Application of Ground Penetrating Radar in Reservoir Leakage Detection in Complex Geological Areas

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Abstract: As a typical nondestructive testing method, ground penetrating radar (GPR) has been widely applied in geological detections of highways and coalmines, but rarely in leakage detection of reservoirs. Taking Taohe Reservoir as an example, this paper deploys multiple GPR detection lines on site, and carries out intensive detection in the upstream/downstream of the reservoir, as well as on the left/right abutments of the dam. In this way, leaks were detected on the left and right dam abutments. The detection results provide a reference for subsequent analysis and treatment of reservoir leakage.

Keywords: Karst area; reservoir leakage; leakage channel; hazard detection.

1. Introduction

In engineering geophysics, there is a variety of detection methods, such as reflection seismology, seismic computer tomography (CT), high-density electrical method, seismic surface wave, and ground penetrating radar (GPR). Among them, the GPR boasts the highest resolution, intuitive images, and convenience in use, providing a key method for leakage testing of dam foundations in reservoirs [1-3]. The GPR has been widely applied in archaeology, buildings, railways, highways, water conservancy, electricity, mining, and aviation. It offers desirable solutions to various tasks, including site survey, route selection, engineering quality inspection, disease diagnosis, advanced prediction, and geological structure research [4,5]. Despite its popularity, the GPR application to dam foundations in reservoirs needs to be improved in two aspects, with the growing test depth: test accuracy and data interpretation. During operation, the reservoirs in karst areas often face leakage in dam body, dam foundation, or reservoir area. The leakage in dam body is mainly induced by the large local/global permeability of the fill, while that in dam foundation and reservoir area mostly stems from karstification or the joint action between karst and fault. The presence and propagation of these hazards and defects could make the dam unstable and even fail, bringing huge disasters.

Therefore, many scholars have combined multiple geophysical methods to detect the leakage sources, leakage channels, and defects [6-12] of dam body and dam foundation in reservoirs through theoretical and practical research. However, the detection of these hazards and defects is immensely complex, owing to the stochasticity of karst development and the unevenness of the fill. Hence, it is highly necessary and urgent to design a geophysical method for detecting the leakage of karst reservoirs with high accuracy and strong operability. Considering the features of various geophysical methods and the complexity of detecting the leakage sources and channels in karst reservoirs, this paper was divided into seven chapters, including research...
overview, principle of GPR, arrangement of survey lines, detection procedure, results analysis and conclusions, which proposed a new seepage detection method of reservoir in karst area. The paper deployed multiple GPR detection lines in Taohe Reservoir, and carried out intensive detection in the upstream/downstream of the reservoir, as well as on the left/right abutments of the dam. In this way, leaks were detected on the left and right dam abutments. The detection results provide a reference for subsequent analysis and treatment of reservoir leakage.

2. Research Overview
Taohe Reservoir lies in Lijiachang, Xihe Village, Nanhuatang Town, about 65km of Yunxian County, Shiyan City, in central China’s Hubei Province. The river above the dam site of Taohe Reservoir is 69.8 km long. The reservoir controls a basin area of 406.0 km², and has a designed storage of 71.6 million m³. There are five pivotal projects of the reservoir: the dam, the spillway, the diversion tunnel, the irrigation and power tunnels, and the power plant behind the dam.

The dam of Taohe Reservoir is a clay-core rock debris dam constructed by the standard for Class III buildings. The maximum height of the dam is 70.0 m; the crest elevation is 401.00 m; the elevation of the original riverbed is 336.00 m. With a normal storage level of 397.00 m, the total storage and dead storage are 71.6 million m³ and 4.10 million m³, respectively. Each year, the reservoir produces 7.80 million kWh of electricity (a multi-year average), and irrigates 76,000 mu of farmland. The navigable length in the reservoir amounts to 14.0 km. In addition, the reservoir can weaken a 50-year flood to a 20-year flood.

The dam area has extremely complex geological conditions: the rock mass is broken, and geological structures like karst and fissures are highly developed. As a result, fissures are intertwined with karst channels across the reservoir. Despite repeated enhancements, Taohe Reservoir still faces a huge amount of leakage, which seriously threatens the normal operation of the reservoir.

3. Principle of GPR
The advanced version of GR radar processing analysis system V3.2 was chosen as the special software for data processing. To ensure accuracy and reliability, the data processing and interpretation were carried out according to the following steps:
Step 1. Sort out the original data and field records according to section and date. After that, preprocess the GPR data through mileage correction, and removal of initial and end invalid data. Query construction and design drawings, as well as the data on engineering geological conditions, based on the mileage of each section.

Step 2. Perform data processing tests on the GPR data from typical sections of dam foundation, using different processing methods, parameters, and steps. The main processing steps include zero-line setting, background denoising, sample point compression and transform, marker segmentation, drift removal, moving average, one-/two-dimensional filtering, gain control, Hilbert transform, deconvolution, wavelet transform, etc. Compare the results of different test schemes, and finalize the processing scheme for GPR data. The workflow of data processing is explained in figure 1.
Figure 1. The workflow of GPR data processing.

Step 3. Process all GPR data by the final processing scheme. After the completion of data processing, check the processing effect comprehensively, and adjust or reprocess the data that have not been well processed, until all processed data meet the interpretation requirements.

Step 4. Before interpretation, (radar image interpreters) review the processed images on sections with different geological conditions, determine the marker layers and anomalies, and analyze the phase, vibration amplitude and frequency, and environment interference of the anomalies. Then, (data processers) determine the unified principles and standards for interpreting the processed GPR images.

Step 5. Interpret and annotate the anomalies on the processed GPR images, according to the unified principles and standards.

4. Arrangement of Survey Lines

A total of 15 GPR survey lines were arranged to detect the leakage-prone areas in Taohe Reservoir: three lines on the top of the dam, three lines on the retaining wall of the reservoir, three lines in the spillway, and seven lines on the left and right abutments. The total length of all survey lines is 4,249.0 m. The specific layout of the survey lines is explained in figure 2, in which the red lines represent the layout of the survey line and the yellow number represents the number of the survey line.
5. Detection Procedure

Through the preliminary tests, the 50MHz double transceiver antennas and 100MHz low-frequency shielded antennas were chosen to optimize the detection depth and resolution in the field tests.

Step 1. Initialization: Determine the test mileage and scope according to field survey and geological conditions.

Step 2. Line arrangement: Deploy the GPR survey lines along the extension direction of the track according to field conditions.

Step 3. Mileage control: Manually mark every 5m of the detection section to ensure the accuracy of the location of the survey line and the starting mileage (figure 3).

Step 4. Data collection and verification

As the first step of detection, confirm the number of mileage piles. After determining the number of the starting pile, (a special person) mark(s) the mileages of the following piles with a tape, and (a recording person) record(s) the starting point, direction, and number of the survey line. After the recording, start collecting the detection data. Once the radar antennas have reached the pre-marked mileage piles, (the host operator) mark(s) the data. After collecting the data on each line, verify if the data markers deviate from the actual mileages to ensure the data accuracy.

Step 5. Elimination of environmental interferences

The electromagnetic wave signals of the GPR are greatly interfered by the numerous high-voltage transmission lines along the survey lines. To ensure the interpretation accuracy, eliminate the interferences of these transmission lines (figure 4).
Step 6. Data sorting
(The field recording person needs to) sort out and analyze the data and records acquired each day, judge the quality of the data, and improve the working method in time.

The GPR detection site is shown in figure 5.
6. Results Analysis

As shown in table 1, a total of 14 suspected unfavorable geological bodies were found in the range of the GPR, including 4 loose textures, 8 cracks, and 3 water-rich bodies.

Table 1. The list of GPR anomalies.

| Line number | Serial number | Starting mileage (m) | Ending mileage (m) | Center mileage (m) | Starting depth (m) | Ending depth (m) | Center depth (m) | Property                  |
|-------------|---------------|----------------------|--------------------|-------------------|-------------------|-----------------|-----------------|----------------------------|
| 1           | 1             | 10.01                | 36.97              | 23.5              | 7.17              | 11.5            | 9.35            | Loose texture             |
| 2           | 2             | 9.89                 | 17.95              | 13.9              | 5.71              | 12.03           | 8.87            | Loose texture             |
| 2           | 3             | 258.63               | 261.55             | 260.1             | 4.51              | 6.86            | 5.68            | Crack                     |
| 8           | 4             | 66.45                | 81.88              | 74.2              | 7.87              | 12.31           | 10.09           | Crack                     |
| 8           | 5             | 121.55               | 131.55             | 126.6             | 7.71              | 12.6            | 10.16           | Crack                     |
| 8           | 6             | 151.5                | 158.44             | 155               | 8.47              | 12.12           | 10.3            | Crack                     |
| 8           | 7             | 172.1                | 188.31             | 180.2             | 9.2               | 12.38           | 10.79           | Crack                     |
| 9           | 8             | 134.68               | 147.62             | 141.1             | 5.14              | 10.16           | 7.65            | Crack                     |
| 9           | 9             | 154.46               | 169.98             | 162.2             | 5.11              | 12.5            | 8.81            | Crack                     |
| 9           | 10            | 183                  | 198.76             | 190.9             | 6.79              | 13.17           | 9.98            | Crack                     |
| 9           | 11            | 141.1                | 197.3              | 169.2             | 16.11             | 34.1            | 25.11           | Crack and water-rich body |
| 11          | 12            | 16.7                 | 23.6               | 20.2              | 6.6               | 10.6            | 8.6             | Loose texture             |
| 12          | 13            | 9.2                  | 14.1               | 11.7              | 9.9               | 16.1            | 13.0            | Loose texture and water-rich body |
| 13          | 14            | 5.1                  | 6.6                | 4.0               | 7.1               | 17.3            | 9.8             | Loose texture and water-rich body |

Figures 6-9 present the anomalies detected by GPR.

(a) GPR spectrum of unfavorable geological bodies.  (b) Location of unfavorable geological bodies.

Figure 6. The detection results of GPR #1.
Through detailed analysis on the GPR data, it was found that:

1. In the data obtained by GPR and high-density electrical method, abnormal responses of different degrees were observed in the following places: 80-110 m from the initial marker and 13-40m in depth; 130-170m from the initial marker and 4-77m in depth; 220-250m from the initial marker and 20-70m in depth. These places are potential leakage sites.

2. Low resistivity was detected at the mileage of 70-110m and depth of 2-12.2m on the fourth passageway from the top of the retaining wall at the right end of the dam, making it a potential leakage site.
(3) Low resistivity was also detected at the right abutment of the spillway next to the retaining wall. This is another potential leakage site calling for enhanced monitoring and investigation.

7. Conclusions
(1) Taking Taohe Reservoir as the object, multiple detection lines were arranged onsite, and intensive GPR detection was carried out in the upstream/downstream of the reservoir, as well as on the left/right abutments of the dam. The detection results show that potential leakage sites include 80-110 m from the initial marker and 13-40m in depth; 130-170m from the initial marker and 4-77m in depth; 220-250m from the initial marker and 20-70m in depth; the mileage of 70-110m and depth of 2-12.2m on the fourth passageway from the top of the retaining wall at the right end of the dam; the right abutment of the spillway next to the retaining wall.
(2) The GPR, as a typical nondestructive detection method, was proved feasible in leakage hazard detection of complex geological areas.

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