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Void Detection Behind a Hydraulic Tunnel Lining Containing Complex Reinforcement Using Combined Non-Destructive Testing Methods

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Abstract. The existence of voids behind the lining has always been a "pain point" in tunnels. In recent years, prestressed concrete linings have been so densely reinforced that voids cannot be accurately detected using a single non-destructive testing method. A standard model of Voids behind the lining with reinforcement parameters, concrete mix ratio, thickness and material inside the void consistent with the actual project was produced. Based on this model, ground-penetrating radar, impact echo and ultrasonic laminar imaging detection tests were carried out and typical mapping of the various methods was obtained. Combined with the applicability of the practical operation in engineering, combined non-destructive testing methods is proposed and verified in actual engineering. The results show that the combined non-destructive testing methods can accurately detect voids of lining, and can take into account the detection efficiency to meet the detection requirements of complex reinforced linings.

Keywords. Hydraulic tunnels, lining voids, combined non-destructive testing, indoor testing, engineering applications

1. Introduction

The water transfer project is an important initiative to address the uneven distribution of water resources, and the hydraulic tunnels are the choke points of the water transfer project. The quality of concrete lining in hydraulic tunnels is the focus of attention, and internal defects such as lining voids have always been a "pain point" in tunnels. With the increasing development of water resources allocation projects in China, prestressed concrete lining structure type is gradually adopted, this type of lining by tensioning the prestressing reinforcement in the concrete lining, so that the lining produces precompressive stress, can make full use of the characteristics of high compressive strength of concrete, can save materials, reduce the occurrence of cracks in the lining structure, resistance to internal water pressure [1]. However, the presence of voids between the prestressed concrete lining and the initial support can be a more serious

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hazard. Not only will the load applied to the lining be discontinuous, weakening the lining's ability to resist external loads, but it may also cause damage to the concrete lining after the prestressing has been applied, making it a weak part of the overall structure and leading to a risk during pressurised operation [2]. Accurate detection of prestressed concrete lining voids is therefore an important prerequisite to ensure safe operation of the project. The prestressed concrete lining is not only configured with a double layer of ordinary reinforcement, but also with dense prestressed steel strands (a section of a water transfer tunnel is shown in figure 1), which brings more interference to the current NDT methods, and the relevant diagnostic rules are not yet sound, leading to "missed" and "misjudged" defects within the prestressed concrete. The problem of "misjudgement" is prominent.

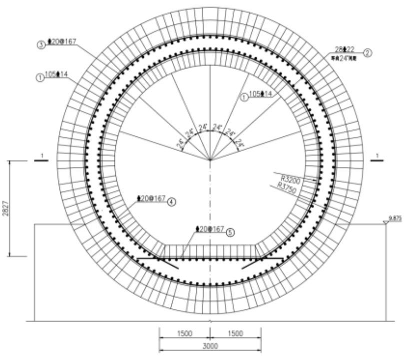

Figure 1. Hydraulic tunnel cross-sections.

2. Testing Methods and Equipment

2.1. Ground-penetrating Radar

The basic principle of ground-penetrating radar is to use the difference of electromagnetic properties between different media, through the transmitting antenna to the detected media to transmit high-frequency pulse electromagnetic waves, receiving antenna to receive the reflected electromagnetic waves and direct waves reflected from different dielectric interfaces in the detected media, using the path of electromagnetic wave propagation in the media, the electromagnetic field strength and waveform will change with the electromagnetic properties and geometry of the medium through the principle, through the study of the reflected wave relative to the direct wave round trip, amplitude, frequency and phase characteristics, to determine the target of hidden objects in the detected media [3,4]. H Qin. et al [5] introduced a deep learning-based automatic recognition method to identify tunnel lining elements. Feng, et al [6] presents a quantitative interpretation algorithm for ground-penetrating radar detection of tunnel lining debonding. In the light of the problem of weak reflection signals shielded by strong reflections from the concrete surface, the detection and the recognition of hidden micro-cracks in the shield tunnel lining were studied using the orthogonal matching pursuit and the Hilbert transform (OMHT method). LING Tong-hua. Et al [7] investigated the detection and identification of hidden microcracks in shield tunnel linings using orthogonal matching tracking and Hilbert transform (OMHT) methods.

This test uses the LTD-2600 radar mainframe and CG900MHz shielded antenna produced (figure 2) by the China Institute of Radio Wave Propagation to carry out the relevant tests.

Figure 2. Ground Penetrating Radar (GPR) equipment.

2.2. Impact Echo Method

The impact echo method was proposed in the 1980s by M. SANSULONE of Cornell University and N.J. CARINO of the National Institute of Standards and Technology. The principle of the impact echo method is to generate low frequency stress waves by transient impact on the concrete surface, when the stress wave propagation encounters defects, boundaries, etc. will be reflected, using the time domain or frequency domain analysis method to analyse the received stress wave signal, you can obtain the depth and thickness of the defects existing inside the measured concrete structure [8]. DG Aggelis [9] use of time domain characteristics, spectral content and wavelet transform reveal the effectiveness of grouting. S Li. et al [10] used a support vector machine (SVM) to classify and identify the typical signals of impact echoes to determine the presence of void defects in the mortar layer. LIU. et al [11] used model tests to investigate the effectiveness of the impact echo method for the detection of defects in steel pipe lining concrete.

The Impact Echo Scanner (IES) (figure 3) was selected for the test, which uses a rolling receiver and a distance measurement system that allows automatic testing along the line of measurement, and the speed of the rolling does not affect the distance of the test interval.

Figure 3. Impact Echo Scanner (IES).

2.3. Ultrasonic Tomography

Ultrasonic Tomography is a procedure for inverting an image of the internal structure of an object based on the scattered waves around the object. Based on voids, foreign impurities, delamination, cracks and other defects in reinforced concrete structures causing anomalies that are inconsistent with the acoustic properties of the surrounding concrete, waveform images are constructed using ray theory to make the determination visual. Array ultrasound detection of internal concrete defects is achieved through the generation and reception of ultrasound beams by multi-array transducers, combined with synthetic aperture focusing technology to achieve two- or three-dimensional imaging of the concrete under test, visually displaying the location and size of defects in the concrete [12,13]. Schabowicz, K [14] verified the applicability of Ultrasonic tomography and its reliability through field trials. Choi H [15] developed developed 3-D internal images (velocity tomograms) for the detection of internal defects in concrete prisms and effectively identified structural damage within reinforced concrete constructions.

The A1040 MIRA low frequency ultrasound section imager was used to carry out the pilot study, as shown in figure 4.

Figure 4. A1040 MIRA low frequency ultrasound section imager.

3. Experimental Design

3.1. Experimental Model

The following principles were followed to produce A standard model of voids behind the lining: ① the reinforcement parameters were the same as the actual project; ② the concrete mix ratio was the same as the actual project; ③ the dimensions of the model thickness direction were the same as the actual project; ④ the medium inside the debonded cavity was the same as the actual project; ⑤ the geometry of the standard hexahedron was used for debonded defects. In this way, the test tests are carried out on the standard model and the results obtained are standard test profiles. This ensures that the parameters tested in the inspection tests are identical to those of the actual project and that the standard mapping obtained is representative of the salient features. The model consists of a pipe sheet model and a lining model with standard voids. The pipe sheet model is 0.4m thick, its design plan and physical drawing are shown in figure 5.

The lining model containing the standard defective lining has a thickness of 0.55m and is equipped with not only a double layer of plain reinforcement but also a layer of prestressed steel strands. At the bottom of the model there are two voids, the dimensions of the defects are shown in table 1, and the design plan and physical drawing are shown in figure 6.

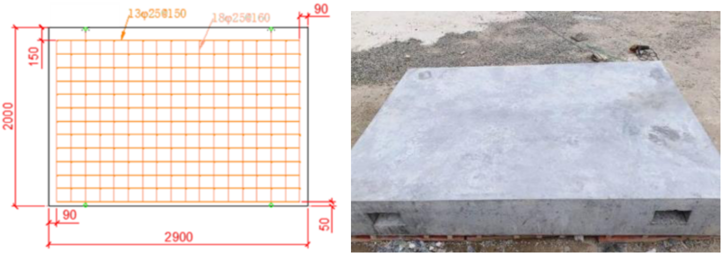

Figure 5. The pipe sheet model.

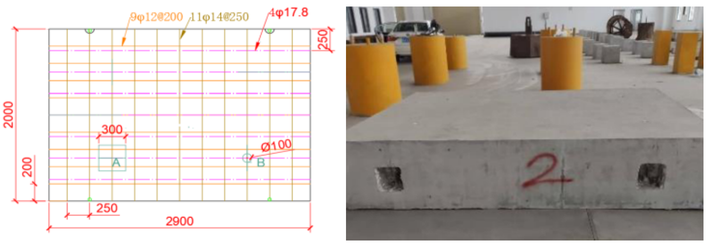

Figure 6. The lining model.

Table 1. Lining model void parameters.

N0.	A	B
Type	Cylindrical	Hexahedron
Diameter/ length(cm)	10	30
Depth(cm)	15	15

3.2. Testing Process

The lining model is superimposed on the pipe sheet model. Set up a test line passing through the decoupling position and test it separately using different testing methods. This leads to an analysis of the validity of the different testing methods.

4. Test Results

4.1. Typical Test Results and Interpretation

4.1.1. Ground-penetrating Radar

The model was tested using the LTD-2600 ground-penetrating radar equipment and the corresponding typical detection profiles were obtained as shown in figure 7. As can be seen, a typical image obtained by ground-penetrating radar shows an increase in reflected energy at the rebar and a thickening of the waveform showing a typical hyperbolic pattern. The amplitude of the electromagnetic wave becomes larger at the location of the void, with enhanced reflected energy, misfracture and large localised masses. Where there are no voids, only slight reflections exist between the pipe sheet and the concrete, and the phase axis chromatographic lines are more regular. The reflected signal near the B voids was evident and was effectively detected. The horizontal dimension of the voids was determined by the lateral extent of the anomalous signal, and the information on the detected voids was basically in line with the preset situation. However, for A, the size of the void is so small that no significant signal appears on the detection pattern.

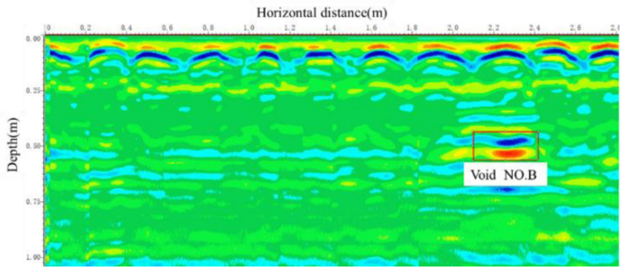

Figure 7. Ground-Penetrating Radar results.

4.2. Impact Echo Method

Inspection tests on the model using an IES scanning impact echo meter. The detection image of the void at location A is shown in figure 8. It can be seen that the impact echo method clearly detects voids that were not detected by ground-penetrating radar. The method has a high detection accuracy, the resulting detection image is intuitive and the size and location of the anomalous areas correspond well to the pre-built defects. However, the method is susceptible to the quality of the concrete surface, where small surface pits and floating slurry can easily lead to signal distortion and the formation of anomalies.

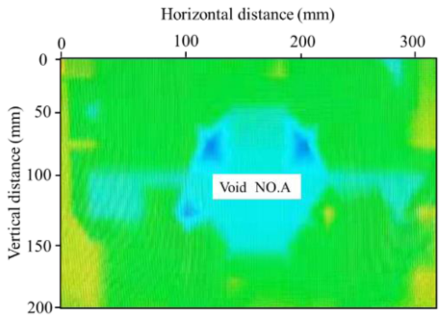

Figure 8. Impact Echo Method results.

4.2.1. Ultrasonic Tomography Technology (UCT)

The inspection test was carried out on the model using an ultrasonic section imager, and the corresponding inspection images were obtained for the void-containing and normal parts of the model as shown in figure 9. It can be seen that: there is no other anomalous reflection except for the regular reflection of the reinforcement in the image of the part without void; there is an anomalous reflector at the top of the void in the image of the part with the exception of the regular reflection of the bottom of the layer and the reinforcement, etc. The anomalous depth position and horizontal dimension of this reflection are consistent with the pre-buried defect.

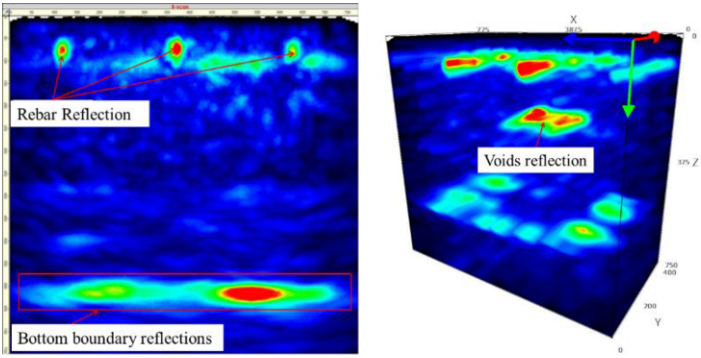

Figure 9. Ultrasonic Tomography Technology results.

4.3. Combined Non-destructive Testing Methods

4.3.1. Applicability of the Various Methods

The advantages and disadvantages of the ground-penetrating radar method, the ultrasonic imaging method and the impact echo method of lining detection are summarised in table 2, based on a lining test study, combined with the applicability of the actual field operation.

Table 2. Advantages and disadvantages of each test method.

Technology	**Ground-penetrating radar**	**IES Impact Echo**	**Ultrasound imaging**
Advantages	High detection efficiency; Suitable for wide range detection	High precision; Ability to identify small voids	Visualisation of results; Less affected by steel
Disadvantages	Highly disturbed by steel reinforcement; Insensitive to small voids	High requirements for surface flatness of the object; Vulnerable to vibration disturbances	Low detection efficiency

4.3.2. Diagnostic Process

Based on the characteristics of each testing method, taking into account the efficiency and accuracy of testing, Combined Non-destructive Testing Methods for lining voids is proposed.

(1) Ground-penetrating radar method for full coverage of the initial survey. The anomalous results are believed, and the anomalous areas are retested with Impact Echo Method. The rebar interferes significantly with the ground-penetrating radar and the detected anomaly-free areas may be hidden by the screening effect of the rebar, which would be "missed" if they were judged to be anomaly-free. This step eliminates the missed detection of anomalous areas by ground-penetrating radar.

(2) Impact Echo Method retest of anomaly-free areas. The no-anomaly area is adopted and Ultrasonic Tomography Technology is used to verify the area with anomalies. Impact Echo Method has a good detection effect on small defects, but is susceptible to the effects of concrete surface quality (e.g. porosity, pockmarks) and

lining vibration, which can be "misjudged" if all abnormal areas are judged as defects. This confidence gathering step eliminates the "misjudgement" of the abnormal areas by the elastic wave method.

(3) Ultrasonic Tomography verifies the presence of abnormal areas. Ultrasonic Tomography results are more intuitive and reliable, but are less efficient and are used as the final verification method. With this "three-step" inspection process and acceptance principle, "missed" and "false" internal defects can be avoided to the greatest extent possible, and the efficiency and reliability of the inspection can be balanced.

5. Engineering Applications

A hydraulic tunnel with a diameter of 6.4m uses 0.4m thick prefabricated pipe sheets for the initial lining and 0.55m thick prestressed concrete for the inner lining. The lining is equipped with a double layer of reinforcement mesh and a double layer of double-ring unbonded prestressing strands. An actual photograph of the tunnel is shown in figure 10.

The orientation of the tunnel is specified for ease of presentation, as shown in figure 11: (1) The left and right sides are distinguished by facing the direction of the water flow. (2) With the top of the vault as 0°, to the left as negative 0 to -180° and to the right as positive 0 to +180°.

Using the proposed Combined Non-destructive Testing Method for the confidence process, a comprehensive analysis determined that there was a dehiscence between -20° and +20° at the top of the arch.

Figure 10. Hydraulic tunnels.

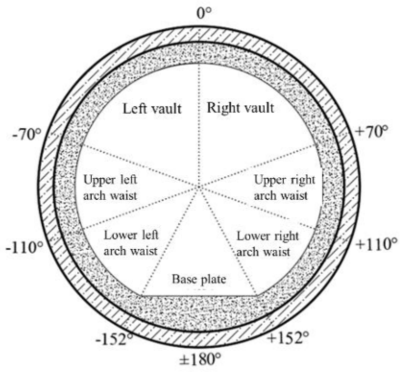

Figure 11. Numbering diagram.

To verify the accuracy of Combined Non-destructive Testing Methods, the borehole endoscope was used to verify the in-hole camera of the debonded area, and the actual image is shown in figure 12, which shows that the void area is locally not in contact with the pipe sheet and the lining; it is locally aggregate filled, less pulpy and more broken, which confirms that the void exists in this part of the deficiency.

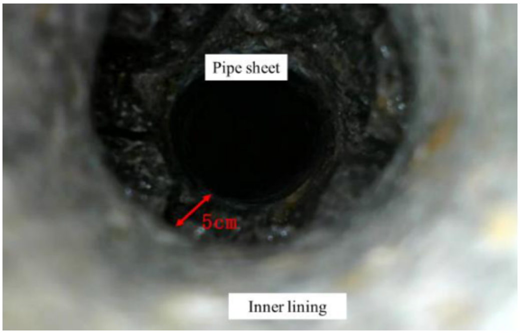

Figure 12. Endoscopic photographs.

6. Conclusion

(1) A model with reinforcement parameters, concrete mix ratios, thickness and materials within voids consistent with the actual project was produced in accordance with the actual project. Detection tests of Ground-Penetrating Radar, Impact Echo Method and Ultrasonic Tomography were carried out based on the model, and typical plots of the various methods were obtained.

(2) Combined with actual operation, the advantages and disadvantages of Ground-Penetrating Radar, Impact Echo Method and Ultrasonic Tomography are compared and analysed. Ground-Penetrating Radar is highly efficient in detecting, but it is easy to miss the diagnosis of small dehiscences; Impact Echo Method is highly accurate, but it is susceptible to interference and easy to misjudge; Ultrasonic Tomography is more accurate, but less efficient and difficult to achieve large area census.

(3) Combined Non-destructive Testing Methods is proposed for the characteristics of various methods and applied in actual projects. The results show that the method can reliably detect the lining voids and can take into account the detection efficiency. It is able to meet the inspection requirements of complex reinforced linings.

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References

[1] Liang Y, et al. Construction technique of circular bonded pre-stressed concrete using post-tension method in Yellow River-crossing tunnel construction in South-to-North Water Diversion Project. Advances in Science and Technology of Water Resources. 2014; 34(02): P.54-58.
[2] Xiao D, et al. Study on the influence of cavitation on the structural stress character of diversion tunnel. Chongqing Jiaotong University. 2020.
[3] Kravitz B, et al. Void detection in two-component annulus grout behind a pre-cast segmental tunnel liner using Ground Penetrating Radar. Tunneling & Underground Space Technology. 2019; 83: 381-392.

[4] Jol HM. Ground penetrating radar: Theory and applications. 2009.
[5] Qin H, et al. Automatic recognition of tunnel lining elements from GPR images using deep convolutional networks with data augmentation. Automation in Construction. 2021; 130(3): 103830.
[6] Yang F, et al. Simulation of lining void area by radar waves and explanatory strategy. Tiedao Xuebao/Journal of the China Railway Society. 2008; 30(5): 92-96.
[7] Ling TH, et al. OMHT method for weak signal processing of GPR and its application in identification of concrete micro-crack. Journal of Central South University. 2019; 26(11): 3057-3065.
[8] Dvoák R and Topolá L. Effect of hammer type on generated mechanical signals in impact-echo testing. Multidisciplinary Digital Publishing Institute, 2021(3).
[9] Aggelis DG, Shiotani T and Kasai K. Evaluation of grouting in tunnel lining using impact-echo. Tunnelling and Underground Space Technology. 2008; 23(6): 629-637.
[10] Li S, et al. Mortar layer void detection of ballastless track using the impact echo method based on support vector machine. IOP Conference Series: Earth and Environmental Science. 2021; 861(7): 072022.
[11] Liu. WH, et al, Detection of concrete defects in steel tube lining by impact echo method. Nondestructive Testing. 2021; 43(11): 47-52.
[12] Moscow. Acoustic control systems has modernized the low-frequency ultrasonic tomograph A1040 MIRA. 2015.
[13] Kuznetsov MS, et al., Experience of using the ultrasonic low-frequency tomograph for inspection of reinforced concrete structures. IOP Conference. 2019; 481(1): 012047.
[14] Schabowicz K. Ultrasonic tomography - The latest nondestructive technique for testing concrete members - Description, test methodology, application example. Archives of Civil & Mechanical Engineering (Elsevier Science). 2014; 14(2): 295-303.
[15] Choi H, Popovics JS. NDE application of ultrasonic tomography to a full-scale concrete structure. IEEE Transactions on Ultrasonics Ferroelectrics & Frequency Control. 2015; 62(6):1076-1085.