Leakage Detection of CFRDs Based on a Multi-source Information Fusion Method

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Abstract. Dam leakage is one of the most important failure causes of concrete face rockfill dams (CFRDs). Causes of dam leakage problems are various and hard to target due to the non-homogeneity of dam materials and the multi-dimensional deformation of CFRDs. This paper effectively performs multi-source information fusion of the safety monitoring, underwater sonar scanning, underwater high-definition cameras, and connection tests to propose a method for seepage detections of concrete face rockfill dams. The proposed method has been successfully applied in the seepage detection of a CFRD.

1. Introduction

Dam leakage is one of the most important failure causes of face rockfill dams.[1] According to incomplete statistics, about 12% of the over-100m-height CFRDs in China suffer from leakage problems in various degrees.[2] For example, the leakage amount of Baiyun CFRD (with highest dam height of 120m) is 1240L/s,[3] the leakage amount of Busi CFRD (120m high) is nearly 3000L/s, and the leakage amount of a CFRD in Yunnan (140m high) is 1800L/s. The impermeable body of a CFRD is composed by the concrete panel and the water-stop structure between the panels on the upstream surface.[4] Water can scour the cushion layer of the support panel and weaken their supportive function because of long-term leaks on dams. The continuous leaking process can severely reduce the safety of a dam, and eventually lead to dam failure.

Unfortunately, there are no mature and efficient methods to detect the leakage of panel dams. At present, leakage detections of panel dams are mostly carried out by single detection methods, such as divers’ underwater inspections, underwater robot video inspections and dam discharge inspections. In some cases, even though divers and underwater robots are used for comprehensive detections, most of the divers and robots provide limited visions due to scanning or fixed-point inspections of the panel surface. The pertinency of detections and the quality of detection results may fail to provide enough information for safety evaluations and reinforcement decision making of CFRDs.

Based on the experience of CFRD designs and the consideration of the applicability of leakage detection methods, this paper presents a multi-source information fusion technique for panel dam
leakage detection by a working flow from the safety monitoring data to the leakage census to the leakage detailed inspection and finally to the leakage verification.

2. Leakage Detection of CFRDs Based on a Multi-source Information Fusion Method

The causes of leakage are complicated, and it is difficult to find out the leakage of dam in one way.[5][6] In order to reduce the detection costs, comprehensively detect the leakage paths and identify the causes of the leakage, a multi-source information detection technology is proposed. This detection method integrates monitoring data analyses, sonar scan surveys from underwater robots to determine the possible leaking areas, underwater high-definition cameras to examine the damaged regions, and connection test verifications.[7] Firstly, the dam monitoring data are used to comprehensively analyze the dam body deformation, the surrounding joint deformation, especially the seepage pressure data behind the face plate and toe plate, so as to preliminarily determine the possible leakage type and leakage area. According to the leakage analysis, targeted detection means are selected. The dam surface is scanned by underwater robot carrying scanning sonar to determine the main abnormal leakage area.[8][9] Then, the damage and leakage degrees are intuitively decided by divers through the underwater robot inkjet cameras or underwater inspections. If there is a centralized leakage channel, a connectivity test is used to verify the leakage channel location.

3. Project Profile

A hydropower station is a large type (type II) project. The checked flood level of the reservoir is 217.75 m, with total storage capacity 450 million m$^3$, the normal storage level 215 m, the corresponding storage capacity 406.5 million m$^3$, the dead water level 180 m, the corresponding storage capacity 63.1 million m$^3$, and the regulating storage capacity 343.4 million m$^3$. This station has an annual regulating capacity. The installed capacity of the power station is 246MW and the annual generating capacity is 858 million kW•h.

The main dam is a concrete-faced rockfill dam with a crest elevation of 220 m, a riverbed toe plate elevation of 105 m, a maximum dam height of 115 m, a dam crest axis length of 882.2 m, dam crest width of 9 m, upstream dam slope ratio of 1:1.4, and a downstream dam slope ratio of 1:1.5. The upstream elevation of the dam is below 155 m and the elevation of the two sides of the toe plate is below 180 m. The downstream dam face is respectively provided with a horse track with a width of 3 m at the elevation of 190 m and 160 m, and a weight body with a top width of 100 m at the elevation of 130 m.

![Figure 1. Dam layout plan](image)
4. Leakage Detection Based on The Multi-source Information Fusion Method

4.1. Analysis of Safety Monitoring Data
An abnormal leakage occurred in the main dam on October 7th, 2015. The reservoir water level was at 214.79 m on that day, the dam leakage was about 0.5~0.7 m$^3$/s, and the water outlet elevation was about 108 m. From April to June 2016, the main dam leakage investigation and treatment was conducted. After the leakage treatment, the amount of leakage behind the dam increased with increasing reservoir water level. In the dry season of 2016 (from November to May), the reservoir water level fluctuated little, and the leakage quantity behind the dam remained at 0.8~1.0 m$^3$/s, with the maximum value of 1.12 m$^3$/s (the reservoir water level was at 215 m). In late April 2017, the second leakage treatment (throwing grade batching and cement-doped cloth) was carried out, which stopped by June 25th of the same year. During this treatment, the leakage was minimized to 0.28 m$^3$/s (with reservoir water level 181.2 m). After the second leakage treatment, the amount of leakage increased with the rise of the reservoir water level, and the maximum amount of leakage became 1.11 m$^3$/s. Before January 12th, 2018, the amount of leakage was basically stable at about 0.8m$^3$/s at high water level, and the amount of leakage dramatically increased to about 1.3m$^3$/s on January 12th. The third leakage treatment started on January 31st, and the cement mixed cloth was still used for the treatment. By April 5th, the water level of the reservoir dropped to 196.05 m, but the leakage was still 1.2 m$^3$/s. By the end of May, the reservoir water level was about 188.00 m, and the leakage was about 1.0 m$^3$/s.

![Figure 2. Leakage process line of the dam](image)

4.2. Sonar Leakage Detection
A total of 26 sonar detection lines were arranged in the bedding and bank slope areas near the dam below the elevation of 155 m, and tagged as N1~N26 from the panel upstream. According to the surface sonar leakage detection data, the cloud map of the leakage velocity partition in the survey area is shown in Figure 3. The obvious leakage area was marked red, the darker the color is, the greater the leakage velocity value is. The area without obvious abnormality is in blue. Figure 3 shows that there are four leakage areas with the leakage velocity exceeding cm/s in the dam surface and the coverage area, one of which is the concentrated leakage area and the other three are the abnormal leakage areas:

(1) Leakage area was located in the left bank of No.29, No.30, which were nearby seams at the bottom of the panel. The region's largest leakage flow rate was 1.04 m/s, with the maximum velocity measuring point located at the dam vertical 0 + 284 (Perpendicular to the direction of the dam axis. The left dam head was 0. Since surface ships could be affected by the wind, and the bottom of the library environment was complex, there might be deviation of observation points. The dam horizontal was 0 + 90 (parallel to the axis of the dam, the dam axis to 0), and it was covered by No.28~ No.31
panels.

(2) No.1 abnormal area was located at the bottom of No.32 and No.33 panels on the left bank and near the surrounding seam. The maximum seepage velocity in this area was up to 2.1 cm/s, and the maximum velocity measurement point was located at 0+336 in the vertical direction of the dam and 0+118 in the horizontal direction of the dam.

(3) No.2 abnormal area was located in the upper part of No.39 panel blanket of the riverbed dam section, and the range of elevation was 150~153 m. The maximum seepage velocity in this area reached 1.08 cm/s, and the maximum velocity measurement points were located at 0+440 in the vertical direction of the dam and 0+102 in the horizontal direction of the dam.

(4) No.3 abnormal area was located at the bottom of the right bank panel No.49 and No.50 and near the surrounding seam. The maximum seepage velocity in this area was 1.27 cm/s, and the maximum velocity measurement point was located at 0+600 in the vertical direction of the dam and 0+102 in the horizontal direction of the dam.

In addition to the above areas, the maximum velocity of leakage in the upper areas of the dam and other parts of the blanket was in the range of $10^{-4}$~$10^{-5}$ cm/s. No obvious abnormal leakage was observed.

4.3. Underwater Vehicle Detection

A detailed examination of the concentrated leakage area identified by the leakage sonar found that the blanket collapsed in the No.29 panel at about 39 m (around 150 m in elevation) under the water, forming a hole with a large suction, which was the concentrated leakage area and the location was consistent with the sonar results. According to the detailed investigation of the concentrated leakage area of No.29 panel, the concentrated leakage area was located at the bottom of No.29 panel, near the peripheral seam, with an elevation of 150~153 m. The water-stop structure of the panel and peripheral seam in this area was damaged, and there are tree trunks and strips on the upper part. The upper part of the concentrated leakage area had formed a funnel shape due to the leakage. The length of the funnel top was about 10m and the width was in the range of 6~8 m.

4.4. Connectivity test

For the connection test of the concentrated leakage area of panel No.29, the food-grade tracer was
injected into the concentrated leakage area through a catheter. After 6.5 hours, the water body of the downstream measuring weir began to change its color, and the connection between the upstream leakage inlet and the output of the measuring weir was verified.

Figure 7. Connectivity test

5. Conclusion
In the main dam leakage detection of a CFRD, the dam safety monitoring data were analyzed to identify potential leakage area, and then the upstream dam surface was investigated by sonar leakage detection technology to determine one centralized leakage area and three leakage abnormal areas. Finally, the leakage area determined by sonar were examined in details by the HD camera tracking technology of underwater robots. It was found that the leakage area of the main dam was located at 150-153m at the bottom elevation of no. 29 panel, and the maximum leakage velocity reached m/s level. In this case, the leakage detection technology based on multi-source information fusion method has been successfully applied in the CFRD leakage detection.

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