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Predictive evaluation of surface spreading extent for the case of accidental spillage of oil on the ground

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Accidental spillage of oil onto the ground surface is a serious management problem. Tools to predict the surface spreading and to define the extent of the area contaminated by the spillage are useful to direct initial emergency actions. In this work, algorithms for the evaluation of surface spreading of oil are derived from existing literature resources. In particular, algorithms using analytical approaches based on the gravity current theory are presented. A simplified method for the estimation of the maximum extent of the liquid pool is also given. Surface oil flow on horizontal and inclined surfaces and on impermeable and porous media is considered. We discuss the appropriate selection of input parameters for different accident scenarios and present an application of the method to a real case.

1. Introduction

Surface spills of oil onto ground can occur during the transport, processing and storage of crude oil and petroleum products (collectively referred to here as oil). Crude oil and petroleum products contain hydrocarbon compounds, some of which are hazardous. Therefore, direct and/or indirect human exposure and harm to the environment can occur if adequate remedial measures are not taken in response to a terrestrial oil spill.

Quantitative methodologies to predict the environmental impact of terrestrial oil spills are required to correctly design and implement the necessary remedial measures, to develop contingency plans, and to estimate the exposure and risk associated with such spills. The extent of the surface of the spreading oil arising from a spillage is one of the principal variables that has to be estimated. This is important, in particular, for any planning of emergency actions required soon after an accident.

The problem of soil and groundwater contamination from oils has largely been studied from the point of view of restoration - in particular, the US-EPA (USA), the ASTM (USA) and APAT (I) have developed many tools for evaluation and support of decision making. However, in the case of restoration, evaluations are typically made in the medium or longer term after an accident. Alternatively, predictive assessment evaluations can be made before an accident occurs. For this situation, the problem is significantly different.

In the field of major risk assessment, and after the Seveso II and III directives, safety reports must also include the prediction and assessment of potential environmental damage resulting from accidents in which dangerous substances are spilled.
Therefore it is important to have in place easily applicable screening tools which support the decision making process aimed at specifying prevention and protection measures. In particular, it is necessary to characterize critical scenarios which require actions for preventive remedies (technical or organizational) and to define an emergency plan.

2. Surface oil spreading prediction

A spill of liquid might occur as a gradual release from a container onto the land, or by way of a catastrophic abrupt release of a large volume of liquid. Intuitively, one knows that the extent of spread of a liquid pool depends on how rapidly it is released. This is especially true for a spill on a porous surface with either a limited or unlimited capacity to absorb the liquid. How far a spill spreads is greatly controlled by infiltration, as well as by the overland flow dynamics. Therefore, the area which is impacted depends generally on the quantity spilled and is limited by any infiltration.
Published studies of rates of surface spreading of spilled oil have largely relied on either analytical or numerical approaches.
For this work, where simplicity of formulation is important, there have been relevant studies in which the surface liquid flow is considered as a special case of gravity current that occurs when a fluid of given density (in this case oil) flows into another fluid of different density (air), and the motion is driven by gravitational forces.
Gravity currents are influenced by three main forces namely, inertial, viscous and gravity. In the early stages, immediately after a release, the dominant forces are gravity and inertia, while at later stages, viscous forces become more important than inertia and the flow is governed by the balance between gravity and viscous forces. The initial stage is very short and for practical purposes can be neglected.
For the gravity-viscous regime, Huppert (1982) developed analytical similarity solutions for gravity current propagation on horizontal and inclined surfaces generated by a line source. Acton et al. (2001) and Spannuth et al. (2006) give similarity solutions respectively for two dimensional and point source viscous gravity currents flowing over a deep porous medium.
Recently, other researchers (Keller et al. 2005) of the PNNL (Pacific Northwest National Laboratory) have studied the problem of spillage of oil onto land with the aim to develop a predictive software tool. However, their code is not yet available.
In a joint research project between the University of Udine (I) and the Queen's University of Belfast (UK) the authors have addressed the need for a predictive computer program.
In this work, a method to make rapid estimates of pool dimensions is proposed which is based on the analytical formulations published by Huppert (1982), Acton et al. (2001) and Spannuth et al. (2006). Here we present only the case of spills on horizontal surfaces.

2.1 Spillages onto flat ground

Huppert (1982) presented a similarity solution for the equations governing the viscous gravity currents for estimating the extent of pool spreading on horizontal impermeable surfaces. In his formulation he supposes that the volume of heavy fluid increases with time like t^{α}, where α is a constant. The volume of liquid spilled V(t) is defined as qt^{α} (therefore, for example, if $\alpha = 0$ there is a constant-volume current or an instantaneous release and if $\alpha = 1$ there is a flow with a constant flux). The equation proposed by Huppert (2006) – here reported with a different notation than in his original work – is:

$$ext_P = \zeta_N(\alpha, n)\left(\frac{g}{3\nu}q^3\right)^{1/(5+3n)} t^{(3\alpha+1)/(5+3n)} \qquad (1)$$

where
$n = 0$ for a line source (Cartesian coordinates)
$n = 1$ for a point source (radial coordinates)
ext_P is the spatial coordinate extension of pool (for n=0 ext_P=x and for n=1 ext_P=r) [L]
g is the gravitational acceleration [L/T^2]
ν is the kinematic viscosity of liquid [L^2/T]
q is the flow rate of spillage. It has units of [L^3/T] for a release from a point source and [L^3/LT] for a release from a line source.
t is time [T]
$\zeta_N(\alpha, n)$ is a coefficent defined by Huppert with values given in table 1.

Table 1. Values of the coefficients $\zeta_N(\alpha, n)$ in Equation (1)

Type of release	n = 0	n = 1
instantaneous release $\alpha = 0$	1.411	0.894
flow rate constant $\alpha = 1$	1.01	0.715
flow rate increase linearly $\alpha = 2$	0.85	0.623

For a two-dimensional flow, Acton et al. (2001) observed that when $\alpha < 3$, in particular for a constant volume, the front of the gravity current comes to rest in finite time as the effects of fluid drainage into the underlying porous medium become dominant. In this case the runout length is independent of the coefficient of viscosity of the current, which sets the time scale of the motion. Therefore, when $\alpha < 3$ the dynamics of the gravity current are dominated by spreading only at early times and the solutions are asymptotic to the non-draining similarity solutions calculated by Huppert (Eq. 1) and define the time of transition. The transition between the early spreading behaviour and the late draining behaviour occurs at the time t_T defined as a function of the permeability k of the porous medium. Analogous considerations have been made in Spannuth et al. (2006) for the case of spillage from a point source. Rearranging the formulations, the time t_T depending on the type of spillage and the flow rate, can be calculated using only the following equation:

$$t_T \approx 0.697^n \left[3^{1-n} \left(\frac{6}{\pi} \right)^n \frac{q^{2-n} \nu^{6-n}}{g^{6-n} k^{5-n}} \right]^{\frac{1}{(6-n)-(2-n)\alpha}} \quad \text{for } \alpha < 3 \qquad (2)$$

2.2 Simplified method to define the extent of an oil pool on porous ground

Using the formulations presented above, if $\alpha < 3$ a rapid way to estimate the maximum extent of the pool on porous ($k \neq 0$) flat ground can be obtained using:

$$ext_P = \zeta_N(\alpha, n)\left(\frac{g}{3\nu} q^3\right)^{1/(5+3n)} t_w^{(3\alpha+1)/(5+3n)} \qquad (3)$$

where, if the spillage happens as an instantaneous release (α=0), $t_w = t_T(\alpha=0)$.
If, instead, the spillage happens with a flow rate with 0<α<3 for a duration of spillage t_{spill} there are then two cases:
if $t_{spill} \geq t_T(0<\alpha<3)$ then in equation (3) $t_w = t_T(0<\alpha<3)$
if $t_{spill} < t_T(0<\alpha<3)$ it is necessary to consider the change of regime at time t_{spill} (before t_{spill} $\alpha \neq 0$, after t_{spill} α=0) and to impose the continuity condition for the velocity of spreading in the switch between the two regimes (the first derivatives with respect to time in Equation (3) must be equal in the two regimes).
In case of spillage onto impermeable surfaces (k = 0) the estimation of pool extent at time t is possible using Equation (1) directly.
In the case of spillage onto porous ground it is necessary to consider multiphase flow and the soil relative permeability for oil. In Equation (3) the permeability of the soil for oil has to be included and is calculated (considering a two-phase system of oil and water) as:

$$k = k_{roil}(S_w) k_i \qquad (4)$$

where
$k_{roil}(S_w)$ is the relative permeability of oil – varying from 0 to 1 (Fetter, 1999)
S_w is water saturation ratio
k_i is the intrinsic permeability of soil

For our predictive application, when S_w is minimum - that is when S_w tends to S_{wi} (irreducible saturation of water) - in first approximation we can use $k_{roil}(Sw) \approx 0.9$ to 1.0. This is the case in which an oil spillage occurs in a region where there has been no rainfall (or other sources of soil moisture). In other words when the soil can be considered as "practically-dry".
Alternatively, when $S_w \rightarrow 1$ (water saturated soil) $k \rightarrow 0$ and the soil surface is almost impermeable. Therefore Equation (1) can be used directly to estimate the pool extent

with time. This is the case when an oil spillage occurs after heavy rainfall that has completely saturated the soil.

Intermediate conditions of water saturation can be considered using values of $k_{roil}(S_w)$ in Equation (4) within the range 0 to 1.

In case of spillage of oil, Equations (1) and (2) must use the oil characteristics - that is $\nu = \nu_{oil}$ and k is calculated using Equation (4).

3. Test on real case of accidental oil spillage onto ground

Figure 1 shows the surface area around a tank truck spill of jet fuel (JP-8) onto a roadway which occurred in the summer of 2004 in Idaho State (US).

Figure 1. Spillage of oil onto roadway in Idaho State (US) (from Keller et al, 2005)

This accident was studied by researchers of the PNNL (Keller et al, 2005). Using the picture and other information, they determined that the total spill area was about 250.8 m^2 (road plus roadside), and the area of the wetted soil above the road was about 153.3 m^2. Given the site is along hills close to a river and with desert-like plants, it is believed the soil is sandy. They assumed a soil porosity of 0.3 and a permeability of typical sands (1×10^{-6} cm^2). They also considered the ground where the spillage happened as flat. A spillage of 7570 litres of JP8 (2000 US gal) was estimated. It was observed that the full spill volume would saturate the soil to a depth of 16.5 cm. A spillage duration of 123 s was estimated. The viscosity of JP8 jet fuel is about twice that of water, or 2.05 cp, and has a density of 0.84 kg/l. Therefore, JP8 is will have a lower conductivity than water, with JP8's saturated liquid conductivity in this sand being about 0.04 cm/s. These data were used by PNNL researchers to test their software (which resolves the equation of gravity current spreading using the finite difference method).

We have used the same data to test our simplified model for the estimation of the main pool spillage characteristics. We have compared the results with the data observed by PNNL and have presented the percentage deviation. Other cases with different hypotheses about the water saturation conditions of soil are also given. The results are shown in the Table 2.

Table 2. Results of simplified method applied to the Idaho State accident

Parameters of oil spillage	Observed by PNNL	Estimations using simplified model			
		test comparison		other cases	
		$k_{roil}(S_w)=1{,}0$	Dev. %	$k_{roil}(S_w)=0{,}9$	$k_{roil}(S_w)=0{,}3$
max extent* (m)	6.98	6.98	-0.09	7.36	12.75
pool area (m^2)	153.3	153.16	0.03	170.18	510.55
penetration (cm)	16.5	16.48	-0.14	14.83	4.94

(*) equivalent radius of the pool

4. Conclusions

The test shows that the simplified model proposed in this work can be used to estimate pool characteristics with a very good degree of agreement with the values observed by PNNL. The deviation of our results from observed data lie within about +/- 0.2%. If an accident occurs in wetter soil conditions, the pool dimensions increase significantly while the depth of penetration into the soil is reduced. The evaluations can be made using algebric formulas in spreadsheets without resorting to numerical calculation methods. The analytical equations given here can be used, in the case of accidental oil spillage onto flat porous ground, as a useful tool to make fast and reasonably accurate predictive evalutations.

5. References

Acton, J. M., H. E. Huppert, and M. G. Worster., 2001 -Two-dimensional viscous gravity currents flowing over a deep porous medium - Journal of Fluid Mechanics 440, 359-380

Fetter C.W., 1999 – Contaminant Hydrogeology – 2nd Edition, Pretince Hall

Huppert, H.E., 1982. - The propagation of two-dimensional and axisymmetric viscous gravity currents over a rigid surface - Journal of Fluid Mechanics 121, 43– 58. Cambridge University Press.

Huppert, H.E., 2006 - Gravity currents: a personal perspective - Journal of Fluid Mechanics 554, 299–322. Cambridge University Press.

Keller J.M., Simmons C.S., 2005– The influence of selected liquid and soil properties on the propagation of spills over flat permeable surface - Rep. PNNL-15058, Pacific Northwest National Laboratory

Spannuth M., Neufeld J, Wett-Laufer J.S. Grae Woster M., 2006 - Axisymmetric viscous gravity currents flowing over a deep porous medium - Presented at the DFD06 Meeting of the American Physical Society- Tampa Bay, Florida – November 19-21, 2006.