Research on dam leakage detection based on visual and acoustic integration: a case study of CFRD

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Abstract. Many safety issues can arise during the long operation time of dams because of various internal and external factors, among which dam leakage problems happen frequently. Dam leakage not only affects the normal functions of a dam, such as power generation, water supply, and irrigation, but also weakens the flood control ability of the structure and increases the risk of dam failure. According to the existing problems in concrete face rockfill dam (CFRD) leakage detection, an integrated leakage detection technology is proposed in this paper. The proposed technology can analyze the dam safety monitoring data and then combine the high-precision sonar and underwater robot detection to provide solutions for dam leakage problems.

1. Introduction
Concrete face rockfill dams (CFRDs) are developing rapidly in China. According to incomplete statistics, as of 2015, more than 600 CFRDs have been built in the world, accounting for nearly 50% in China.[1] However, among the CFRDs over 100m, 12% of them are damaged to some extent, and dam leakage is one of the most important failure factors of CFRDs. Due to the particularity of the materials used to build CFRDs, many factors will cause dam leakages, such as the uncoordinated deformation of the rockfill body and the impermeable body, the uneven construction quality, and the uncontrollable external force.[2] The leakage detection of CFRDs has always been limited. How to find the leakage point quickly and efficiently is a difficult problem in the dam industry. In this paper, an integrated visual and acoustic leakage detection technology is proposed. The proposed technology combines high-precision sonar leak detection technology, underwater robot high-definition camera, inkjet tracer technology and connectivity test to provide guidance for dam safety monitoring and operations.

2. Project profile and leakage situation

2.1 Project profile
Liaoye reservoir is located in Liangping county, Chongqing, China. The normal water level of the
reservoir is 500.0 m with a total storage capacity of 16.29 million m³. The dam is a concrete faced rockfill dam (CFRD) with highest dam height 66.2 m, width of the dam crest 6.0 m, upstream slope 1:1.405, and downstream slope ratio 1:1.4. Its panel is divided into 37 sections, and the dam body adopts the conventional partition, including cushion area, transition area, the main rockfill area, and the downstream rockfill area. The bedding area and the transition area are gradation of limestone. The main and downstream rockfill areas are hard sandstone. This reservoir project including the main and auxiliary dam, spillway, water tower and water tunnel; therefore, Liaoye reservoir is a level III medium-sized engineering structure.

2.2 Dam leakage
Liaoye reservoir has started its impoundments since December 2011. In the past few years, the leakage volume of the dam was basically maintained at 30 ~ 40L/s when the water level was high, and the seepage monitoring instruments operated normally. On December 8, 2015, when the reservoir water level became 493.88 m, several seepage points appeared along the downstream dam foot, and the leakage volume increased to 84.4L/s. After the reservoir water level was reduced, the leakage volume decreased slightly. On May 6, 2016, 74.5mm of rain fell on the dam site making the reservoir water level rise rapidly with a sudden increase of the leakage amount again. The heavy rainfall in early June 2016 raised the reservoir water level to 492.78 m. On June 1, the leakage quantity behind the dam exceeded the measuring range of the measured water weir by 120L/s, and the maximum measured value of the estimated leakage quantity in the channel behind the dam became 381L/s. After that, the maximum measured leakage basically maintained at about 330L/s.

3. Preliminary analysis of the causes of dam leakage

3.1 Analysis of relationship between reservoir water level and leakage
At the early stage of this leakage development, the amount of leakage increased with the rise of reservoir water level. With continuous development of the leakage volume, the leakage volume did not decrease when the reservoir water level decreased, indicating that the dam body might have a leakage channel and the dam anti-seepage structure was damaged. From the characteristics of the failure of Zhushuqiao CFRD and Baiyun CFRD, the failure of panel structure or the failure of water-stop structure may occur in Liaoye CFRD.\[3\][4]

3.2 Analysis of safety monitoring data
Liaoye reservoir is a medium-sized reservoir, and the necessary monitoring instruments are set according to the standard requirements. The dam foundation is set with seepage pressure meter. The panel and joints are set with seam meter, temperature meter, etc.. The dam is set with water weir, and the two dam abutments are set around the dam observation seepage pressure meter. Safety monitoring data show that the measured values of four peripheral joints on the right bank are obviously abnormal, with the maximum displacement exceeding 15 cm. In the seepage pressure of the dam body on the right side of 0+280 section pb3-1, the seepage pressure value is relatively large (Table 1). If the monitoring results are accurate, water stop cracks and breakages exist in the right bank peripheral joints and panels.

| Pore water pressure gauge | Buried elevation of pressure gauge (m) | Corresponding average water level elevation (m) | contrast (m) |
|--------------------------|---------------------------------------|-----------------------------------------------|-------------|
| PB1-1                    | 452.20                                | 452.78                                        | 0.58        |
| PB1-2                    | 472.00                                | 473.01                                        | 1.01        |
| PB1-3                    | 492.00                                | 492.77                                        | 0.77        |
| PB2-1                    | 452.20                                | 451.09                                        | -1.11       |
| PB2-2                    | 472.00                                | 471.88                                        | -0.12       |
| PB2-3                    | 492.00                                | 492.71                                        | -0.71       |
### 3.3 Dam settlement analysis

The field survey shows mismatches between the panels, mismatches between the panels and the surrounding joints, and deformation of the top water stop. Severe loss of packing flexibility under the top water stop and impermeable cover exist. No surface packing bulges were observed for the water stop at the surrounding joints below 490m, which largely resulted from the deformation of the surrounding joints (Figure 1.). Many cracks on the road at the top of the dam on the right bank were observed. After the grouting treatment, the cracks opened again. According to the settlement observation, the total settlement of the dam was about 72cm, more than 1% of the dam height, and the settlement of the right bank was larger than that of the left bank. The settlement deformation of right bank dam after impounding was large, which is directly related with the dam leakage.

|   |   |   |
|---|---|---|
| PB3-1 | 452.00 | 458.51 | 6.51 |
| PB3-2 | 477.00 | 472.42 | -4.58 |
| PB3-3 | 492.00 | 492.49 | 0.49 |

#### Figure 1. Right bank panel dislocation and water stop deformation

#### Figure 2. Right bank dam crest road crack diagram

### 4. Integrated visual and acoustic leakage detection results

#### 4.1 New sonar detection

The underwater sonar seepage detection technology utilizes the excellent conduction characteristics of sound waves in water and the doppler principle to detect the flow leakage field. The underwater sonar detection technology of Liaoye reservoir adopts the Three-Dimensional Velocity Vector Sonar Measuring Instrument which has a high detection accuracy and 300m detection depth.[5] During the detection, the detection control lines are arranged parallel and perpendicular to the dam axis in the upstream of the dam, and the measuring points are arranged according to the 4m×4m grid. The leakage abnormal areas found in the detection process are encrypted and detected, and the encrypted grid is controlled by 2m×2m. The detection results showed that there was a centralized leakage zone located in the right bank panel MB33 with an elevation range of 462.5m, and the maximum leakage velocity in the centralized leakage zone was 0.82m/s. The cloud image of sonar detection area is shown in figure 3.
4.2 Underwater vehicle detection

The underwater robot detection technology is an unmanned detection method, where the underwater robot carries the detection equipment to the underwater target position for detection. This detection technology can overcome the limitation of diving detection and provide large operation depth, long working time, high safety degree and strong functionality. During the leakage detection of the Liaoye reservoir dam, an underwater robot carried a high-resolution camera to observe the underwater panel, and transmitted data through the umbilical cord cable, so as to observe the water flow movement at the entrance of the centralized leakage point in real time. As shown in figure 4.

4.3 Connectivity test

The connectivity test can directly reflect the connectivity between the upstream leakage point and downstream leakage point. A high concentration tracer fluid was introduced from the crack upstream of the dam with a hose. The water adsorption force at the leakage inlet was used to suck the colored liquid into the channel, and the value of the leakage velocity was determined by observing the distributions of the leakage points of the downstream tracer and the discoloration time of the water. After the tracer was injected into the upstream leakage point of Liaoye reservoir with a catheter, the water body of the downstream outlet water weir turned red in about 6 hours, and the tracer color reflected that the concentration increased with time, indicating that the upstream and downstream leakage points of the dam had good connectivity.
5. Conclusion

The leakage is one of the main types of failure for concrete face rockfill dam, and since the leakage location is often underwater, the problem is not easy to target. An oversized leakage can cause cushion material losses and eventually becomes a more serious leakage. Based on the analysis of the leakage monitoring data of Liaoye reservoir and the summary of the appearance and performance defects of the dam, the location of the leakage point was obtained. The results are basically consistent with those obtained by sonar detections and underwater vehicle inspections, which confirms the good accuracy of the analysis results and the good reliability of the integrated visual and acoustic leakage detection method proposed in this paper. This study provides a good reference for the leakage detection of CFRD.

Acknowledgments

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