Experimental Research on the Pipe Grouting Quality Based on Antenna Array Radar

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Abstract: Experimental research on the pipe grouting quality is carried out by detecting the concrete test piece with high-frequency antenna array radar. First, the principle of detecting the pipe grouting quality with ground-penetrating radar is introduced, and then the pipe grouting situation is researched systematically and completely with three methods, including the oscillogram of a single wave, grey-scale image (2D imaging) and slice image (3D imaging) of antenna array radar, and the research results are verified with an indoor test model. The results show that: Pipe can be positioned precisely with antenna array ground-penetrating radar; for failure of judgment of the grouting fullness of metal pipes and the grouting fullness situation of non-metal pipes, the pipe grouting quality can be identified with the oscillogram of a single wave, grey-scale image (2D) and slice image (3D) respectively; Radar detection 3D image can present the position of a pipe in the structure intuitively and accurately, and, the pipe material and the pipe grouting fullness can be judged by comparing the radar detection 3D image and the 3D slice image.

1. Introduction
As regards concrete samples, pipe grouting is a concealed work, the prestress system is not designed with an access hole, and there are no other inspection measures in construction, so pipe grouting quality is not easy to be evaluated. Currently, commonly used methods for pipe grouting detection include the core drilling method, impact echo method, ultrasonic impulse method and radar method. The comparison of these methods is as shown in Table 1.

Detecting pipe grouting quality with the radar method has several advantages, including high resolution, intuitive image, convenient and fast operation, but it is not applicable to metal corrugated pipes. Domestic and foreign scholars have begun to study the application of ground-penetrating radar in the detection of prestress pipes. Research on the routing and position of prestress pipes with ground-penetrating radar is very mature and well established. Through qualitative analysis of the prestress pipe grouting quality, the position of prestress pipe grouting defects can be judged roughly via the oscillogram of a single wave and the grey-scale image (2D imaging) captured by radar, but research on detection of pipe grouting quality with the radar method is not systematic or perfect.

Table 1 Comparison of Common Used Methods for Pipe Grouting Detection

| Name                  | Detection method and principle                                                                 | Advantages          | Disadvantages                                                                 |
|-----------------------|-------------------------------------------------------------------------------------------------|---------------------|--------------------------------------------------------------------------------|
| Drilled core method   | This method is commonly used in detection of prestress pipe grouting quality.                  | Intuitive, reliable and accurate | ① Inconvenient operation, high costs and poor general usability;  
  ② Only the grouting situation of a small part of the grouting channel within the drilling scope can be reflected, and wrong judgment or missing judgment is likely to be caused by judging the whole pipe's grouting situation based on the grouting situation of this small part;  
  ③ After drilling and taking out the core, the...
structure is damaged partially.

**Impact echo method**

A short-time mechanical shock (slightly knock the surface of the concrete with a hammer) generates a low-frequency stress wave which is transmitted to the inside of the structure, reflected by defects and the bottom of the component, and then the reflected wave is received by a mounted sensor for analysis, so that the grouting situation can be known.

Simple, fast and convenient operation, light equipment, small interference, repeatability

Low efficiency, low resolution, being hard to detect the non-metal prestress pipe grouting quality

**Ultrasonic impulse method**

Defects are judged through analyzing the relative change of acoustic parameters of an ultrasonic impulse wave spread in concrete, including sonic time (or sound speed), amplitude, frequency, etc.

High sensitivity, high positioning precision, wide applicable scope and convenient operation

① It is not applicable to defects on the near surface.
② It is defect-oriented, so missing inspection is likely to happen.
③ It is not applicable to materials where ultrasonic waves attenuate significantly.

**Ground penetrating radar method**

Electromagnetic pulses are transmitted to the structure via the antenna, and reflected waves from different medium interfaces of the structure are received.

High resolution, intuitive images, fast and convenient operation

It cannot be used for detection of metal prestress pipe grouting; Ordinary rebar will severely interfere radar signals.

This paper uses high-frequency antenna array radar to detect prestress pipe grouting. Based on the 3D slice image formed and the oscillogram of a single wave and grey-scale image (2D imaging), the application of ground-penetrating radar in the detection of prestress pipe grouting quality is researched systematically and is verified with an indoor test model.

**2. The principle of pipe detection with antenna array radar**

According to pipe materials, there are mainly two types of pipes: non-metal corrugated pipe and metal corrugated pipe. For metal corrugated pipes in low-frequency fields, electromagnetic waves can only reach a very shallow depth in the metal and almost all the electromagnetic waves will be reflected. When detecting pipe grouting with a ground-penetrating radar, the antenna frequency is far smaller than the electronic bondage frequency in metal, so electromagnetic waves cannot penetrate the metal surface to detect the inside of the pipe. Metal corrugated pipes can shield electromagnetic waves, so ground-penetrating radar can be used to detect pipe position, but cannot be used to detect pipe grouting situation.

In most cases of engineering detection, the reflecting antenna is near from the receiving antenna, and incidence and reflection are almost vertical, so the reflection coefficient is:

\[ R_{12} = \frac{\sqrt{\varepsilon_{r1}} - \sqrt{\varepsilon_{r2}}}{\sqrt{\varepsilon_{r1}} + \sqrt{\varepsilon_{r2}}} \]  

Wherein: \( \varepsilon_{r1} \) - represents the dielectric constant of the upper interface; \( \varepsilon_{r2} \) - represents the dielectric constant of the lower interface;

It is known from the above equation that there is only transmission but no reflection when the dielectric constant of two medium is the same; As the dielectric constant on two interfaces varies significantly, the bigger the reflection coefficient, and the stronger the reflection strength.

### Table 2 Electromagnetic Parameters of Common Medium

| Medium    | Relative dielectric constant | Conductivity (ms/m) | Speed of electromagnetic waves (m/ns) |
|-----------|------------------------------|---------------------|---------------------------------------|
| Air       | 1                            | 0                   | 0.3                                   |
| Concrete  | 4–10                         | 1                   | 0.09–0.15                             |
| Iron      | 300                          | \( 10^{20} \)       | 0.017                                 |
According to the speed formula and reflection principle of electromagnetic waves, under certain conditions, as the speed of electromagnetic waves is higher, the relative dielectric constant of medium which carry electromagnetic waves will be smaller; when electromagnetic waves are incident from a high-speed medium to a low-speed medium, that is, electromagnetic waves are incident from a medium with a relatively small dielectric constant to a medium with a large dielectric constant, the reflection coefficient is "1" which is smaller than 0, and the phase of the reflected wave field is opposite to that of the incident wave field, and when the reflection coefficient is "2" which is greater than 0, the phase of the reflected wave field and that of the incident wave field are the same.

Thus, for metal corrugated pipes whose grouting situation is not known, electromagnetic waves are reflected on the metal surface, and the phase of the reflected wave is opposite to that of the incident wave; For non-metal corrugated pipes whose grouting situation is not known, electromagnetic waves pass through the concrete, non-metal corrugated pipes and then enter the air or concrete, and the phase of the reflected wave and that of the incident wave are the same. Phase changes in detection of different materials of pipes with radar are shown as in Figure 1.

(a) Phase change of radar waves in detection of non-metal pipes

(b) Phase change of radar waves in detection of metal pipes

Figure 1 Schematic of Phase Change of a Single Wave in Pipe Detection with Radar

For different grouting situations of non-metal corrugated pipes, if a pipe is not filled with concrete slurry during grouting, there will be air in the pipe, and there will only be concrete in the pipe if the pipe is filled with concrete slurry during grouting. Since the dielectric constant of air is smaller than that of concrete, the attenuation constant of electromagnetic waves in air is smaller than that in concrete. The electric field intensity of electromagnetic waves in air is larger than that in concrete, so less electromagnetic waves will be damaged, and the reflection amplitude is larger when passing through non-metal corrugated pipes which are not filled with concrete slurry; when electromagnetic waves pass through non-metal corrugated pipes which are filled with concrete slurry, more electromagnetic waves will be damaged, and the reflection amplitude is less.

3. Antenna array radar

By virtue of reflection of high-frequency electromagnetic waves, underground target objects can be detected. High-frequency electromagnetic waves are transmitted towards the ground via a single antenna, received by the other antenna, recorded in the manner of waveform of reflected waves of impulses and finally processed to generate a 2D radar image. Dual-polarized antenna array radar has two pairs of built-in antenna polarons (two transmitting polarons and two receiving polarons) which are laid out vertically. One pair of polarons are parallel to the antenna's layout direction (detection line direction), and one pair of polarons are vertical to the antennal layout direction, which can realize the purpose of one-way scanning and collection of two-way data and then 3D image can be generated. Detecting target objects with the antenna array radar can significantly reduce impacts of target objects on the detection effect, improve the working efficiency and collect more comprehensive and detailed information of target objects, such as shape, position, etc.

During research on the pipe grouting situation, Italian Aladdin antenna (see Figure 2) (antenna frequency: 2000MHz) and the corresponding mainframe are used. Aladdin antenna is of double antennas (two transmitting antennas (TX) and two receiving antennas (RX)). See Figure 3 for antenna layout. Using Aladdin antenna, one-way scanning and collection of two-way data can be realized, and
3D images can be generated.

Figure 2 Italian Aladdin Antenna

Figure 3 Layout Way of Aladdin antenna

4. Radar identification method for detection of pipe grouting

When detecting pipe grouting with a ground-penetrating radar, radar detection images are usually used for identification, mainly including oscillogram identification, grey-scale image (2D) identification and 3D slice identification.

4.1. Oscillogram identification

The fullness of pipe grouting is judged based on the amplitude and polarity of reflected waves. Before pipe grouting, the grouting situation is identified based on the reverse direction of reflected waves and incident waves. The less full the pipe grouting, the more air present in the pipe, the greater the difference in the electromagnetic properties of the medium, the stronger the reflected wave, and the greater the reflected amplitude. Therefore, the less full the pipe grouting, the more air present in the pipe, the greater the amplitude of reflected wave.

4.2. Grey-scale image (2D) identification

The premise of detection with a ground-penetrating radar is that there is an electrical property difference, that is, as the difference of relative dielectric constants is greater, information on the radar image displayed will be more obvious, and, as such a difference is smaller, information on the radar image displayed will be less obvious. If a pipe is not filled with concrete slurry, there is air in the pipe, electromagnetic waves will attenuate slowly, the difference between relative dielectric constants inside and outside the pipe will be greater, the radar detection grey-scale image will be stronger, and the hyperbola's shape will be more complete. For pipes filled with concrete slurry, electromagnetic waves attenuate significantly, the difference between relative dielectric constants inside and outside the pipe will be smaller, and the radar detection grey-scale image is weaker.

4.3. 3D image identification

Pipes with different grouting situations are detected with radar, detection results are processed with post-processing software. There are differences between pipes filled with concrete slurry and pipes not filled with concrete slurry in terms of the waveform, reflection strength and two-way traveling time, so the situation can be judged based on the 3D depth slice. For different grouting situations, the amplitude values, wavelengths and other parameters of reflected waves will be different too, so colors of 3D depth slice images are different. Based on slices of different depth of concrete, distribution and grouting of buried objects on the plane direction can be easily seen, and 3D images can clearly display the shape, size and position of buried objects.

5. Experimental study

5.1. Specimen design

Dimensions of the test piece are 2000mm×1800mm×200mm. Non-metal corrugated pipes and metal
pipes (inner diameter: 70mm) are buried in concrete in advance, and grouting is carried out to simulate prestress pipes in actual projects. There are three grouting situations: no grouting, half grouting and full grouting. The plan view and lateral view of the test piece are shown as in Figure 4 and Figure 5. The test piece after concrete pouring is shown as in Figure 6. In the figure, 1, 2 and 3 are metal pipes, and 4, 5 and 6 are non-metal pipes.

Figure 4 Design Plan View (unit: mm)  Figure 5 Design Side View (unit: mm)

Figure 6 Test Piece after Concrete Pouring

5.2. Detection line layout
When identifying the pipe grouting fullness with radar imaging, high-frequency radar detection is applied. In 3D detection, detection vertical to the pipe layout direction and parallel to the pipe layout direction with single-antenna radar should be carried out respectively. Antenna array radar is only used to carry out detection vertical to the pipe layout direction.

When detecting pipe grouting with the radar method, the detection line can be vertical to the grouting channel or intersect obliquely with the grouting channel. In this experiment, the detection line is vertical to the pipe layout direction. The 3D image detection space is 1cm. 48 detection lines are laid out. Layout of detection lines and the moving direction of the antenna are shown as in Figure 7.
5.3. Detection result analysis

5.3.1. Oscillogram detection result
When there are different pipe grouting fullness degrees, the detection results (oscillograms of a single wave) of the detection line 24 are selected (Figure 8). In Figure 8, reflected waves ① to ⑥ represent grouting metal pipe 1, non-full grouting metal pipe 2, full grouting metal pipe 3, no-grouting non-metal pipe 4, non-full grouting non-metal pipe 5 and full grouting non-metal pipe 6 respectively. According to the single-wave graphs of three metal pipes in Figure 8 (a), when the electromagnetic wave enters steel pipes after passing through the concrete, that is, the electromagnetic wave enters a high-speed medium from a low-speed medium, the phase of radar wave is opposite to that of the incident wave. In Figure 8 (b), compared with the reflected wave ⑥ of full grouting pipe, the amplitude of reflected waves ④ and ⑤ of non-full grouting pipes is greater. The direction of the reflected wave ④ of non-grouting pipe is opposite to that of the reflected wave ⑤ of non-full grouting pipe, but the amplitude of the reflected wave ④ is greater than that of the reflected wave ⑤. Thus, non-metal pipe grouting cannot be judged with radar oscillograms. Non-metal pipe grouting fullness can be judged through comparing the size of amplitudes on the single-wave graph. As the pipe grouting fullness is worse, the amplitude of a single wave will be larger.

5.3.2. Grey-scale image (2D) detection result
Grey-scale image for radar detection of pipe grouting with detection line 24 is shown as in Figure 8.
In Figure 9, pipes 1-3 are metal pipes, and pipes 4-6 are non-metal pipes. According to reflection phases, the first three reflection phases are displayed as white-black-white, representing metal pipes; the last three reflection phases are displayed as black-white-black, representing non-metal pipes, which is the result of the electrical property difference between corrugated pipes and metal. When electromagnetic waves enter the metal pipe (high-speed medium) from concrete (low-speed medium), the phase of the radar wave is opposite to that of the incident wave; when electromagnetic waves enter the non-metal pipe (low-speed medium) from concrete (high-speed medium), the phase of the radar wave is the same as that of the incident wave.

During detection of metal pipes 1-3, the radar detection grey-scale image is strong, and the hyperbola is complete, so grouting fullness cannot be judged. During detection of non-metal pipes 4-6, pipe 4 and pipe 5 are not filled with concrete slurry, the radar detection grey-scale image is strong, and the hyperbola is complete, while radar detection grey-scale image of pipe 6 is weak, and the hyperbola is incomplete.

So, when pipe grouting fullness is identified based on the radar detection grey-scale image, pipe grouting fullness can be judged through comparison of strength of grey-scale images and completeness of the hyperbola. As the grey-scale image is weaker, the hyperbola will be more incomplete.

5.3.3 3D image detection result
When high-frequency antenna array radar is used for detection, the detection result can be processed with post-processing software to form a 3D image (Figure 10). The 3D image is given depth slice processing, and the slice at the position of 3.5cm of the pipe is selected (Figure 11).

According to the 3D detection image, the top of six hyperbolas in Figure 9 is the position of the top margin of the pipe detected in the test piece. In such a way, the position of the pipe in the test piece can be observed intuitively.

According to the slice image 10, it can be observed that there are black and white areas nearby positions 0.1m, 0.9m, 1.1m and 1.4m which are corresponding to pipe 1, pipe 4, pipe 5 and pipe 6.
respectively. The slice image of metal pipe 1 is white, and that of the rest three pipes is black. So, it can be judged that the rest three pipes are of different materials from pipe 1. According to the design of the test piece, it can be known that the rest three pipes are non-metal pipes. For three non-metal pipes, the image of pipe 4 and pipe 5 has a large black area, and there is a small difference between the image of pipe 4 and pipe 5; the black area in the slice image of pipe 6 is small and light. There are big differences among black areas of three non-metal pipes, which is caused by the different pipe grouting situations. Pipe 4 and pipe 5 are not filled with concrete slurry and have air in them, so, the reflected wave is strong, while pipe 6 is filled with concrete slurry, so its reflected wave is weak. Therefore, the material of pipes and pipe grouting fullness can be judged through comparison of 3D slice images.

6. Conclusion
(1) Pipe can be positioned precisely with antenna array ground-penetrating radar;
(2) The grouting fullness of metal pipes cannot be judged using the ground-penetrating radar method. Non-metal pipe grouting quality can be identified with oscillogram of a single wave, grey-scale image (2D) and 3D slice image respectively.
(3) Radar detection 3D image can present the position of a pipe in the structure intuitively and accurately, and, the pipe material and the pipe grouting fullness can be judged by comparing the radar detection 3D image and the 3D slice image.

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