Analysis and Prediction of Methane Invasion Distance Considering Real Ground Boundary

Fanxi Bu, Yang Liu,* Shuangqing Chen,* Zhe Xu, Yongbin Liu, Minghu Jiang, and Bing Guan

ABSTRACT: Natural gas has become a global energy consumption hotspot because of its large reserves and clean combustion. Due to soil corrosion, construction damage, and natural disasters, leakage accidents of buried natural gas pipelines often occur. In this paper, the steady simulation method was used to study the methane invasion limit state (MILS) and the methane invasion limit distance (MILD) under the conditions of hardened surface ground (HSG), unhardened surface ground (UHSG), and semihardened surface ground (SHSG), and the transient simulation of methane invasion distance (MID) under the condition of HSG with the largest MILD was carried out. The results showed that regardless of ground conditions, with the increase of leakage time, the diffusion range of methane in soil will not increase all the time, and there was a limit state (MILS). The distribution range and concentration of methane in the soil under HSG condition were the largest, followed by the SHSG condition, and the UHSG condition was the smallest. When the ground condition changed from UHSG to HSG, the MILD increased from 3.41 to 9.32 m. The HSG condition will increase the MILD and the range of dangerous areas. The buried depth of the pipeline had a serious impact on the MILD. When the buried depth of the pipeline increased from 0.3 to 1.5 m, the MILD increased from 1.75 to 3.49 m under the condition of UHSG and exceeded 10 m under the condition of HSG. The average error of the MID prediction model was 2.37% under the condition of HSG, which can accurately predict the leakage of buried pipeline. The MID provides a reference for the layout of urban underground gas leakage monitoring points. The MILD can provide guidance for the safe distance between natural gas pipeline and structures in the design code of natural gas pipeline.

1. INTRODUCTION
Currently, energy is the driving force to promote the development of all countries in the world. Natural gas has become a global energy hotspot with its huge reserves.1 More than 90% of the world’s total natural gas storage exists in the form of natural gas hydrate in deep-sea clay silt or muddy sediments, which is difficult to exploit.2,3 In 2017, China carried out the world’s first natural gas hydrate (NGH) production test in the clay silt of the northern South China Sea and achieved great success.4 In 2020, China successfully carried out the second natural gas production test with horizontal wells and produced 86.14 × 10^4 m^3 natural gas in a month,5 which confirmed the feasibility of deep-sea natural gas development. Compared with other fossil energy sources, natural gas not only has huge reserves but also has the characteristics of clean combustion, reducing carbon dioxide emissions. The average H/C ratios of wood, coal, petroleum, and natural gas are 0.1, 0.5, 2.0, and 4.0, respectively.6

Buried natural gas pipeline network is the most common mode of natural gas transportation.7 Due to corrosion, third-party construction damage, and natural disasters, leakage accidents of buried natural gas pipelines occur frequently.8 The leakage of buried natural gas pipeline not only causes resource waste and economic loss9 but also affects the soil and leads to vegetation damage.10,11 Methane leakage below the seafloor will lead to methane hydrate formation and marine pollution.12,13 Its flammable and explosive characteristics pose a serious threat to human life and property safety.14 On July 4, 2017, a gas leak accident occurred in Songyuan City, Jilin Province, China, and the natural gas gathered in the municipal hospital complex through the sewer, causing an explosion accident, resulting in 5 deaths and 89 injuries.15 To achieve sustainable development and energy conservation and emission reduction, the United States had started the research of natural gas pipeline transportation of hydrogen.16,17 Germany added less than 10% hydrogen to the natural gas pipeline network and planned to increase it to 20% by 2020.18 The explosion limit range of hydrogen is wider and more destructive than...
methane. Therefore, the safety problem in the process of energy use is of great significance, and the prevention and risk analysis of buried natural gas pipeline leakage accident is the premise of further promotion of natural gas.

Experiment is an effective method to study the leakage and diffusion characteristics of natural gas. Chamin et al. studied the effects of shallow soil moisture and atmospheric conditions on methane transport in soil by combining experiment and numerical simulation. Bonnau et al. used experimental methods to study the effects of leakage diameter, pipeline operating pressure, pipeline buried depth, and soil type on the leakage and diffusion results of small holes in buried natural gas pipelines and emphasized the formation of ground cavities and other new phenomena. Houssin-Agbomson et al. conducted an experimental study on the accidental leakage of high-pressure gas transmission pipeline with a leakage diameter of 12 mm and accurately evaluated the leakage risk by changing the effects of gas properties, initial gas pressure, and soil type on the diffusion of gas in the soil. Xie et al. analyzed the gas diffusion in soil by experimental method and measured the change of methane volume fraction with time. Yan et al. developed a full-scale experimental system, which divided the experimental process into release stage and dissipation stage, to study the change of methane concentration in soil under different leakage rate and leakage direction of low-pressure pipeline.

On the other hand, there are a few numerical simulation studies on buried natural gas pipelines. Ebrahimi-Moghadam et al. studied the leakage of medium-pressure natural gas pipeline by numerical simulation and established the precise calculation model of leakage of above-ground and buried natural gas pipeline. Wilkening and Baraldi compared the diffusion process of hydrogen and natural gas small hole leakage in high-pressure pipeline by the computational fluid dynamics (CFD) method. Bezaatpour et al. considered the soil anisotropy, soil stratification, soil matrix water content, and soil slope and regarded natural gas as real gas. The unsteady numerical simulation method was used to study the influence of various factors on gas diffusion. Wang et al. used numerical simulation method to study the process of natural gas pipeline pinhole leakage and analyzed the influence of pipeline pressure, leakage diameter, and soil type on the diffusion characteristics of natural gas. However, in this study, the influence of ground conditions on the leakage and diffusion characteristics of natural gas has not been involved.

In this study, we investigated the diffusion characteristics of methane leakage in the soil under different ground conditions. Three ground conditions were defined: hardened surface ground (HSG), unhardened ground (UHSG), and semi-hardened ground (SHSG). Meanwhile, the methane invasion distance (MID), methane invasion limit state (MILS), and methane invasion limit distance (MILD) of methane diffusion in soil were defined. The steady numerical simulation method was used to study MILS and MILD under different ground conditions, and the effects of pipeline operating pressure, leakage diameter, buried depth of pipeline, and soil type on methane diffusion characteristics were analyzed. The MID transient simulation was carried out for the HSG condition with the largest MILD, and the effects of pipeline operating pressure, leakage diameter, and buried depth on methane diffusion process were analyzed. The correlation between MID and each parameter was established under the condition of HSG, and the MID prediction equation was obtained. The MID provides a reference for the layout of urban underground gas leakage monitoring points. The MILS and MILD under different ground conditions provide a safe reference distance for emergency evacuation.

2. METHODS

2.1. Physical Model. A two-dimensional model cannot consider the resistance effect of soil in three directions in the process of natural gas leakage and diffusion, which increases the calculation error. Therefore, this study used a three-dimensional model to study the diffusion process of methane leakage from buried natural gas pipeline. To study the diffusion state of methane, three ground conditions, the hardened surface ground that methane diffusion cannot pass through, the unhardened surface ground that methane diffusion can pass through, and the semihardened surface ground that was the combination of the two, were proposed. Because this study mainly focuses on the diffusion process of methane in soil after natural gas pipeline leakage, it does not pay attention to the flow state of gas in the pipeline. To reduce the amount of calculation and the difficulty of mesh generation, the pipeline part was omitted.

Before the physical model was established, the model size was preanalyzed, the physical models with radii of 5, 8, and 10 m were established, respectively, and the steady-state calculation of three ground surface conditions was carried out using basic case 3 in Table 5. The results showed that the physical model with a radius of 10 m can realize the research scope of steady-state calculation. Meanwhile, the larger model size was detrimental to transient monitoring due to the slow transient simulation diffusion. To better display the cloud images effect, a physical model with a radius of 10 m was used for research. The three-dimensional rectangular coordinate system was established with the center of the leakage hole as the origin, as shown in Figure 1.

2.2. Mathematical Model. To simplify the mathematical model, the following assumptions were put forward:

![Figure 1. Schematic diagrams of the physical model of (a) hardened surface ground, (b) unhardened surface ground, and (c) semihardened surface ground.](https://doi.org/10.1021/acsomega.1c04322)
(a) The flow of natural gas in medium-pressure pipeline and the diffusion process in soil are adiabatic flow of ideal gas.\(^{31,32}\)

(b) The soil is regarded as isotropic porous media.\(^{2,5}\)

(c) The operating pressure of the pipeline remains unchanged before and after the leakage.\(^{2,5}\)

(d) The spatial structure of soil in the whole calculation area does not change after the leakage.\(^{2,8}\)

(e) Natural gas has no chemical reaction with surrounding soil and air.\(^{2,8}\)

(f) Before the leakage, the soil pores are filled with air.\(^{3,3}\)

(g) Ignore the moisture in the soil.\(^{3,3}\)

Based on the above assumptions, the governing equations of the diffusion process of natural gas in soil are composed of conservation of mass, conservation of momentum, transport equation, gas state equation, and turbulence equation. (1) Conservation of mass:\(^{2,3,5}\)

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_i)}{\partial x_i} = 0
\]

(1)

(2) Conservation of momentum:\(^{2,3,6}\)

\[
\frac{\partial \rho u_i}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \mu \frac{\partial u_i}{\partial x_j} \right) + \rho g_i + S_i
\]

(2)

The flow of fluid in porous media needs to increase the momentum source term composed of viscous loss term and internal loss term (\(S_i\)). Based on the basic assumption of isotropic porous media in soil, the resistance in all directions is the same, where \(1/\alpha\) is the viscous resistance coefficient (1/m\(^3\)) and \(C_2\) is the inertial resistance coefficient (1/m), as shown in the following formula.

\[
S_i = -\left( \frac{\mu}{\alpha} u_i + \frac{C_2 \rho}{2} u_i u_i \right)
\]

(3)

The parameters of the above equation are determined by the Ergun equation, and the simulation results are in the best agreement with the real leakage condition, where \(\Delta p\) is the pressure drop (Pa), \(\Delta L\) is the length in the direction of pressure gradient (m), \(\mu\) is the dynamic viscosity of gas (Pa·s), \(\phi\) is the soil porosity, and \(d_i\) is the mean diameter of soil particles (mm), as shown in the following formula.

\[
\frac{|\Delta p|}{\Delta L} = 150 \frac{\mu u}{d_i^2} \left( 1 - \phi^2 \right) + 1.75 \frac{\rho u^2}{d_i} \left( 1 - \phi^2 \right)
\]

(4)

According to the comparative analysis of eqs 3 and 4, the viscous resistance coefficient (1/\(\alpha\)) and inertial resistance coefficient (\(C_2\)) of soil porous media can be obtained as follows.

\[
\frac{1}{\alpha} = 150 \left( 1 - \phi^2 \right) \frac{d_i^2}{\phi^3}
\]

(5)

\[
C_2 = 3.5 \left( 1 - \phi \right) \frac{d_i}{\phi^3}
\]

(6)

(3) Transport equation:\(^{2,8}\)

\[
\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} = \frac{\partial}{\partial x_j} \left( \mu \frac{\partial u_i}{\partial x_j} \right)
\]

(7)

(4) Equation of state:\(^{3,7}\)

\[
\rho v = RT
\]

(8)

\[\text{(5) Turbulence model}\]

In this study, the \(\kappa-\varepsilon\) standard two-equation model was used. The model \(\kappa-\varepsilon\) is based on the turbulent kinetic energy equation \(\kappa\) and turbulence dissipation rate \(\varepsilon\) to form the \(\kappa-\varepsilon\) two-equation model, as shown in eqs 9 and 10.

\[
\frac{\partial}{\partial x_i} \left( \rho \kappa u_i \right) = \frac{\partial}{\partial x_j} \left[ \mu \left( \frac{\partial k}{\partial x_j} \right) \right] + G_k + G_b + Y_M - \rho \varepsilon
\]

(9)

\[
\frac{\partial}{\partial x_i} \left( \rho \varepsilon u_i \right) = \frac{\partial}{\partial x_j} \left[ \mu \left( \frac{\partial \varepsilon}{\partial x_j} \right) \right] + C_\mu \frac{\varepsilon}{\kappa} G_k - C_2 \frac{\varepsilon^2}{\kappa}
\]

(10)

In these equations, \(G_k\) is the turbulence kinetic energy generation due to the mean velocity gradients, \(G_b\) is the turbulence kinetic energy generation due to buoyancy, \(Y_M\) is the effect of fluctuating expansion on total dissipation rate in compressible turbulence, and \(\mu\) is the turbulent viscosity. The specific calculation method is shown in the following formula, and other relevant values are shown in Table 1.\(^{3,7,4,0}\)

\[
\begin{align*}
G_k & = \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \frac{\partial u_i}{\partial x_j} \\
G_b & = -\frac{\varepsilon}{\rho P_i} \frac{\partial \rho}{\partial x_i} \\
Y_M & = 2 \rho \varepsilon \frac{\kappa}{\gamma RT} \\
\mu_t & = \rho C_p \frac{\kappa^2}{\varepsilon}
\end{align*}
\]

Table 1. Constants of the \(\kappa-\varepsilon\) Turbulence Model

| constant | \(C_{1t}\) | \(C_{2t}\) | \(\sigma_t\) | \(\sigma_s\) | \(C_p\) |
|----------|-----------|-----------|-----------|-----------|---------|
| value    | 1.44      | 1.92      | 1.0       | 1.3       | 0.09    |

2.3. Numerical Method and Grid Generation. The finite volume method of ANSYS FLUENT software in pressure-based solver mode was used for the study. For the coupling method of velocity and pressure in simulation calculation, simple algorithm was used for steady simulation calculation and PISO algorithm was used for transient simulation calculation.\(^{3,7,4,1}\) To ensure the accuracy of calculation, the second-order upwind discretization format was adopted. For steady simulation, the calculation residual was less than \(10^{-6}\) and the calculation was stopped to ensure the absolute convergence. For transient simulation, the time step size was set as 0.1 s, the number of time steps were 72,000, and the maximum iteration was 100 steps. The methane diffusion process within 2 h of natural gas pipeline leakage was studied.

Gambit software was used to mesh the fluid computing domain. The hexahedral structured grid was used to divide. To ensure the independence of the grid and reduce the computation, the grid independence was verified by dividing four grid levels. Taking the vertical line of the center of the leak...
hole as the center, the cylinder with a radius of 1 m was divided by the interface and the local mesh in the cylinder was encrypted.

2.4. Boundary Conditions. 2.4.1. Boundary Type. In this study, the ground was divided into three conditions for analysis. For hardened surface ground, natural gas leakage cannot pass through the ground into the atmosphere, so wall boundary was used. For unhardened surface ground, natural gas will pass through the ground and enter the atmosphere after leaking in the soil, and the pressure outlet was used for setting. For semihardened surface ground, hardened surface area and unhardened surface area were set, respectively. The interface was used to connect the local encryption area of the mesh, and the specific boundary type definition is shown in Table 2.

| boundary location          | boundary type       |
|----------------------------|---------------------|
| leakage hole               | mass flow inlet     |
| hardened surface ground    | wall                |
| unhardened surface ground  | pressure outlet      |
| soil boundary around       | pressure outlet      |
| bottom soil boundary       | pressure outlet      |
| mesh densification boundary| interface           |

2.4.2. Mass Flow Rate. Because the pipeline part was omitted in the calculation domain of the three-dimensional model, the error caused by the reversal flow phenomenon of the pipeline downstream of the leakage hole was ignored. If the pressure inlet was used for calculation, then the leakage gas at the leakage hole will be reduced, and the larger the leakage diameter, the larger the calculation error. Therefore, in this study, the mass flow inlet was used for calculation and the mass flow calculation method was based on the precise gas leakage calculation model of buried medium- and low-pressure pipelines, as shown in eqs 15–17. However, in the actual gas leakage event, the pressure in the formation will increase to some extent due to gas leakage, resulting in the change of leakage rate. According to the research results of Wang et al., the leakage rate of the leakage hole of the buried pipeline gradually decreased and basically reached the equilibrium state after 100 s. The change of leakage rate in the whole process was only 0.029%, indicating the feasibility of constant mass flow inlet. The pipe diameter was calculated as 200 mm, and the natural gas composition was regarded as 100% methane.42,43

\[
Q = 0.117(1 + \beta^4)d^2p_i, \quad d \leq 15 \text{ mm} \tag{15}
\]

\[
Q = 0.0677(1 + \beta^4)d^2p_i, \quad 15 \text{ mm} < d \leq 80 \text{ mm} \tag{16}
\]

\[
\beta = \frac{d}{D} \tag{17}
\]

where \(Q\) is the gas volume flow under standard state (Nm³/h), \(d\) is the leakage diameter (mm), \(D\) is the pipe diameter (mm), and \(p_i\) is the absolute pressure (bar).

2.4.3. Turbulent Boundary Conditions. Turbulence intensity and hydraulic diameter were used to define turbulent boundary conditions. Turbulence intensity is defined as shown in eqs 17 and 18.44 For the definition of hydraulic diameter, the hydraulic diameter of pipeline is equal to the pipe diameter and the hydraulic diameter of leakage hole is equal to the leakage diameter.45

\[
I = 0.16Re_{D_h}^{-1/8} \tag{18}
\]

where \(I\) is the turbulence intensity, \(D_h\) is the hydraulic diameter, and \(Re_{D_h}\) is the Reynolds number based on the hydraulic diameter.

2.4.4. Soil Types. Because of the different porous media characteristics of different types of soil, the internal resistance and porosity are different. In this study, sandy, loam, and clay were taken for investigation, as shown in Table 3.28 The thermal properties of porous media were set according to the thermal properties of soil, and the specific parameters are shown in Table 4.47

| soil type | \(d_f\) (mm) | \(\varphi\) | \(1/\alpha\) (1/m³) | \(C_s\) (1/m) |
|-----------|-------------|------------|-------------------|--------------|
| sandy     | 0.5         | 0.25       | 2.16 × 10¹⁰       | 3.36 × 10⁵   |
| loam      | 0.05        | 0.43       | 2.45 × 10¹¹       | 5.02 × 10⁵   |
| clay      | 0.01        | 0.3        | 2.72 × 10¹¹       | 9.07 × 10⁶   |

| property | unit | value |
|----------|------|-------|
| conductivity | W/m K | 2.9 |
| heat capacity | J/kg K | 732.69 |
| density | kg/m³ | 2650 |

2.5. Simulation Scenarios. Steady simulation was used to study the effects of pipeline operating pressure, leakage diameter, buried depth, and soil type on the diffusion characteristics of methane in hardened surface ground, non-hardened surface ground, and semihardened surface ground after natural gas pipeline leakage. Transient simulation was used to study the diffusion characteristics of methane in soil under hardened surface ground. The operating pressure of the pipeline was the same as that of the urban medium-pressure natural gas transmission pipeline, and the absolute pressure (\(p_i\)) was 3–5 bar. The research range of leakage diameter (\(d\)) was 0–80 mm. According to the GB 50028-2006 code for design of city gas engineering, five buried depths (\(H\)) of pipelines were selected. Sandy, loam, and clay (\(S\)) were selected for the study. The specific working conditions are shown in Table 5.

Because the ground conditions have different effects on the diffusion of methane on the ground, hardened surface ground (HSG), unhardened surface ground (UHSG), and semihardened surface ground (SHSG) were defined to study. Hardened surface ground (HSG): the ground where methane cannot pass through the soil and enter the atmosphere, such as dammed cement roads, asphalt roads, and buildings. Unhardened surface ground (UHSG): after passing through the soil, methane will pass through the ground and enter the atmosphere, such as soil road section and vegetation cover. Semihardened surface ground (SHSG): it is composed of hardened and unhardened surface ground. After methane passes through the soil, part of it passes through the ground and enters the atmosphere, such as the border area of roads and buildings. The diffusion diagram of methane under three ground conditions after leakage is shown in Figure 1.

The ground is the main area of human activities, and methane reaching the ground will pose a threat to human life and property safety. The methane invasion distance (MID), methane invasion
limit state (MILS), and methane invasion limit distance (MILD) of methane leakage diffusion were defined. Methane invasion distance (MID): the distance from the farthest boundary of methane diffusion on the ground to the corresponding point on the ground in the vertical direction where the center of the leakage hole is located. After the leakage of natural gas pipeline, methane will pass through the soil and reach the ground, and the diffusion distance and concentration on the ground gradually increase. The MID boundary was divided by the lower explosion limit of methane (5 vol %), and the monitoring line \((y = 0, \ z = H)\) was used to monitor the MID in the ground \(x\) direction, as shown in Figure 2. Methane invasion limit state (MILS): if the leakage of natural gas pipeline is not found in time, the MID will gradually increase and finally reach the limit stable state. Methane invasion limit distance (MILD): methane invasion distance in methane diffusion limit state. After the leakage of buried natural gas pipeline, the MID increased gradually. With the increase of leakage time, the MID will not expand all the time. When a certain concentration reached a certain boundary, there will be a dynamic equilibrium interface where the forward diffusion velocity was equal to the rear methane recharge velocity. This paper studied the MID based on the lower explosion limit of methane (5 vol %), and the monitoring line \((y = 0, \ z = H)\) was used to monitor the MID in the ground \(x\) direction, as shown in Figure 2. Methane invasion limit state (MILS): if the MID increased gradually and reached the limit stable state.

### Table 5. Working Conditions

| scenario | \(p_1\) (bar) | \(d\) (mm) | \(H\) (m) | \(S\) |
|----------|----------------|------------|----------|------|
| case 1   | 3              | 40         | 0.9      | loam |
| case 2   | 3.5            | 40         | 0.9      | loam |
| case 3   | 4              | 40         | 0.9      | loam |
| case 4   | 4.5            | 40         | 0.9      | loam |
| case 5   | 5              | 40         | 0.9      | loam |
| case 6   | 4              | 5          | 0.9      | loam |
| case 7   | 4              | 20         | 0.9      | loam |
| case 8   | 4              | 60         | 0.9      | loam |
| case 9   | 4              | 80         | 0.9      | loam |
| case 10  | 4              | 40         | 0.6      | loam |
| case 11  | 4              | 40         | 1.2      | loam |
| case 12  | 4              | 40         | 1.5      | loam |
| case 13  | 4              | 40         | 0.9      | sandy |
| case 14  | 4              | 40         | 0.9      | clay |

3. RESULTS AND DISCUSSION

#### 3.1. Grid Independence

Four grid levels were divided to monitor the diffusion of methane in loam under the condition of hardened surface ground, as shown in Figure 3. With the increase of the number of grids, the methane concentration on the monitoring line increased gradually. The average errors between the four grid levels were 5.02, 4.89, and 1.13% respectively. Therefore, the 111 950 grid level was selected to reduce the error caused by the number of grids to less than 2% so as to ensure the accuracy of calculation and reduce the amount of calculation. The mesh around and above the leakage hole was refined to improve the accuracy of the calculation.

The steady simulation method was used to calculate some conditions in Table 5, and the MILS in soil was analyzed. The MILD of buried natural gas pipeline leakage under the conditions of HSG, UHSG, and SHSG was compared, and the influence of pipeline operating pressure, leakage diameter, buried depth of pipeline, and soil type on MILD was analyzed.
encrypted. The maximum equisize-skew of the grids was 0.367076, and the active elements were 100%. The results of grid generation are shown in Figure 4.

3.2. Model Validation. The buried pipelines numerical simulation results of Ebrahimi-Moghadam et al.25 were used to verify the steady simulation method. The cuboid physical model (5 × 2 × 5 m³) was reestablished. The lengths to the left of the pipeline leakage hole and to the right were 3 and 2 m, respectively, and the diameter of the pipeline was 163.6 mm. The initial of the pipeline was the pressure inlet, the end of the pipeline was the pressure outlet, and the ground and soil boundary was the pressure outlet so that the physical model and boundary conditions were consistent with them. The experimental results of Yan et al.24 were used to verify the transient numerical simulation results. According to the experimental method, the cuboid model (5 × 3 × 3 m³) was reestablished. The buried depth of the pipeline was 0.9 m, the pipe diameter was 200 mm, and the leakage diameter was 5 mm. The simulated gas composition was 2.5% methane and 97.5% air, the volume flow rate was 12 L/min, and the average soil porosity was 0.1335. Monitoring points were set at sensor 4 (1.5, 0, 0.8 m) and sensor 9 (1, −1, 0.5 m). The results showed that the average errors of steady numerical simulation and transient numerical simulation results were 3.89 and 4.98%, respectively. The accuracy of the numerical simulation method in this paper was verified, as shown in Figure 5.

3.3. Influence of Ground Conditions on the MILS and MILD. 3.3.1. Pipeline Operating Pressure. Ground conditions had a serious impact on MILS and MILD. The distribution range and concentration of methane in the soil under the condition of HSG were the largest, followed by that under the condition of SHSG, and that under the condition of UHSG was the smallest. When the basic case 3 was changed from HSG to UHSG, the MILD decreased from 9.32 to 3.41 m. After the leakage of buried natural gas pipeline, methane will pass through the soil porous media to the ground, and the ground conditions will affect the next step of methane diffusion. The HSG will prevent methane from passing through the ground and entering the atmosphere, so it will increase the horizontal distribution range and concentration of methane in the soil. However, the UHSG has no hindrance to methane, methane will directly enter the atmosphere through the ground, and the horizontal distribution range of methane in soil is small. Therefore, HSG will increase the concentration and distribution range of methane in soil. The methane concentration and distribution range at the junction of hardened and unhardened surface areas of SHSG were between HSG and UHSG. Regardless of the kind of ground conditions, the diffusion range of methane in soil will

![Figure 5. Reliability verification of (a) steady numerical simulation method and (b) transient numerical simulation method.](image-url)

![Figure 6. MILS under different pressures.](image-url)
not increase all the time, and there was a limit state (MILS). The pipeline operating pressure had little influence on MILS and MILD. When the pressure increased from 3 to 5 bar, the concentration distribution of methane in soil was basically unchanged under the conditions of HSG, UHSG, and SHSG, as shown in Figure 6.

3.3.2. Leakage Diameter. The increase of leakage diameter will increase the concentration and range of methane distribution under MILS and increase the MILD. When the leakage diameter increased from 5 to 80 mm, the MILD increased from 7.02 to 8.92 m under HSG condition and from 2.13 to 3.43 m under UHSG condition. Meanwhile, with the increase of leakage diameter, the distribution range of methane high concentration area above the leakage hole will increase significantly, as shown in Figure 7. Compared with the pipeline operating pressure, the increase of leakage diameter will increase the methane leakage from natural gas pipeline to soil and increase MILD.

3.3.3. Buried Depth of Pipeline. The MILD increased from 1.75 to 3.49 m when the buried depth of pipeline increased from 0.3 to 1.5 m under the condition of NHG. When the buried depth of the pipeline reached 1.5 m under HSG condition, the MILD had exceeded 10 m, as shown in Figure 8. Increasing the buried depth of the pipeline will increase the vertical and horizontal diffusion distances of methane in the soil, increase the distribution range and concentration of methane in the soil under MILS, and increase the MILD. The buried depth of pipeline had a serious impact on MILS and MILD.

3.3.4. Soil Type. Under the conditions of HSG, UHSG, and SHSG, changing the soil type had little effect on the distribution and concentration of methane under MILS, as shown in Figure 9. Different soil types have different viscous resistance, inertial resistance, and porosity, which will affect the diffusion process of methane. However, in this part of the study, the results of steady-state diffusion of methane in soil showed that soil type had little effect on MILS.

The y = 0 plane was used to divide the model into SHSG, and the x = 0 plane was used to study MILS and MILD under the condition of SHSG. The area with x < 0 was the area covered by HSG, and the area with x > 0 was the area covered by UHSG. When methane leakage reached MILS, the HSG conditions increased the distribution range and concentration of methane and increased MILD, as shown in Figure 10.

To study MILD under MILS, monitoring line was used to monitor the MILD, as shown in Figure 11. The results were consistent with the cloud image study of MILD, the pipeline operating pressure and soil type had little influence on MILD, and the leakage diameter and pipeline buried depth will increase MILD. For MILD of the SHSG condition, the MILD of hardened surface area was consistent with that of the HSG condition, the MILD of unhardened surface area was consistent with that of the UHSG condition, and the MILD at the junction of hardened area and unhardened area was between that of the HSG condition and UHSG condition. Compared with the UHSG and SHSG, the HSG condition will expand the MILD and increase the range of dangerous area.

3.4. Study on MID under the Condition of Hardened Surface Ground. Through the study of MILS and MILD, it is known that the HSG condition will increase the distribution range and concentration of methane in soil under MILS and increase the MILD. Meanwhile, it is more difficult to detect methane leakage under HSG condition than under UHSG.
condition. Therefore, in this section, the transient numerical simulation method was used to study the diffusion characteristics of methane in soil under HSG condition.

3.4.1. Influence of Pressure on MID. With the increase of leakage time, the distribution range of methane in soil expanded gradually and the distribution concentration increased gradually. At the beginning of the leakage, the MID increased rapidly and then the increase rate decreased. The MID of methane increased from 1.53 to 3.25 m when the leakage time was from 600 to 7200 s under a pressure of 4 bar. The MID increments were 0.31, 0.28, 0.29, and 0.29 m respectively when the pipeline operating pressure increased from 3 to 5 bar after 600, 1800, 3600, and 7200 s, as shown in Figure 12. Compared with Figure 13, it can be seen that after the leakage of buried natural gas pipeline, the pipeline operating pressure had little effect on the diffusion process of methane in soil and MID.

3.4.2. Influence of Leakage Diameter on MID. With the increase of leakage diameter, the distribution range and concentration of methane in soil at different leakage times increased significantly, and leakage diameter had a serious impact on the diffusion process of methane. When the leakage diameter was reduced to 5 mm and the leakage occurred for 600 s, the methane diffusion distance had not reached the ground. When the leakage occurred for 7200 s, the maximum volume fraction of methane on the ground was only 35%. The increase of leakage diameter accelerated the diffusion rate of methane in soil, as shown in Figure 14.

With the increase of leakage diameter, the distribution concentration and range of methane on the monitoring line gradually increased and MID expanded. When the leakage diameter increased from 5 to 80 mm, the MID increments of 600, 1800, 3600, and 7200 s were 1.95, 2.37, 2.38, and 2.53 m, respectively, as shown in Figure 15. The influence of the change of leakage diameter on MID was about 8 times of that of the pipeline operation pressure, and the increase of leakage diameter had a serious impact on MID.

3.4.3. Influence of Buried Depth on MID. At the initial stage of leakage, the buried depth of pipeline had a great influence on MID. When the leakage occurred for 600 s, the MID decreased significantly when the buried depth of the pipeline increased from 0.3 to 1.5 m, as shown in Figure 12. Compared with Figure 13, it can be seen that after the leakage of buried natural gas pipeline, the pipeline operating pressure had little effect on the diffusion process of methane in soil and MID.

Through methane volume fraction on the monitoring line, it can be seen that the buried depth of the pipeline had a greater impact on MID at the initial stage of the leakage and had a smaller impact on MID after 3600 s of the leakage. When methane leaked for a period of time, the change of MID with the

---

Figure 8. MILS under different buried depths.

| HSG | | | | | |
| UHSG | | | | | |
| SHSG | | | | | |
Figure 9. MILS under different soil types.

Figure 10. MILS in SHG condition under different scenarios.
buried depth was not a simple linear relationship. After 3600 s of leakage, the change of MID first increased and then decreased with the buried depth. When the leakage time was 7200 s, the MIDs of five kinds of pipeline buried depth conditions, which increased from 0.3 to 1.5 m, are 2.13, 3.14, 3.25, 3.17, and 3.14 m, respectively, as shown in Figure 17.

In addition to the pipeline operating pressure, leakage diameter, and pipeline buried depth, the direction of leakage hole will also have a certain impact on the MID. When the leakage hole is vertically upward, the methane concentration is symmetrically distributed with the vertical direction of the leakage hole as the center. When the leakage hole direction changes, the methane ejected from the leakage hole will increase the MID in the leakage direction and reduce the anti-upward MID under the action of inertia.

3.5. Prediction Equation of MID on Hardened Surface Ground. According to the MID under different working conditions, the MID and its related parameters were analyzed using the least-square method and multiple regression theory and the multiple nonlinear regression model was established and solved by Matlab mathematical calculation software. Finally, the correlation between MID and different pipeline operating pressures, leakage diameters, and buried depths was established, and the MID prediction equation was obtained. Because of the delay effect of methane in soil, methane cannot reach the ground directly when the buried natural gas pipeline leaks in the first time, so the initial time is 300 s. When the MID result is negative, it means that methane diffusion does not reach the ground. The specific form of MID prediction equation is shown in eq 20.

\[
\begin{align*}
\text{MID} &= -4.4821 \times 10^{-4} (p_1 \cdot d)^{1/4} + 1.6109 d^{1/4} \\
&\quad + 0.1491 H + 0.39 t^{1/4}
\end{align*}
\]

if: MID < 0, MID = 0

\[
\begin{align*}
3 \leq p_1 \leq 5 \text{ bar} \\
0 \leq d \leq 80 \text{ mm} \\
300 \leq t \leq 36000 \text{ s}
\end{align*}
\]

s. t. hardened surface ground

where \( p_1 \) is the absolute pressure (bar), \( d \) is the leakage diameter (mm), \( H \) is the pipeline buried depth (m), \( t \) is the leakage time (s), and MID is the methane invasion distance (m).

To ensure the accuracy of the calculation results of the MID prediction equation and prolong the application time, the calculation results of the MID prediction equation within 10 h were compared with the numerical simulation results under the three working conditions in Figure 18a. As seen, the calculation results of MID prediction equation were in good agreement with
the numerical simulation results. As can be seen from the MID calculation error in Figure 18b, the calculation error of the prediction equation was large at the initial stage of leakage, with the maximum error reaching 16.12%. With the increase of leakage time, the calculation error of MID prediction equation decreased gradually and the average error was 2.37%, which verified the accuracy of the prediction equation. This is due to the delay effect of methane diffusion in soil, which increases the calculation error of MID prediction equation at the initial stage of leakage. Therefore, the MID prediction equation can accurately predict the leakage within 10 h and obtain the constraints of eq 21.

The MID prediction equation is a function of time \( t \), and the MID gradually increases and tends to MILD with the extension of time. The MID prediction equation was derived from time \( t \) to obtain the change of MID growth rate \( \delta \) with time \( t \), as shown in eq 22. It can be seen that with the increase of time \( t \), the MID growth rate decreased gradually and the \( \delta \) limit tended to 0. Meanwhile, it can be seen from Figure 18a that with the increase of leakage time, the \( \delta \) real value was smaller than the predicted value. Therefore, the MID will gradually approach the MILD and reach the equilibrium state.

\[
\delta = 0.0975 \times \frac{1}{t^{1/4}}
\]

4. CONCLUSIONS

To ensure the safety of energy use, the risk of leakage of buried natural gas pipeline was analyzed in this paper. The steady numerical simulation method was used to study the MILS and MILD under the conditions of HSG, UHSG, and SHSG, and the MID transient simulation was carried out for the HSG condition with the largest MILD. Based on the Results and Discussion section, the following conclusions were drawn:

1. Regardless of the kind of ground conditions, the methane invasion distance (MID) in soil will not increase all the time after natural gas pipeline leakage, and there was a
(1) It is suggested that the horizontal distance between natural gas pipeline and buildings should be more than the MILD in the construction.

(2) Within the scope of the study, the leakage diameter and buried depth of pipeline had a great influence on MILD. In the process of increasing the leakage diameter from 5 to 80 mm, the MILD increased from 7.02 to 8.92 m under HSG condition and from 2.13 to 3.43 m under UHSG condition. When the buried depth of the pipeline increased from 0.3 to 1.5 m, the MILD increased from 1.75 to 3.49 m under the condition of UHSG, and the MILD had exceeded 10 m under HSG condition. The influence of pipeline operation pressure and soil type on MILD was small.

(3) Ground conditions had a serious impact on MILS and MILD. The distribution range and concentration of methane in the soil under the condition of HSG were the largest, followed by that under the condition of SHSG, and that under the condition of UHSG was the smallest. When the ground condition changed from HG to UHSG, MILD decreased from 9.32 to 3.41 m. For MILD of SHSG condition, the MILD of hardened surface area was consistent with that of HSG condition, the MILD of unhardened surface area was consistent with that of UHSG condition, and the MILD at the junction of hardened surface area and unhardened surface area was between those of HSG condition and UHSG condition. Compared with the UHSG and SHSG, the HSG condition will expand the MILD and increase the range of dangerous area.

(4) Compared with the operating pressure and buried depth of the pipeline, the leakage diameter had a greater impact on the leakage and diffusion process of methane under the condition of HSG. When the leakage diameter increased from 5 to 80 mm, the MID increments of 600, 1800, 3600, and 7200 s were 1.95, 2.37, 2.38, and 2.53 m, respectively.
The average error of MID prediction model was 2.37% under the condition of HSG, which can realize accurate prediction of MID in buried natural pipeline leakage. The MID provides a reference for the layout of urban underground gas leakage monitoring points. The MILS and MILD under different ground conditions can provide guidance for the safe distance between natural gas pipeline and structures in the design code of natural gas pipeline.

Figure 16. Influence of buried depth on CH₄ concentration distribution in soil.

Figure 17. Influence of buried depth on CH₄ concentration distribution on monitoring line at (a) t = 600 s, (b) t = 1800 s, (c) t = 3600 s, and (d) t = 7200 s.

(5) The average error of MID prediction model was 2.37% under the condition of HSG, which can realize accurate prediction of MID in buried natural pipeline leakage. The MID provides a reference for the layout of urban underground gas leakage monitoring points. The MILS and MILD under different ground conditions can provide guidance for the safe distance between natural gas pipeline and structures in the design code of natural gas pipeline.

Figure 18. Verification of (a) MID prediction model and (b) calculation error.

## AUTHOR INFORMATION

**Corresponding Authors**

Yang Liu — School of Petroleum Engineering, Northeast Petroleum University, Daqing 163318 Heilongjiang, China; orcid.org/0000-0001-5514-9820; Email: ly001@nepu.edu.cn

Shuangqing Chen — School of Petroleum Engineering, Northeast Petroleum University, Daqing 163318 Heilongjiang, China; Email: csqing2590@163.com

**Authors**

Fanxi Bu — School of Petroleum Engineering, Northeast Petroleum University, Daqing 163318 Heilongjiang, China

Zhe Xu — Gas Technology Institute of Petrochina Kunlun Gas Co. Ltd., Harbin 150001 Heilongjiang, China

Yongbin Liu — Gas Technology Institute of Petrochina Kunlun Gas Co. Ltd., Harbin 150001 Heilongjiang, China
Complete contact information is available at:
https://pubs.acs.org/10.1021/acsomega.1c04322

Funding
This work was supported by the National Natural Science Foundation of China (nos. 52074090 and 52104065), China Postdoctoral Science Foundation (no. 2020M681064), Heilongjiang Postdoctoral Foundation (no. LBH-Z20101), Petroleum and Natural Gas Engineering Scientific Research Personnel Training Foundation (no. 15041260503), Youth Science Foundation of Northeast Petroleum University (no. 2019QNL-09), and Northeast Petroleum University Scientific Research Foundation (no. 2019KQ54).

Notes
The authors declare no competing financial interest.

- Nomenclature

- Subscript

- References

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