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Diffusion simulation and safety assessment of oil leaked in the ground

Bo Liang, Hui-qing Lan*, Nan Lin

Key Laboratory of Vehicle Advanced Manufacturing, Measuring and Control Technology (Ministry of Education), Beijing Jiaotong University, Beijing, 100044, China

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ABSTRACT

Oil leaked in the ground causes pollution of land and groundwater, and even leads to an explosion. Therefore, it is significant to make a research on safety assessment of diffusion of oil in the ground after oil leakage accident happened. Taken a perforation-caused leakage accident of oil in buried piping in China as an example, the computational fluid dynamics method of multiphase flow in porous media was used to determine the distribution of leaked oil in the ground in this paper. Then, an onsite drilling test was carried put and it's found that the simulation of distribution of leaked oil agreed with the test result. Finally, on the base of the simulation results, fuzzy synthetic evaluation method was carried out and hazardous areas of oil leaked in the ground were put forward.

1. Introduction

With the economic development, the continuous urbanization and industrialization are the inevitable trends. During the construction of urbanization and industrialization, a lot of piping for oil, gas transmission are laid widely in the ground. However, due to the corrosion, installation, third party damage and other damages of piping, oil leakage accidents in buried piping have happened now and then. Oil leakage has caused serious pollution to the environment and groundwater, therefore the safety problems of buried oil piping has aroused more and more public attention.

Liu et al. (2015) studied a new leak detection and location method for oil and natural gas pipelines based on acoustic waves, and then the propagation model was established and modified, which could detected and located the leakages in oil and natural gas pipelines. But there were still many problems unsolved, for example how the oil diffused especially the leaked oil in buried piping and environment safety assessment for oil diffusion areas. Agaoglu et al. (2015) wrote a review of the state-of-the-art on interphase mass transfer between immiscible fluids in porous media with focus on the factors that have significant influence on this process. Huyakorn et al. (1994) established a three-dimensional numerical model of three-phase flow to study the movement of non-aqueous phase liquids (NAPLS) through porous and fractured media, which is a remediation program designed for the heterogeneous system of leakage of light or dense NAPL in the ground. Panday et al. (1994) used five simulation examples to demonstrate the three-dimensional multiphase flow model proposed by Huyakorn. Therrien and Sudicky (1996) used finite element technique to simulate the solute transport in soil. Huber and Helming (2000) used the discretization of finite volume method to study a multiphase flow in porous media, and described the influences of texture interfaces in different geological structures on the flow process. Mikyska et al. (2009) found that interaction between the gravitational force and the capillary force on the interfaces of soil with different capillarity properties determines the fate of NAPLs in the subsurface. A multiphase flow code has been applied to study the NAPL behavior on the inclined interfaces. Kashul et al. (2015) used an optical imaging of 3D multiphase liquid distribution method, and the natural aquifer was simulated by a transparent soil substitution with similar macroscopic behavior of natural sand and injected with a green-dyed sucrose solution to simulate dense NAPL contamination. Six sandbox experiments were performed to explore the individual effect of flow velocity, and the combined effects of flow velocity and layered lenses on a DNAPL migration in porous media (Zheng et al., 2015). El-Amin et al. (2015) developed a mathematical model and numerical simulation to describe the imbibition of nanoparticles–water suspension into two-phase flow in a porous medium. Agaoglu et al. (2016) used a two-dimensional pore network model to study the influence of sub-grid scale properties on interphase mass transfer. Vasudevan et al. (2016) studied the applicability of numerical model for simulating various hydro-geological scenarios considering non-uniform source distribution at a petroleum contaminated site. The flow of NAPL in porous media involves fluid-mechanical study of gravity currents. Gravity currents were driven by horizontal differences in buoyancy and play a central role in fluid mechanics. Huppert (2006a,b) reviews some of the material that has built on gravity currents and fluid flows along a rigid horizontal surface below fluid of lesser density is analysed using a

* Corresponding author.
E-mail address: hqlan@bjtu.edu.cn (H.-q. Lan).

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lubrication-theory approximation. Federico et al. (2012a,b) established a diffusion model of non-Newtonian power-law gravity currents in porous media, analysed horizontal spreading of power-law gravity currents in a porous layer and the self similar solutions of radial flow and different injection rate were derived, the result showed that functions of injection rate and flow behavior index. Due to the stratification of porous media, Federico et al. (2014) also established a gravity flow model of power law fluid in a stratified porous media, analysed the limits of the model and confirmed it through laboratory experiments.

On the other hand, uncertainty plagues every effort to model subsurface processes and every decision made on the basis of such models. Chen et al. (2000) proposed an integrated simulation and risk-assessment approach, which includes a multi-phase and multi-component modeling system for simulating flow and transport of petroleum constituents in the subsurface and a fuzzy relation analysis model for assessing environmental risks under uncertainty. Given this pervasive uncertainty, Tartakovsky (2013) wrote a review of hydrogeologic applications of recent advances in uncertainty quantification, probabilistic risk assessment, and decision-making under uncertainty. Neves et al. (2015) used a new framework to test the Lebanon oil spill, employing ensemble oil spill modeling to quantify the risks and uncertainties due to unknown spill characteristics. Valdor et al. (2016) resented a tool that can assess the risk of oil spilled in near-shore areas by Geographical Information System. Also, the safety assessment of oil spill has been reported by fault tree analyses and other systems-based approaches. Aljaroudi et al. (2015) an integrated risk-based assessment scheme to predict the failure and the failure consequences of offshore crude oil pipelines, the assessment provided an estimate of the risk in monetary value and determined whether the estimated risk exceeded a predefined target risk.

The above studies were carried out to study diffusion and migration of NAPL under different conditions, but the diffusion and migration process of leaked oil in buried piping were relatively little, and no onsite test has been performed. Therefore, based on the mathematical model and physical model of multiphase flow in porous media, a numerical simulation of computational fluid dynamics (CFD) was used in this paper to analyze leakage process and diffusion range of oil in buried piping. And the risk assessment of hazardous area was carried out by using fuzzy synthetic evaluation model, the results could provide some supports for determination of the safety zone and formulation of emergency response plan for oil leakage accidents.

2. Model

The geological layer is a complex stratum structure, including concrete, sand, gravel and so on. Moreover, there are water and air in pores of geological layer, which causes percolation of leaked oil in geological layer and becomes a complex multiphase flow problem. It is assumed that concrete is so dense that oil and water can't seep through; oil and water can't be mixed; there is the same porosity for the same depth layer in the ground. A simplified soil model was chosen, and linear porosity was used to simulate the heterogeneous porous media along the different depth layers in the paper.

2.1. Multiphase seepage mathematical model

The mathematical model of three-phase flow in porous media was used to simulate the diffusion of leaked oil in the ground, and three laws regarding the conservation for flow must be obeyed, i.e. mass conservation equation, Eq. (1); momentum conservation equation, Eqs. (2)–(5); and energy conservation equation, Eqs. (6) and (7).

Mass conservation equation:

$$\frac{\partial \rho_i}{\partial t} + \nabla(\rho_i v) = 0 \tag{1}$$

Momentum conservation equation:

$$\frac{\partial(\rho_i u)}{\partial t} + \nabla(\rho_i u v) = \nabla(\mu \nabla u) - \frac{\partial p}{\partial x} + \left(\frac{\mu}{a}u + c_2\frac{1}{2}\rho_i|u|u\right) \tag{2}$$

$$\frac{\partial(\rho_i v)}{\partial t} + \nabla(\rho_i u v) = \nabla(\mu \nabla v) - \frac{\partial p}{\partial y} + \left(\frac{\mu}{a}v + c_2\frac{1}{2}\rho_i|v|v\right) \tag{3}$$

$$a = D_p^2\varepsilon^3/[150(1-\varepsilon)^2] \tag{4}$$

$$c_2 = 3.5(1-\varepsilon)/(D_p\varepsilon^3) \tag{5}$$

Energy conservation equation:

$$\frac{\partial}{\partial t}\{\varnothing\rho_i E_i + (1-\varnothing)\rho_s E_s + \nabla[\vec{v}(\rho_i E_i + p)]\} = \nabla\left[k_{eff}\nabla T - \left(\sum_j h_j J_j\right) + (\vec{\tau}\vec{v})\right] + S_i^h \tag{6}$$

$$k_{eff} = \varphi k_i + (1-\varphi)k_s \tag{7}$$

Besides, the equation related to the material properties needs to be used to deal with the parameters of oil diffusion: pressure (p), velocity (v), saturation (S), and temperature (T). All of them are all functions of time (t) and coordinates (x, y, z), as shown in Eq. (8).

$$p = p(x,y,z,t)\ ,\ v = v(x,y,z,t)\ ,\ S = S(x,y,z,t)\ ,\ T = T(x,y,z,t) \tag{8}$$

2.2. Physical model

In this paper, an oil leakage accident buried piping in China was taken as an example. The basic information regarding the oil piping was shown in Table 1. According to excavation survey on the leakage point, it was found that the location of leakage was at the upper right 45° from the center of the pipe. The pipe diameter was 0.25 m, and the aperture of leakage was about 20 mm, so it was a small-hole leakage. A corresponding simulation model of leakage oil in the buried piping was built (Fig. 1 (a)), and the soil range of leakage diffusion was a rectangular area of 100 m × 7.6 m. The pipe was located at 3 m in the ground (Fig. 1 (b)). Boundary conditions for the model were set as in Table 2.

3. Leakage analysis

3.1. Analysis of initial state of leakage

In fact, the initial leakage was an instantaneous process, and it was similar to a jet phenomenon when the oil was ejected from the orifice because of the pressure difference between the inside and outside of leaked orifice. Generally, the jet was a kind of flow with turbulent diffusion. The oil was emitted from the orifice and transferred to the surrounding soil by changes of momentum, heat and mass. There was a submerge jet, which was a liquid jet flowing into the same media. The submerge jet would exchange momentum and mass with the ambient static media, and the entrained soil would flow along with the jet. Then a vortex happened, which would make sand wear with the orifice of

Table 1
Basic data of the oil piping in China.

Specifications (mm)	Pipe material	Pressure	Oil	Depth of burial (m)	Length (m)	Protective coating type
φ250	API·5L·X 42	1.6 MPa	3# kerosene	3	1200	Primer + Glass cloth + Finish