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Application Research of GPR in Quality Detection of Urban Underground Jacked Pipes Construction

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Abstract. Nowadays, pipe jacking method is usually adopted in the construction of urban underground pipelines. In order to ensure the construction quality of pipe jacking method, geophysical non-destructive prospecting methods are used for detecting the compactness around the jacked pipes. Based on the theory of ground penetrating radar (GPR), the void models of jacked pipes with two different materials (i.e. cement pipe and steel pipe) were established, and the finite element method was used to simulate the 2D forward modeling of GPR. At the same time, combined with the urban underground jacked pipes construction project in Xiangtan city, Hunan province, China, GPR was used to carry out field prospection of the quality of jacked pipes construction. The results of forward simulation and practical applications show that good results can be obtained when GPR is used to detect the construction quality of cement pipes, which is the same as that of using GPR to detect the construction quality of tunnel. But the collected signals are not effective when the steel pipes are detected, which is because the radar signal cannot penetrate the steel pipe, and there are multiple reflections between the radar antenna and the pipe wall. Therefore, new non-destructive prospecting methods are needed for void detection of steel jacked pipes.

1. Introduction

With the development of society, the improvement of people's living standards and the continuous advancement of urbanization, the development and utilization of underground space have become more and more common. Especially in the current urban construction, it is obvious that the municipal pipeline engineering and the underground passage engineering are increasing. The underground pipelines of urban roads were generally designed to be shallow, and most of them were constructed by open-cut method in the past. But this method not only hindered traffic, but also caused damage to the safety of near-surface pipelines and buildings. Comparative with the open-cut method, the pipe jacking method does not require excavation, and has no damage to the surface structure, which also

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can greatly reduce the impact on road traffic and the surrounding environment. In recent years, the pipe jacking method has been widely used in the pipeline construction of urban power cable tunnels, municipal pipes, communication pipes, power plant circulating water cooling systems [1-2], etc.

The underground pipe jacking technology is a kind of non-destructive examination technology. It is an underground pipeline laying process that uses a hydraulic cylinder to gradually jacking up the pipe jacking machine and the pipe joint to be laid from the pipe jack working well into the receiving well in the underground. Although the pipe jacking construction has little impact on the surrounding environment, it will disturb the surrounding soil during construction, causing deformation of the soil and the pipeline itself. Taking the application of pipe jacking method in highway pipeline laying as an example, the deformation of the stratum caused by the shallow pipe jacking across the roadbed poses a certain risk to the road pavement [3-4]. Thus, in order to avoid the safety hazard caused over-excavation and disturbance of the surrounding soil of the pipe in the underground construction, the pipe jacking is generally required to be grouted and reinforced outside the pipe after construction. If the grouting is not grouted or the grouting filling is not dense, the surrounding soil of the pipe will gradually settle and gradually spread to the ground, resulting in road surface settlement, collapse or cracking of the concrete layer of the road surface.

Before the grouting around the pipe, it is necessary to detect the voids and compacting conditions around the jacked pipe. At present, there are many theoretical studies on the analysis of soil disturbance in the back of the sinking well in the world [5-11]. However, there is a little literature about the detection of voids and density around underground jacking pipe. Therefore, taking the underground pipe jacking project currently under construction in Xiangtan City, Hunan Province, China as an example in this paper, the authors have analyzed and studied the related problems of ground penetrating radar technology in the detection of voids of the pipe jacking.

2. Methodology

Ground penetrating radar is abbreviated as GPR. It is a new non-destructive examination technology. It has the advantages of continuous, non-destructive, high-efficiency and high-precision. GPR emits high-frequency electromagnetic waves into the medium in the form of broad frequency band short pulses. The frequency of the high-frequency electromagnetic waves GPR emits ranges from $n\times 10$MHz to 2.5GHz. When electromagnetic waves encounter the interface of the medium, reflection phenomenon occurs. The reflection coefficient is determined by the relative permittivity of the medium on both sides of the interface. Through processing the radar reflected signal and interpreting image, the purpose of identifying the internal structure of the medium can be achieved. The technology of GPR has been widely used in the quality acceptance of road engineering and tunnel engineering [12]. Therefore, it is naturally cited in the detection of the voids of the pipe jacking project. However, the pipe jacking project is very different from the tunnel project. For example, the initial lining and the second lining of the tunnel are cement mortar, cement concrete and other materials, but the jacking pipe has cement pipe, steel pipe, etc. Is the Ground Penetrating Radar technology still suitable in this case? The author will explore the adaptability of the technology of GPR for the corresponding situation. The finite element method is used for forward modeling.

In a homogeneous isotropic, linear, and time-independent medium, substituting the excitation source into the Helmholtz equation, we can obtain the following relationships [13]:

$$\frac{\partial^2 E}{\partial t^2}-\frac{1}{\mu\varepsilon}\nabla^2 E+\frac{\sigma}{\varepsilon}\frac{\partial E}{\partial t}=S_{\mathrm{E}} \tag{1}$$

$$\frac{\partial^2 H}{\partial t^2}-\frac{1}{\mu\varepsilon}\nabla^2 H+\frac{\sigma}{\varepsilon}\frac{\partial H}{\partial t}=S_{\mathrm{H}} \tag{2}$$

where E is electric field intensity (V/m), H is magnetic field intensity (A/m), μ is magnetic permeability (H/m), ε is permittivity (F/m), σ is conductivity (S/m), S_E is electric field source, and S_H is magnetic field source.

3. Application and forward modeling

3.1. Application

Xiangtan Urban Construction Investment Management Co., Ltd. has used pipe jacking method when burring rainwater and sewage pipes at the intersection of East Second Ring Road and Xunda Avenue in Xiangtan. The specific positions of the pipe jacking are in the A0+222~A0+260 of the Schindler Avenue, the Z11+200～Z11+480 of the East Second Ring Road (the east and west sides) and the L0+040～L0+300 of the auxiliary roads. The inner diameter of the sewage pipeline is 1m cement pipe, the inner diameter of the rainwater pipes is 1m or 1.8m cement pipe, and the wall thickness of the 1 m inner diameter pipe is 0.1m. The buried depth of the pipe jacking of the whole project is about 7~9 m. The elevation of the construction area is 57.01~65.94 m, and the original landform is low hills. According to the geotechnical investigation report in the early stage of the project, within the scope and the depth of exploration, the composition of the stratum from top to bottom is: miscellaneous fill, residual silty clay and underlying strongly weathered and moderately weathered argillaceous limestone. No obvious lava development is observed during the survey.

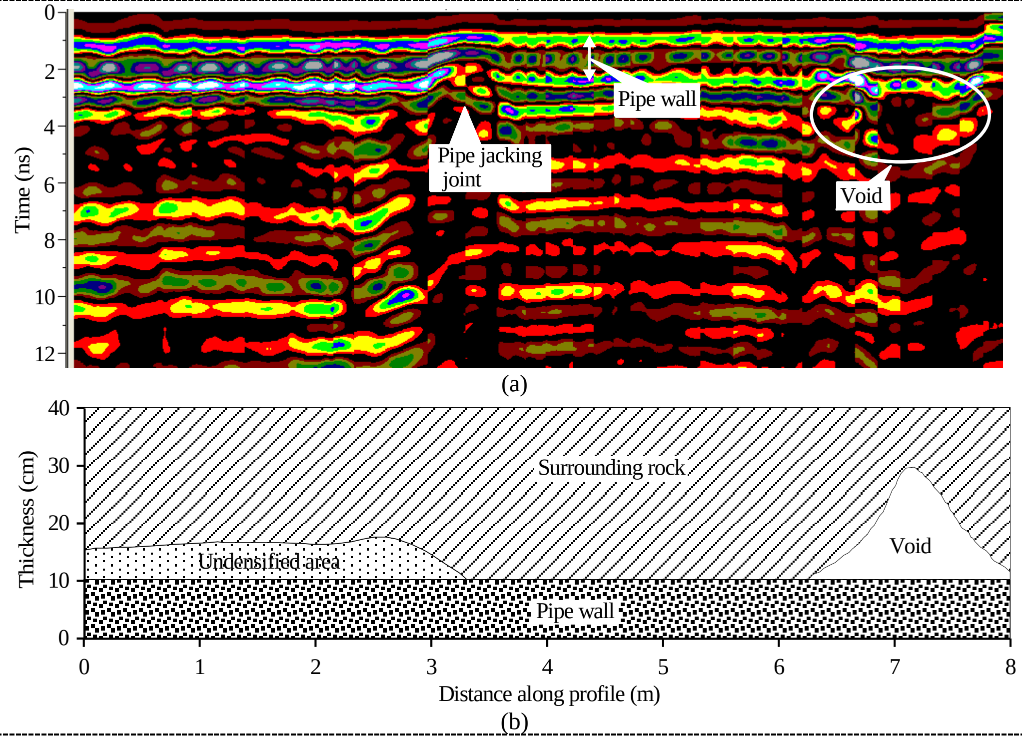

Figure 1. (a) Schematic diagram of the GPR detection results and (b) interpretation results of radar images.

In order to ensure the construction quality of the pipe jacking, the LTD-2100 GPR and 900 MHz antenna are used to detect the voids around the pipe jacking. In particular, it is necessary to find out the voids of the top of the pipe to provide a scientific basis for grouting construction. Figure 1 is a GPR image of the top of the cement pipe inside the pipeline. The specific location is located between the W2 and W4 of the sewage well. The detection method is the same as that of the top of the tunnel. The antenna and the pipe wall are well coupled. The wheel controls the distance, the sampling point spacing is 2 cm, and the antenna moves in the direction of the pipe. It can be seen from Figure 1(a)

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that the thickness of the pipe wall and the position signals of the pipe jacking joint are clearly visible, especially the in-phase axis of the double-layer steel mesh in the precast cement concrete pipe is continuous, and the point reflection signal of the single steel bar is clear. The discontinuity of the in-phase axis appears on the outer side of the radar image and on the outside of the tube wall, and is judged as the void area. After verification of the post-grouting hole, the height of the void area is about 28 cm. The geological interpretation of the top of pipe jacking in Figure 1(a) is shown in Figure 1(b). Based on the results of GPR, the void and density around pipe jacking can be quickly inferred.

The radar technology has a good application effect in the detection of voids of the pipe jacking. It has been highly recognized by the owner and the construction unit. In the past three years, the sewage pipe network and the rainwater pipe network project of road section were all tested by ground penetrating radar technology in the sections of Tanxia Road, Baota Road, Dongpu Road, Xiaishisi Road and Xixia Road of Xiangtan City, Hunan province, China. The voided area and the non-compacted area around the pipeline have been found, which provides a basis for grouting treatment and prevents the collapse of the upper stratum of the pipeline.

The pipe jacking materials used in the aforementioned pipe jacking engineering are all cement concrete prefabricated pipes. Ground penetrating radar technology is used to detect that the outer void area is the same as the tunnel lining hollow detection method. It is relatively mature technology, which has been recognized by the majority of science and technology workers. However, in the pipe jacking project, in addition to the use of cement concrete prefabricated pipes, steel pipe materials are often used. As shown in Figure 2, the figure shows the sewage pipe under construction near the family area of Xiangtan Steel Group Co., Ltd. The pipe is a steel pipe with an inner diameter of 1.2m and a thickness of 14mm. it can be seen from Figure 2 that due to over-excavation and the like, there is a significant void near the top of the steel pipe in the shaft. In order to understand the emptying situation of the whole project, the owner and the construction unit hope to quickly and accurately ascertain the scope and size of the void area around the top pipe. So we carry out the test and exploration work of the ground penetrating radar.

Figure 2. A photo of pipe jacking construction.

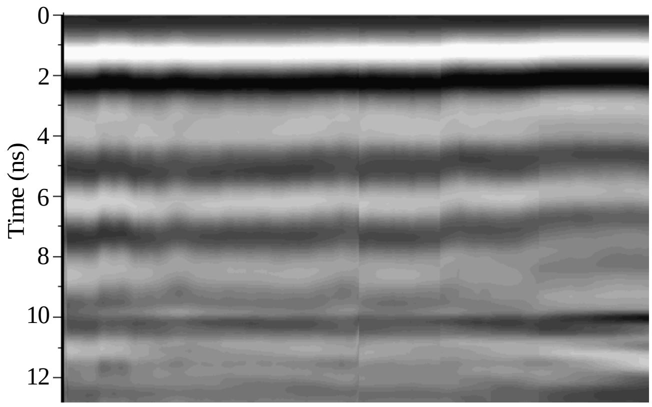


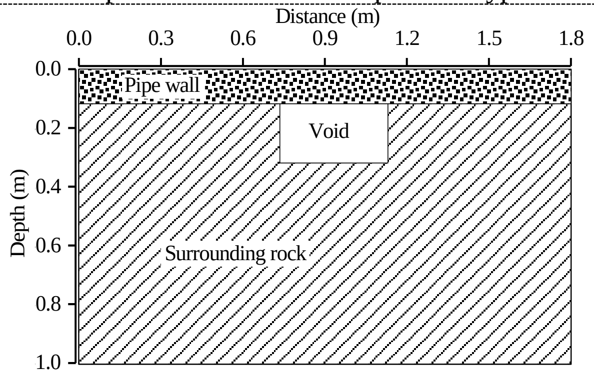
Figure 3. The GPR image for steel pipe jacking construction.

In the same way as the detection method, equipment and acquisition parameters in Figure 1, the radar detection is performed on the top at the pipe jacking inside the steel pipe jacking shown in Figure 2, and the radar antenna moves along the extending direction of the pipe. Figure 3 is a radar image that is detected upward inside the steel pipe. By the figure of detection results, we can see that the signal reflection is strong, the plurality of strongly reflected signal axes are parallel, and the travel time interval of the reflected signal has an equidistant feature. In fact, these phenomena are caused by multiple reflections between the radar antenna and the surface of the steel pipe. It can be said that the radar signal does not penetrate the pipe jacking, and it is impossible to detect the void condition around the top tube. In particular in Figure 3, the radar signal has not changed at the location of the obvious void area near the hole of the steel pipe (Figure 2).

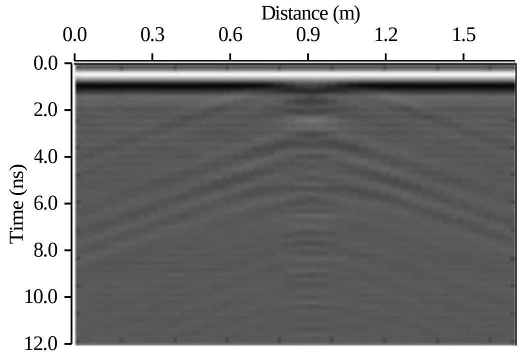
3.2. Forward modeling

In order to understand the theoretical detection image of ground penetrating radar on steel pipe and cement concrete pipe, we carry out simulate analysis on different models by using finite element method.

As shown in Figure 4(a), the two-dimensional model size is 1.8 m×1.0 m during simulation. It is assumed that the surrounding rock is soil, its relative permittivity ε_r is 20, the electrical conductivity is 0.0125 $S\cdot m^{-1}$. There is a rectangular hollow area with a length of 0.4 m and a height of 0.2 m in the surrounding rock. The void area is filled with air, its relative dielectric constant is 1, the conductivity is 10^{-9} $S\cdot m^{-1}$. The relative dielectric constant of the cement tube is 6, and its conductivity is 0.0002 $S\cdot m^{-1}$. The thickness of pipe wall is 12 cm. The time interval of sampling is 0.5 ns, and the number of sampling point is 1024, the center frequency of the radar antenna is 900MHz, and the time window size is 12ns. The track pitch is 1 cm at plotting the simulation results. The simulation results are shown in Figure 4(b). It can be seen from the simulated image that the reflected signal of the GPR is strong overall, and the reflected signal of the vacant area exhibits a clear hyperbolic curve. The radar signal has multiple reflections at the top of the hyperbola.



(a)



(b)

Figure 4. (a) Model for voids around jacked cement pipe and (b) GPR forward modeling results.

The schematic diagram of the ground penetrating radar forward simulation of the steel jacked pipe is showed in Figure 5. The size of the calculated model and related parameters are the same as those in Figure 4. However, the wall thickness of the steel pipe is 14 mm, and its relative dielectric constant ε_r is 300, the conductivity is 0.1 $S\cdot m^{-1}$, and the time interval of sampling is 0.5ns. When plotting the radar simulation results, the track pitch is also 1cm.

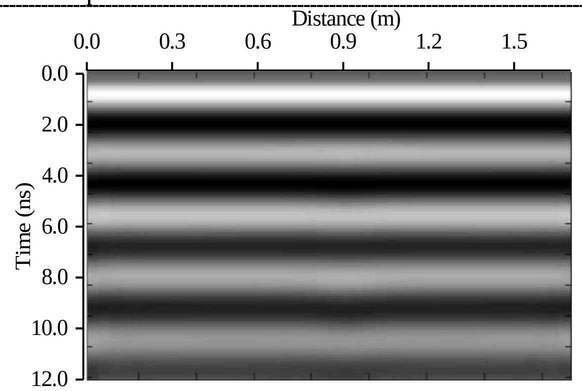


Figure 5. Schematic diagram of GPR forward modeling for voids around jacked steel pipes.

In the Figure 5, the forward simulation image of the ground penetrating radar shows that there are many horizontal in-phase axes in the image, which are caused by multiple reflections of the radar signal on the antenna and the surface of the steel pipe, and even in the void area of model, the amplitude of the multi-reflection signal in the same phase axis does not show a significant reflection arc in Figure 5. This tells us that the GPR can achieve better results in the detection of the voided area at the top of the cement jacking pipe, but in the steel pipe jacking pipe is not obvious. This can also be seen from the actual collection results (Figure 3).

When the jacked pipe is made of steel, the GPR acquisition signal is very poor, which is theoretically understandable. Firstly, the steel is a good conductor, with a very small resistivity (about 10Ω•m or less). The attenuation is very fast when the electromagnetic signal propagates in it. Secondly, the relative dielectric constant ε_r of the steel is large (generally for $n\times10^2$). The value in the front forward model is 300, but the relative dielectric constant of air is 1. When the electromagnetic signal propagates from the air to the steel pipe, the reflection coefficient R of the radar signal on the surface of the steel pipe can be calculated as:

$$R = \left[(\varepsilon_1)^{1/2} - (\varepsilon_2)^{1/2}\right]\times\left[(\varepsilon_1)^{1/2} + (\varepsilon_2)^{1/2}\right]^{-1} = \left(1^{1/2} - 300^{1/2}\right)\times\left(1^{1/2} + 300^{1/2}\right)^{-1} \approx -0.9 \quad (3)$$

This value is approximately equal to -1. The result means that the radar signal is almost all reflected back to create multiple reflections back and forth between the radar antenna and the steel top tube. The proportion of signals entering the steel medium is very small, with only ten percent of all signals.

4. Conclusions

The practical application of GPR in the detection of voids around underground jacked pipes is studied, and theoretical discussion conducted in this paper. The research results show that the GPR is feasible for the detection of voids in cement jacked pipes, which is gradually being promoted applied in practice. And the effectiveness of ground penetrating radar will be weakened when it detects the steel jacked pipes. In practical application, the signal reflection is quite frequent, which makes it difficult to detect the hollowness behind the steel pipes. The limitations of ground penetrating radar applied to steel jacked pipes have been theoretically proved by the finite element method simulation of ground penetrating radar signals. The authors believe that new non-destructive examination methods should be studied, and new equipments should be developed to be applied to the underground pipes of different materials in the future practical application.

Acknowledgments

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