Application of Ground Penetrating Radar in Leakage Detection of Concrete Face Rockfill Dam

Xiulin Li$^{1,2}$, Lifei Fan$^3$, Hao Huang$^{1,2}$, Jutao Hao$^{1,2}$ and Meng Li$^{1,2,3}$

$^1$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
$^3$Laurel Geophysical Instruments Limited, Beijing, China

Abstract. The ground penetrating radar (GPR) technology is one of the advanced and effective methods of detecting hidden hazards in dams due to its features of quickness, accuracy, high resolution, intuitive image, and less constraints on geological conditions of the field. In this paper, the effectiveness of GPR in dam leakage detection was tested based on its application on a concrete face rockfill dam. Firstly, a preliminary judgment on the possible leakage sites was made according to on-site inspection and monitoring data analysis. Combined with the detection results of GPR, the actual sites of the leakage passages is finally determined, which can provide technical support for plugging in the next step.

1. Introduction

The leakage passages of dams are generally located in dam foundations, dam bodies and the auxiliary structures. There have been many calamities caused by leakages without proper treatment at home and abroad. In order to find out the leakage passages and eliminate hidden dangers, more and more geologists have employed geophysical exploration methods to check dams and achieved favorable results. At present, geophysical exploration methods for dams can be classified into four categories, high-density resistivity method, GPR, transient electromagnetic method, and surface wave method, among which GPR has become one of the advanced and effective methods for detecting hidden dam dangers due to its features of quickness, accuracy, high resolution, intuitive image, and less constraints on geological conditions of the field.

1.1. Principle of GPR leakage detection

GPR transmits high-frequency electromagnetic waves (10 MHz to 2 GHz) from the surface to the ground in the form of broadband short pulses through the transmitting antenna. The receiving antenna receives electromagnetic waves that have been reflected by the formation and returned to the surface. When the electromagnetic wave propagates in the medium, its path, intensity, and waveform will change with the differences in electrical properties and geometry of the medium. Based on the two-way travel time, amplitude, and waveform of the received wave, image processing and data analysis are used to distinguish the subterranean stratigraphic interface and determine the spatial location and structure of the probe.

The factors that affect the detection performance of GPR are antenna center frequency, conductivity and dielectric constant of the medium. The center frequency of the antenna and the
conductivity of the medium are inversely proportional to the depth of detection. The main factor influencing the effect within the detection depth range is the dielectric constant difference between the detected target body and its surrounding medium. Table 1 lists the dielectric constants and electromagnetic wave propagation parameters that are common in leak detection. It can be seen that if there are defects such as cracks, voids, and looseness in the dam body, electrical characteristics are obviously different comparing with the physical properties and the density of the uniform and compacted dam body, which provides a good theoretical basis for the use of GPR to detect leakage.

Table 1. The common electrical parameters of media for leakage detection.

| medium  | relative dielectric constant | conductivity (mS/m) | attenuation coefficient (dB/m) |
|---------|------------------------------|---------------------|-------------------------------|
| air     | 1                            | 0                   | 0                             |
| water   | 80                           | 0.01                | 2000                          |
| clay    | 5~40                         | 2~1000              | 1~300                         |
| quartz  | 5~30                         | 1~100               | 1~100                         |
| dry sand| 3~5                          | 0.01                | 0.01                          |
| granite | 4~6                          | 0.01~1              | 0.01~1                        |

To accurately determine the results in the dam leakage detection, it is necessary to understand the variation of radar reflected wave. For dams with uniform physical properties, large dry soil density, and compacted dam body, radar reflected waves are characterized by weak energy, continuous horizontal events and a single frequency. When local leakage occurs, a clear electrical interface will be formed because the conductivity of the medium will increase due to the change in water content. Leakage characteristics can be attributed to cracks, voids and loose dam bodies. For the characteristics of radar reflected waves, the cracks are mainly represented by the interruption and misalignment of the wave groups, and the voids mainly manifest as arcs or isometric reflections. A near-horizontal reflection wave groups appear when a dam section is loose and there is a horizontal thin layer. On opposite sides of the normal dam body, the reflected wave groups exhibit a lateral characteristic change or interruption.

1.2. Research purpose
A concrete face rockfill dam has been leaking since it was put into operation, and it is urgent to find out these leaks and conduct repairs. This paper describes the detailed inspection process. The possible locations of leakage are preliminarily judged based on the on-site observation and monitoring data analysis. Then GPR is introduced to determine the specific location of the leakage channels, which provides practical experiences for similar projects for reference.

2. Project Overview
The Lagu River Reservoir is located in the middle reaches of the Lagu River that is a first-level tributary of the Xinzhuang River belonging to the Jinsha River system. It is a water conservancy project with comprehensive utilization in farmland irrigation and water supply for people and livestock in the countryside. The dam site is in the northwest of Huaping County, Lijiang City, Yunnan Province, China, 62 km away from Huaping, and 420 km away from Kunming.

The dam is a concrete face rockfill dam, with a crest elevation of 2201.00 m, a parapet wall top elevation of 2202.2 m, and a normal reservoir level of 2195 m. The crest is 267.7 m wide and 8 m long, and the maximum dam height is 84 m. The upstream and downstream slope ratio is 1:1.4. It is a medium-sized project of grade III, with a total storage capacity of about 12.780 million m$^3$, of which the dam is in class 2, the other major buildings in class 3, and the secondary buildings in class 4.
3. On-site survey and monitoring data analysis

3.1. On-site survey
During the period of on-site inspection from May 18 to May 23, 2017, the water level of the reservoir was 20m lower than the normal water level. No significant leakage was found on the right side of the dam body and on the right abutment. One place of water gushing was on the left side of the bottom of the dam, and several leakage points were on the left side of the slope. Downstream seepage sites are shown in Fig. 1. According to the information provided by the Operator, the leakage amount of gauging volume reached the maximum value of 206.4 L/s when the reservoir water level reached the maximum of 2191 m on September 20, 2016. Therefore, the leakage paths must be found out and reinforced as soon as possible.

![Figure 1. Leakage in left dam body and left rock mass.](image)

3.2. Piezometer monitoring results Analysis
Six vibrating wire piezometers were arranged in the dam, which were basically in the 0+154~0+160 cross section at the center of the longitudinal axis of the dam.

Four piezometers were laid in sequence from upstream to downstream within the foundation of the riverbed. There was a positive correlation trend between the osmotic water head and the reservoir water level. The numerical value was reasonable and no obvious abnormality appeared. As the loose structural layers (pebble, gravel and sandy loam) on the surface of the riverbed, left bank and right bank of the dam site were removed and the base surface was strongly-weakly weathered bed rock, it was judged that there was no problem of seepage stability in the foundation.

Two piezometers buried in the dam body in the first stage of the flood dam were basically unaffected by the changes in the reservoir water level. Water head of one piezometer with irregular fluctuation was near 1.8 m, and the other one was near -0.5 m. Taking into account that these two piezometers were located at dam heel and were protected by a 2m-thick clay layer and a 3m-thick stone slag layer upstream of the dam, the small pressure head indicated that there was no leakage in the first stage of the flood dam.

3.3. Piezometer tube monitoring results analysis
The three piezometer tubes arranged from upstream to downstream in the cross section of the 0+185 dam body were not infiltrated, indicating that there was no obvious leakage in the middle of the dam.

According to the design requirements, four piezometer tubes were installed on both sides of the downstream. Based on the monitoring results, those tubes could not measure the seepage line of the abutment most of the time. Even if measured, the reliability of the data was unfavorable. Therefore, it is not possible to determine the position of penetration by these four piezometers alone.
In view of the above reasons, three piezometer tubes were added to the positions of the left and right abutments and left jetty head respectively. When the water level in the reservoir fell, the decline in the infiltration water level of the three piezometers was less than the reduction in the reservoir water level, which was consistent with the characteristics of water seepage in rock mass. The change in the water level of the left abutment was faster than that of the right abutment. In term of the on-site survey, it can be concluded comprehensively that the infiltration only takes place on the left abutment.

4. GPR leak detection
GPR leakage detection should employ continuous profile scanning method, which means that the transmitting antenna and the receiving antenna always keep a fixed distance along the line. Multi-channel data can be continuously recorded and averaged to reduce the random errors generated during detection. It is possible to intuitively reflect the characteristics of the subsurface reflection interfaces without reprocessing the echoes.

4.1. Detection parameters and data processing method
The GSSI SIR4000 GPR used in this detection was equipped with a Model 3200 MLF multiple (adjustable) low-frequency unshielded antenna. The main frequencies of antenna were 16 MHz, 20 MHz, 35 MHz, 40 MHz, and 80 MHz. The on-site inspection was performed in a spot measurement mode, and then each measurement point was assembled using radan7 software to form a complete wave train graph of the measured section.

As the crest was wider and the dam was deeper, the 16 MHz antenna with the largest detection depth and the lowest frequency was selected for the detection. The main parameters of the host set are as follows: sample points 2048, time window 1000ns, delay -100, IIR superposition 256 times, IIR low pass filter 40 MHz, and high pass 5 MHz. The narrower berm leaded to the fact that the antenna could not be fully deployed and the 80 MHz antenna was used for detection. The main parameters of the host set are as follows: sample points 1024, time window 500ns, delay -100, IIR superposition 128 times, IIR low pass filter 160 MHz, high pass 20 MHz.

4.2. Survey line layout
A total of 3 survey lines were set up, and each of them is for the crest, the upper and lower berms, respectively. The crest line started from the left side bank slope and ended at the right side of the spillway, making a spot test every 0.5 m. The 34th point was the starting point of the dam body at a distance of 17 m from the left side bank. The upper and lower berms were measured once every 1 m, with each line from the left drain to the right drain. The on-site inspection was shown in Figure 2.

4.3. Test results of the crest
The full section wave train graph of the crest is shown in Figure 3, where the left side of the vertical line is the left bank slope and the right side till the end of the spillway is the dam body. The profile shows that the color is getting darker at regular intervals, which is exactly the position close to the street lamp as observed in the field. It can be seen that the street lamp has a great influence on the unshielded antenna. However, there are no abrupt changes in elevation image of each elevation, which does not affect the judgment of the results. On the whole, the dam body is densely packed and there is no obvious abnormalities found. As the lithology of the left bank slope is distributed as limestone, the dissolution of limestone often results in unfavorable geological phenomena such as channels, caves, and karst fissures. The left bank slope radar wave diagram shows increased local signal amplitude, the lowered frequency, and misaligned event axis which is consistent with the above-mentioned signal characteristics of ill geologic bodies. It is inferred that there is a possibility of leaky passages. On the contrary, if the limestone rocks are relatively dense and well-integrated, there will be no significant dielectric differences in the electromagnetic wave signals, and therefore the reflected waves will be relatively weak. Figure 4 is an enlarged view of the left side.

![Figure 3. The full section wave train graph of the crest (From upstream to downstream).](image)

![Figure 4. Partial enlarged view of the left abutment.](image)

4.4. Test results of the upper berm

The wave train graph of the upper berm is shown in figure 5. Based on the characteristics of the radar reflected wave signals, the overall reflection wave of the survey line is weak and the frequency is single, indicating that the internal filling of the dam body is relatively dense. However, in a range of 30m from the left drainage ditch and at a depth of 10~25m, the reflected wave shows an increase in amplitude and a decrease in frequency, and the reflection wave group is interrupted and shifted at the same phase, and is partially arc-shaped. It indicates that the interior of this area is wholly in a loose and unconsolidated state and there may be a leakage path.

4.5. Test results of the lower berm

The wave train graph of the lower berm is shown in figure 6. It shows that the waveform of the part 4 to 10m under the surface is turbulent, the overall reflected wave amplitude is strong, and a near-horizontal reflection wave groups with local misalignment appears. Signal with this type of characteristics occurs when there is an overall loose dam body and a horizontal thin layer, indicating that the dam body filling is overall uncompacted. What needs to be specifically stated is that the building 10m below the surface is relatively dense, and it is found that the space 10m below is exactly the first stage of the flood dam according to design drawings. This shows that the flood dam body mass is favorable, and the filling body above is relatively loose and uncompacted.
5. Conclusion

GPR detection shows that the left bank slope is likely to be a seepage channel, which is completely consistent with the monitoring data analysis. It indicates that the GPR is a highly effective method for the detection of hidden defects in concrete faced rockfill dams, and this case can be a reference of GPR employed to detect leakage at home and abroad.

Although the advantages of GPR are obvious, underground structures are commonly complicated. It is advisable to utilize GPR cooperating with the traditional engineering survey methods (drilling and static exploration), supplemented by other geophysical methods (high-density electrical method, transient electromagnetic method, surface wave method, etc.) if permitted. A comprehensive comparative analysis of multiple test results is helpful for improving the detection accuracy.

Acknowledgments

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