Technology of detecting deep underground metal pipeline by magnetic gradient method

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Abstract. The application of trenchless technology, such as pipe pulling, pipe jacking, directional drilling and so on, makes the deep buried underground pipeline more and more in the project, and most of the geophysical exploration technology has poor detection effect, which makes it become the difficulty in the underground pipeline detection. This paper mainly expounds and analyzes the principle and construction method of magnetic gradient method for detecting deep underground pipelines, and introduces the application of magnetic gradient method in the detection of deep underground pipelines with two natural gas pipelines in Shijiazhuang road project.

1. Introduction
With the development of society and economy, the construction and application of communication, power transmission, oil industry, natural gas, water conservancy and other underground pipeline engineering are increasingly extensive. At the same time, with the vigorous development of modern technology, the underground pipeline laying technology has been greatly improved, especially the application of trenchless technology in deep buried pipeline engineering, such as pipe pulling, pipe jacking, pipe fixing directional drilling and other technologies. Although the trenchless technology of pipeline greatly solves the problems in the process of pipeline construction, it puts forward higher requirements for pipeline detection methods. In addition, in recent years, trenchless technology such as horizontal directional drilling has developed rapidly in pipeline construction, especially in laying various underground pipelines across rivers, railways, highways, buildings, etc. Long-distance (L > 300m) and deep buried (H > 5m) pipelines for horizontal directional crossing often appear. However, most of the underground pipeline detection instruments on the market have a nominal exploration depth of less than 5m, and even after the improvement of the equipment, the detection effect of the deep underground pipeline is still poor, which leads to the detection problem of the trenchless deep buried pipeline[1-3]. Therefore, the research on the method and technology of deep buried pipeline location and depth detection will provide new technical support for the modernization of urban trenchless underground pipeline construction in China, and also provide reliable guarantee for the accuracy of pipeline information system, which is of great significance for improving the technology of underground pipeline network in China.

After entering the 21st century, conventional pipeline detection methods have been unable to meet the detection needs of deep buried pipelines, so various advanced detection methods have been developed and applied. According to the theory of infinite horizontal cylinder magnetic field, Fang et al. (2004) used high-precision magnetic method to detect a certain section of west east gas pipeline in Hangzhou with a buried depth of about 8m, and achieved good results[4]. They determined the plane position through the magnetic field anomaly, and calculated the buried depth of the pipeline through
the ratio circle intersection method. Wang et al. (2005) studied the variation characteristics of the theoretical curve of the magnetic gradient in the vertical direction of the horizontal metal pipeline[5]. They used the magnetic gradient method to accurately detect the location of the oil pipeline with a buried depth of 10.5 m, and pointed out that the detection accuracy of the depth was almost close to the level of the direct method, and the error can be controlled within ± 20cm, which proved that the method has good application effect. Zhang et al. (2010) studied a series of electromagnetic field characteristics of the pipeline, and proposed that when using the pipeline instrument to detect the ultra deep underground pipeline, the remote grounding direct connection, low frequency and appropriate power (to ensure that the current is large enough) should be used to suppress or eliminate the influence of interference anomalies[6]. Si et al. (2009) proposed a detection method based on the principle of attitude measurement for small-diameter trenchless deep buried pipeline, derived the three-component attitude orientation formula of magnetic force and gravity acceleration and curve construction formula, and the instrument developed based on this principle has achieved good results in the detection of deep buried pipelines crossing rivers, roads, buildings, etc[7]. Wang et al. (2012) used a variety of geophysical methods such as electromagnetic induction method (pipeline instrument), geological radar, high-density electrical method, high-precision magnetic survey to detect the underground pipelines laid by trenchless detection, and achieved certain results[8]. Therefore, on the basis of summing up the previous research results, through several engineering practices and explorations, we applied the magnetic gradient method to solve the problem of deep buried underground metal pipelines laid by non-excavation technology, and achieved good detection results.

2. Characteristics of deep buried underground pipelines

Deep buried pipeline, also known as ultra deep pipeline or ultra deep pipeline, refers to the pipeline whose top buried depth is more than 3m. It is mainly because of the adoption of Trenchless Pipeline Laying technology that the buried depth of the pipeline is generally greater than that of the excavated pipe[9].

| Pipeline type                                      | Acceptance criteria                      |
|---------------------------------------------------|------------------------------------------|
| Water supply pipeline                             | pipe diameter≥100mm                      |
| Drainage (including rainwater and sewage) pipeline | pipe diameter≥200mm or square ditch≥400X400mm |
| Gas pipeline                                      | All measurements                         |
| Power pipeline                                    | All measurements                         |
| Communication pipeline (telecommunication, mobile, Unicom, cable TV, military optical cable, etc.) | All measurements                         |
| Industrial pipeline                               | All measurements                         |
| Street lamp pipeline                              | All measurements                         |
| Integrated pipe ditch                             | All measurements                         |
| Unknown pipeline                                  | All measurements                         |

Table 1 selection standard of underground pipeline detection [10]

Generally, there are many kinds of underground pipelines, mainly including water supply pipes, drainage pipes, gas pipes, power cables and street light cables, telecommunication cables, heating pipes, civil air defense channels, etc. Table 1 shows the detection and selection standards of common underground pipelines. Because there are many kinds of underground pipelines, correspondingly, the types and changes of geophysical field formed by pipelines are also large. The detection of underground pipeline is not only affected by the material of the pipeline itself, but also by the geological conditions such as the local burial conditions. Therefore, the working environment is complex. So, the detection equipment has higher requirements, which must meet the requirements of the regulations. It should not only be economical and practical, be able to track the pipeline
continuously, locate and determine the depth quickly and accurately, but also have a variety of frequencies, be suitable for different working environments, high resolution and strong anti-interference performance.

The geophysical exploration is the main method for detecting underground pipelines, and its principle is to use the differences in physical properties of underground pipelines to detect target bodies. There are obvious physical property differences between different underground pipelines and surrounding rocks such as resistivity, wave velocity, wave impedance, density, magnetic susceptibility, and heat dissipation rate, which are the prerequisites for the application of geophysical methods for underground pipeline detection[11]. Underground metal pipelines are generally highly magnetic. The magnetic method is to use the magnetic difference between the underground pipeline and the surrounding medium, measure the vertical distribution of the magnetic field, identify the magnetic anomaly caused by the underground pipeline, detect the underground pipeline to roughly determine its direction and buried depth, and then quantitatively calculate its exact value. The magnetic gradient method is one of the methods of magnetic exploration.

3. Magnetic gradient method

3.1. Principle of magnetic gradient method
Metal pipes such as steel pipes or cast iron pipes laid underground are generally highly magnetic. The buried depth of underground pipeline has little change in strike, so the magnetic field formed by underground ferromagnetic metal pipeline is similar to that of infinite horizontal cylinder. For the pipeline with radius r, horizontal cross-sectional area s and magnetic field intensity j, the vertical component Z of the magnetic field is located on the surface section with vertical pipeline trend. When the dip angle of effective magnetization \( i = 90^\circ \) and the strike of pipeline is north-south, the expression of each magnetic field component can be simplified as[12]:

\[
Z = 2M \frac{h^2 - x^2}{(h^2 + x^2)^2} \\
H = -2M \frac{2hx}{(h^2 + x^2)^2} \\
\Delta T = 2M \sin I \frac{h^2 - x^2}{(h^2 + x^2)^2}
\]

Where \( M = j \cdot S \) is the effective magnetic moment, \( i \) is the effective magnetization dip angle, and \( j \) is the projection of the magnetization \( J \) in the observation plane. Suppose that the angle between the pipeline trend and the projection of the magnetization on the ground surface is \( A \), the magnetization angle is \( I \), and the expressions of the effective magnetization intensity \( j \) and the effective magnetization angle \( i \) are as follows: \( j = J \sqrt{\cos^2 I \sin^2 A + \sin^2 I} \).

![Fig.1 Z, H and \( \Delta T \) curves of infinite horizontal cylinder](image)

When the pipeline is magnetized vertically \( (i = 90^\circ) \), \( \Delta T = Z \). The Z, H and \( \Delta T \) curves of infinite horizontal cylinder are shown in Figure 1.
The magnetic field gradient is the rate of change of magnetic field in space. According to the vertical gradient $Z$ and horizontal gradient $H$ of the vertical magnetic field of the underground pipeline, 
\[
\frac{\partial H}{\partial x} = \frac{\partial Z}{\partial x} = -\frac{\partial H}{\partial R}
\]
can be easily obtained. That is, the vertical gradient of the horizontal magnetic field is equal to the horizontal gradient of the vertical magnetic field, and the horizontal gradient of the horizontal magnetic field is equal to the negative vertical gradient of the vertical magnetic field.

According to the expression of vertical gradient $Z_a$ and horizontal gradient $H_a$ of total magnetic field, it can be found that the resolution of magnetic field gradient is higher than that of magnetic field intensity. By means of drilling, the magnetic gradiometer is put into the borehole to measure the $Z_a$ curve change of ferromagnetic material in the vertical direction from top to bottom, which can get a better effect. In the borehole close to the metal tube, the change of $Z_a$ gradient value with depth is very obvious. At the depth close to the ferromagnetic material, the gradient value changes strongly, just like an "S" type. In the borehole slightly away from the ferromagnetic material, the change amplitude of the gradient value decreases correspondingly.

3.2. Operation method of magnetic gradient method
Magnetic gradient detection can be used as a verification method to ensure the reliability of detection pipeline depth. By comparing the detection results of magnetic gradient and other related geophysical methods, the effectiveness of other related geophysical methods is evaluated.

First, according to other geophysical methods combined with the pipeline laying data to determine the plane position of the natural gas pipeline, the error is limited to 5m, and then a hole is drilled in a safe range on the side of the deep buried pipeline, and its depth is set to 20-25m. After the hole is formed, the hollow plastic pipe is lowered into the drilled hole, and the whole hole is protected. Each sleeve is connected by a pipe hoop, and a plug is provided at the bottom of the hole, and a small leaking hole is provided on the plug to prevent mud from flowing into the pipe. Immediately, the probe of the magnetic gradient instrument is placed in a plastic tube, and the magnetic field intensity values of each point are measured upward at intervals of 0.20m from the bottom of the hole. We can determine the buried depth and plane position of the buried pipeline according to the change of the magnetic field intensity. The test schematic diagram is shown in Figure 2, and the explanation principle is shown in Figure 3.

4. Example analysis
The test site is located in Jianshe North Street, Shijiazhuang City, Hebei Province. Due to the road reconstruction, the underground pipeline should be reburied. It is necessary to detect the underground pipeline in this section by means of geophysical prospecting to determine whether there is a deep buried natural gas pipeline laid by trenchless technology and its location, so as to provide a basis for the further construction of the project. Through field test, GPR cannot meet the requirement of detection depth. In addition, because the surface is a concrete pouring cement pavement, the shallow seismic method and high-density electrical method cannot be used. Considering that the natural gas...
pipeline is generally made of steel pipe by electric welding, which is a strong ferromagnetic material. There is a strong magnetic field around it, and the magnetic gradient will change obviously at the pipeline position, so we plan to use the magnetic gradient method for detection. On the basis of the investigation, according to the road trend, the direction of the magnetic gradient detection section is preliminarily determined, and a survey line with 12 holes and 2 m equal spacing is arranged. The layout of the survey line drilling is shown in Figure 4. After the hole is formed, PVC casing is used to protect the wall, and the magnetic probe is put into the hole to measure the gradient value of the vertical component of the magnetic field in the hole. Based on the comprehensive analysis of several drilling gradient curves in the exploration profile and combined with the drilling situation, we have well determined the plane position and buried depth of the two natural gas pipelines. The line magnetic gradient detection curve and interpretation results are shown in Figure 5.

From the magnetic gradient curve in Figure 5, it can be seen that there is an obvious magnetic gradient anomaly (i.e. "s" curve) at the burial depth of about 5.6 m for holes K5 and K6, and the anomaly value of hole K5 is the largest, so it is inferred that there is a natural gas pipeline near hole K5 at the burial depth of 5.6 m. In the same way, there is obvious magnetic gradient anomaly at the burial depth of about 6.2 m for K8 and K9 holes, and the anomaly value of K8 hole is the largest, so it is inferred that there is a natural gas pipeline near K8 hole at the burial depth of 6.2 m. According to the detection results, the construction unit dug the natural gas pipeline in these two places respectively, which verified the accuracy of the detection results.

5. Conclusion
In this paper, the spatial section and cross-section of the magnetic gradient method are shown intuitively, and the criteria of the buried depth of the pipeline are given. It is proved that the magnetic gradient method, which is an effective method, can accurately measure the location and buried depth of trenchless metal pipeline. The magnetic gradient method is better than the conventional geophysical method in detecting underground metal pipelines, but the detection accuracy of this method is affected by the hole forming quality. When using this method to detect deep buried pipelines, other methods need to cooperate to determine the location of pipelines, so as to avoid excessive drilling and damage to pipelines during drilling.

In general, due to the application of Trenchless Technology in urban deep buried pipeline engineering, more and more deep buried pipelines are encountered in the project now, while other
geophysical methods have different limitations. Based on the successful experience of magnetic gradient method in this paper, it has a certain extension value for the exploration of such deep buried underground pipelines in the future.

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