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NUMERICAL STUDY ON THE DIFFUSION CHARACTERISTICS OF OIL LEAKAGE FROM SUBMARINE BURIED PIPELINES

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Abstract. *Submarine pipelines may be ruptured by the erosion of produced fluid within the pipeline, seawater outside the pipeline, also the influence of external forces, which may cause oil-gas leakage and seriously pollute the marine environment. To accurately predict the transport and diffusion of oil leakage from subsea pipelines, this paper used the realizable k-ε turbulence model combined with Volume of Fluid (VOF) method and porous medium model to calculate the unsteady flow of crude oil leakage from the submarine buried oil pipeline, and analyzes the effect of soil porosity, oil leakage rate, and pipeline burial depth on the crude oil diffusion trajectory, diffusion range and the interaction between oil, water and soil. Meanwhile, the reliability of the numerical model was verified by comparison with available experimental data. The results showed that the soil porosity directly affects the diffusion of crude oil, and the higher the soil porosity, the wider the lateral diffusion range in the soil region. Therefore, lower soil porosity will increase the diffusion distance of crude oil in the horizontal direction, the vertical resistance of crude oil in the soil is much greater than the horizontal resistance. Hence, the faster the initial leakage rate of crude oil, the greater the resistance of the porous medium of seabed soil, and the faster the diffusion rate decreases near the leakage port. Then it gradually diffused to the interface between soil and seawater and separated into countless droplets or oil clusters of different sizes. The pressure at the pipeline leakage site and the diffusion range of crude oil in the sea mud enhance with the increase of the leakage velocity. In addition, a fitting formula for estimating the horizontal diffusion distance of crude oil in the soil, the time required to reach the seabed and the diffusion range in seawater under specific conditions has also been formed. The research results can provide theoretical support for accurately predicting the leakage range of submarine oil and gas pipelines and formulating emergency rescue plans.*

Keywords: *Submarine buried pipeline; oil leakage; fluid dynamics; diffusion law; jet flow; numerical simulation.*

1. INTRODUCTION

Submarine oil pipelines are prone to perforation failure and oil leakage due to erosion, corrosion, and aging during operation (Wang *et al.*, 2013). Crude oil spilled at sea will not only cause massive resource losses but also causes an incalculable pollution to the marine environment (Wei, 2017). Given the serious consequences caused by the leakage of submarine oil buried pipelines, it is necessary to study the leakage and diffusion pattern of submarine oil pipelines, and also determine the temporal and spatial distribution of oil and seawater phases, which is of great significance for emergency decisions and reduce accident risks.

The research on oil spills of underwater pipelines is mainly carried out in two stages: the migration and diffusion process of crude oil in seawater after spilling from the leak point, and the process of drifting in the sea after the spilled oil reaches the sea surface. However, there are relatively few studies on the migration and diffusion process. Yapa and Li (1997) and Zheng and Yapa (1998) proposed a three-dimensional complex numerical model based on Lagrangian integration to simulate underwater leaking floating jets. The model considers shear entrainment and forced entrainment, the model equation includes both the diffusion and dissolution term of the oil spilled into the surrounding water environment, and the studies above mostly build oil spill models for shallow water basins. Johansen (2000) and Zheng *et al.* (2003) established the DeepBlow model and CDOG model for deepwater oil spills, which can describe the separation process of deepwater oil and gas spills also the migration and diffusion process of oil spills. De Padova *et al.* (2023) is based on two-dimensional (2D) smoothed particle hydrodynamics (SPH) method to simulate the diffusion process of submarine oil spill in water, which is different from VOF simulation in finite volume method performed under rigid cover free surface conditions, SPH simulations also reproduce free surface perturbations due to interactions with jets, an inherent simplicity when dealing with different phases involving density differences.

In recent years, Wang (2008) considered the oil spill emulsification based on Yapa and Zheng's Lagrangian integral model, simulated the oil spill trajectories under different Froude numbers, layer numbers, and oil spill velocity ratios of submarine pipelines. Based on the Lagrange integral method and the Lagrange particle tracking method, Chen *et al.* (2015) studied the distribution of oil droplets in the water during the eruption stage, the buoyancy plume stage, as well as the convective diffusion stage. Although, Zhu *et al.* (2017) uses the Reynolds-Average-Navier-Stokes (RANS) equation, the realizable k-ε turbulence model and the volume of fluid (VOF) model to simulate multiphase flow. According to the author, the diffusion range is wider; secondly, leakage parameters such as leakage size and leakage rate affect the floating time and diffusion concentration, while the marine environment affects horizontal migration and surface drift; in addition, the oil density has a significant impact on underwater diffusion, but has a limited impact on water surface drift. Zhu also found that viscous force is not the main force of oil spill in dispersed droplets. On the other hand, Yang *et al.* (2018) developed a numerical model of underwater oil spill based on Lagrangian integral method (PDM) and Lagrangian particle method (ADM) to solve the situation including unsteady water flow, oil diffusion and dissolution, and density stratification based on the oil spill diffusion process. The seabed leakage time, lateral migration distance and also surface diffusion range of crude oil are estimated when the crude oil reaches the sea surface, and experimental data are introduced to verify the validity of CFD prediction. At last, Li *et al.* (2023) conducted numerical research on the multi-point leakage diffusion of submarine pipelines, and established a regression model for rapid prediction of oil diffusion through fitting; The change of temperature has little effect on the spread distance of crude oil plume. Based on the above studies, there is little influence of the burial depth of submarine pipelines on the law of oil spill diffusion, and none of them considers the deviation between the flow around the pipeline and the burial depth of submarine pipelines and the actual existence. For this reason, it is difficult to provide better support for the disposal of oil spill accidents.

This paper uses the Realizable k-ε turbulence model combined with VOF method and porous medium model to establish an oil spill behavior model for submarine oil pipelines based on previous research work. The unsteady simulation of external flow field under the shallow water area was carried out to study the influence of initial oil spill velocity, pipeline burial depth and soil porosity on oil spill process. By analyzing the leakage diffusion process of submarine buried oil pipelines and the influence of horizontal diffusion distance and also vertical migration height, some guidance for oil spill emergency response is provided.

2. METHODOLOGY

2.1 Governing Equations

The Reynolds-averaged Navier-Stokes equations for fluid motion are as follows:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \tag{1}$$

$$\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u}\mathbf{u}) = -\nabla p + \nabla \cdot [(\mu \; + \mu_t) \times \nabla \mathbf{u}] + \frac{1}{3}\nabla \cdot [(\mu + \mu_t) \nabla \mathbf{u}] \tag{2}$$

where, ρ is the density of the mixture, kg/m^3; μ is the dynamic viscosity of the mixture, Pa·s; μ_t represents the turbulence dynamic viscosity, Pa·s; $\mathbf{u}$ denotes the velocity vector, m/s; p is the pressure, Pa; t is the time, s.

The Navier–Stokes equations are closed by the Realizable k-ε turbulence model. The mixed phase density can be expressed as:

$$\rho = \rho_o \alpha_o + \rho_w (1 - \alpha_o), \tag{3}$$

where, ρ_w is the density of seawater, kg/m^3; ρ_o is the density of crude oil, kg/m^3; α_o is the volume fraction of crude oil.

2.2 Turbulence Model

In this paper, the Realizable k-ε turbulence model was adopted to close the oil spill control equation (Van Maele and Merci, 2006). This model constrained the magnitude of the normal stresses and improved the probable problem of the negative normal stresses at large time-averaged strain rate in standard k-ε turbulence model, making the flow characteristics more consistent with the physics of turbulence. The transporting equations of the Realizable k-ε turbulence model (Shih *et al.*, 1995) are as follows:

$$\frac{\partial}{\partial t}(\rho k) + \nabla \cdot (\rho k \mathbf{u}) = \nabla \cdot [(\mu + \frac{\mu_t}{\sigma_k})\nabla k] + P_k + P_b - \rho \varepsilon, \tag{4}$$

$$\frac{\partial}{\partial t}(\rho\varepsilon) + \nabla \cdot (\rho\varepsilon\mathbf{u}) = \nabla \cdot [(\mu + \frac{\mu_t}{\sigma_\varepsilon})\nabla\varepsilon] + \rho C_1 S_\varepsilon - \rho C_2 \frac{\varepsilon^2}{k + \sqrt{\nu\varepsilon}} + C_{1\varepsilon}\frac{\varepsilon}{k}C_{3\varepsilon}P_b + S_\varepsilon, \tag{5}$$

where, $C_{1\varepsilon}$, $C_{2\varepsilon}$, $C_{3\varepsilon}$, σ_k, and σ_ε are model constant; $C_{1\varepsilon}$=1.44, $C_{2\varepsilon}$=1.92, $C_{3\varepsilon}$=0.9, σ_k=1.0 and σ_ε=1.2. k and ε are turbulent kinetic energy and turbulent dissipation rate, P_b denotes the turbulent kinetic energy due to the influence of buoyancy, and P_k is the turbulent kinetic energy generated by the viscous forces.

$$C_1 = \max\left[0.43, \frac{\eta}{\eta + 5}\right], \text{ where } \eta = S\frac{k}{\varepsilon},\ S = \sqrt{2S_{ij} \cdot S_{ij}}, \tag{6}$$

The turbulent viscosity μ_t can be obtained from the turbulent kinetic energy k and dissipation rate ε:

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon}, \tag{7}$$

where C_μ is the viscosity coefficient, usually equal to 0.09.

2.3 Volume of Fluid Model

The free interface of the oil-water two-phase mixture can be traced using the volume of fluid (VOF) model, by introducing the fluid volume fraction α_q to represent the percentage of the q phase medium in the unit. α_q=0 denotes that there is no q phase medium in the cell, 0< α_q <1 indicates that the q phase in the unit has an interface cell with other phases, and α_q=1 revealed that the cell is filled with q phase medium. The movement of crude oil and seawater should be considered in the leakage and diffusion process for submarine oil pipelines, also α_q at the free surface should satisfy the equation:

$$\frac{\partial\alpha_q}{\partial t} + \mathbf{u} \cdot \nabla\alpha_q = 0, \text{ where } q = 1, 2, \sum_{q=1}^{n} \alpha_q = 1 \tag{8}$$

In the VOF method, the parameter φ is determined by the physical property parameters and the volume fraction function of each phase fluid in the control volume, which can be calculated by the following formula:

$$\varphi = \sum \varphi_q \alpha_q, \tag{9}$$

2.4 Porous Medium Model

The subsea soil regions can be simplified using a porous medium model for numerical computations in the context of subsea buried pipeline areas. By introducing a fluid region with additional resistance sources, the complexity of establishing a porous geometry can be avoided. The seabed soil is assumed to be a water-saturated porous medium environment, after the leakage of the buried submarine pipeline, the leaking medium will pass through the porous medium gap in this area and then diffuse into the seawater. Among them, the porous medium model is numerically modeled by adding a source term to the energy equation:

$$\frac{\partial}{\partial t}(\gamma\rho_f E_f + (1-\gamma)\rho_s E_s) + \nabla \cdot (\mathbf{u}(\rho_f E_f + p)) = \nabla \cdot \left[\lambda_{\text{eff}}\nabla T - \left(\sum_i h_i J_i\right) + (\tau \cdot \mathbf{u})\right] + S_h, \tag{10}$$

where E_f is the total energy of the fluid medium, J; E_s is the total energy of the solid medium, J; γ is the porosity of the solid medium; S_h is the fluid enthalpy source term, J/kg; λ_{eff} is the effective thermal conductivity of the porous medium, W/(m·K), the effective thermal conductivity of the porous medium region can be calculated from the thermal conductivity of the solid and the thermal conductivity of the fluid as follows:

$$\lambda_{\text{eff}} = \gamma\lambda_l + (1-\gamma)\lambda_s, \tag{11}$$

where λ_l is the thermal conductivity of the liquid; λ_s is the thermal conductivity of the solid medium.

And the source term includes a viscous loss term (Darcy) and an inertial loss term as follows:

$$S_i = -(\mathbf{D}\mu\mathbf{u} + \mathbf{C}\frac{1}{2}\rho\,|\mathbf{u}|\,\mathbf{u}), \tag{12}$$

Assuming that the seabed soil is a homogeneous porous medium environment with uniform particles and isotropy, the viscous resistance and inertial resistance in different directions are the same, and the above formula can be simplified as it follows:

$$S_i = -(\frac{\mu}{a}\mathbf{u} + C_2\frac{1}{2}\rho\,|\mathbf{u}|\,\mathbf{u}), \tag{13}$$

where a is the permeability, μm^2; C_2 is the internal resistance coefficient.

3. RESULTS AND DISCUSSION

3.1 Physical Model

The oil spill model in this paper chooses the deep seabed buried pipeline with a water depth of 20m. In addition, to improve the numerical accuracy, as well as reduce the influence of the inlet and outlet boundaries on the diffusion and migration of the pipeline, the inlet boundary of the flow field is selected to be 4m away from the center of the pipeline, the field outlet boundary is 16m from the pipe center point. Hence, a 20×15m two-dimensional rectangle is selected as the local calculation flow field, and the buried depth of the pipeline is 1.5m, 2.0m, 3.0m from the seabed boundary. The numerical calculation related to the basic parameters are shown in Tab. 1, and the computational domain and boundary conditions are shown in Fig. 1.

As the submarine pipeline is affected by the corrosion of the medium transportation and the erosion of the ocean current, it is prone to perforation, which leads to the problem of oil spillage. As stated by Lin (2019), the perforation diameter is generally in the range of 0.006m to 0.08m. A damaged submarine pipeline with an outer diameter of 0.2 m is selected in this paper, which is located 4 m downstream from the seawater inlet. It is assumed that the overflow section is circular and the bottom of the outer surface is tangent to the seabed soil surface, and the diameter is set to 0.04 m, and the initial overflow angle of the oil spill hole just above the top of the pipeline is set to 0°, so that the crude oil can overflow outward at a certain speed in the vertical section, thus Simulate oil spill trajectories at different pipeline depths.

Table 1. Numerical calculation related to basic parameters.

Parameter	Unit	Value	Parameter	Unit	Value
Computational domain size	m	20×15	Sea surface wind speed v_m	m/s	1
Damaged sea pipe diameter D	m	0.2	Sea surface current speed v_T	m/s	0.05
Oil spill diameter d	m	0.04	Crude oil spill rate v_{oil}	m/s	5
The distance from the center of the pipe to the inlet L	m	4	The angle between the oil spill hole and the horizontal β_1	°	0
Crude oil density ρ_{oil}	kg/m^3	838	Crude oil viscosity v_{oil}	kg/(m·s)	0.009477
Sea water density ρ_{sw}	kg/m^3	1025	Sea water viscosity v_{sw}	kg/(m·s)	0.0017425

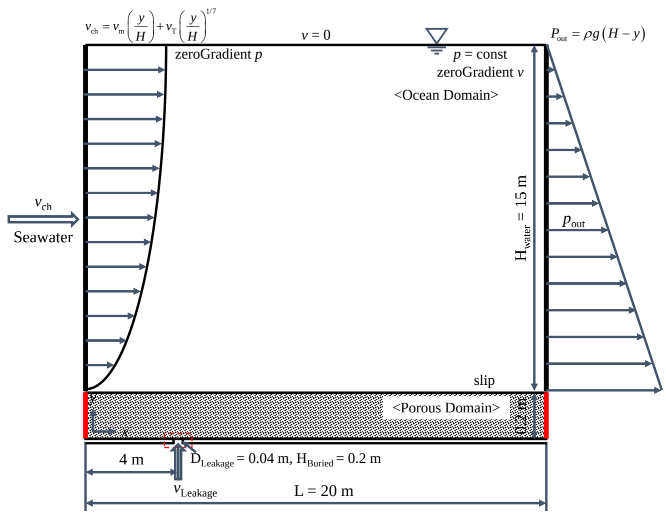


Figure 1. Computational domain and boundary conditions.

3.2 Boundary Conditions

The oil spill hole of the submarine pipeline adopts the velocity inlet, and the no-slip boundary condition is applied for the bottom of the seabed and the wall of the pipeline in the computational domain. Considering the influence of ocean currents, the velocity inlet is used for the inlet wall on the left side of the computational domain, and the boundary conditions for the outlet wall and top area on the right side are set as free outflow boundary conditions by defining UDF functions DEFINE_PROFILE (inlet-velocity, thread, position) and DEFINE_ PROFILE (outlet-velocity, thread, position), which use the formula recommended by the American Bureau of Shipping to calculate the relationship between the current and the water depth (Li et al. 2016).

$$v_{\mathrm{ch}} = v_{\mathrm{m}}\left(\frac{y}{H}\right) + v_{\mathrm{T}}\left(\frac{y}{H}\right)^{1/7}, \tag{14}$$

where v_{ch} is the current velocity at a distance y from the seafloor, m/s; v_m is the sea surface wind speed, m/s; v_T is the speed of the ocean current, m/s; H represents water depth, m; y is the calculating height from the bottom of the sea, m.

3.3 Calculation Method

The unsteady pressure-based solver was used for the solution, also enabling the VOF method, porous medium model and the turbulence model. In the unsteady calculation, Δt is set to 0.005s, the total number of steps is 6000, and the calculation time is the 20s. Using the PISO algorithm for pressure-velocity coupling, as well as combining the second-order upwind style discrete convection-diffusion term equation. Secondly, the maximum residual error is used as the criterion for the convergence of the solution, the convergence accuracy is 10^{-5}.

Considering the influence of ocean current velocity, the numerical calculation process is divided into two steps: (1) the simulation of the ocean current flow field in the computational domain; (2) the coupling between the leakage source and the initial ocean current field is introduced to determine the diffusion process of underwater crude oil.

Making some assumptions about the leakage and diffusion process of submarine buried oil pipelines in the whole numerical simulation process: (1) the whole process is constant pressure uninterrupted leakage; (2) the energy transfer between crude oil and seawater is ignored; (3) the water-oil two phase-flow is incompressible, transient and isothermal flow; (4) the physical and chemical properties of the fluid are constant; (5) Gravity and drag forces are taken into account.

3.4 Model Validation

ANSYS ICEM software was used to divide the computational domain into two-dimensional grids, the Quad grids were selected and expanded in Map form. To ensure the accuracy of the numerical simulation results and improve the reliability of the numerical simulation, the mesh-independence verification was carried out by dividing a single grid node at the scale of 1mm, 5mm, and 20mm respectively, as shown in Tab. 2. The results showed that the maximum errors of pressure fluctuations at different points and vertical migration distances were all within 10%. In addition, this paper validates the CFD model using a 2D simulation model by repeating the experiments of Ji *et al.* (2020) and the experiment is in a still water environment, and the maximum relative error of the mean is in the range of 4.9-8.7%. The number of planar grids finally selected is 146286 under the premise that the calculation cost is controllable.

Table 2. Comparison of experimental and numerical results under different mesh numbers.

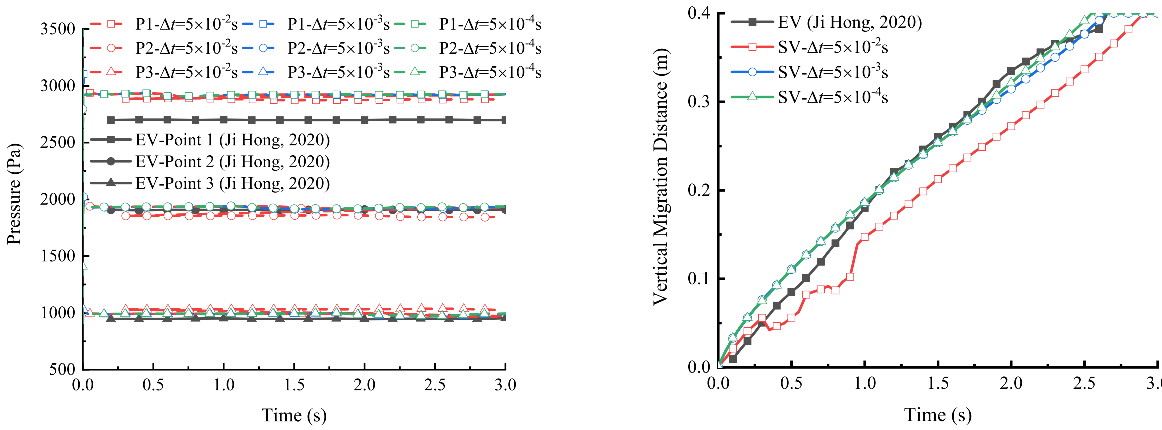
Mesh	Length(mm)/Nodes	Total Elements	EV-Pressure Error			EV-VMD Error
			P1/%	P2/%	P3/%	%
Mesh 1	20	7686	7.11	3.44	9.50	9.55
Mesh 2	5	146 286	8.72	1.69	4.92	6.10
Mesh 3	1	2 889 606	9.03	1.52	3.71	4.31

(1) EV-Experiments Value; SV-Simulation Value. (2) VMD-Vertical Migration Distance. (3) P1-Point 1; P2-Point 2;P3-Point 3.

At the same time, this work selects 3 different time steps Δt=5×10^{-2}s, Δt=5×10^{-3}s and Δt=5×10^{-4}s to test the effect of the time step Δt on the numerical simulation. The results show that the difference in pressure fluctuation between the three time steps is very small, and except for the Δt=5×10^{-2}s, the vertical migration upward distance trend is similar. Meanwhile, the comparison between the experiment and the simulation of the vertical migration height of the underwater crude oil spill, which is consistent with the change of the rising height in the experimental data, and the time to reach the sea surface the error is basically below 6%, as shown in Fig. 2. For this reason, considering the trade-off between numerical accuracy and computational cost, the final selected time step is Δt=5×10^{-3}s, which can provide reasonable results for capturing the diffusion behavior of underwater oil.

3.5 Leakage Affects Parameter Selection

When crude oil leaks from a submarine buried pipeline, the crude oil diffuses into the seawater through the seabed soil under the pressure of the pipeline. During its diffusion process, factors such as the physical parameters of crude oil medium, pipeline size, leak hole diameter, water depth, pipeline buried depth, seabed soil porosity, leakage velocity, and seawater flow rate will all affect the diffusion law of crude oil. Among them, there are many studies on the physical parameters of crude oil medium, pipeline size, leakage hole diameter, water depth factors. Thus, this paper will focus on the three factors of pipeline burial depth, seabed soil porosity and leakage velocity influence of leakage diffusion law of submarine buried pipeline.



(a) Comparison of Pressure of Measuring Points. (b) Comparison of Vertical Migration Distance.

Figure 2. Comparison of Pressure and Vertical Migration Distance Fluctuations in Experiments and Numerical Simulation with Different Time Steps. (EV-Experiments Value; SV(Others)-Simulation Value)

Accordingly, steel pipelines with a water depth of 60m or less should be buried for protection, and the total buried depth (pipe top to mud surface) should not be less than 1.5m; Shallow flexible pipes with a water depth of 150m or more should be buried for protection, and the total buried depth (pipe top to mud surface) should not be less than 2.0m; the pipes crossing the channel, waterway and adjacent to the anchorage should be protected by gravel protection. The total buried depth (pipe top to the mud surface) should not be less than 2.0m; when the pipeline transporting hazardous chemicals crosses the waterway, it should be protected by gravel, and the total buried depth from the top of the pipe to the mud surface should not be less than 3.0m, which refer by the recommended practices for risk assessment of pipeline burial and protection in SY/T 7063 "Recommended Practices for Risk Assessment of Submarine Pipelines". Consequently, the recommended method for selecting the buried depth of the pipeline is three depending on the different depths 1.5m, 2m, 3m respectively. Secondly, the buried above the pipeline mostly uses local materials, covering concrete briquettes, crushed stones, et cetera. According to the different needs, and chooses two different porosities of 0.267 and 0.375. In addition, when a submarine pipeline leaks, its crude oil leakage rate will drop to a certain value after reaching the peak value. Hence, a stable oil leakage rate is used to simulate the buried leaking pipeline, and 0.36m/s, 0.72m/s, 1.08m/s are selected. /s, 1.44m/s, and 1.80m/s five different leakage velocities to study the influence of the above different factors on the law of leakage diffusion.

3.6 Analysis of Influencing Factors of Seabed Soil Factors on Buried Pipeline Leakage

3.6.1 Effects of different buried depths on crude oil passing through soil

Figure 3 shows the time taken for crude oil to reach the seabed with different buried depths, porosity and leakage velocity. By simulating the effects of three different burial depths of 1.5m, 2m, and 3m on the seabed oil spill, it is found that under the same conditions, the deeper the burial depth, the longer it takes for the oil spill to pass through the soil area and reach the seabed. Among them, when the porosity is 0.267 and the oil leakage rate is 1.80m/s, the time to reach the seabed at a burial depth of 1.5m is 1.5s, the time to reach the seabed at a burial depth of 2 m is 2.5 s, and the time to reach the seabed at a burial depth of 3m is 5.0s.

3.6.2 Effects of Velocity of Crude Oil Passing Through the Soil with Depth

Figure 4 presents the variation curve of the velocity of crude oil in the soil with depth at different initial leakage velocities. The results show that the diffusion trend of crude oil in the soil is similar under different initial leakage velocities, pipeline burial depths and soil porosity, leakage velocities are faster at first, afterwards there is a decline, it decreases slowly, the initial diffusion distance increases rapidly, after that, gradually decreases and finally remains stable. This happens because the oil enters the soil from the leakage port in the form of a jet, which has a relatively large jet velocity. Affected by soil inertial resistance, viscous resistance, and capillary resistance, the velocity of spilled crude oil drops sharply after contacting the soil, as well as the resistance it suffers is proportional to the velocity. As the amount of leakage continues to increase, the resistance encountered when crude oil displaces water in the soil pores increases. At this time, the speed basically approaches 0, and the crude oil cannot diffuse quickly, which tends to stabilize after reaching a certain distance. The greater the initial leakage rate, the smaller the slope of the curve, indicating that the diffusion rate of crude oil in the soil slows down and the vertical diffusion distance decreases. When the buried depth of the pipeline is constant, the lower the soil porosity, the faster the oil leakage will rise from the leakage hole to the soil surface, and

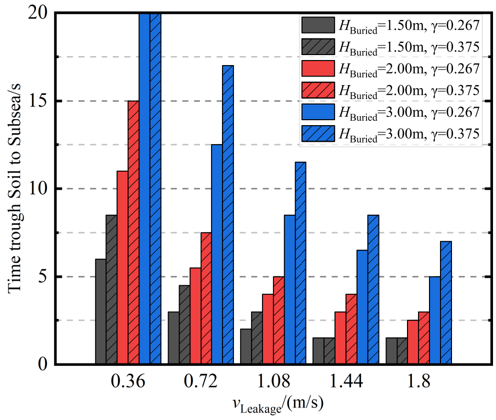
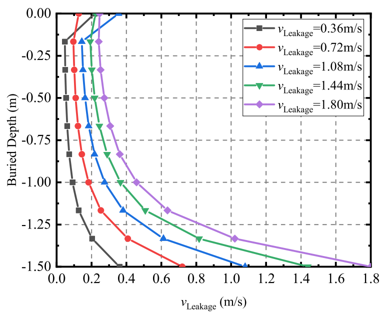
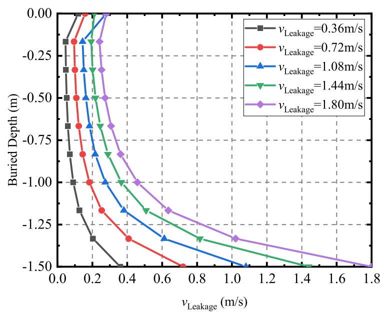


Figure 3. Time trough Soil to Subsea.

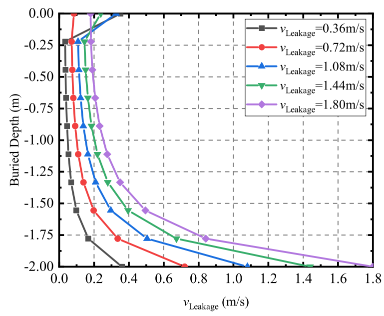
the wider the diffusion range of crude oil in the soil; when the soil porosity is constant, the deeper the buried depth of the pipeline, the curve as the slope increases, the leakage rate decreases faster, the greater the diffusion distance and range of crude oil in the soil after leakage, and the more serious the pollution to the environment.



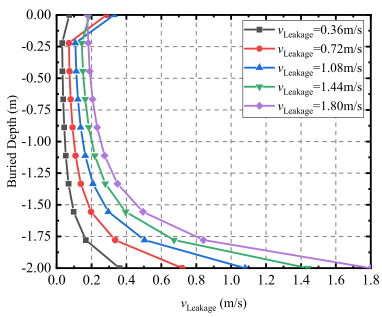
(a) H_{Buried}=1.5m, γ=0.267.



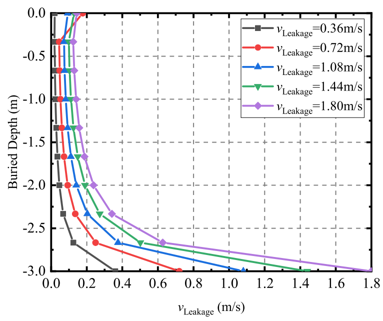
(b) H_{Buried}=1.5m, γ=0.375.



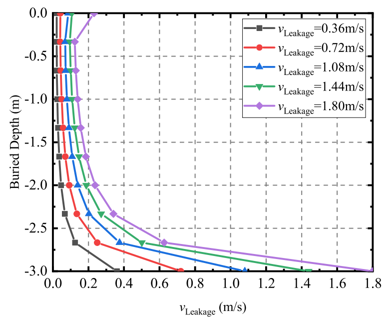
(c) H_{Buried}=2.0m, γ=0.267.



(d) H_{Buried}=2.0m, γ=0.375.



(e) H_{Buried}=3.0m, γ=0.267.



(f) H_{Buried}=3.0m, γ=0.375.

Figure 4. Variation Curves of Crude Oil Velocity in Soil with Depth at Different Initial Leakage velocities.

3.7 Analysis of Influencing Factors of Submarine Buried Pipeline Leakage Working Conditions

Regression analysis was carried out on the numerical results under multi-factor conditions, and a parameterized fitting formula was obtained to quickly calculate the horizontal diffusion distance of crude oil leakage in the seabed soil area and the time it took to reach the seabed. Two important outcomes to focus on in assessment and contingency planning.

Equation 15 describes the relationship between the oil spill velocity, seabed soil porosity and burial depth, and the horizontal diffusion distance in the seabed soil region; the fitting uses Levenberg-Marquardt general global optimization Algorithm, the fitting parameters satisfy the linear regression equation, the Root of Mean Square Error (RMSE) is equal to 0.213, the Correlation Coefficient (R) is equal to 0.988, and the Determination Coefficient (DC) is 0.977, which indicates the effectiveness and precision of regression model.

$$W_{\text{Porous}} = -2.219\times10^4+5.382v_{\text{Leakage}}-1.348v_{\text{Leakage}}^2+2.064H_{\text{Buried}}-0.315H_{\text{Buried}}^2+1.423\times10^5\gamma-2.216\times10^5\gamma^2, \quad (15)$$

Equation (16) describes the relationship between the velocity of oil spill in the seabed soil area, seabed soil porosity and buried depth, and the time taken to reach the seabed; the fitting uses Levenberg-Marquardt general global The optimization algorithm, the fitting parameters satisfy the linear regression equation, the Root of Mean Square Error (RMSE) is equal to 1.330, the Correlation Coefficient (R) is equal to 0.947, and the Determination Coefficient (DC) is 0.897. Compared with Eq. (15), there are certain errors in the validity and accuracy of the regression model fitted by Eq. (16).

$$t_{\mathrm{Porous}} = -3.981 - 14.802 v_{\mathrm{Leakage}} + 4.062 v_{\mathrm{Leakage}}^2 + 6.991 H_{\mathrm{Buried}} - 0.426 H_{\mathrm{Buried}}^2 + 33.465\gamma - 26.372\gamma^2, \quad (16)$$

where t_{Porous} is the time it takes for the spilled oil to travel through the soil area to the seabed; W_{Porous} is the horizontal diffusion distance of crude oil in the soil area; v_{Leakage} is the leakage rate of crude oil; H_{Buried} is the buried depth of the submarine pipeline; γ is the porosity of the seabed soil.

In summary, the horizontal diffusion width and rise time of crude oil in seabed soil can be quickly estimated by the two equations above to obtain data consistent with numerical simulation.

3.7.1 Influence of Initial Leakage Velocity on Oil Spill Maximum Vertical Migration Depth

Figure 5 represents the volume fraction distribution of crude oil leakage and migration in seawater under different working conditions at t=20s. The results show that after the oil spills overflow from the soil-seawater interface in the form of oil droplets or oil clusters, an uninterrupted oil column jet is formed, and part of the oil droplets will form a swirling counter-current due to turbulent flow. During the ascent process, it is affected by the lateral current and quickly deviates, in the form of a buoyant jet along the upper right of the current direction Tilting until the momentum drops to zero, it begins to break up into a large number of small oil droplets of varying sizes. Afterwards, the size of oil droplets decreases continuously, the distance between oil droplets increases continuously. Meanwhile, the flow of leaked oil in the porous soil medium will be affected by its own gravity, and the flow of oil will also produce a wake effect, which makes the crude oil seep downward along the wall of the leak port. The faster the initial leakage rate, the wider the horizontal distance of crude oil diffusion in seawater, and the wider the area covered, and the diffusion displacement in the horizontal direction is greater than that in the vertical direction, and the time it takes to diffuse to the sea surface is shorter. For the soil with lower porosity, the resistance of the porous medium encountered by crude oil permeating through the soil is smaller, and therefore diffuses at a faster rate in the seawater.

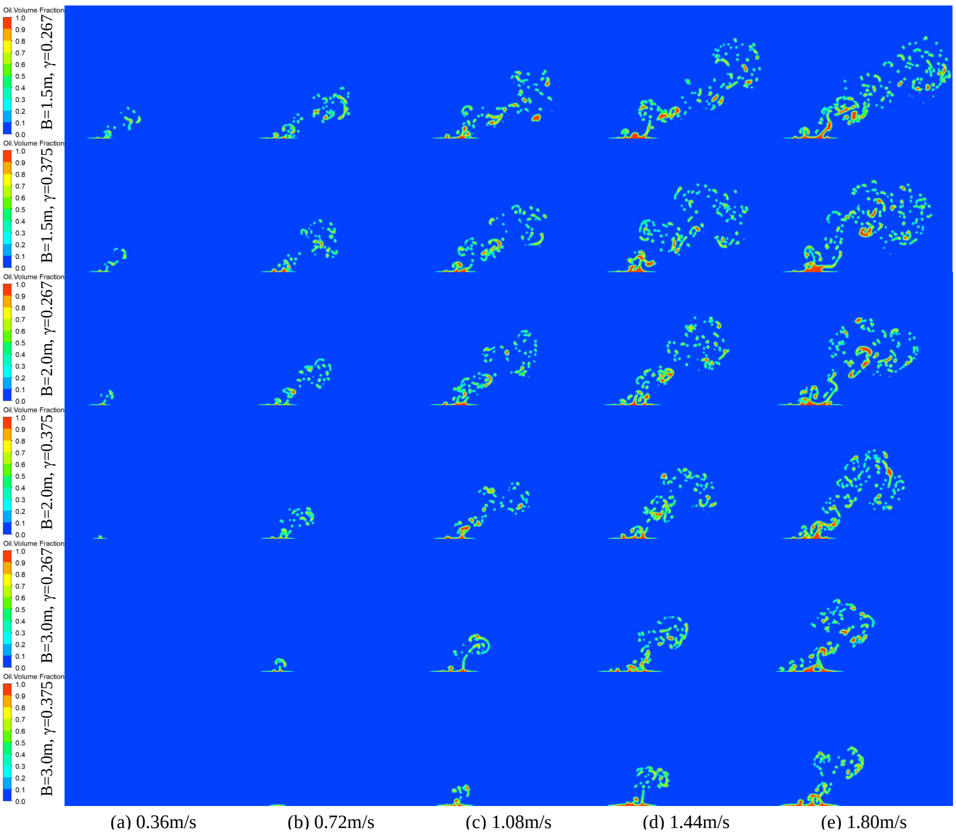
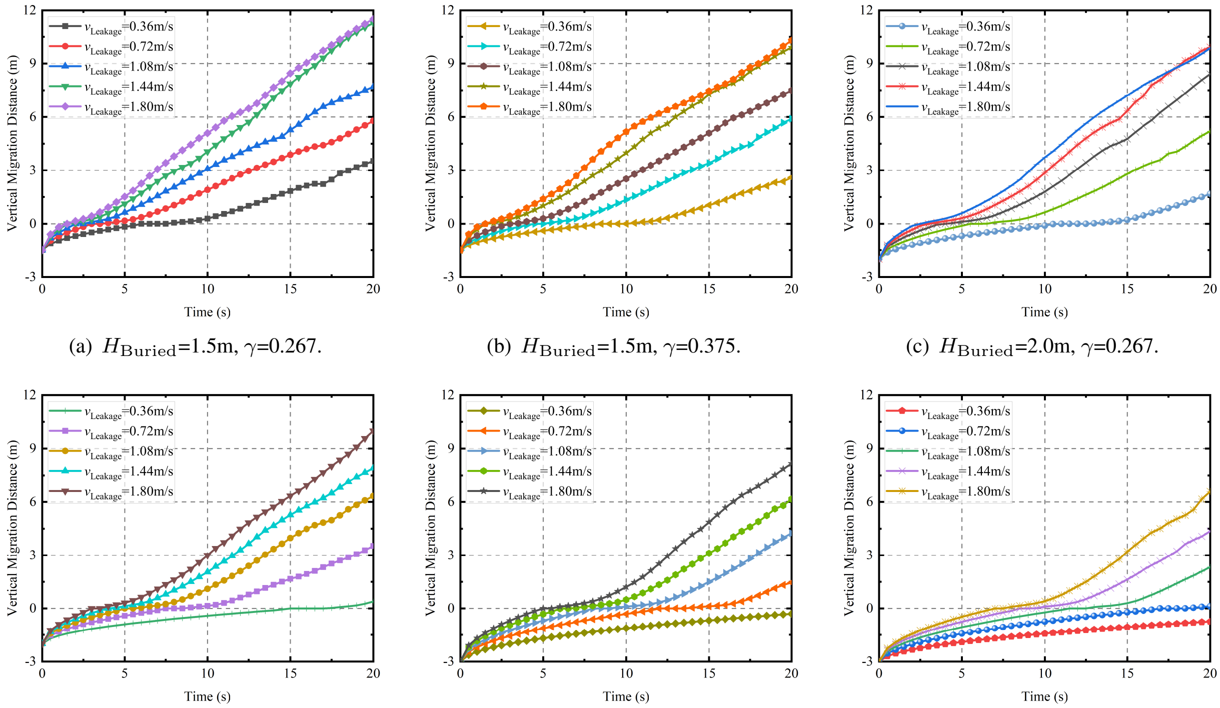


Figure 5. Volume Fraction Distribution Diagram of Crude Oil Leakage and Migration in Seawater Under Different Working Conditions at t=20s. (B—Buried Depth H_{Buried})

Figure 6 presents the distribution of crude oil at different buried depths at t=20s, porosity, and the vertical migration distance in seawater under the conditions of initial leakage velocity. The results show that the larger the initial leakage velocity, the faster the diffusion rate of crude oil in soil and seawater. Crude oil diffuses and permeates at a slow rate in the soil, and migrates in the seawater at a faster diffusion rate after crossing the interface between soil and seawater, and the diffusion distance in the vertical direction becomes larger. This is because crossing the soil needs to overcome the resistance of the porous medium and its own gravity, so the diffusion distance in the vertical direction is smaller. When the buried depth of the pipeline is shallow, the diffusion rate of crude oil leakage in the soil and seawater is faster, the diffusion distance in the vertical direction is larger, and the time required to reach the same diffusion distance is shorter, and finally reaches the sea level. The time is also shorter. In the same situation, when the soil porosity is low, the diffusion rate of crude oil in soil and seawater is faster, the slope of the curve is larger, crude oil passes through the soil area at a faster rate, and the vertical migration rate in seawater in the same time The greater the distance, the shorter the time required to reach sea level.



(a) H_{Buried}=1.5m, γ=0.267. (b) H_{Buried}=1.5m, γ=0.375. (c) H_{Buried}=2.0m, γ=0.267.

(d) H_{Buried}=2.0m, γ=0.375. (e) H_{Buried}=3.0m, γ=0.267. (f) H_{Buried}=3.0m, γ=0.375.

Figure 6. The Vertical Migration Distance in Seawater of Crude Oil to under Different Buried Depths, Soil Porosity, and Initial Leakage Rates at t=20s.

Equation 17 describes the relationship between oil spill time, leakage velocity, seabed soil porosity, buried depth, and vertical migration distance in the seawater area; the fitting uses the Levenberg-Marquardt method for general Global optimization algorithm, the fitting parameters satisfy the linear regression equation, the Root of Mean Square Error (RMSE) is equal to 0.445, the Correlation Coefficient (R) is equal to 0.996, and the Determination Coefficient (DC) is 0.992, indicating that the regression model is consistent with Eq. (15). Compared with Eq. (16), it has higher efficiency and accuracy, which can quickly estimate the oil leakage in seawater under the current medium conditions.

$$H_{\text{Seawater}} = -3.318 \times 10^8 + 1.468 \times 10^5 t + 8.223 \times 10^5 t^2 + 17.496 v_{\text{Leakage}} - 3.998 v_{\text{Leakage}}^2 \\ -6.315 H_{\text{Buried}} + 0.289 H_{\text{Buried}}^2 + 3.975 \times 10^3 \gamma - 6.218 \times 10^3 \gamma^2, \quad (17)$$

where, H_{Seawater} is the vertical migration distance of crude oil at a specified time, m.

4. CONCLUSIONS

The Realizable k-ε turbulence model combined with the volume of fluid (VOF) and porous medium model is used to simulate the unsteady flow of crude oil leakage from the submarine buried crude oil pipeline and analyze the influence of different buried depth, porosity and initial crude oil leakage velocity on the leakage and diffusion of crude oil in soil and seawater. The main conclusions are as follows:

(1) With the increase of burial depth, the degree of horizontal diffusion of crude oil in seabed soil pores increases and is greater than its burial depth; secondly, the decrease of soil porosity will lead to the increase of the horizontal diffusion range of the soil area and the corresponding increase of the diffusion speed of crude oil in the soil. The resistance in

the longitudinal direction is much greater than the horizontal resistance; in addition, the faster the initial leakage rate of crude oil, the greater the resistance of the seabed soil, and the closer the diffusion rate is to the leakage port, the faster the decline.

(2) The diffusion range of crude oil in seabed soil and seawater increases with the increase of leakage flow rate, the time it takes for the leaked crude oil to cross the soil from the damaged opening to reach the seabed is less, and the time it takes for the leaked crude oil to reach a uniform height in seawater is also corresponding reduce.

(3) Data analysis is performed on the horizontal diffusion distance of crude oil in seabed soil, the time it takes to reach the seabed, and the horizontal diffusion range in seawater to form a fitting formula for estimating crude oil in seabed soil and seawater under specific conditions. In summary, when evaluating the pollution degree of an oil spill accident, it is necessary to consider the soil environment of the accident site to reasonably judge the underwater pollution range of crude oil. The results provide a certain reference for the migration, diffusion and control of submarine oil spills.

5. ACKNOWLEDGEMENTS

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