Feasibility study of detecting gas leakage in buried pipeline based on resistivity method

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Abstract. Urban gas pipe networks are mostly buried underground and it is hard to monitor, detect and locate the leakage area effectively. The primary structure of the soil could change before and after aeration, so the detection method of gas leakage based on resistivity method has some physical basis. Based on the theoretical research of the predecessors, corresponding geoelectric model is established by combining two typical gas leakage geological models to study the influences of testing device, leakage mode and leakage intensity on the distribution characteristics of gas leakage geoelectric field. Obtained by using forward and inverse numerical computation methods, the theoretical resistivity profile image is compared with the resistivity profile measured by outdoor gas leakage simulation experiment to evaluate comprehensively the feasibility and effectiveness of detecting gas leakage of buried pipelines based on resistivity differential characteristics. The research results show that resistivity method could describe the spatial distribution location effectively and the electrical resistivity has positive correlation with leakage pressure. And the pressure inside the pipeline also determines the migration path of the gas leakage, which diffuses outwards in the shape of “smoke ring” in high-pressure leakage.

1. Introduction
As a long-distance transporter, the pipeline plays important roles in transregional deployment of gas resources. In recent years, with gradual increase of the occurring frequency and intensity of gas leakage, safety maintenance, health monitoring and detection of leak source of pipeline infrastructure has become one of the public security problems that remain to be solved. To locate fast and effectively the source of leakage, relevant scholars both at home and abroad have conducted plenty of studies. So far, the detection methods of gas leakage sources are mainly divided into three categories, namely, manual inspection, sensor detection, and numerical simulation [7,11]. Manual inspection adopts mainly the way of GIS + hand-held terminal and it has been replaced gradually by UAV remote sensing system. Sensor detection mainly uses optical sensors, acoustic sensors, pressure sensors, and gas sensors to detect temperature, sound wave, infrasonic wave, and concentration, among which acoustic emission technology in geophysical exploration has high sensitivity and can detect many abnormal state in the pipeline immediately. So, detection technology based on acoustic emission has been applied in detection of various gas pipeline leakage [9,10,13,14]. Numerical simulation
calculation mainly forward model the main parameters, such as pressure, temperature, concentration, flow quantity and flow rate using the fluid dynamics software (Fluent), and then simulate the dynamic changing process of gas leakage with mass conservation, pressure point analysis and other software [3].

Resistivity imaging technology is another minimally invasive geophysical technology, which detects the target layer mainly by observing the resistivity of the underground medium. At present, the research results of using resistivity method to detect gas leakage are few. However, resistivity method has good detection resolution on spatial distribution and migration of underground CO₂ [1]. And the group led by Guo et al. constructed various geoelectric models aiming at leakage of cold spring gas in submarine sediment, which have verified that resistivity imaging technology is effective in detecting gas zone; meanwhile, they also designed a seabed-based field electricity monitoring system, which has realized real-time monitoring of methane gas leakage in the settled layer during exploration of hydrates [8,12].

The resistivity imaging technology is used to conduct a more systematic study on gas pipeline leakage in this paper. To detect more accurately the scope of gas leakage, geoelectric models are constructed with three parameters, that is, test device, leakage mode and leakage intensity by the method of forward and inverse numerical modeling. The theoretical resistivity profile map is obtained by using the method of numerical computation, which is analyzed by comparing with the actually measured profile of the simulated outdoor buried gas leakage. By comprehensively analyzing the resistivity detection profile of the leakage process of buried pipeline gas, the feasibility of the proposed method is discussed further.

2. Basis of physical property detection and theoretical study

2.1. Basis of physical property detection
Studies show that there are mainly three typical failure modes after the soil is filled with air, which are extension of the primary fissures, movement of soil particles along the holes and local airbag formed within the soil, respectively [4]. Similarly, the failure mode of the surrounding soil caused by gas leakage (geological model of gas leakage) can be summarized into the following two modes: high pressure gas expands the primary pores and extends to the surface (Figure 1a: treelike model); local air sacs are formed and extend to the surface (Figure 1b: treelike and gasbag models). Geological model of gas leakage is shown in Figure 1.

![Figure 1. Two geological models of gas leakage in buried pipelines](image)

After the soil is filled with gas, the gas will fill in the primary fissures of the soil layer, making them expand further. Related research shows that when gas is contained in the rock and the soil layer, the resistivity will increase with the increase of the gas content. This electrical characteristic can be used as the basis of physical property detection in this study.

2.2. Calculation principle
The distribution law of the geoelectric field of each gas leakage model with different parameters is obtained by forward calculation using the known geoelectric model. The forward simulation adopts
The finite element method, that is, the partial differential formula is solved based on electric potential field to obtain the functional extremum. Based on the electric field differential formula and the boundary condition, the variational problem is:

\[ F(u) = \int \left[ \frac{1}{2} \sigma (\nabla u)^2 + \sigma \Delta u \right] \text{d}u + \int \left[ \frac{1}{2} \sigma \frac{\cos(r,n)}{r} u^2 + \frac{\sigma \cos(r,n)}{r} u_0 u \right] \text{d}\Gamma \]

(1)

\[ \delta F(u) = 0 \]

(2)

where, \( u \) is abnormal potential; \( \sigma \) is the parameter of dielectric conductivity; \( n \) is the direction of out-of-bound zoning law; \( r \) is the vector radius, \( \Gamma \) is the boundary.

The resistivity data in the finite element forward model is inversed by damped least square method to obtain the theoretical resistivity profile, which is compared with geoelectric model. The core of least square inversion is to solve the correction value vector \( \Delta m \) when the target function \( \Psi \) is the least. The formula of the target function \( \Psi \) after smooth constraint is:

\[ \Psi = \| \Delta d - A \Delta m \|^2 + \lambda \| C \Delta m \|^2 \]

(3)

where, \( \Delta d \) is residual vector; \( \Delta m \) is the corrected parameter of the vector; \( A \) is the partial derivative matrix; \( \lambda \) is Lagrange constant; \( C \) is smoothness matrix.

3. Numerical simulation of gas leakage geoelectric field

3.1. Geoelectric model

According to code for design of city gas GB50028-2006, it is stipulated that the piping diameter of the simulation is 0.2 m and the embedding depth is 2.5 m. The stratum parameter is shown in Table 1. The resistivity parameters of each stratum are quoted in Appendix F: the code for grounding design of AC electrical installations DL/T 621-1997. The resistivity of the soil layer is 1000 \( \Omega \cdot \text{m} \) under aerated condition and the pipeline (steel pipe) is 20 \( \Omega \cdot \text{m} \) [2].

| Layer | Corresponding stratum | Resistivity (\( \Omega \cdot \text{m} \)) | Depth (m) |
|-------|------------------------|----------------------------------------|-----------|
| No.1  | Miscellaneous fill     | 200                                    | 0-2.5     |
| No.2  | Clay                   | 100                                    | 2.5-7     |

Based on the geological model of gas leakage of the buried pipeline (Figure 1), corresponding geoelectric model is established with Earth Imager2D software (Figure 2) to analyze the response law of the geoelectric field during leakage. This paper studies mainly the electrical response characteristics and the changing rules of gas leakage from buried pipelines under the condition of three variables, i.e., test device, leakage mode and leakage intensity.

![Figure 2. Resistivity synthesis model (a: treelike model; b: treelike and gasbag model)](image-url)
3.2. Resistivity simulation of different testing devices
The geoelectrical response characteristics of different resistivity test devices to the same target are significantly different. To select appropriate device to simulate gas leakage, the dipole-dipole device, tri-pole device, and Wenner-Schlumberger device (WS) are adopted in this study to analyze the geoelectric field response characteristics of the leakage geological model in Figure 1(a) [6].

Figure 3 shows the theoretical resistivity profile of different testing devices under the same geological condition. It could be seen from Figure 3 that all three devices have good responses to identification of stratification, pipeline location and diffusion area of gas leakage, and that the location of the abnormal high-resistance area is consistent with the location of the resistivity synthesis model. WS is obviously more sensitive to gas leakage area than the other two. It is analyzed that the reason might be that high-sensitivity region of dipole-dipole device appears under the transmitting dipole and the receiving dipole and its sensitivity isolines are almost vertical; so, it has obvious effects on detection of objects with certain extension. The resistivity inverse profile image of the pipelines in Figure 3(a) is more distinct than that in Figure 3(b) and (c). The sensitivity of tri-pole device to two abnormal regions is similar to that of the dipole-dipole device, but with lower resolution. The sensitivity of the WS device appears directly below the measuring electrode and has some horizontal and vertical resolution. Therefore, it has the best resolution and sensitivity to aerated soil fissures extending vertically. In subsequent studies, Wenner-Schlumberger (WS) will be taken as the major measuring device.

![Figure 3. Theoretical resistivity profile with different devices (a: dipole-dipole; b: tri-pole; c: WS)](image_url)

3.3. Resistivity simulation of different leakage modes
By analyzing Figure 1, it could be seen that there are two failure modes in the aerated state of the soil layer. Corresponding geoelectric models are established for two typical gas leakage geological models (Figure 2). With the same testing device and other conditions, the differences of the geoelectric field distribution in the leakage states of two modes are analyzed.

It could be concluded from Figure 4(a) and (b) that the gas accumulation area show high-resistance anomalies during treelike leakage, treelike and gasbag leakage. However, since gasbag leakage expands horizontally, it expands little vertically. From Figure 4(b), it could be seen that high-resistance anomaly response in gasbag accumulation area is obviously lower than that in treelike leakage.

![Figure 4. Theoretical resistivity profile of different leakage modes](image_url)
3.4. Simulation of leakage resistivity at different intensity

The air pressure in the gas pipeline varies under different working conditions, usually between 0-4 MPa. When the gas pressure in the gas pipeline varies, the expansion degree and diffusion scope of soil crack during the leakage vary also. In this simulation, the geoelectric response characteristics of the same leakage mode (treelike leakage) are calculated under three air pressures (a: small leakage; b: medium leakage; c: large leakage).

The above geoelectric model is calculated and the simulation results are shown in Figure 5(a), (b) and (c). It can be seen from the figure that with the same external condition, as the leakage pressure increases, both the resistivity and the range of influence increase, showing significant positive correlation. On the contrary, when the leakage pressure is lower than some characteristic value, it is impossible to detect effectively the leakage area with the feature of resistivity difference, as shown in Figure 5(a).

![Figure 5. Theoretical resistivity profile at different intensity](image)

4. Outdoor simulated detection of buried pipeline gas leakage

4.1. Experimental system

To conduct geoelectric simulation test on gas leakage of buried pipelines, buried pipeline model is established, which could simulate gas leakage of buried pipelines authentically. Considering the safety of the experiment, the air compressor is used to pressurize the pipelines, and the maximum pressure of the system is designed as 1.2 MPa. Figure 6 shows the simple framework of the testing system. To simulate the real leakage process, the testing system adopts manual pressure regulating valve and magnetic valve to simulate the leakage, among which the pressure regulating valve could adjust the gas pressure within the pipelines and the magnetic valve could be used to simulate the outburst of the leakage.

![Figure 6. Testing system of buried pipeline gas leakage](image)
4.2. Acquisition system and sensor layout
The resistivity test uses the network parallel electrical equipment which was independently developed
by the research group. To monitor effectively the geoelectric response characteristics of gas leakage of
buried pipelines, first, the pipelines are buried 0.5 m underground, and magnetic valve is installed at
the leakage mouth, which is a circular hole with the diameter of 5mm, as shown in Figure 7(a), (b). Then,
the pipeline is refilled and compacted; and last, resistivity observing system is configured at the
leakage mouth of the buried pipelines to form a three-dimension testing space. The resistivity sensor
unit is made by cable and copper bar, as shown in Figure 7(c), (d). Since the leakage mouth is
connected to the pipelines by magnetic valve, the actual distance between the leakage mouth and the
ground surface is 0.25 m, which is located at the exact center of the resistivity observing system.

![Figure 7. Acquisition system and sensor layout](image)

4.3. Data processing and analysis
In this test, three pressures (0.4, 0.6 and 0.8 MPa) are adopted to simulate different degrees of gas
leakage from buried pipelines. Since resistivity test can only obtain steady data, continuous leaking
method is used in this test to dynamically detect and simulate the pipeline leakage.

To differentiate more clearly the distribution scope of gas leakage zones under different pressures,
the inversed resistivity of each layer is extracted from the three-dimension testing system, and then the
initial inversed resistivity of the corresponding zone is extracted under the condition of no leakage.
After that, two groups of resistivities at the same location are compared in proportion. The obtained
ratio is defined as the relative resistivity, and finally the relative resistivity at different positions is
used for plotting.

Figure 8 (a), (b) and (c) is the three-dimension slice map of the actually measured resistivity at 0.4,
0.6 and 0.8 MPa leakage, respectively. When the gas pressure is small, gases surrounding the leakage
mouth will migrate laterally, showing abnormal resistivity in the transverse zone, as shown in the slice
map at the depth of -0.22 m in Figure 8 (a). With the increase of gas, it begins to migrate gradually in
vertical direction, till the surface. For example, local high-resistance abnormal zones appear at the
depths of -0.03 m, -0.08 m and -0.15 m in Figure 8 (a).

![Figure 8. Three-dimension slice map of relative resistivity at 0.4, 0.6 and 0.8 MPa](image)

As the pressure within the pipeline increases, the flow rate and pressure of the leaked gas increase
sharply, which could disturb greatly the compactness of the soil at the moment of leakage. Then,
vertical fracture channel is generated. The three-dimension slice map of the relative resistivity also
shows good connectivity. At the same time, it could be seen from Figure 8 (b), (c) that with the increase of the gas pressure, the scope of high-resistance abnormal zone will also expand correspondingly.

The above three experiments show that when the soil is invaded by gas, the gas distribution area will exhibit obvious high-resistance abnormal characteristics, and the size of the abnormal zone shows clear correspondence with the size of the gas distribution zone. Based on the experimental condition, when the intensity of the pressure in the pipeline is less than 0.6 MPa, the compactness of the soil in the leakage zone is disturbed little and distribution of resistivity abnormal zone lacks continuity. When the gas pressure in the pipeline is higher than 0.6 MPa, with the increase of the pressure, both the high-resistivity anomaly and the distribution range of the gas leakage area increase. During the leakage of high-pressure gas in the pipeline, the gas leakage path expands outwards in the shape of “smoke ring”, which could be depicted in the image of the measured resistivity.

5. Conclusions and prospect

By constructing geoelectric models of gas leakage in different states, large-scale theoretical calculation of resistivity detection image is conducted, and the results are compared with the simulation experiment results of small-scale outdoor gas leakage. The results of these two types of researches have verified preliminarily that resistivity method could detect gas leakage under different leakage modes and certain gas leakage state. The following conclusions are obtained:

(1) Research results indicate that WS device has good effects in detecting gas leakage of buried pipelines and the vertical migrating pathway in the detection image is easier to be identified than short-distance lateral migration pathway.

(2) The results of physical simulation experiments show that when the gas in the pipeline is low, the leaked gas will first migrate horizontally, and with the aggregation of the gas, vertical fissures are generated. When the pressure in the pipeline is high, the instantaneous leakage of gas will first migrate vertically, and the gas leakage path will expand outwards in the shape of “smoke ring”. In addition, the resistivity of the gas leakage zone is positively related to the leakage pressure.

(3) Distribution of gas leakage zones obtained at different detection scales shows the same high-resistance abnormal characteristic. However, the detection precision could be affected by the size of the detection system, the burying media of the pipeline, the types of the detection device, the material of the pipeline and the gas leakage pathway, which should be studied further.

In conclusion, based on the proposed geoelectric numerical computation and the physical modeling calculation, it has been verified preliminarily that resistivity method is feasible in detecting gas leakage of buried pipelines. However, it is affected greatly by the geological conditions of the buried pipelines in actual application and its range of application still remains to be improved. According to the research results of Liu et al., in the future, micro-fissure of soil could be monitored by natural electric field, and the failure state of the soil caused by gas shock could be predicted by the law of self-potential fluctuation, which, compared with relative resistivity, has leading advantages in time domain [5]. At the same time, complete sets of electrical equipment that could be used to monitor gas leakage of buried pipeline should be developed with focus so as to improve the sampling rate and the imaging precision.

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