Research on Concrete Damage Detection Based on Electrical Resistivity Tomography Technology

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ABSTRACT: Nondestructive detection technology of concrete structure building is of great importance to ensure the safety and durability of structures. As an emerging industrial nondestructive testing technology, resistivity tomography has a broad application prospect in the damage detection of concrete structures. Based on the resistivity tomography and its physical theory, this paper uses the fully embedded electrode design and the four-electrode measurement method for imaging detection of crack damage, and verifies the reliability and feasibility of the experiment design by virtue of analogue simulation software, and carries out objective evaluation and comparison with the quality of detection images through combination with the image evaluation indexes. The test results indicate that this method can be applied to the nondestructive detection of concrete structures.

Keywords: concrete; crack; resistivity tomography; damage detection

1 RESEARCH BACKGROUND

Since its advent, concrete material has become the building material that is the most widely used to a maximum extent at home and abroad due to its good mechanical properties, durability, economical efficiency and easy-molding properties, and it has played an important role in transportation, hydraulic engineering, industrial engineering, and other national defense construction and basic national economic construction, which has become an indispensable building material. Viewing from statistical data, China’s concrete production and consumption amount are huge. Commercial concrete output in 2015 was 1.64 billion cubic meters, with a year-on-year growth rate of 5.6% compared to 1.55 billion cubic meters in 2014. In a longer period in future, the main building materials will be still concrete materials. Concrete structures still have a broad prospect for development and application \( [1,2] \).

In recent years, there are also common problems, such as crack or damage to the concrete structures due to chemical corrosion and invasion, design defect, construction problems or natural disasters, resulting in greatly reducing the bearing capacity and service life of structures, and even leading to structural collapse, bringing a huge economic damage to people, and threatening people’s life safety \( [3-5] \). Large-scale concrete structures (high-rise buildings, large-scale buildings, bridges, nuclear power plants) are prone to structural damage under the influence of unfavorable factors (such as construction and external loads), resulting in significant safety problems. Health monitoring technology and damage diagnosis are particularly important for concrete structures and their key components. On this basis, this paper uses resistivity tomography to conduct relevant researches on the damage detection of concrete structures \( [6,7] \).

2 RESEARCH PROGRESS OF RESISTIVITY TOMOGRAPHY

In 1987, Japan’s Shima first proposed “resistivity tomography” and explained the method of inversion interpretation \( [8] \). In the 1990s, MCOHM21 instrument used for the actual detection of resistivity tomography was first successfully researched by Japan’s OYO Corporation \( [9,10] \). Since then, tomography has entered a period of rapid development. Kimmo Karhunen and others respectively conducted resistivity tomography for mortar specimen poured with polyurethane, horizontal rebar, vertical rebar and plastic plate, and the results proved that the media contained in the speci-
men can be probed and positioned by ERT technology, thereby indicating that ERT technology has a potential application in detecting the thickness of concrete protective cover, estimating the crack depth and detecting the concrete moisture distribution. Milad Hallaji and Mohammad Pour-Ghaz of North Carolina State University in the United States used ERT imaging technology to image the size and position of the concrete artificial damage site through painting sensitive conducting layer on the surface of concrete structures, and conducted real-time monitoring of the development process of beam cracks in the bent beam experiment, and ultimately concluded that the use of two-dimensional sensitive conducting layer, and combination with ERT technology can effectively detect concrete surface micro-cracks and its development.

Resistivity tomography has been applied in engineering geophysical exploration and the domestic research progress has been relatively rapid in recent years. Meng Qi, et al. researched the application for resistivity tomography in fault detection. Li Zhuoqiu, et al made a series of researches on the related characteristics of sensitive concrete and electrical imaging applications, and improved the conductivity by adding conducting media in the concrete, thereby improving the sensitivity and resolution of resistivity tomography.

3 RESISTIVITY TOMOGRAPHY AND CONCRETE RESISTIVITY TESTING

3.1 Principle of resistivity tomography

3.1.1 Principle of resistivity tomography

The current (voltage) excitation is uploaded to the periphery of the measured matrix. When the distribution of electrical resistivity in the matrix changes, the electric potential in the matrix will also change, thereby leading to corresponding change in the detection current (voltage) at the periphery of the matrix, while the change in the current (voltage) at the boundary of the matrix can reflect the changes in the electric resistivity in the matrix. Therefore, through inverse problem solving of the voltage detection value of the periphery of the matrix, the image reconstruction algorithm can be used to reconstruct the resistivity distribution in the matrix, thereby conducting visual detection of the matrix.

3.1.2 Physical theory of resistivity tomography

Resistivity tomography is a detection technology based on electromagnetic field theory. Maxwell equation describes the relationship between electric field intensity E, magnetic field intensity H, magnetic induction intensity B and electric displacement vector D, charge density σ and current density J as follows:

\[ \nabla \cdot H = J + \frac{\partial D}{\partial t} \]  \hspace{1cm} (1)

\[ \nabla \cdot E = -\frac{\partial B}{\partial t} \]  \hspace{1cm} (2)

\[ \nabla \cdot B = 0 \]  \hspace{1cm} (3)

\[ \nabla \cdot B = \sigma \]  \hspace{1cm} (4)

Thereinto, t is the power on time.

For resistivity tomography, there is also a need to add Ohm law satisfied by the conduction current, voltage in the medium and electrical resistivity. The differential form (5) is:

\[ J = \frac{E}{\rho} \]  \hspace{1cm} (5)

Thereinto, J means vector of volume current density; ρ means electrical resistivity; E is electric field intensity.

Current continuity equation can be obtained by taking the degree of divergence from equation (1), which indicates that the sum of the change rate of charge volume density and the divergence algebra of current density is always equal to zero:

\[ \nabla \cdot J + \frac{\partial \rho}{\partial t} = 0 \]  \hspace{1cm} (6)

For the integral form of the current continuity equation (7), its physical significance indicates that the volume integral of divergence of a vector \( \nabla \) is equal to the surface integral of normal component located at the peripheral surface.

\[ \int (\nabla \cdot J) \, dv + \frac{\partial \rho}{\partial t} \, dv = 0 \]  \hspace{1cm} (7)

or

\[ \oint J \cdot dS = \int \frac{\partial \rho}{\partial t} \, dV \]  \hspace{1cm} (8)

The physical significance of equation (8) indicates the total current from any closed surface S in a section of volume current density J.

Electric potential \( \phi \) changes along the direction of the electric field intensity. Their relationship can be expressed as follows:

\[ E = -\nabla \cdot \phi \]  \hspace{1cm} (9)

Combined with equations (5), (6) and (9):

\[ \nabla \cdot \nabla \phi = \frac{\partial \rho}{\rho} \]  \hspace{1cm} (10)

Resistivity tomography belongs to the constant current field model. There is no current source in the matrix, and the divergence of the current density in the matrix is:

\[ \nabla \cdot J = 0 \]  \hspace{1cm} (11)

Thereinto, J means the conductance current density; \( \omega \) means electrical conductivity; E is electric field intensity.
medium is zero. Therefore, according to Maxwell equation and hypothesis of quasi-stationary field, at any part in the matrix,

$$\nabla \cdot \frac{\partial \rho}{\partial t} = 0 \quad (11)$$

According to equations (5), (9) and (11): 

$$\nabla \cdot \frac{\nabla \varphi}{\rho} = \nabla \left( \frac{1}{\rho} \nabla \varphi + \frac{1}{\rho} \nabla^2 \varphi \right) = 0 \quad (12)$$

Then, Poisson equation can be expressed as:

$$\nabla^2 \varphi = -\frac{\rho}{\epsilon} \nabla \varphi \quad (13)$$

Poisson equation: to look for the electric field based on a given charge density

$$\nabla^2 \varphi = \frac{\sigma}{\epsilon} \quad (14)$$

In the equation, charge volume density is $\sigma=0$, which satisfies Laplace equation; Laplace equation is applied to the potential distribution function and resistivity distribution function;

$$\nabla \left( \frac{1}{\rho(x, y)} \cdot \nabla \varphi(x, y) \right) = 0, (x, y) \in \Omega \quad (15)$$

$(x, y) \in \Omega$ (meet Euclidean space, continuous differentiable)

Its boundary conditions are:

$$\varphi(x, y) = f(x, y), (x, y) \in \Omega \quad (16)$$

Potential distribution function is the voltage distribution at the periphery of matrix, which can be measured and known.

3.2 Concrete resistivity test

3.2.1 Concrete conduction mechanism

The conductivity of common concrete is between the insulator and conductor. In the early period of concrete structure forming, the moisture content of the concrete was relatively high, conductive ions could move with moisture in concrete, and the resistivity could reach $10^{-1}$-$10^{4} \Omega$m. With continuous reduction of moisture in concrete, concrete conductivity continues to decline until completely dry. At this time, the resistivity value is in the range of $10^{-4}$-$10^{10} \Omega$m, which can be almost regarded as an insulator. In order to make concrete have a relatively stable and better electrical conductivity, transmission channels must be provided for the electrolyte ions in the concrete or metal and semiconductor electronics.

The research shows that the conductivity of concrete just poured is mainly determined by water-cement ratio, temperature of mixture and number of soluble salt and other factors. For common cement concrete with the water-cement ratio of 0.35-0.60, the resistivity is 300-600 $\Omega$m$^{-1}$ [16]. Concrete resistivity has a great change from stir molding to later maintenance. The research of change in resistivity in these periods can provide data support for the application of resistivity tomography in concrete, and also provide data reference for the construction of electric field in the resistivity tomography.

3.2.2 Concrete resistivity test method

The research uses the four-electrode measurement method to measure the concrete resistivity [17]. That is, four detecting electrodes are equidistantly arranged on the surface of specimen or pre-embedded in the specimen and keep conductive contact with specimen, in order to measure the potential difference between the internal electrode couples at the current of external electrode couples, or measure the current passing through the external electrode couples at the loaded voltage of internal electrodes. The four-electrode measurement method is used and theoretically requiring that the specimen can be deemed as uniform homogeneous semi-infinite body in size. The contact point between the electrode and the specimen is regarded as an ideal geometric point (that is, point contact). The point contact way of measuring electrodes pre-embedded in the concrete specimen is used in this test.

4 DAMAGE DETECTION OF CONCRETE RESISTIVITY TOMOGRAPHY

4.1 Damage detection of concrete crack

4.1.1 Specimen production

(1) Specimen mix design

In this test, water-cement ratio is 0.5, and sand ratio is 2. The specific ingredients of the specimen are shown in Table 1 below.

| Water-cement ratio | Component use amount (Kg/m$^3$) | Mixture ratio |
|--------------------|----------------------------------|---------------|
| 0.5                | 800                              | 1:2:0.5       |

| Water cement | Component use amount (Kg/m$^3$) | Mixture ratio |
|--------------|----------------------------------|---------------|
| 600          | 1600                             | 1:2:0.5       |

(2) Specimen production and maintenance

The specimen prepared in this test is a prismoid specimen, with the size of 120mm×40mm×40mm. The standard curing box is used for maintenance of poured specimen, with the curing temperature of 20±1°C and relative humidity of 90%. After 24h, there is a need to take out the specimen and place in the room for natural curing, with the indoor temperature
of 15-20°C, and relative humidity of 15-40%, and also measure the resistivity and moisture content.

4.1.2 Test design
In order to research the imaging effect of the resistivity tomography system and the recognition ability of the resistivity tomography detection system to the location, size and shape of the concrete damage, a specimen shown in Figure 1 is designed for testing. The specimen is a short cylinder with a radius of 100 mm and a height of 30 mm at the bottom. The damage in the specimen is formed by pre-embedding plastic foam with a predetermined size. Pre-embedded damage is the artificial damage of square pre-embedded hole with diameter of 50mm and the artificial damage of circular pre-embedded hole with diameter of 25mm.

After completion of the test design, in order to verify the reliability of the system and the feasibility of the test design, based on the analogue simulation software COMSOL with MATLAB, the imaging results of this test are numerically simulated. The numerically simulated specimen model size and material properties are identical to this test. The simulated imaging results are shown in Figure 2 below. Figure 2(a) shows the finite element meshing of the numerical analysis model, and Figure 2(b) shows the damage imaging results of simulated boundary voltage values.

The simulated imaging results clearly show that the resistivity tomography system can detect the specific location, size and shape of the damage, indicating that the system is reliable and the test design is feasible.

4.1.3 Electrode design
Fully embedded electrodes are easy to produce, and the test is easy to operate. In this test, fully embedded electrodes are also used, which are directly pre-embedded in the specimen during pouring, as shown in Figure 3 (bold black line is the location of pre-embedded crack).

4.1.4 Damage detection
The resistivity of specimen should also be measured during resistivity tomography, and a pair of insulating rods must be padded under the specimen during imaging detection of the damage. According to the imaging detection results of fully embedded electrodes, it is found that the imaging detection results remain basically unchanged after one week. Therefore, in this test, the damage detection is given to the specimen twice: that is, the first damage detection imaging is conducted for the specimen under standard curing conditions after 24 hours of curing, and then the second damage detection imaging is conducted after 7 days. Finally measured imaging results are shown in Table 2.

| Specimen type          | Imaging detection time |
|------------------------|------------------------|
| 50mm of crack specimen | 24h                    |
| 100mm of crack specimen| 7 days                 |

4.2 Evaluation index of concrete damage detection results

4.2.1 Image evaluation theory
Image evaluation theory mainly includes subjective image quality evaluation and objective image quality evaluation. Based on its mathematically description and strong applicability, in recent years, objective image quality evaluation methods have drawn the attention of most scholars and research institutes. Many researchers are devoted to the research of this method. The following is a detailed introduction of this method. According to the degree of need for reference images, objective image quality evaluation methods can be divided into three types: 1. Full refer-
ence evaluation method; 2. Partial reference evaluation method; 3. No reference evaluation method.

(1) Full reference image quality evaluation method
The method needs to provide all the information of the distorted image and original image. Its evaluation model is shown in Figure 3.

For the case of testing, comparing or optimizing the image codec system, in terms of research results, this method now has more achievements, so it is more suitable. For example, the traditional PSNR (peak signal to noise ratio), image texture evaluation model SSIM, MSE (mean square error) and image similarity evaluation method based on the image color histogram belong to this category.

a) Image similarity evaluation index based on the image color histogram
The image color histogram is defined as follows:

Supposing that \( S(X_i) \) is the number of pixels with a certain eigenvalue of \( X_i \) in the image \( P \), \( N = \sum_j S(X_j) \), \( N \) is the total number of pixels in \( P \), normalization processing is given to \( S(X_i) \), namely:

\[
h(X_i) = \frac{S(X_i)}{N} = \frac{S(X_i)}{\sum_j S(X_j)}
\]

(17)

The color histogram of image \( P \) is:

\[
H(P) = (h(X_1), h(X_2), \ldots, h(X_n))
\]

(18)

According to the above definition, the definition of similarity based on the image color histogram can be obtained. Supposing that two images are \( G \) and \( P \), and the corresponding histograms are \( H(G) \) and \( H(P) \), the similarity \( S(G, P) \) (range: 0–1) of two images based on the image color histogram can be defined as follows:

\[
S(G, P) = \sum_{i=0}^{n} \min(H(G(X_i)), H(P(X_i)))
\]

(19)

In the equation, \( n \) - the maximum value that can be taken under a certain pixel; the value of 8-bit image is 255.

b) MSE/PSNR

As two traditional objective evaluation methods with statistical characteristics, mean square error (MSE) and peak signal to noise ratio (PSNR) are simple calculations of the difference between the original image and the image to be evaluated by using mathematical statistics method. The two evaluation methods are essentially the same, and the calculation principle is shown in equations (20) and (21).

\[
MSE = \frac{1}{MN} \sum_x \sum_y [I(x, y) - I_0(x, y)]^2
\]

(20)

\[
PSNR = 10 \log_{10} \frac{m^2}{MSE}
\]

(21)

Thereinto, \( M, N \) are the size of image; \( I(x, y) \) is the gray value of original image located at \( (x, y) \); \( I_0(x, y) \) is the gray value of the image to be compared located at \( (x, y) \); \( m \) is the maximum value that can be taken under a certain pixel.

(2) Partial reference (RR) image quality evaluation method
When the image is evaluated without obtaining complete information of original image, but only with the feature data information that can represent the original image, the image to be evaluated can only be represented by the feature representation that is the same with original image. The quality of image to be evaluated can be determined by comparing with the acquired data and the data for original image.

(3) No reference image quality evaluation method
At present, most of the evaluation ways to this method are specific to the same distorted image. These images have a different level of decline in quality, but the reasons for decline in quality are different.

4.2.2 \textit{Image similarity evaluation index}

Image similarity evaluation is to use an index to evaluate the similarity between the damage detection imaging and actual damage situation. If the similarity is higher, it indicates that the quality of damage detection imaging is better. In case of failure to directly acquire the damage situation in the actual project, the model of the measured object can be established by the simulation software according to the test data, and the simulation damage imaging detection results of the model can be used as the basis for the similarity evaluation. In this research, the damage is pre-embedded, and the damage image can be acquired, so the actual damage image is used as the basis for evaluation of damage imaging detection.

For the image similarity index, according to the former statement in 4.2.1, this paper intends to use full
reference evaluation method. Based on the fact that there is currently free of a very comprehensive objective evaluation index, this paper selects a simpler basic measurement method of the mean square error (MSE), peak signal to noise ratio (PSNR) and image similarity based on image color histogram for similarity evaluation of the above imaging detection results.

The mathematical expressions of mean square error (MSE) and peak signal to noise ratio (PSNR) are shown in equations (20) and (21), while the mathematical expressions of the measure of image similarity based on the image color histogram are shown in equations (17) to (18).

4.3 Analysis of concrete damage detection results

4.3.1 Damage detection imaging evaluation results of fully embedded electrode specimen

The meanings of three image evaluation indexes are as follows: if the mean square error (MSE) value is larger, that is, the similarity of detection results is lower; if the peak signal to noise ratio (PSNR) is greater, the similarity is higher, that is, the similarity of detection results is positively correlated; the calculation value of similarity based on the image color histogram can be used to directly represent the similarity of detection results, and its range is 0~1. In the first week, the fully embedded electrode has a greater fluctuation in the imaging detection, but after one week, it tends to be stable and has a higher quality of imaging detection.

4.3.2 Damage detection imaging evaluation results of a single hole damage specimen

![Figure 4. Damage detection evaluation results of fully embedded electrode specimen.](image)

As can be seen from the above evaluation results, the quality of imaging detection image is relatively good one day after pouring and molding specimen, but the quality of imaging detection image is slightly decreased after one week. The change rules of the quality of imaging detection image are opposite to that of the quality of imaging detection image of a single hole damage specimen, but similar to that of the quality of imaging detection image of multiple hole damage specimens, indicating that the detection ability of the currently used resistivity tomography system to a single hole damage is stronger than that of multiple hole damage.

5 CONCLUSION

In this paper, the research on the conductivity of concrete structures can provide data reference for the resistivity tomography detection system, and provide test basis for setting the electrical parameters of the structural model in the imaging system. Through the resistivity tomography test of the pre-embedded hole damage and crack damage, this paper explores the
system detection ability to the hole damage and crack damage, and analyzes and discusses the test results through image evaluation index, obtaining the following main conclusions: the resistivity tomography system developed can effectively detect the location and general shape of the hole damage, but the imaging accuracy needs to be improved; the soft-field characteristics of the electric field indeed have an adverse impact on the resistivity tomography technology, and its impact needs to be reduced or avoided in the next test; the system can detect the general location of the crack, but the imaging results of its shape and length need to be further improved.

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