Appendix J2

Delft3D – PART Oil Spill Model Previous Applications including stochastic modes:

- Environmental Impact Assessment for a new LNG terminal in Hong Kong

- NSW-MEP: Maritime and marine risk assessment of calamitous (oil) spills, on behalf of Noordzee Wind, July 2006. (deterministic and stochastic modes)

- F.M. Kleissen (2003) Modelling transport and fate of oil in the marine environment, WL|Delft Hydraulics R&D, January 2003 WL | Delft

- Hydraulics (2002) Oil spill modellig in Abu Dhabi, Report Z3122, on behalf of Abu Dhabi Water and Electrcity Authority.

6.5   Oil spill module

The Delft3D-PART Oil Spill model calculates the transport, spreading, evaporation and dispersion of an oil patch. Transport is either 2D or 3D. Oil can either be floating on the water surface, or it can be transported as a dispersed phase in the water column. Oil dispersion, also referred to as entrainment, is generated by breaking waves (due by wind) according to a formulation of Delvigne et al. (1986). Evaporation is based on a simple first order decay process.

Release of oil

Oil can be spilled as an instantaneous release or as a continuous release. The radius of an instantaneous release may follow from the standard input menu of the release, but may also be specified by the following formulation (Fay and Hoult, 1971):

$$R_0 = \frac{k_2^2}{k_1} \left[\frac{V_0^5 g \left[\frac{\rho_w - \rho_0}{\rho_w} \right]}{v_w^2} \right]^{1/12} \qquad [17]$$

with:

V_0	=	initial volume of the oil spill (m^3)
ρ_0	=	oil density (kg/m^3)
ρ_w	=	density of water (kg/m^3)
g	=	gravity constant
v_w	=	kinematic viscosity of water (10^{-6} m^2/s)
k_1, k_2	=	constants of Fay (1.14 and 1.45)

You should specify the oil density ρ_0 as input. The radius describes a patch after the so-called 'gravity inertial phase' which lasts in the order of 5 minutes for most spills. The thickness of the floating patch is then usually less than 1 mm. It is not recommended to use this description for continuous releases, but to specify the radius of the release according to the information that is available.

Wind induced advection of surface oil

The advection of surface floating oil is subject to wind effects. This is widely published in literature. For example, Labelle and Johnson (1993) carried out simulations of oil-spill trajectories for which each trajectory was constructed using vector addition of the current field and 3.5 percent of the instantaneous wind. A drift angle was computed as a function of wind speed (inversely related to wind speed). In a review by the Task Committee on Modelling of Oil Spills of the Water Resources Engineering Division of ASCE (1996), it has been reported that the majority of spill models use a simplified linear superposition technique to approximate spill motion. The currents induced by winds and waves are normally lumped together and represented by an empirically based drift factor and deflection angle dependent on the local wind speed and direction. Drift speeds typically vary

from 2.5-4.4% of the wind speed. The deflection angles vary between 0 and 25 degrees to the right/left of the wind direction (northern/southern hemisphere). The most detailed description of drift of oils is by Youssef and Spaulding (1993). Here also the drift speed is specified as typically between 2.5 and 4% of the wind speed with a mean value of 3.5%, and deflection angles between 0 and 25 degrees, with a mean of 15°. Yousseff and Spaulding deal in detail with the effects of waves on the transport.

A representation of the effect of wind in Delft3D-PART is implemented for oil. For a reasonable behaviour of surface floating oil under windy conditions, it is essential for the wind to affect the advection of the surface floating oil. The most important effect is drift as a percentage of the wind speed. The relationship that describes this effect is specified as

$$C_{wd} * (V_w - V_f)$$
[18]

with C_{wd} the wind drag, V_w the wind speed and V_f the current speed. This relationship is only applied to surface floating oil because the dispersed oil will be transported correctly by the currents of the hydrodynamic model and not be directly influenced by wind.

Another factor that affects the transport of the oil is governed by the aforementioned deflection angle, which is an angle between the wind direction and oil advection. This is essentially caused by the fact that the effects of the waves is under the influence of Coriolis and that the wave induced transport is at an angle of the wind. This angle is an empirical parameter. This parameter is chosen to be a constant and it is therefore assumed that the angle does not depend on the wind speed. The deflection angle will depend on the latitude. The deflection angle is included in the PART model as an additional parameter. The deflection angle would therefore essentially be a calibration parameter, depending on latitude and wind strength.

The drift of the surface oil is implemented in the 3-dimensional mode. When the flow is in a 2D mode, the advection by wind drift at the surface is included in the vertical profile that is derived in Delft3D-PART (see Section 6.4), thus an additional wind drift is not required.

Evaporation of oil

Evaporation of floating oil is implemented as a first order decay process. Decay can be specified by a decay constant as usual in the menu of process parameters (this can be done with a time-series), or by defining a fixed fraction of oil that decays each day.

It is known that oil contains fractions that do not evaporate. For example, Reed (1989) adopted in his model a mass transfer coefficient that uses the molecular weight of the volatile fraction of the oil spill.

In the oil module of PART, a volatile fraction has been introduced, albeit simplified compared with the implementation of Reed (1989). It is assumed that the volatile fraction F_{vol} evaporates as a first order process (i.e. exponential), and that the non-volatile fraction does not evaporate at all. This is achieved by the introduction of the following:

$$\frac{dF_v}{dt} = -\left(\frac{F_{vol} - F_v}{1 - F_v}\right)k \qquad [19]$$

Where F_v is the evaporated fraction and k the evaporation rate constant. The numerator in the equation should always be positive and if $F_{vol}-F_v < 0$ then the evaporation is set to zero.

The oil viscosity will change during the evaporation process. In the literature, descriptions of the dependency of the viscosity as a function of the evaporated fraction exist and is generally given as:

$$\eta = \eta_0 e^{(C_v F_v)} \qquad [20]$$

This equation is given for the dynamic viscosity. Assuming that the density is approximately constant throughout the simulation, then the same function can be used to describe the kinematic viscosity. Reed (1989) states that the value of C_v in his model is equal to 1 for gasoline, kerosene and light diesel fuel and 10 for other petroleum products. In the PART model, this is implemented by assuming that C=1 is used for light oils (kinematic viscosity less than 500 cSt) and C=10 for the heavy oils (viscosity greater than 500 cSt).

Dispersion (entrainment) of oil

Dispersion of floating oil, or entrainment of oil in water, is implemented as a zero order decay process, i.e. the entrainment rate is independent of the floating oil concentration. The dispersion rate of oil depends only on the wave energy that is dissipated by the patch, and the type of oil.

The dispersion rate Q (kg/m²/s) of oil is given (see Delvigne and Sweeny, 1988; NOAA, 1994; Delvigne and Hulsen, 1994) by:

$$Q = \int_{d\min}^{d\max} Q(d)dd$$

$$Q(d) = C^{"}D_e^{0.57}F_{wc}N(d)d^3$$

$$N(d) = N_0 d^{-2.3}$$

$$D_e = 0.0034\rho_w g H_0 / \sqrt{2}$$

$$H_0 = \frac{0.243U_w^2}{g} \qquad [21]$$

$$F_{wc} = \frac{f_w}{t_p}$$

$$t_p = 8.13U_w / g$$

$$f_w = \max(0.0; 0.032(U_w - 5.0))$$

with:

Q   =   dispersion rate (kg/m²/s)

Q(d)	=	dispersion rate per unit of diameter for droplets of diameter d ($kg/m^2/s$)
d	=	oil droplet diameter (m)
d_{min}	=	minimal oil droplet diameter (m)
d_{max}	=	maximal oil droplet diameter (m)
C''	=	oil constant (calibration parameter, depending on kind of oil)
N(d)	=	oil particle size distribution function
N_0	=	normalisation constant distribution function
D_e	=	dissipation of wave energy per unit surface area (J/m^2)
F_{wc}	=	number of waves that break per wave period (-)
t_p	=	peak wave period (s)
U_w	=	wind speed (m/s)
f_w	=	fraction of sea covered by white caps (-)

Here, white capping is formulated according to Holthuijsen and Herbers (1986) with the initial wind speed for white capping equal to 5 m/s. The minimal droplet size d_{min} can be taken zero as a good approximation. The crux is knowledge of parameters d_{max}, N_0 and the calibration constant C''.

According to NOAA (1994), after resurfacing of particles back into the oil slick, dmax can be taken equal to 70 microns. In this approximation, it is assumed that after each breaking wave a quasi-steady state distribution of droplets results, i.e. the resurfacing of particles back into the oil slick due to buoyancy goes fast compared with the dissipation of wave energy by the oil slick. Defining a new calibration constant C_0 the following expression results for Q:

$$Q = 5.08.10^{-8} C_0 S_{cov} D_e^{0.57} F_{wc} \qquad [22]$$

with

Q	=	dispersion rate ($kg/m^2/s$)
C_0	=	oil constant (calibration parameter)
S_{cov}	=	proportion of the sea surface covered by the oil in the relevant area
D_e	=	dissipation of wave energy per unit surface area (J/m^2)
F_{wc}	=	number of waves that break per wave period (-)

The calibration parameter C_0 depends on the kind of oil: oil with a high viscosity disperses hardly for a wind speed of 10 m/s whereas oil with a low viscosity disperses fast for such a wind speed.

An order of magnitude of C_0 follows from Delvigne and Hulsen (1994, Table 2 and Figure 4 of that publication). Since Delvigne and Hulsen do not take into account a steady state assumption their values can only be a first estimate for Delft3D-PART. Estimates of the dispersion constant C_0 are:

$C_0 \approx 2000$ for Ekofisk with standard oil viscosity v=8 cSt (at 20 °C)
$C_0 \approx 50$ for Heavy Fuel Oil with standard oil viscosity v=3000 cSt (at 20 °C)

Since viscosity is temperature dependent C_0 depends both on oil type and on temperature. Temperature dependence may be neglected for low viscous oils with v<100 cSt (Delvigne and Hulsen, 1994).

Delvigne and Hulsen (1994) have shown that there is a relationship between the C_0 and the oil viscosity. Since viscosity is an oil characteristic and used as input of the model, this relationship is included in the model. The relationship used in the modified PART(Oil) model is based on the data published by Delvigne and Hulsen (1994). The data was examined and a log-log plot revealed that this relationship can be specified by two equations (Figure 6-2). The equations used and the goodness of fit with the data are indicated in the figure.
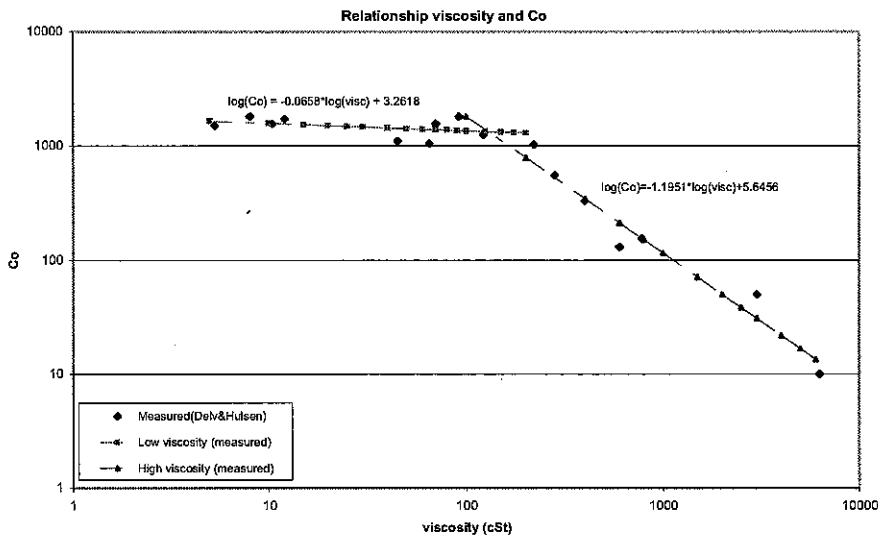

Figure 6-2   Relationship between viscosity and the dispersion parameter C_o (Delvigne and Hulsen (1994)

In order to calculate the entrainment flux, some representation of surface area for each surface oil particle is required. In the oil module an area for each particle is derived, based on the mass of surface oil associated with this particle (Kleissen, 2003). This is calculated using an assumed oil layer thickness. Validation with the oil budget model ADIOS has resulted in an optimal value of 0.00005m. This value of 0.05mm ($50\,\mu$ m) is also similar to the value of $70\,\mu$ m generally used to define the oil droplets that remain in suspension.

Emulsification

Water-in-oil (w/o) emulsions form a viscous cream, or floating, coherent semi-solid lumps, often called *chocolate mousse*. The process depends on oil composition. The formation of w/o emulsions reaches a maximum between 10 and 100 hours (Wheeler, 1978). The emulsification process itself is relatively rapid. It has been reported that emulsification takes place fully in the laboratory in 0.1-3 hours (Fingas et al, 1999).

Emulsification is virtually an irreversible process (Wheeler, 1978) and changes the liquid to a heavy, semi-solid material (Fingas et al., 1996) with a high viscosity. Viscosity can be as high as 4.10^6cP (Bos, 1980).

The emulsification process is implemented in PART following the algorithm presented by Mackay and others (Mackay et al., 1980, Zagorski and Mackay, 1982), in which the rate of water uptake $\tilde{F}_{wc}$ is given by:

$$\tilde{F}_{wc} = C_1 \left(U_w + 1\right)^2 \left(1 - \frac{F_{wc}}{C_2}\right)$$ [23]

with U_w the wind speed, F_{wc} the water content and C_1 and C_2 model parameters. C_1 is given as 2.10^{-6} for emulsifying oils and 0 for others, whilst C_2 is a constant controlling the maximum water content and is suggested to be 0.25 for home heating oil and 0.7 for crude and heavy fuel oil (Reed, 1989). In several other publications, however, the maximum water content for these heavy oils is said to reach values of 75-80% (for example, Huang et al.,1983). The switch of C_2 between 0.25 and 0.75 is made at a viscosity of 500cSt, whilst the value of C_1 (0 or 2.10^{-6}) is selected by the user and thus dependent on the emulsion formation tendency of the oil in question.

The main effect of emulsification (increase in the water content) in the model is the change in viscosity and is given as:

$$\frac{\mu}{\mu_0} = e^{\left(\frac{2.5 F_{wc}}{1.0 - C_3 F_{wc}}\right)}$$ [24]

As with the change of viscosity as a function of the evaporated fraction, it is assumed that the density does not change significantly, compared with the changes in viscosity and is assumed constant. Thus the implementation in the PART(Oil) model uses the kinematic viscosity in the aforementioned equation instead of the dynamic viscosity. The constant C_3 is suggested to be 0.65 (Reed, 1989).

Emulsification does not only affect viscosity (and therefore the dispersion (entrainment) process) but also evaporation. According to Fingas (1994), the effect of emulsification is that the viscosity rises two to three orders-of-magnitude, the spreading rate decreases by a similar value and evaporation nearly ceases.

In order to achieve a link between the emulsification and evaporation in PART(Oil), the water content of the emulsion is used to reduce the evaporation rate. In the implementation in PART, it is assumed that the evaporation ceases when the water content has reached its maximum. This maximum water content is oil type dependent. The evaporation rate is adapted when emulsification occurs by reducing the volatile fraction. This is implemented as follows:

$$F_{ew} = \frac{C_2 - F_{wc}}{C_2} F_{vol}$$ [25]

Where F_{vol} is the volatile fraction of the spilled oil and F_{ew} the adapted volatile fraction, replacing the volatile fraction F_{vol} in equation [19]. Thus, when the water content reaches its maximum C_2, the adapted volatile fraction reduces to zero and the evaporation halts.

The onset of emulsification can be delayed until evaporation causes the oil characteristics to reach the criteria for emulsification. This delay has been implemented in PART(Oil) by introducing a fraction evaporated oil at which emulsification is initiated (E_v).

Oil density

The density of the oil is affected by evaporation and emulsification. Density is also a function of temperature. In PART, the ADIOS formulation is used, without the dependency of the evaporated fraction and temperature. Hence, in PART, the density can only change when the oil emulsifies. The density is then a linear interpolation of the densities of water and oil, according to their relative content:

$$\rho_{em} = F_w \rho_w + (1 - F_w) \rho_{oil},$$

where

$$\rho_{em} = \text{Density emulsion (kg/m}^3\text{)}$$
$$F_w = \text{Water fraction}$$
$$\rho_{em} = \text{Water density (kg/m}^3\text{)}$$
$$\rho_{em} = \text{Oil density (kg/m}^3\text{)}$$

[26]

Sticking of oil

Oil may stick to land and cause damage to ecological sites. In order to simulate the process of oil sticking to land or to the bed of the water column, a sticking probability must be specified. A particle may come into contact with land due to wind effects or horizontal dispersion and it may come into contact with the bed due to vertical dispersion or settling. The particle sticks to the land or bed if a randomly chosen number between 0 and 1 is smaller than the sticking probability given.

Settling of oil particles

Dispersed oil may settle. However, this velocity is generally negative since oil particles are lighter than water. Most oil and refined products are less dense than water, which means they will float when initially spilled. Experience has shown that oil slicks that initially float will remain buoyant even after weathering. The two circumstances under which oil has been noted to sink occur when the oil is mixed with mineral sediment in the water column or when it is burned in-situ, creating a residue that may be of high density.

Weathering of oil

In addition to the processes mentioned earlier, other weathering processes may affect the presence of oil. Processes such as oxidation, bacteriological decay can in PART be simulated by means of a first order decay, for which a decay parameter can be specified.