results are shown in figure 4.

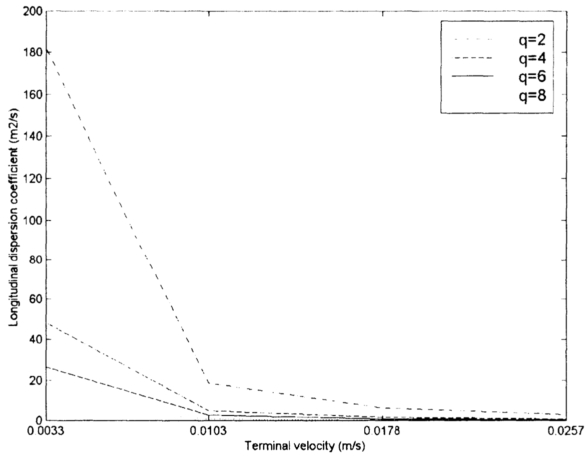

Figure 4: Horizontal dispersion coefficient calculated from equation for size interval and velocity given.

Curves are similar in shape than those obtained from simulations (figure 3): smaller particles and high velocity shear currents having a higher a longer elongation or spreading. However, they are different in magnitude, being higher those calculated from numerical simulations using a semiabsorbent condition at boundaries. In fact, they will be also higher than those turbulent dispersion coefficients calculated from simulations made using reflectant boundary conditions (figure 5).

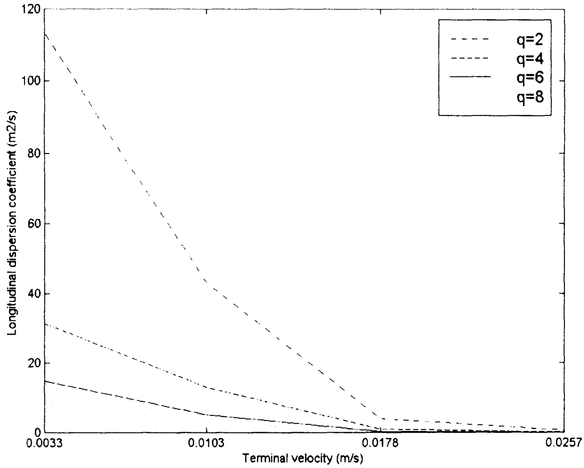

Figure 5: Horizontal dispersion coefficients calculated from simulations with reflectant conditions at boundaries, for size interval and velocity profile given.

The above explains results obtained from simulations when oil as formed by particles following size distributions described in section 3. So then, elongation will be higher for oil whose particles follow the size distribution A, which has a higher number of smaller particles, and for higher velocity gradients (figure 6). A mixing time for each particle size distribution can be defined:

$$T_d = \frac{1}{N}\sum_{i=1}^{p} n_i T_z^i \tag{10}$$

where n_i is the number of particles belonging to the size interval i and T_z^i is the corresponding mixing time (eqn 6), and N is the total number of particles. Results show that mixing time for distribution A will be the lower one of the three distributions used: $T_d(A) > T_d /(B) > T_d(C)$.

Introducing the mixing time in the equation for calculating dispersion coefficients, it is obtained

$$K_x^d = c_d T_d \bar{u}^2 \tag{11}$$

That will be lower than coefficients calculated from simulations as happened to those calculated for each size particle.

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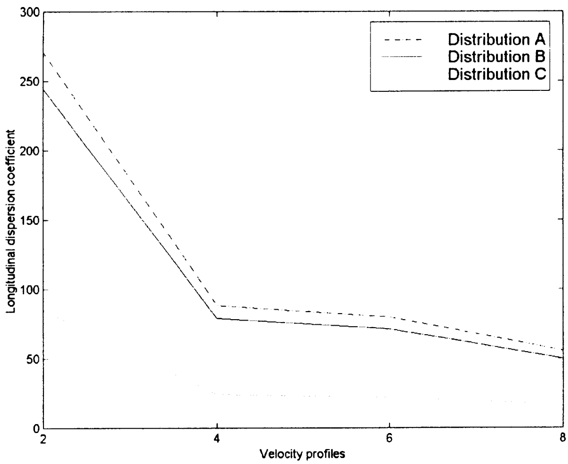

Figure 6: Horizontal dispersion coefficients calculated from simulations for oil size distribution and velocity profile given.

Results have been showing differences in oil slick elongation using different oil particles sizes and distributions as expected. Therefore, working with particles could bring nicer results in terms of representing areas covered by oil but could mislead calculus made in terms of oil put into the water column or into the atmosphere by evaporation.

It has also seen differences in using absorbent and reflectant conditions at boundaries. Semiabsorbent conditions seems to be a more natural way to represent oil particle movement since its upward component due to the terminal velocity will lessen the possibility in putting back the oil into the water column as it is made using reflectant conditions, where the net component will be a help in getting oil back into the water column, and not the turbulence as it should be.

It should be thought that intrusion depth of oil particles could limit oil mixing as it can be seen in results from using reflectant condition. However, being semiabsorbent conditions a more natural condition, results show a more complicated way of interacting terminal velocity and shear dispersion that shown in equations above. A more complete study will be then necessary.

It is also observed that differences between dispersion coefficients calculated from simulations using semiabsorbent and reflectant conditions at boundaries, diminishes as particle size grows being both coefficients the same for larger particles, indicating that turbulence are not influencing oil particle movement along with boundary conditions. On the other hand, it is seen that particles having an intrusion depth around the channel depth, have dispersion coefficients from simulations using reflectant conditions, are practically equal to those calculated from passive particles, indicating that buoyancy would not influence results, behaving like passive particles. The opposite happens to smaller particles whose terminal velocities are less important than turbulence.

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