Research on visualization of concrete crack depth detection based on tracer electromagnetic method

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Research Article

**Keywords:** Crack depth detection, Visualization, Tracer, Electromagnetic method, Hand-held radar

**Posted Date:** January 3rd, 2023

**DOI:** https://doi.org/10.21203/rs.3.rs-2385110/v1

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Abstract

The invisibility of concrete cracks due to their expansion to the inside has resulted in no effective crack depth detection technology to date. The traditional concrete crack depth detection methods have the problems of insufficient accuracy and low detection efficiency. To solve these problems, this paper proposes a new concrete crack depth detection method based on the combination of tracer and handheld radar. The method uses tracer diffusion to the bottom of the crack propagation, and then maps the location of the air-tracer interface by radar waves, thus visualizing the crack depth information. This paper elaborates the detection principle of this new method, conducts numerical analysis and simulation to verify the feasibility, makes standard concrete crack specimen, carries out relevant experimental studies, selects distilled water and saturated NaCl solution as tracer to verify the feasibility of the method, and compares and analyzes the detection effect of these two tracers by comparing the experimental test data with the actual depth of the specimen.

1 Introduction

Cracks are the most common problem affecting concrete structures\cite{1, 2}, which compromise the safety, strength, and durability of the structures\cite{3}. Therefore, it is necessary to carry out a comprehensive detection of cracks in concrete components to accurately grasp the trend of cracks and geometric parameters such as length, width and depth. Current non-destructive testing methods, including infrared thermography and ultrasonic methods, can detect the shape, length and width of apparent cracks in concrete in a mature and accurate way, both in theory and in terms of instrumentation\cite{4, 5}. However, there have been no significant advances in the detection of crack depths in recent decades and there is currently no NDT technique that can accurately detect the depth and location of crack development. While in fact, the detection of crack depth is even more important as the depth to which cracks extend into the structure directly determines the load-bearing performance of the component for important elements. At present, the detection methods for the depth of cracks in concrete structures are mainly divided into the impact elastic wave method\cite{6} and the ultrasonic method\cite{7}. The impact elastic wave method\cite{8, 9} generates high signal energy, propagates over a long distance and is less affected by moisture and other impurities filling the concrete cracks, but has a large error in the energy attenuation test, and is only applicable to the detection of single cracks and cannot detect multiple cracks. In addition, the detection object is only applicable to wide planes such as dam surfaces, and not to narrow structures such as beams or columns. Ultrasonic method\cite{10} is divided into single plane acoustic-wave method, double-sided slanting measurement method, borehole pair measurement method, negative wave method, positive wave method and initial wave phrase reverse method. The requirements for the concrete structure and processing conditions of the borehole pair measurement method and the double-sided slanting measurement method are high, and the detection accuracy is low. The single plane acoustic-wave method only requires that the concrete structure has a measurable surface\cite{11}, which has relatively high detection accuracy and is widely used in engineering practice. However, it requires high uniformity of concrete quality. The traditional single plane acoustic-wave method\cite{12, 13} uses dual probes for multi-point
detection, which is cumbersome and inefficient. In addition, it requires the use of coupling agent to ensure the transmission of ultrasonic signals. The quality of probe coupling will directly affect the detection accuracy. The negative wave method and positive wave method are generally used together with the initial wave phrase reverse method. The acoustic time value for ranging in such methods has contingency and error, which affects the accuracy of the detection results. At present, radar method is also used in engineering technology to detect the depth of cracks, but it cannot avoid the impact of dust accumulation in the cracks on the detection results, and it is commonly used in the detection of large cracks on dams. In summary, due to the invisibility of the crack expanding into the concrete, the conventional technology cannot directly and effectively detect the depth of concrete crack propagation.

The purpose of the radar detection method is firstly to obtain radar images, which reflect the electrical distribution of the medium\[14\]. Based on the core of the detection method, this paper innovatively proposes the assumption of actively improving the electrical capacity of the cracks, and transforms the enhanced electrical distribution of cracks into target distribution. Based on this assumption, and combined with the characteristics of water absorption of cracks, the tracer with strong reflection effect on electromagnetic waves is injected into cracks. The tracer flows to the crack tip under the action of crack capillary water absorption or gravity, and then emits electromagnetic waves to the crack through radar, the reflected electromagnetic waves can map the internal contour of crack, so that the depth of crack propagation can be seen directly from the radar image. This means that the tracer electromagnetic method is used to detect the depth of cracks in concrete structures. Compared with the traditional crack detection technologies, the tracer electromagnetic method does not need coupling agent, nor does it require point-by-point ranging and calculation of sound time, the principle of detection is clear, and the detection efficiency and accuracy is improved.

This paper mainly introduces the detection principle of this method and analyzes the feasibility of this method. And a concrete specimen with prefabricated cracks is designed. The detection effects of distilled water and saturated NaCl solution as tracers are tested respectively with a hand-held radar, and the test results are compared and analyzed. The relevant conclusions can provide reference for the follow-up research on the development depth and shape of oblique cracks based on the tracer electromagnetic method.

2 Detection Principle And Feasibility Analysis

2.1 Operating principle of hand-held radar

Based on the detection of the dielectric difference between the target and the surrounding medium, the hand-held radar emits high-frequency electromagnetic waves of a certain center frequency to the measured object. The high-frequency electromagnetic waves enter the medium in the form of broadband narrow pulses. When the high-frequency electromagnetic wave encounters an interface or target with electrical differences in the transmission process, the electromagnetic wave will be reflected and scattered\[15\], and the reflected waveform from the interface or target will be analyzed, where the positive
and negative peaks of the waveform are expressed in black, white or gray scale, respectively. The in-phase axis or isochromatic lines can directly reflect the profile of the interface or target, so as to achieve the purpose of localization. The propagation of radar wave in the measured object follows the wave equation theory, and the propagation path, electromagnetic field strength and waveform of the reflected wave will change with the electrical properties of the medium it passes through\textsuperscript{[16]}. Therefore, the location of the target can be inferred by analyzing the time, amplitude, frequency and phase characteristics of the received radar reflection wave\textsuperscript{[17]}. The schematic diagram of the working principle of the hand-held radar is shown in Fig. 1.

As shown in Fig. 1, the depth $h$ of the crack can be calculated by using the two-way travel value $t$ of the reflected wave received by the hand-held radar, the propagation speed $v$ of the electromagnetic wave in the measured object and the spacing $2d$ between the transmitting and receiving antennas:

$$h = \sqrt{\frac{t^2}{2} - d^2} \quad (1)$$

Where, $v$ is the propagation velocity of electromagnetic wave in the medium. And $v$ can be calculated according to the relative dielectric constant of the medium\textsuperscript{[18]}, namely:

$$v = \frac{c}{\sqrt{\epsilon_r}} \quad (2)$$

Where: $c$ is the speed of light in vacuum ($c = 0.3$m/ns); $\epsilon_r$ is the relative dielectric constant of the measured object.

2.2 Detection principle of tracer electromagnetic method

Tracer electromagnetic method uses a radar to track the electromagnetic signal of the tracer, thereby mapping the location and depth of crack propagation tip. Wherein, the tracer is a kind of liquid with strong reflective property to electromagnetic wave, which can be used to detect the development depth of cracks by making use of the great difference between its dielectric constant and air, as well as its strong reflective property to electromagnetic wave and its own fluidity. The principle of detection is that the tracer enters the crack and flows towards the bottom of the crack under the pressure of filling or gravity, and when it reaches the bottom of the crack, the crack is scanned by radar. The tracer stored at the bottom of the crack is clearly displayed on the radar scanning image. The true development location and depth of the crack are determined by the position of the tracer on the radar image.

2.3 Feasibility analysis

2.3.1 Numerical theoretical analysis
As can be seen from Formula (2) that the propagation speed of high-frequency electromagnetic waves transmitted by hand-held radar in concrete medium is mainly determined by the relative dielectric constant in the medium. During the propagation of electromagnetic waves, reflected wave and transmitted waves are generated on interfaces with different electromagnetic properties, as shown in Fig. 2. The reflection and transmission follow the law of reflection and transmission, and the reflected energy of electromagnetic wave signal is determined by the reflectivity $\gamma$.

$$\gamma = \frac{\sqrt{\epsilon_1} - \sqrt{\epsilon_2}}{\sqrt{\epsilon_1} + \sqrt{\epsilon_2}}$$

Where, $\epsilon_1$ and $\epsilon_2$ are the relative dielectric constants of the medium above and below the reflective interface respectively.

As can be seen from Formula (3) that the reflection coefficient depends on the difference of the relative dielectric constant of the media on both sides of the interface. The greater the difference of the relative dielectric constant, the stronger the reflected energy, that is, the more obvious the electromagnetic wave reflection. Table 1 shows the relative permittivity of several common media.

<table>
<thead>
<tr>
<th>Media</th>
<th>Relative dielectric constant $\epsilon_r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>1</td>
</tr>
<tr>
<td>Concrete</td>
<td>6—8</td>
</tr>
<tr>
<td>Dry grit</td>
<td>4—6</td>
</tr>
<tr>
<td>Wet grit</td>
<td>25</td>
</tr>
<tr>
<td>Fresh water</td>
<td>81</td>
</tr>
<tr>
<td>Sea water</td>
<td>81</td>
</tr>
</tbody>
</table>

As can be seen from Table 1 that there is a large electrical difference between water and air, and the difference between their relative dielectric constants is much higher than that between concrete and air. If cracks appear in the concrete, the crack expands to the interior of the concrete and produces an air cavity. An air-concrete interface will be formed at the bottom of the cracks, and a weak reflected echo signal will be generated when the radar electromagnetic wave propagates to the interface. In addition, because the crack cavity tends to absorb dust, resulting in dust to accumulate at the bottom of the crack propagation, while the dry dust is close to the relative dielectric constant of the concrete, and the radar electromagnetic waves will be reflected at the air-dust interface, causing misjudgment of the location of the crack propagation end by the inspector. And when the concrete cracks are filled with water or aqueous solution, the original air-concrete interface (weak reflection interface) is replaced by the air water/aqueous solution
Due to the large difference in electrical properties between air and water, this interface will produce strong reflection echoes. In conclusion, the tracer electromagnetic method is feasible to detect the depth of cracks in theory.

### 2.3.2 Numerical simulation analysis

In this part, the simulation model is established to compare the difference of electromagnetic wave reflection ability between air water/water solution interface and air concrete interface, so as to further verify the feasibility of tracing electromagnetic method to detect crack depth.

#### 2.3.2.1 Finite difference time domain

Finite difference time domain (FDTD) is a numerical method for solving Maxwell's equation. Maxwell's differential equation is transformed into a difference equation by discretizing the continuous electromagnetic field in time and space, and separating the electric field and magnetic field components in time and space. The main features of this solution method are shown in Table 2\(^{[19]}\).

<table>
<thead>
<tr>
<th>Discrete space</th>
<th>Discrete element</th>
<th>Time-domain discretization</th>
<th>Solution method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Computational domain</td>
<td>Structural grid</td>
<td>Center</td>
<td>Show solution</td>
</tr>
<tr>
<td>All discrete</td>
<td></td>
<td>Differential dispersion</td>
<td></td>
</tr>
</tbody>
</table>

#### 2.3.2.2 Simulation process and results

Based on FDTD, radar wave reflection detection is carried out for air concrete interface and air water solution interface respectively. The simulation model is shown in Fig. 3. The medium of model 1 from top to bottom is air and sea water respectively, and the medium of model 1 from top to bottom is air and sea water respectively. Each model is 1m long (x-axis direction) and 0.8m high (y-axis direction). An electromagnetic wave absorbing layer (Perfectly Matched Layer, PML) is set at the boundary, and the side length of the grid is 0.001 m. 600MHz Ricker is selected as the simulated excitation source, and the receiver is parallel to the transmission source and located at 0.1m on the right side. During the simulation, the excitation source and receiver complete the detection scanning from left to right along the outer boundary of the air medium.

The propagation process of radar wave with time in Model 1 is shown in Fig. 4, and the propagation process of radar wave with time in Model 2 is shown in Fig. 5, where color shades characterize the strength of the wave signal, the darker the color, the stronger the wave signal, and the lighter the color, the weaker the wave signal. It can be seen from these two figures that the radar wave diffuses from the transmitting source in the form of spherical wave. When the radar wave contacts the air-sea interface or the air-concrete interface, due to the electrical differences between the media on both sides of the interface, one part of the radar wave is reflected back to the air in the form of spherical wave as the...
reflected wave, and the other part enters the sea water or concrete as the transmitted wave. Comparing Fig. 4 and Fig. 5, it can be seen that when the radar wave touches the seawater surface from the air, the reflected color is a little darker, indicating that the radar wave signal reflected by the air-seawater interface is stronger. And because seawater has higher conductivity, it makes the energy of the transmitted wave decay more rapidly within the seawater. Therefore, it can be verified that the air-seawater interface has better electromagnetic wave reflection compared to the air-concrete interface.

3 Precast Concrete Standard Crack Specimen

3.1 Specimen model design

Standard specimens of concrete were made for crack depth test. The specimen size is length × wide × Height = 1200mm × 200mm × 200mm, the material mix ratio is cement: water: sand: gravel = 1:0.51:1.81:3.68, and the concrete strength grade is C20. In order to eliminate the possible interference caused by the strong reflected electromagnetic wave of the reinforcement to the tracer detection of concrete cracks, the specimen is not equipped with longitudinal reinforcement and stirrup. Under the condition that adjacent cracks do not interfere with each other, five groups of vertical cracks with different opening widths are preset in this specimen. The parameters and numbers of preset cracks (arranged from left to right) are shown in Table 3. In order to make the hand-held radar used in this test accurate, a steel bar with a diameter of 7 mm and a length of 200 mm is embedded at the specified location. The steel bar is perpendicular to the long side of the concrete. The use parameters of the known location of the steel bar can be used to reverse adjust and calibrate the use parameters of the hand-held radar. The design model of the specimen is shown in Fig. 6, and the location calibration of embedded reinforcement and preset concrete cracks is shown in Fig. 7, which is a schematic plan formed by expanding and connecting the two long sides and the upper top surface of the concrete test piece.

<table>
<thead>
<tr>
<th>No.</th>
<th>1#</th>
<th>2#</th>
<th>3#</th>
<th>4#</th>
<th>5#</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>200mm</td>
<td>200mm</td>
<td>200mm</td>
<td>200mm</td>
<td>200mm</td>
</tr>
<tr>
<td>Width</td>
<td>0.2mm</td>
<td>1mm</td>
<td>0.4mm</td>
<td>2mm</td>
<td>0.3mm</td>
</tr>
<tr>
<td>Depth</td>
<td>35mm</td>
<td>45mm</td>
<td>40mm</td>
<td>50mm</td>
<td>20mm</td>
</tr>
</tbody>
</table>

3.2 Specimen fabrication

The wooden mold was processed according to the design drawing, and the steel pieces of appropriate specification were cut according to the prefabricated crack parameters. Surface of the steel pieces was evenly coated with lubricating oil and inserted into the design position of the cracks in the mold, as shown in Fig. 8a. Then the concrete was poured, and the surface was smoothed out after full pounding.
with a vibrating bar, as shown in Fig. 8b. All steel pieces were pulled out after the initial setting of concrete, and the formed pre-cracked concrete specimen was shown in Fig. 8c.

After the concrete specimen was cured, the actual crack width was measured using a crack gauge whose accuracy is 0.01mm and the actual crack depth was measured using a steel straightedge whose accuracy is 1mm to obtain the real test reference data. The test results are shown in Fig. 9 and Fig. 10. The actual widths of 1#~5# cracks are 0.22mm, 1.00 mm, 0.39mm, 2.05mm and 0.30mm respectively, and the actual depths of 1#~5# cracks are 37mm, 46mm, 40mm, 50mm and 20mm respectively.

4 Test Process And Results

4.1 Test materials and equipment

(1) Tracer

Distilled water and saturated NaCl solution are used as the tracer in this test, as shown in Fig. 11. The physical characteristic parameters of both at room temperature are shown in Table 4.

<table>
<thead>
<tr>
<th>Media</th>
<th>Relative dielectric constant $\varepsilon_n$</th>
<th>Electrical conductivity $\sigma$ (ms•m$^{-1}$)</th>
<th>Attenuation coefficient $\alpha$ (dB/m)</th>
<th>Refractive index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distilled water</td>
<td>81</td>
<td>0.01</td>
<td>0</td>
<td>1.33</td>
</tr>
<tr>
<td>Saturated NaCl solution</td>
<td>81</td>
<td>30000</td>
<td>1000</td>
<td>1.58</td>
</tr>
</tbody>
</table>

(2) Tracer syringe

The capacity of the tracer syringe used in this experiment is 200 ml, and the inner diameter of the injection needle hole is 0.1 mm, as shown in Fig. 12a.

(3) Hand-held radar

The hand-held radar used in this test was the 3D perspective scanning test system (STRUCTURESCAN MINI), which has a 22cm long and 14cm wide working surface, a 14cm probe spacing and a center frequency of 2.6GHz, as shown in Fig. 12b.

4.2 Test process and results

(1) Hand-held radar instrument parameter calibration
Based on the known depth of the pre-buried reinforcement, the hand-held radar parameters were adjusted in reverse, setting the dielectric constant to 6.5 and the detection depth to 20cm, as shown in Fig. 13.

(2) Crack depth detection

The test procedure consisted of three tests, which were tested from 1 # to 5 # in turn as follows.

a. Detection of crack depth without tracer injection using a hand-held radar.

b. Detection of crack depth after distilled water injection using a hand-held radar.

c. Detection of crack depth after injection of saturated NaCl solution using a hand-held radar.

In the process of b and c, the tracer needs to be injected until there is fluid flow from both ends of the crack. In order to ensure that there is only a thin layer of tracer in the crack, in this test, when there is no tracer flowing out on both sides of the crack, the radar is used for depth detection. The depth detection results of each crack are shown in Fig. 14.

4.3 Analysis of results

The detection depth of each crack was read from the 2D radar scanning image, and analyzed and compared with its corresponding actual depth, as shown in Table 5. The relationship between the detection depth with saturated NaCl solution as the tracer and the actual depth is shown in Fig. 15.

<table>
<thead>
<tr>
<th>Crack number</th>
<th>Crack width (mm)</th>
<th>Actual depth (mm)</th>
<th>Testing depth (mm)</th>
<th>Absolute error (mm)</th>
<th>Relative error (Absolute value)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Distilled water</td>
<td>Saturated NaCl solution</td>
<td>Saturated NaCl solution</td>
</tr>
<tr>
<td>1#</td>
<td>0.22</td>
<td>37</td>
<td>/</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>2#</td>
<td>1.00</td>
<td>46</td>
<td>45</td>
<td>45</td>
<td>1</td>
</tr>
<tr>
<td>3#</td>
<td>0.39</td>
<td>40</td>
<td>38</td>
<td>38</td>
<td>2</td>
</tr>
<tr>
<td>4#</td>
<td>2.05</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>0</td>
</tr>
<tr>
<td>5#</td>
<td>0.30</td>
<td>20</td>
<td>/</td>
<td>18</td>
<td>2</td>
</tr>
</tbody>
</table>

It can be seen from the 2D scanning image of the crack radar in Fig. 14. For 1# crack, the crack depth is not detected with or without the injection of distilled water or saturated NaCl solution, probably because the crack width is narrow, which makes the reflecting surface of the air-tracer formed in the crack cavity narrow, leading to weak reflection of electromagnetic waves from the reflecting surface. For 2# crack 3#
and 4#, the crack depth is not detected before the tracer is injected, but the crack depth is detected after the distilled water or saturated NaCl solution is injected, which indicates that the air-tracer interface can better reflect electromagnetic waves than the air-concrete interface. For 5# crack, the crack depth is not detected when no tracer is injected and distilled water is injected, but is detected after the saturated NaCl solution is injected. It shows that the reflection effect of air-NaCl solution interface is better than that of air-distilled water interface.

According to the analysis in Table 5 and Fig. 15, when the crack width is \( \leq 0.22 \text{mm} \) and the crack depth is \( \leq 37 \text{mm} \), distilled water or saturated NaCl solution is used as the tracer, and the crack depth cannot be detected. When the crack width is \( \geq 0.30 \text{mm} \), the saturated NaCl solution can be used as the tracer to detect the crack depth of 20mm. When the crack width is 0.30 ~ 2.05mm, the detection results become more and more accurate with the increase of the crack width. When the crack width exceeds 1mm, the relative error rate of the detection results is less than 2%. The error rate may be related to the height of the tracer in the crack. The smaller the crack width is, the stronger its capillarity is. Under the action of capillary force, the tracer in the crack fades slowly, causing the position of the air-tracer interface in the fracture to be higher than the bottom of the fracture, which leads to a large error in the detection result of the crack depth.

In summary, the depth of cracks can be effectively detected by injecting tracer into the cracks and combining with hand-held radar. The distilled air-water interface and saturated NaCl solution-air interface can effectively reflect electromagnetic waves, effectively improving the detection accuracy of crack depth. According to Table 4, the electrical conductivity of saturated NaCl solution and attenuation coefficient are much greater than the relevant parameters of distilled water, indicating that saturated NaCl solution contains a large number of charged particles. The free movement of charged particles not only offsets the electromagnetic waves entering the solution, but also reflects electromagnetic waves to the outside world, increasing the ability to reflect electromagnetic waves. Therefore, saturated NaCl solution has stronger reflection on electromagnetic wave than distilled water.

5 Conclusions And Outlook

5.1 Conclusions

(1) It is feasible and effective to use tracing electromagnetic method to detect crack depth.

(2) In this experiment, the reflection of electromagnetic waves at the air-concrete interface is weak, and the depth of concrete microcracks cannot be directly detected by handheld radar. The air-tracer interface can form an effective reflection of electromagnetic waves, and the stronger the tracer's reflection of electromagnetic waves, the better the crack depth detection effect.

(3) It is more accurate and effective to use the tracer electromagnetic method to measure cracks with large width. When using this method to detect the depth of micro cracks, the capillary effect of micro cracks on the tracer may interfere with the measurement results of the crack depth.
The way of detecting the cracks depth of concrete structures with tracer electromagnetic method is simple with clear principles, low requirements for the required testing environment, intuitive judgement and high efficiency, promising to become a widely used means of non-destructive testing.

5.2 Outlook

In view of the initial experimental verification of the proposed and envisaged new method for detecting the depth of cracks in concrete structures in this paper, the feasibility of the tracer electromagnetic method for detecting the depth of cracks has now been verified through the detection of vertical cracks. In the future, tracers with stronger reflection of electromagnetic waves will be selected and formulated, and the method will continue to be used to investigate the depth and direction of diagonal cracks in concrete elements, expanding the scope of application of the technique.

Declarations

Ethics approval and consent to participate

We have read and understood the publishing policy, and submit this manuscript in accordance with the ethics approval and consent to participate.

Consent for publication

All the authors listed have approved the manuscript that is enclosed.

Availability of data and material

The data and materials are only reflected in the manuscript and are not provided additionally. We declare that all the data and materials are true and reliable, and we are responsible for the authenticity of the data and materials.

Competing interests

I declare that the authors have no competing interests as defined by Springer, or other interests that might be perceived to influence the results and/or discussion reported in this paper.

Funding

This work was supported by the National Natural Science Foundation of China (Grant No. 52109162), the National Key Research and Development Program of China (Grant No. 2021YFC3090104), and Fundamental Research Funds for Central Public Welfare Research Institutes (Y421007, Y421003).

Authors' contributions

Author Contributions: Conceptualization, Yulei Wang. and Lei Tang.; methodology, Yulei Wang. and Lei Tang. and Shenghang Zhang.; testing participation, Yulei Wang. and Hui Tian. and Jiahui Liang.; testing
analysis, Yulei Wang. and Lei Tang. and Shenghang Zhang.; writing—original draft preparation, Yulei Wang. and Lei Tang.; writing—review and editing, Yulei Wang. and Lei Tang. and Yu Jia. All authors have read and agreed to the published version of the manuscript.

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Acknowledgements

This work thanks to all the authors for their contributions, as well as the support of the Funding, and also thanks to the research platform provided by Nanjing Hydraulic Research Institute.

References


Figures
Figure 1

Schematic diagram of the working principle of hand-held radar

Figure 2

The propagation path of electromagnetic wave
Figure 3

Simulation model

(a) The 31th ns

(b) The 34th ns

(c) The 47th ns

(d) The 55th ns
Figure 4

Snapshot of radar reflected wave of model 1

(c) The 47th ns

Figure 5

Snapshot of radar reflected wave of model 2
Figure 6

Concrete specimen design

Figure 7

Layout of crack location
Figure 8

Specimen making process
Figure 9

Measuring the actual width of concrete cracks

Figure 10

Measuring the actual length of concrete cracks
Figure 11

Saturated NaCl solution and distilled water

a Tracer syringe  b STRUCTURESCAN MINI
Figure 12

Testing equipment

![Image showing testing equipment with labels for a Radar scan rebar diagram and b On-screen display.]

Figure 13

Calibration of instrument parameters
Figure 14

Radar 2D scan of 5 kinds of cracks
Figure 15

Relationship diagram of detection depth and versus actual crack depth using saturated NaCl solution as tracer.