Experimental study on ground penetrating radar in quality inspection of asphalt concrete impervious facing of pumped storage power station

Xiulin Li$^{1,2}$*, Jutao Hao$^{1,2}$ and Zhengxing Wang$^{1,2}$

1 China Institute of Water Resources and Hydropower Research, Beijing, China
2 State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, Beijing, China
94060568@qq.com

Abstract. As a new technology of non-destructive testing, the ground penetrating radar (GPR) has the characteristics of non-destructive, accurate, high efficiency and low cost. Based on the successful application experience of GPR in asphalt pavement detection, the feasibility of GPR to detect asphalt concrete impervious facing is proved through laboratory verification, radar forward modelling and field test. Many random blisters and cracks appear in the asphalt concrete impervious facing of the Zhanghewan Pumped Storage Power Station selected for field tests. The detection by the GPR showed that the defects occurred only in the upper anti-seepage layer, and the drainage layer and the lower anti-seepage layer had no obvious defects, which were fully consistent with coring results. Therefore, GPR is a fast, non-destructive and reliable technique for detecting asphalt concrete impervious facing. At present, China is in the period of large-scale construction of pumped-storage power stations, and the demand for rapid inspection and maintenance engineering is also increasing. The method of the ground-based radar will certainly play a greater role in the rapid detection of impervious structural defects in asphalt concrete facings.

1. Introduction

1.1. Context

Asphalt concrete is a kind of building material made of asphalt (the cementing material) and aggregate (crushed stone, sand, filling material, etc.) which are mixed at a specified ratio and degree of consolidation. Because of its good impermeability, asphalt concrete is often used in water resources and hydropower engineering projects, such as earth-rock dam, reservoir, river channel, dike and revetment. In the 1950s and 1960s, asphalt concrete was used in Europe to prevent seepage in large reservoirs. In recent years, as the asphalt concrete anti-seepage projects of pumped storage power stations such as Tianhuangping, Zhanghewan, Xilongchi and Baoquan have been successively completed, the anti-seepage design and construction technology of domestic hydraulic asphalt concrete has developed rapidly.

The impervious section form of asphalt concrete facing is usually divided into duplex and simple form. According to the importance degree, safety requirement and geological condition of the project, the section form is determined by the technical and economic requirements. The traditional composite section structure is generally divided into 5 layers from top to bottom, including sealing layer, upper
anti-seepage layer, drainage layer, lower impervious layer and levelling cementation layer. Considering the asphalt concrete impervious layer of its permeability coefficient can reach $1 \times 10^{-8} \text{cm/s}$ or less, so many projects have chosen the simple section to eliminate the structural form of the drainage layer and the lower impervious layer in the compound section.

Regardless of simple or composite impervious section, asphalt concrete facing put into operation sometimes have irregular blisters and cracks. Deterioration of the blister will cause facing cracking and increase the possibility of facing leakage. Once the entire impervious section is destroyed, a large amount of water will flow to the bottom of the reservoir. If there are water-sensitive weak layers in the foundation rock, the long-term effects of water seepage may affect mountain stability and lead to serious consequences. The common method of detecting asphalt concrete face defects is drilling core sampling method, which has low efficiency, poor representation, the inevitable destroying the integrity of the original impervious body, so it is urgent to find a rapid and accurate detection of non-destructive testing (NDT) means to replace coring.

GPR has been established as one of the most recommended NDT methods for routine sub-surface inspections. The use of GPR in civil engineering applications began to appear in the mid-1970s and the 1980s. GPR has been widely applied in defect inspection of highway asphalt pavement, which has the advantages of saving labour, greatly shorten the testing time, reducing road surface damage, getting a lot of information etc. It provides a capability of collecting successive pavement layer thickness data with air-coupled horn antenna at relatively high-speed conditions. The frequency range that has been found to be useful for such an application lies within the limits of 100MHz to 2GHz.

As the asphalt is the main adhesive material, the asphalt concrete impervious facing structure of pumped storage power station is more complex than the highway asphalt surface structure. The air-coupled antenna can realize the detection of highway asphalt surface layer thickness, but the precision cannot meet the defect detection requirements of the asphalt anti-seepage facing. At present, there are no methods that can be used at home and abroad for reference. With the increase of the pumped storage power station of the asphalt concrete face, the defects of the asphalt facing will also increase. Therefore, it is of great significance to study the internal defects of the asphalt concrete impervious facing by GPR.

1.2. Working principle of GPR

GPR emits high-frequency electromagnetic pulse waves to the measured object through the transmitting antenna. Using the difference in the electromagnetic properties of the underground medium, reflections and transmissions are generated at the interfaces of different electrical interfaces, i.e., the dielectric constants are different, and the receiving antenna receives the reflected echo and records reflection time. Based on the kinematic and dynamic characteristics amplitude, waveform and frequency of echo, the structure and physical properties of the medium are analyzed and deduced to detect internal defects. Now GPR has become a high resolution near surface geophysical technology in civil engineering widely used in nondestructive testing. The calculation formula for the parameters of GPR is as follows:

1.2.1. Two-way travel time $t$ of electromagnetic waves.

$$
t = \frac{\sqrt{4z^2 + x^2}}{v} \approx \frac{2z}{v} \tag{1}
$$

Where $z$ represents the buried depth of target body; $x$ is the distance between the transmitting and receiving antennas, which can be ignored because $z$ is much larger than $x$ due to the integration of the transmitting and receiving antennas; and $v$ is propagation velocity of the electromagnetic wave in a medium. The wave velocity $v$ is obtained by using time $t$ and depth $z$. 

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1.2.2. Propagation velocity of electromagnetic wave in medium $v$.

\[
v = \frac{c}{\sqrt{\varepsilon_r \mu_r}} \approx \frac{c}{\sqrt{\varepsilon_r}}
\]

(2)

Where $c$ is propagation velocity of the electromagnetic wave in a vacuum (0.29979m/ns); $\varepsilon_r$ is the relative dielectric constant of the medium; $\mu_r$ is the relative permeability of a medium, generally valued at 1. According to (2) formula, the relative dielectric constant of the medium can be calculated by combining (1).

1.2.3. Reflection coefficient of electromagnetic wave $R$. When the electromagnetic wave propagates in the underground, reflections and transmissions occur at the interfaces of different electrical interfaces, i.e., the dielectric constants are different. Whether the defect can be identified effectively depends on the electrical difference between the defect and the pavement material. When the relative dielectric constants of the upper and lower interfaces are $\varepsilon_1$ and $\varepsilon_2$, the reflection coefficient $R_{12}$ can be expressed as follow:

\[
R_{12} = \frac{\sqrt{\varepsilon_1} - \sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1} + \sqrt{\varepsilon_2}}
\]

(3)

By (3) we can see that the greater the difference of dielectric constant at the two sides of the reflecting interface, the greater the reflection coefficient, the stronger the reflection of the electromagnetic wave, the easier the resolution of the dielectric interface, and the better the detection effect. The dielectric constants of asphalt concrete are as follows: dry asphalt 2~4, moist asphalt 10~20, air 1, water 81. It is obvious that the dielectric constant of the material has a great difference. Therefore, it is theoretically feasible to make use of GPR to carry out voids, water content, compaction, and other defects in asphalt concrete facing.

1.2.4. Relationship between recording time $t$ and depth $z$ of detection.

\[
z = \frac{1}{2} vt \approx \frac{ct}{2} \cdot \frac{1}{\sqrt{\varepsilon_r}}
\]

(4)

1.3. Research objective

This paper describes a new method for detecting defects in asphalt concrete impervious facing using GPR. It can quickly and accurately detect the type and location of internal defects, evaluate facing degradation, and provide technical support for repair and reinforcement schemes.

Firstly, the feasibility of the scheme was validated by laboratory model validation and forward simulation, and then combined with the facing of the upper reservoir of the Zhanghewan pumped storage power station to test the effectiveness of field defect detection. The test results are displayed in 3D, which makes the defect determination more intuitive and convenient.

2. Testing asphalt defects in laboratory by GPR

Radar measurements were carried out using GSSI equipment (SIR4000+2600MHz antennas). The formed asphalt concrete circular face slab was used to design voids, water and other defects to test the radar detection effect.

The diameter of the asphalt concrete circular plate was 50cm, and the thickness was 10cm. First, a 3cm-thick wood strip was placed between the panel and the concrete floor to simulate a void, and then a plastic bag with water was filled in the gap to simulate a 3cm aquifer. The experimental photo was shown in Figure 1.
Figure 1. GSSI4000(left) void(middle) aquifer(left).

The radar head wave of all frequency antennas of GSSI radar is negative. When the electromagnetic wave is transferred from the asphalt panel with large dielectric constant to the dielectric medium with small dielectric constant, the reflection coefficient is positive, and the obvious negative wave will appear. The reflection coefficient is negative when the electromagnetic wave is transferred to the greater water of the dielectric constant, and there will be a positive wave. Radar scan results interactively interpreted using RADAN software is shown in Figure 2. There is a clear distinction between layers of media, with yellow representing the asphalt panel, red representing the air, and blue representing the water. The results of the indoor experiments prove that the geological radar is technically feasible to find the internal defects of asphalt facings.

Figure 2. GPR interactive interpretation diagram.

3. GPR forward simulation

To achieve an accurate interpretation of actual radar data, a surveyor must know the characteristics of radar reflection section in advance. Therefore, the forward simulation, as the basis of inversion and interpretation, has become one of the main contents of theoretical research of GPR.

The forward simulation mainly includes the diffraction iterative method based on the physical optics and the ray tracing method based on the geometry optics. This simulation adopts GPRSIM software developed by Geophysical Survey Systems, Inc. The principle of software is finite-difference time-domain method, which has the characteristics of simple modelling, simple parameter setting, ray path display, vertical horizontal polarization, migration and result visualization.

The design of a 30cm humid asphalt panel contains 2 elliptical defect models, with an oval major axis of 5cm, a minor axis of 2cm, and a centre depth of 20cm. The relative permittivity value is 9 for wet asphalt panels, 81 for water, and 1 for air. The pulse emission frequency of the forward modelling is 2600MHz, and the impulse response is set to the time window 10 ns, scan/channel 512, and the antenna direction response is set by software default. Figure 3 shows simulation record of GPR for asphalt panel defects.
Through the analysis of the ground penetrating radar forward modelling, the following conclusions are drawn: the reflection amplitude of the air model is negative, and the reflection amplitude of the water cut model is positive. It is easy to distinguish whether the inside of the cavity is water or air, which provides an important theoretical basis for on-site detection.

4. Asphalt concrete imperious facing structure

4.1. General situation
Zhanghewan Pumped Storage Power Station is located on the main stream of Gantao River near the town of Ceyu in Jingxing County, Shijiazhuang City, Hebei Province, China. The upper reservoir adopts a simple asphalt concrete facing full-reservoir basin to prevent seepage. The impervious area of the slope and the bottom are respectively 200,000m² and 137,000m², and the total area is 337,000m². The sections from top to bottom are 2mm seal layer of mastic, 10cm upper anti-seepage layer, drainage layer (reservoir slope 8cm, bottom 10cm) and lower impermeable levelling cementation layer (8cm), as shown in Figure 4. The foundation under the face is made of gravel cushion, the horizontal width of the rockfill dam section is 2m, the vertical thickness of the rock slope excavation section is 60cm, and the bottom thickness is 50cm.

The upper reservoir was built in September 2007. In December 2007, the first unit of the power station was connected to the grid. In February 2009, all 4 units were connected to the grid for power generation. So far, the power station has been operating normally, and the upper reservoir has not been emptied and overhauled. After a few years of operation irregular blisters and cracks appeared on the facing. The bulge diameter was generally 10 to 40 cm, and the crack length was 5 to 40 cm. Based on the owner's analysis in 2015, the water vapour in the drainage layer exerted pressure during the high temperatures in summer, and the facing was lifted up to create a blister. According to this, a vent hole was provided at the top of the asphalt concrete. The observation of facing bulging through the past year did not improve.
4.2. Defect description
According to the on-site comprehensive survey, there are currently four major defects in the facing: (1) Facing pressure blisters (Fig. 5), that is, the bulge is caused by the pressure inside the facing, which is manifested as local uplift of the facing, cracking or uncracking of the surface; (2) the facing is only cracked, and there is no bulge or flow around; (3) Bleeding upheaval, the appearance of which is that the facing is partially dropped and up-lifted, and there is a lateral sag or transverse crack at a certain distance above the bulging bulge; (4) The mastic grease on the surface sealing layer flows, bulges, breaks, and is empty. Basined on statistical results of defects, the pressure swellings are the most, followed by flowing packs, and only 1 crack is found. From the distribution point of view, the defects of the facing are mainly concentrated in the inlet and outlet and the arc section where the construction is very difficult. It is preliminarily judged that the defects are related to the quality of the construction. From the elevation, the facing defects are mainly distributed in the water level fluctuation area, which may be related to the frequent changes of the daily water level in the pumped storage power stations.

5. Defect detection of asphalt concrete facing by GPR

5.1. Determination of dielectric constant
The inspection used the United States GSSI company SIR-4000 geological radar equipped with 2600MHz high frequency antenna, and acquisition time window was 10ns. At first the asphalt concrete facing with good appearance was selected and measured by time mode. Secondly, data were analysed by radan7 software. Finally, the ideal scanning profile (figure 6) was obtained after a series of data processing, such as time zero correction, filtering, migration, depth conversion, gain display and image analysis. In the figure, the interface between the impervious layer and the drainage layer was determined. According to the design thickness of the upper anti-seepage layer 10cm to adjust the value of the dielectric constant of the radar data processing software, the dielectric constant was 7.1. Subsequent data analysis used it as a criterion for defect judgment.
5.2. Typical defect detection

The 3D image formed by assembling multiple sets of test data by certain rules can visually show the spatial orientation and size range of the defects, which was conducive to the scientific assessment of the severity. Each survey area had horizontal and vertical survey lines around the defect centre. The distance between survey lines was 20cm, and the survey area was 2m×2m. It was ensured that the measured surface was larger than the defect area, so that it was easy to find out whether there were hidden defects or not. The schematic diagram was shown in Figure 7. The vertical detection was carried out sequentially from top to bottom and from left to right, that was, beginning from A-A and ending at K-K; horizontal detection was performed in order from left to right and from top to bottom, i.e., 1-1 began 11-11 and ended. The representative defects such as pressure blistering, cracks and bleeding upheaval were selected for detailed inspection. Table 1 shows the statistics of the test sites.

Table 1. Statistical table of typical measuring points.

| NO. | stake number | Elevation(m) | defect               |
|-----|--------------|--------------|----------------------|
| 1   | 0+325        | 802          | pressure blistering  |
| 2   | 0+375        | 804          | crack                |
| 3   | 0+332        | 806          | bleeding upheaval    |

5.2.1. Blister. Figure 8 is a 3D perspective view of a typical pressure blistering. The analysis shows that there is a cavity with a diameter of about 50cm inside the upper anti-seepage layer and the interior is filled with water. No obvious defects are found in the drainage layer and the levelling cementation layer.

5.2.2. Crack. Figure 9 is a 7 cm horizontal slice from the surface. The cracks in the upper impermeable layer are about 70cm long. The interior of the impervious layer is accompanied by
internal hollowing. No obvious defects are found in the drainage layer and the levelling cement layer, which indicates that the cracks started from the drainage layer and developed from inside to outside.

5.2.3. **Bleeding upheaval.** The slice indicates that the bleeding upheaval is caused by the flow of the asphalt on the upper impervious layer, as shown in figure 10. Drainage layer and leveling cementation layer show no obvious defects either.

6. **Core verification**

Core verification was performed when the radar inspection had been completed. The core drill bit Φ30 cm was drilled until it reached the gravel cushion, ensuring that the core sample contained a complete three-layer of the upper anti-seepage layer, the drainage layer, and the lower anti-seepage layer.

The left core sample rushes out when the expansion bolt is applied to the facing approximately 5 cm below the facing, and the thickness of the upper barrier layer is 4 to 5 cm. The middle core sample is taken from the crack location and is impermeable. There are penetrating cracks in the layer, and the entire upper penetrating layer breaks into two parts. The upper impervious layer has a reinforced grid at the bottom, and the lower one is also densely mixed with the asphalt mixture instead of the drainage layer. The right core sample taken from flowing bulge indicates the upper impermeable layer, the drainage layer and the lower impermeable layer form a whole. There is no obvious defect inside.

7. **Conclusion**

This paper first uses laboratory verification and forward modelling to verify the feasibility of detecting the internal quality defects of asphalt concrete facings by the geological radar. This technology has been successfully applied to the site detection of asphalt concrete impervious structural defects in
Zhanghewan pumped storage power station. The results of GPR show that the phenomenon of blistering and cracking occurred in the upper impermeable layer, and there is no obvious defect in the drainage layer and the levelling cementation layer. The result of core verification is consistent with that of GPR. It can be seen that GPR provides a fast, non-destructive and highly reliable testing method for the detection of impervious structure of asphalt concrete facing. At present, China is in the period of large-scale construction of pumped-storage power stations, and the demand for rapid inspection and maintenance engineering is also increasing. The method of the GPR will certainly play a greater role in the rapid detection of impervious structural defects in asphalt concrete facings.

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