Studying and Analyzing Leak Locations in Deeply Buried and High-Resistivity Pipeline Based on a DC Potential Method

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ABSTRACT It is not uncommon for underground water supply or heating pipelines to break and leak, but such events can cause serious inconvenience to the lives of residents. The accurate and timely detection of the leak locations is the primary objective in solving pipeline rupture issues. Based on the direct current (DC) resistivity method, which provides a stable signal, convenient interpretation, and strong anti-interference ability, we adopted the pole-pole device form of the DC potential method to detect the locations of leaks in high-resistivity water supply or heating pipelines. A finite element numerical simulation method was used to study the characteristics of the leakage point potential distribution with and without metal pipeline interference. The numerical simulation results show that the pole-pole DC potential method has strong anti-interference ability and can effectively locate locations of leaks in pipelines with metal interference. The numerical simulation results were verified by physical experiments. The research results show that the pole-pole DC potential method can effectively detect the locations of leaks in high-resistivity pipelines.

INDEX TERMS DC resistivity exploration, finite element numerical simulation, leak detection, geophysical prospecting.

I. INTRODUCTION

The construction and maintenance of water supply and heating pipelines are the foundation that ensures the normal operation of a city. With the development of cities, the water supply and heating pipes in some old urban areas have been in disrepair for many years and are prone to rupture [1]. Especially in the winter, due to the low temperature, heating pipes are likely to rupture, thus significantly impacting the heating of cities and leading to the inconvenience of residents, as shown in Fig. 1 (pictures from the Internet). Finding out the locations of leaks in time is the most important thing for the restoration of normal water supply and heating.

At present, the methods commonly used to detect leaks in water supply and heating pipes include the listening method [2]–[4] and the ultrasonic instrument detection method [5], [6]. The listening method is greatly affected by external factors. When the leakage points are far away or the surrounding industrial noises are large, the position of the leakage points cannot be accurately heard. The ultrasonic detection method mainly uses the ultrasonic motion generated by the leakage points to locate the location. But the quality of inspection is seriously affected when the pipes are deep-buried, or the amount of water leakage is small. In addition to the above mainstream detection methods, there is also a ground-penetrating radar method based on electromagnetic waves [7]. However, the signal of this method is greatly interfered by urban industry. When there is a large amount of metal or cables above the pipes, the pipes below cannot
be detected. In addition, there are some methods that can accurately detect pipeline cracks and leak locations, but many sensors need to be placed directly on pipelines. They are only suitable for detecting micro-cracks in exposed pipelines on the surface and cannot detect the location of leaks in deep-buried pipelines [8]–[10]. Existing leak-point location detection instruments are represented by correlators, but they are expensive and complicated to operate.

We once proposed to use a pole-dipole device for leak detection, but this method is complicated to explain, and the construction efficiency is low [11]. In order to accurately and quickly locate leak locations in water supply or heating pipes, we start from the basic principle of the DC resistivity method [12], which is commonly used in geophysical shallow geological exploration [13] and propose using pole-pole DC potential method for detecting the locations of leaks. This method involves supplying a steady-state current to the metal valve or water inlet of a high-resistivity pipeline. When there is a leak in the high-resistivity pipeline, the medium around the water pipe contacts the water in the pipe through the leak, and the current that originally existed in the pipe passes the leakage point spreads into the surrounding medium, the horizontal position of the leakage point is detected by observing the potential on the ground surface. Compared with the traditional method, this method is not affected by the magnitude of the flow rate, the size of the leakage point, or the temperature of the water and is only related to whether the water in the tube is in direct contact with the medium outside the tube. First, numerical simulation was used to analyze the feasibility and anti-interference ability of the method. Then, physical experiments were designed to verify the numerical simulation results. The numerical simulation and physical experiment results indicate that the DC potential method to detect the location of leaks of water supply and heating pipes with high resistivity has strong anti-interference ability and accurate positioning. Also, we propose a post-processing method, which can be used to quickly locate and display the leakage points.

II. METHOD AND PRINCIPLE
Traditional DC exploration arranges power supply electrodes and measures electrodes on the surface to detect underground electrical anomalies. The data measured by the measuring electrodes reflect the comprehensive effect of the electrical information in the underground space. It is difficult to determine the horizontal and vertical positions of an abnormal body due to the volume effect when the abnormal body is deeply buried and small.

In order to prevent water supply or heating pipes from being corroded by the surrounding soil, PVC pipes or thermal insulation steel pipes wrapped with polyurethane are mostly used. The materials used are all insulators. Therefore, the current only exists in the pipe, and the potential signal cannot be observed on the ground surface when the power is supplied to the pipe valve if the pipe is intact. The current passes through the leakage point to form a point current source if the pipe is corroded or the pressure breaks the pipe and causes a leak, as shown in Fig. 2. In the figure, the DC potential measuring instrument is used to receive the potential at the surface. The spatial location of the water supply or heating pipe rupture can be judged by the surface potential distribution and the known pipeline information.

The potential of any point on the surface and underground can be expressed by the following formula when the point current source is underground [14].

\[
U = \frac{\rho I}{4\pi \left( \frac{1}{R} + \frac{1}{R'} \right)} = \frac{\rho I}{2\pi R} \tag{1}
\]

where \(\rho\) is the resistivity of the uniform half-space, \(I\) is the power supply current, \(R\) is the distance between any point and the current source, \(R'\) is the distance between any point and the virtual current source. When the measuring point is on the surface, \(R = R'\). Since the pipeline is generally buried in the quaternary soil at a small depth, it can be considered that the pipe is located in a uniform half-space. We use the pole-pole device form to for detection, that is, power is supplied to one point and the potential at a certain point is detected, as shown in Fig. 2.

III. NUMERICAL SIMULATION AND ANALYSIS
Since urban water supply and heating pipes are generally circular, the finite element method that can be used for complex models [15], [16] is used for numerical simulation. A tetrahedral mesh is used for model division.

A. FINITE ELEMENT METHOD THEORY
In the case of a uniform half space, the boundary value problem of the 3D potential is expressed by the following formula [17]:

\[
\nabla \cdot (\sigma \nabla u) = -2I \delta (A) \in \Omega \\
\frac{\partial u}{\partial n} = 0 \in \Gamma_s \\
\frac{\partial u}{\partial n} + \frac{\cos (r, n)}{r} u = 0 \in \Gamma_\infty
\tag{2}
\]
where \( \sigma \) is the conductivity, \( \Omega \) is the study areas, \( \Gamma_s \) s the ground boundary and \( \Gamma_\infty \) is the infinity boundary. Construct the functional according to (2) as:

\[
I (u) = \int_{\Omega} \left[ \frac{1}{2} \sigma (\nabla u)^2 - 2I \delta (A) u \right] d\Omega. \tag{3}
\]

The variation of (3) is the following formula:

\[
\delta I (u) = \int_{\Omega} [\sigma \nabla u \cdot \nabla \delta u - 2I \delta (A) \delta u] d\Omega
= \int_{\Omega} [\nabla \cdot (\sigma \nabla u \delta u) - [\nabla \cdot (\sigma \nabla u) + 2I \delta (A) \delta u]] d\Omega \tag{4}
\]

By substituting the first equation of (2) into (4), we can obtain the following equation:

\[
\delta I (u) = \int_{\Omega} \nabla \cdot (\sigma \nabla u \delta u) d\Omega = \int_{\Gamma_1+\Gamma_\infty} \frac{\delta u}{\delta n} d\Gamma \tag{5}
\]

By substituting the second and third equations of (2) into (5), we can obtain the following equation:

\[
\delta I (u) = \int_{\Gamma_1+\Gamma_\infty} \frac{\delta u}{\delta n} \delta u d\Gamma = \int_{\Gamma_\infty} \frac{\delta u}{\delta n} \delta u d\Gamma
= -\int_{\Gamma_\infty} \frac{\cos (r, u)}{r} u \delta u d\Gamma
= -\frac{1}{2} \int_{\Gamma_\infty} \frac{\cos (r, u)}{r} u^2 d\Gamma \tag{6}
\]

After moving items,

\[
I (u) + \frac{1}{2} \int_{\Gamma_\infty} \frac{\cos (r, u)}{r} u^2 d\Gamma = 0 \tag{7}
\]

Therefore, the boundary value problem of 3D potential is equivalent to the following variational problem:

\[
F (u) = \int_{\Omega} \left[ \frac{1}{2} \sigma (\nabla u)^2 - 2I \delta (A) u \right] d\Omega
+ \frac{1}{2} \int_{\Gamma_\infty} \frac{\cos (r, u)}{r} u^2 d\Gamma \tag{8}
\]

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

The area integral of (8) is divided into multiple-element integrals by tetrahedral elements and linear interpolation. The integral unit is shown in Fig. 3. The numbers 1, 2, 3 and 4 in the figure are the vertices of each tetrahedral element, and P is any point inside the element.

The potential of point P can be obtained by linear interpolation based on the potential of the four vertices.

\[
u = N_1 u_1 + N_2 u_2 + N_3 u_3 + N_4 u_4 \tag{9}
\]

In the formula, \( u_1, u_2, u_3 \) and \( u_4 \) are the potentials corresponding to vertices 1, 2, 3 and 4, respectively. \( N_1, N_2, N_3 \) and \( N_4 \) are shape functions shown as the following formulas, which are determined by the vertex coordinates, volume of the tetrahedron and coordinate of P.

\[
N_1 = \frac{1}{6V} \begin{bmatrix} x y z \\ x_2 y_2 z_2 \end{bmatrix} \begin{bmatrix} 1 \\ x_1 y_1 z_1 \end{bmatrix} \begin{bmatrix} x_3 y_3 z_3 \end{bmatrix} \begin{bmatrix} x_4 y_4 z_4 \end{bmatrix}
N_2 = \frac{1}{6V} \begin{bmatrix} x y z \\ x_1 y_1 z_1 \end{bmatrix} \begin{bmatrix} x_3 y_3 z_3 \end{bmatrix} \begin{bmatrix} x_4 y_4 z_4 \end{bmatrix} \begin{bmatrix} x_2 y_2 z_2 \end{bmatrix}
N_3 = \frac{1}{6V} \begin{bmatrix} x y z \\ x_1 y_1 z_1 \end{bmatrix} \begin{bmatrix} x_2 y_2 z_2 \end{bmatrix} \begin{bmatrix} x_4 y_4 z_4 \end{bmatrix} \begin{bmatrix} x_3 y_3 z_3 \end{bmatrix}
N_4 = \frac{1}{6V} \begin{bmatrix} x y z \\ x_1 y_1 z_1 \end{bmatrix} \begin{bmatrix} x_2 y_2 z_2 \end{bmatrix} \begin{bmatrix} x_3 y_3 z_3 \end{bmatrix} \begin{bmatrix} x_4 y_4 z_4 \end{bmatrix}
\]

Then the first term of formula (8) can be written as the following formula:

\[
\int_{\Omega} \frac{1}{2} \sigma (\nabla u)^2 d\Omega = \frac{1}{2} u^T K_1 u \tag{11}
\]

where \( u = (u_1 \cdots u_4)^T \), \( K_1 = (k_{ij}) \),

\[
k_{ij} = \int_{e} \frac{dN_i}{dx} \frac{dN_j}{dx} + \frac{dN_i}{dy} \frac{dN_j}{dy} + \frac{dN_i}{dz} \frac{dN_j}{dz} dxdydz,
\]

\[i, j = 1, 2, 3, 4.\]

The second term of formula (8) can be written as the following formula:

\[
\int_{\Omega} 2I \delta (A) u d\Omega = u_A I \tag{12}
\]

The formula (12) is the integral only related to the current source point \( u_A \). If one surface \( \Gamma_{123} \) of the element falls on the boundary of infinity, the third term of the first formula of (8) can be reduced to the following formula.

\[
\frac{1}{2} \int_{\Gamma_{123}} \frac{\cos (r, n)}{r} u^2 d\Gamma = \frac{1}{2} u^T K_2 u \tag{13}
\]

where

\[
K_{2e} = \frac{\sigma \cos (r, n)}{2r} \begin{bmatrix} N_1 N_1 & N_1 N_2 & N_1 N_3 & 0 \\ N_2 N_1 & N_2 N_2 & N_2 N_3 & 0 \\ N_3 N_1 & N_3 N_2 & N_3 N_3 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}
\]

Add up (11) to (13) and expand them into the overall matrix.

\[
F (u) = \sum F_e (u) = \sum \frac{1}{2} u^T (K_{1e} + K_{2e}) u_e - u_A I
\]
The potential value of each node can be obtained by solving the (15) [18]. In order to verify the accuracy of the algorithm, a uniform half-space geoelectric model was established for numerical simulation, and the results were compared with those of the analytical formula (1). The current was 1 ampere, the buried depth of the point current source (leakage point) was 10 m, and the resistivity was 100 \text{varOmegacdot m}. The results of numerical simulation and the analytical solution are shown in Fig. 4. When the measurement point is located above the leakage point, the potential is the largest. As the distance between the measurement point and leakage point increases, the potential gradually decreases. The potential curves of the numerical simulation and the analytical solution are basically the same. The curve with black solid triangle marks is the relative error between the numerical simulation result and analytical solution. Within 100 m of the horizontal distance between the measurement point and leakage point, the maximum error does not exceed 1%, which fully meets the accuracy required by the numerical simulation.

\begin{equation}
\mathbf{K} = \sum \mathbf{K}_e = \sum (\mathbf{K}_{1e} + \mathbf{K}_{2e})
\end{equation}

\begin{equation}
\mathbf{P} = (0 \cdots u_A \cdots 0)^T
\end{equation}

\begin{equation}
\mathbf{Ku} = \mathbf{P}
\end{equation}

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B. MODEL DESIGN WITH METAL INTERFERENCE AND ANALYSIS OF NUMERICAL SIMULATION RESULTS

Through the designed leakage point model of the water supply pipeline without metal pipeline interference, the DC potential distribution characteristics of the water supply and heating pipelines under the condition of water leakage were studied. As shown in Fig. 5(a), the coordinates of the leakage point are (0, 0, −9.5), and the diameter is 0.2 m. The coordinates of the power supply point are (90, 0, −10) inside the pipe. In actual work, we connect the power cord to the metal valve of the water pipe or the water inlet to achieve the purpose of supplying power to the water pipe. Potential were received in the XOY plane (x: [−50:50], y: [−50:50]) on the ground. Fig. 5(b) is the result of the tetrahedral mesh. Fig. 5(c) is the simulation result under the condition of no metal pipeline interference. The gray shaded part is the buried high-resistance pipeline. A certain voltage is applied to the metal valve of the high-resistance pipeline with a leakage point, and the current flows out through the leakage point. The potential observed on the surface is distributed in the form of concentric circles with the leakage point as the center.

C. MODEL DESIGN WITH METAL INTERFERENCE AND ANALYSIS OF NUMERICAL SIMULATION RESULTS

After years of development in a city, the underground pipelines are intricate and complex. In addition to buried water supply or heating pipelines, the underground space also contains metal pipelines that interfere with the potential distribution. The models with metal pipeline interference were used to simulate and study the stability and reliability of detecting the leak locations in high-resistivity water supply
pipeline based on the DC potential, as shown in Fig. 6. Fig. 6(a) is the model of metal pipelines at different positions directly above the leakage point of the water supply pipeline. The radius of the metal pipeline is 0.5 m, and the resistivity is $0.1 \text{ varOmegadot m}$. The vertical distances between the metal pipeline and the water supply pipeline are 1.5 m, 4.5 m, and 7.5 m, respectively. Fig. 6(b) is the model with a certain horizontal distance between the metal pipeline and the leak. The horizontal distance is 5 m, and the vertical distance is 1.5 m, 4.5 m, and 7.5 m, respectively.

Fig. 7 shows the simulation results for a metal pipeline located directly above the leak point. The black shadow is the location of the water supply pipeline, and the red shadow shows the location of the metal pipeline. Fig. 7(a) is the simulation result when the vertical distance between the metal pipeline and the leakage point is 1.5 m. The potential observed on the ground is no longer in a concentric circular distribution. The electric potential observed far away from the horizontal position of the leak point is distributed in an ellipse with the metal pipeline as the long axis. The electric potential observed close to the horizontal position of the leak point is distributed in an ellipse with the vertical line of the metal pipeline as the long axis. The leakage point is the intersection of the long axis and the short axis. Fig. 7(b) is the simulation result of the vertical distance between the metal pipeline and the leakage point of 4.5 m. As the vertical distance between the metal pipeline and the leakage point increases, the potential distribution received on the ground is weakened by the influence of the metal pipeline. Fig. 7(c) shows the simulation result of the vertical distance between the metal pipeline and the leakage point of 7.5 m. The vertical distance between the metal pipeline and the ground is 2.5 m, which is close to the measuring points, and the surface potential distribution is more severely affected by the metal pipeline. The potential distribution is consistent with Fig. 7(a).

Fig. 8 shows the simulation results when the horizontal distance between the metal pipeline and the leak is 5 m. Regardless of the distance between the metal pipeline and the leakage point, its impact on the surface potential distribution is small.

In general, we know the orientation of the water supply and heating pipeline, so we do not need to measure the potential at every point on the ground but only need to detect the potential distribution directly above the pipeline. The data at $y = 0 \text{ m(along the high resistivity pipe with a leak)}$ in Fig. 8(b) are used to draw the potential curve, as shown in Fig. 9.
It can be seen from the figure that the potential is the largest directly above the leakage point. As the distance from the leakage point increases, the potential decreases rapidly, and the interference of the metal pipeline in the model decreases.

D. NUMERICAL SIMULATION OF MULTIPLE LEAKS IN THE PIPELINE

To test whether the method can distinguish multiple leaks, we designed a model with two leaks for numerical simulation, as shown in Fig. 10. The coordinates of the first leakage point are \((0, 0, -9.5)\), and they are fixed. The coordinates of the power supply point are \((90, 0, -10)\), inside the tube, and the diameter is 0.2 m. The coordinates of the power supply point are \((90, 0, -10)\) inside the pipe. In actual work, we connect the power cord to the metal valve of the water pipe or the water inlet to achieve the purpose of supplying power to the water pipe. The distance between the first leakage point and the second leakage point is \(d\), with \(d = 10, 15, 20, 30, \ldots, 90\).

Fig. 11 shows the numerical simulation results when the distance between the first leak and the second leak is different. The potential contour maps show that when the distance between two leaks is less than 10 m, the two leaks cannot be distinguished. As the distance between the leaks increases, two extreme values appear on the potential contour lines, which correspond to the two set leaks, respectively.

Usually, we know the orientation of the water supply and heating pipeline. Fig. 12 shows the potential curves directly above the pipeline when the distance between two leaks is different. From the picture, we know that as the distance increases, the first extreme value and second extreme of the potential curves both decrease. Also, because the first leakage point is closer to the power supply point than the second leak, the second extreme value is smaller than the first extreme.
value. We can detect the minimum distance between two adjacent points of 15 m by the pole-pole DC potential method.

In summary, the DC potential method to detect leaks in high-resistivity water supply or heating pipelines is less affected by the overlying metal pipelines. The detection efficiency is greatly improved by finding the positions of the extreme points of the survey lines and drawing vertical lines through the points to locate the leakage point.

IV. PHYSICS EXPERIMENTS

A. PHYSICAL MODEL DESIGN

Two physical experiments were conducted to verify the accuracy of the numerical simulation results and the feasibility of the DC potential method to detect the horizontal position of leakage points in high-resistivity pipeline. As shown in Fig. 13, two physical experiments were designed: with metal interference and without metal interference. Fig. 13(a) is the photo of the physical experiments. The DC resistivity meter was produced by Chongqing Geological Instrument Factory, China. The water supply pipe was a PVC pipe with a diameter of 10 cm and was filled with water. There was a leak on the PVC pipe. The metal pipe consisted of two aluminum tubes with a diameter of 2 cm. The power supply voltage of the instrument was 24 V, which was less than the voltage that human body can withstand 32 V. Fig. 13(b) shows the physical experiment model. The blue points are the measurement points, and the distance between these points is 20 cm. We observed a total of 110 points of data in every experiment. The pole-pole device form was used to measure the potential. The diameter of the leakage point was 0.5 cm. The red curves are the power supply wires. Point A on the PVC pipe was connected to the instrument by a power supply wire, and point B was placed at infinity. The black curves are
the receiving wires. Point M was placed at each observation point and connected to the instrument by a receiving wire, and point N was placed at infinity. The depth of the PVC pipe was 50 cm, and the metal pipe was located 30 cm above the PVC pipe.

**B. RESULTS AND ANALYSIS OF PHYSICS EXPERIMENTS**

Fig. 14 shows the results of physical experiments. The black shadow is the water-filled PVC pipe with a depth of 50 cm, and the red shadow is a metal pipe with a depth of 20 cm. Fig. 14(a) is the result of the physical experiment without metal interference. The potential decreases outward in the form of concentric circles. The maximum potential is at (80,120), which is the location of the leakage point of the PVC pipe. Fig. 14(b) shows the result of physical experiment with metal interference. The potential distribution is less affected by metal interference, and the potential signal observed on the ground is still stable.

Fig. 15 shows the potential curve directly above the pipeline. It can be seen from the figure that the potential is the largest directly above the leakage point under the influence of metal interference. The potential decreases outward in the form of concentric circles. The maximum potential is at the position of the leakage point as the center, and the potential above the leakage point is the largest.

V. CONCLUSION

According to the above present research work, we can arrive at the following conclusions:

1) The potential measured by the pole-pole method on the ground spreads outward in concentric circles with the position of the leakage point as the center, and the potential above the leakage point is the largest.

2) The surface potential is affected by the metal pipes and no longer spreads outward in the form of concentric circles. The potential along a long horizontal distance from the leakage point is distributed in an ellipse with the metal pipe as the long axis, and the horizontal position of the leakage point is the intersection of the long axis and the short axis of the ellipse.

3) Usually, we know the horizontal position and buried depth of the pipeline. We can observe the potential directly above the pipeline in actual detection, and the potential is highest above the leak point.

4) Numerical simulations show that the pole-pole DC potential method can detect multiple leaks in high resistivity water supply and heating pipelines. This method can be used to distinguish the two leaks when the distance between the two leaks is greater than 15 m.

5) Compared with traditional methods, the pole-pole DC potential method has the characteristics of high efficiency, stability and strong anti-interference ability.

VI. DISCUSSION

Based on the above research, we note the following important information:

1) Since the basic principle of the pole-pole DC potential method lies in the diffusion of the electric field, it is related to whether the water flow in the pipe is in contact with the medium outside the pipe, and has nothing to do with the flow rate, the size of the leakage point and the temperature of the water.

2) In actual construction, a power supply line is connected to the metal valve or water inlet of a high-resistivity pipeline, and a measurement point is established every 10 m or 20 m directly above the water supply and heating pipeline; each measurement takes approximately 30 s.

3) Since water supply and heating pipelines may be connected to electronic devices, it is necessary to conduct research on how to avoid the influence of electronic components.

VII. LIMITATION OF THE STUDY

Any method applied to a new field will have a development process, and this method is no exception. This article only simulates a simple model. However, Leak detection in real field is a complicated issue where many factors can more or less affect the result for most sensors. Therefore, the next study will consider the actual situation, fully analyze various influencing factors and study how to eliminate various effects.

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