THE VIDEO-SONAR INTEGRATED METHOD FOR LEAKAGE DETECTION AND ITS APPLICATION

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ABSTRACT

The leakage problem is an important factor affecting the overall safety of reservoir dams. The effective and accurate detection of leakage has always been a key challenge in the field of dam safety. In the past few decades, different technologies and methods have been widely adopted for leakage detection of dams, which can be categorized into five classes according to their function and mechanism, i.e., electromagnetic methods, elastic wave methods, tracing methods, video-based methods and others. It is usually difficult for these methods to precisely locate the leakage or defects in dams solely, since that each of them has limitations. In this paper, the video-sonar integrated method is presented for leakage detection of reservoir dams. It combines sonar measuring technique, unmanned underwater detection with high resolution video recording, tracer method and hydraulic connectivity test, which shows the capability of detecting the concentrated leakage beneath deep water. The present method has been utilized in a 126m high CFRD (concrete faced rockfill dam) whose leakage rate was up to 1300L/s, successfully locating the leakage point. The video-sonar integrated method presented in this study could provide practical references for similar projects.

Keywords *: Dam leakage, anti-seepage system, leakage detection, video-sonar integrated method*

1. INTRODUCTION

In water conservancy and hydropower projects, the design of anti-seepage system is one of the most important parts of engineering design and construction. However, due to various reasons, leakage has always been the most common type of defects in reservoir dams [1]. Dam leakage affects the normal performance of the power generation, water supply, irrigation and other engineering benefits of the reservoir, and even severely threatens the flood control of the project, raising the risk of dam failure. Therefore, study on leakage detection technologies and treatment measures is of great significance and practical importance to guarantee the safe operation of the reservoir dam.

In engineering practice, a large number of dams with excessive leakage problem have undertaken rehabilitation and repair for several times [2], but with little effect. The major reason is that the leakage entrance and the leakage origin have not been well detected and investigated. Effective and precise detection of the leakage entrance is an important prerequisite for the evaluation of dam safety and the subsequent leakage repair. However, due to the fact that leakage problems of dams are quite complex and hard to detect underwater, especially for high dams and large reservoirs, when the leakage is always beneath in deep water, the velocity is extremely low and the leakage paths are unconcentrated. Underwater leakage detection has become an urgent and key issue in the field of dam safety and engineering [3].

On the one hand, due to the various types of dam buildings and different working conditions, the patterns and origins of leakage vary remarkably. The application of an individual method sometimes has disadvantages such as low efficiency, poor accuracy and time-consuming. It is usually necessary to adopt multiple feasible methods for the leakage detection, for the reason that different test means could mutually verify and complement each other, and provide convincible results [4,5].

On the other hand, with the rapid development of the world's dam engineering technology in recent years, particularly in China, a considerable number of high dams have been constructed. With respect to the leakage defects of the high dams, which are located deeply below the water level, conventional detection methods are difficult to be implemented. For the high dam cases, the detection scope is wider and the underwater environment is more complicated.

For this reason, this paper summarizes the technical characteristics and application effects of different leak detection methods. And the video-sonar integrated leakage detection method is proposed for dam leakage in deep water. This method combines monitoring data analysis, sonar detection, underwater high resolution video, tracer method, and hydraulic connectivity test, which could defect the underwater leakage defects of dams efficiently and precisely. An engineering case on a 126m concrete faced rockfill dam (CFRD) with the video-sonar integrated leakage detection method is also presented, which could provide practical references for similar projects.

2. STATUS OF LEAKAGE DETECTION METHODS FOR RESERVOIR DAMS

2.1 Common leakage detection methods

With the development of modern technology, leakage detection methods for reservoir dams has been rapidly developed and improved, based on different techniques such as acoustic waves, electrical signals, magnetic resistivity, optical imaging and temperature tracing, etc. According to the technical characteristics and mechanisms, common leakage detection methods can be divided into 5 categories, i.e., electromagnetic methods, elastic wave methods, tracer methods, and video-based methods and others.

The electromagnetic methods utilize the electrical and magnetic properties of rocks/soils and their response to either naturally occurring or artificially induced electromagnetic (EM) stimuli to explore the interior defects of the dam, usually including the magnetotelluric method, ground penetrating radar method and high density resistivity method.

The elastic wave methods are usually adopted for non-destructive evaluation (NDE) and detection of the damage of concrete, which are also applied for the leakage detection of concrete and embankment dams, for example, the elastic wave computer-aided tomography (CT), acoustic emission (AE) measurement, instantaneous Rayleigh wave and seismic tomography.

Tracer methods including the isotope tracing method, hydraulic connectivity test and hydrochemical analysis, are commonly used to detect and locate the leakage route.

Video-based methods undertake a direct inspection and discovery of unhidden dam defects through video recording at close range, like the underwater photography by divers, detection with underwater remotely operated vehicle (ROV), underwater plume tracing and photography, borehole televiewer log, etc.

Other leakage detection methods such as the flow-field method and temperature field analysis can also be carried out to detect the leakage entrance and leakage route inside the dam body.

2.2 Develop trend of leakage detection methods

Leakage has become a common problem for reservoir dams, and there is an urgent need for detection techniques that can quickly and accurately identify the leakage entrance and leakage route. The current status and developing trend of leakage detection methods are summarized as follows:

(1) More comprehensive detection methods are required. Investigation by an individual detection method often cannot fully reflect the characteristic of the dam leakage, and the detection results cannot be verified, restricting the accuracy of the detection. In practical engineering applications, multiple feasible methods are often required to carry out comprehensive detection and verification. Several comprehensive detection methods, which usually involve two or more geophysical techniques have been proposed recently for leak detection [5]. To gain a detailed interpretation and evaluation of the test results, monitoring data analysis and numerical simulation could also be used for comprehensive leak detection.

(2) Leakage detection methods should overcome the limit for large water depth. In recent years, an increasing number of high dams with very large storage capacity have experienced excessive leakage problems. At these circumstances, leakage entrances are located in deep water which are hard to detect. Attributable to the complexity and harshness of the deep-water environment, existing underwater detection methods are restricted by the poor efficiency and the severe risk. For example, the depth of conventional air diving should not be more than 60 m, and the depth of conventional helium-oxygen diving should be 60-150 m (less than 120 m is appropriate) [6], based on the diving medical research. Therefore, the unmanned underwater detection with ROV will be promising and feasible for deep-water leakage detection in reservoirs of very high dam.

(3) Leakage detection accuracy needs to be improved. The existing geophysical detection methods are difficult to balance the contradiction between the detection range and the detection accuracy. Many methods can only provide a salary range and grade of the leakage, and the detection accuracy is not adequate, which makes it difficult to precisely locate the leakage entrance of the dam. Since that the underwater environment is unclear, new methods with high accuracy for detecting the leakage entrance underwater are particularly needed [7].

(4) Requirements for a high-resolution visualization of detection results are proposed. The current commonly used leakage detection methods usually produce insufficient detection results with poor interpretation, and are difficult to detect the leakage route inside the dam. Three-dimensional (3D) spatial visualization technology with high-resolution of great significance for underwater leakage detection. It can provide a comprehensive interpretation of the dam leakage, including the precise location of the entrance and the distribution of the leakage route, which will be helpful to the subsequent leakage treatment and rehabilitation.

3. RESEARCH ON THE VIDEO-SONAR INTEGRATED METHOD

The leakage problems of reservoir dam are often complicated in origin and usually hidden under water, especially for the case of high dams. For the leakage beneath in deep water, the velocity is extremely low and the leakage routes are unconcentrated. At these circumstances, leakage detection faces the difficulties in low efficiency, limitative precision and poor implementation in practice.

Underwater leakage detection has become an urgent and key issue in the field of dam safety and engineering. This paper presents the video-sonar integrated leakage detection method, which combines monitoring data analysis, underwater sonar detection, underwater high resolution video recording, tracer method, and hydraulic connectivity test. In this method, the monitoring data analysis is conducted at first to interpret the abnormal seepage phenomenon and to guide the subsequent detection by instruments; underwater sonar detection is then adopted to measure the velocity field in the reservoir and to determine the anomaly leakage zones; underwater remotely operated vehicle (ROV) is employed to capture high resolution video around the anomaly leakage zones with tracer method to accurately locate the infiltration point; and finally the hydraulic connectivity test is carried out to validate the presence of the leakage path. It enables leakage detection from wide area velocity sketchy survey to the precisely locating and detailed investigating of the leakage entrance. And the different test means could mutually verify and complement each other.

Deformation and seepage instrumentation systems are required to be installed in the foundation and dam body when the dam is constructed, and seepage monitoring is necessary to decide if abnormal seepage happens in the dam. The monitoring data analysis is always used to identify the service status of a dam. For instance, the relationship between the leakage rate and the reservoir's water level can be analyzed to evaluate the status of the anti-seepage body, the relationship between the monitoring results of the osmotic pressure and the reservoir's water level helps reflect the develop trend dam leakage, and from the deformation monitoring data the potential damaged zones of dam body and leakage entrances can be assessed.

Underwater sonar detection utilizes several sonar probes to detect the anomaly leakage zones where the flow velocities are relatively large. The sonar probes are dropt down into deep water to measure the seepage velocity, on the reservoir bed or at the bottom of a borehole. Based on sonar measurements, the velocity fields on the reservoir bed can be efficiently detected. This method provides a general inspection to the upstream face of the dam, the reservoir bed and the bank slope to locate the anomaly leakage zones. And it produces different forms of visualization images of the velocity field, such as the 2D contour maps and the 3D velocity vectors maps.

Underwater unmanned detection is undertaken by a ROV as a carrying platform, with high resolution cameras, image sonar, inkjet devices, lights, crack width measuring instruments and other detection devices. It can take high resolution video recording on the upstream face of the dam or around the anomaly leakage zones found by sonar detection. To confirm the leakage entrance and its location, tracer experiments can also be undertaken along with the ROV video recording.

After the leakage entrance on the upstream face of the dam is located, the hydraulic connectivity test could be conducted to verify the presence of the leakage route. In this test, a large amount of pigments is required to be released near the leakage entrance, and the pigments will be absorbed by the water infiltration. If the outflow from the measuring weir afterwards the dam toe changed its color as the released pigments, it indicates that the presence of a percolated leakage route inside the dam body.

The flow velocity detection accuracy of the video-sonar integrated leakage detection method is 10^{-3} cm/s, which is 100 times higher than the existing methods, and the detection water depth exceeds more than 150m. This new leakage detection method shows high efficiency and adequate precision, and has been successfully applied in a large number of dams in China and around the word.

4. ENGINEERING APPLICATION

This section provides an engineering application case of the video-sonar integrated leakage detection method on a high concrete faced rockfill dam (CFRD) in Cambodia. This dam belongs to a large scale hydropower plant project located in the southwest of Cambodia. The normal water level of the reservoir is 215.0m and the total storage capacity is 450 million m3. The reservoir's water-control project includes the main dam, auxiliary dam, spillway water intake tunnel. The main dam is a CFRD with a maximum dam height of 126m, crest elevation of 220m, crest length of 882.3m, and crest width of 9.0m. The upstream dam slope ratio is 1:1.4, and the downstream dam slope ratio is 1:1.5. There are 77 concrete face slabs and 71 plinths in total on the upstream face of the dam. The concrete face slab is 0.3 m thick at the top and 0.63m thick at the bottom. The foundation of the plinths is mainly sandstone and mudstone. The weighted cover zone and upstream blanket zone are located below the elevation of 155.0m on the concrete face slab.

The reservoir was impounded in November 2013, and the commercial operation of the hydropower plant started in August 2014. The main dam began to leak in October 2015, and the leakage rate increased continuingly. In 2018, the maximum leakage rate has reached 1300L/s. The picture of the leakage at the measuring weir (located at the downstream dam toe) is shown in Fig.1.

Fig. 1 : Leakage at the measuring weir

The excessive leakage could deteriorate the dam structure and cause the seepage failure of granular materials in cushion and transition layers. In order to conduct the leakage treatment and repair to guarantee the safe operation of the dam, it was urgently necessary to find the leakage entrance as soon as possible. The video-sonar integrated leakage detection method was successfully applied to precisely detect the underwater leakage in this dam.

4.1 Monitoring data analysis

According to the analysis on the monitoring data of leakage rate, seepage pressure and deformation of the dam body, the following conclusions were drawn:

(1) There was a close correlation between the dam's leakage rate and the water level of the reservoir (see Fig. 2). The leakage rate increased gradually with the rise of water level. And when the water level of the reservoir was lowered down, the leakage rate showed a slight decrease. From 2016 to 2018, the leakage rate of the dam generally increased at similar water levels. Such a trend is basically consistent with the observations and experiences in the leakage problems caused by the damage of concrete slabs in Baiyun Dam[8] and Zhushuqiao Dam [9] in China.

(2) The measured value of the osmometer PA-01 (located at an elevation of 161.50m) beneath the No. 30# concrete slab had a positive correlation with the reservoir's water level. The measured osmotic pressure at the osmometer PB-02 (located at an elevation of 132.00m) beneath the No. 30# concrete slab also had a positive correlation with the reservoir's water level, with a maximum osmotic pressure head of 27.23m.

(3) The settlement deformation of the dam has been relatively large and still not completely converged. The deformation at the peripheral joints was significantly large, especially those peripheral joints of No. 28#~32# concrete slabs at the left side of the dam.

Based on the monitoring data analysis of the dam leakage, it was found that that leakage of the dam might be caused by the damage or failure of the anti-seepage system including the impervious concrete slabs and the sealing structures in the joints, and the leakage entrance was more likely to be located near the peripheral joints at the left side of the dam. The specific implementation of the underwater leakage detection was as follows: a wide area velocity sketchy survey was carried out at first on the bed of the reservoir with underwater sonar detection, then a detailed inspection at the concrete slabs and joints is undertaken by the underwater unmanned high resolution video recording with tracer method, hydraulic connectivity test was finally performed to validate the presence of the leakage route.

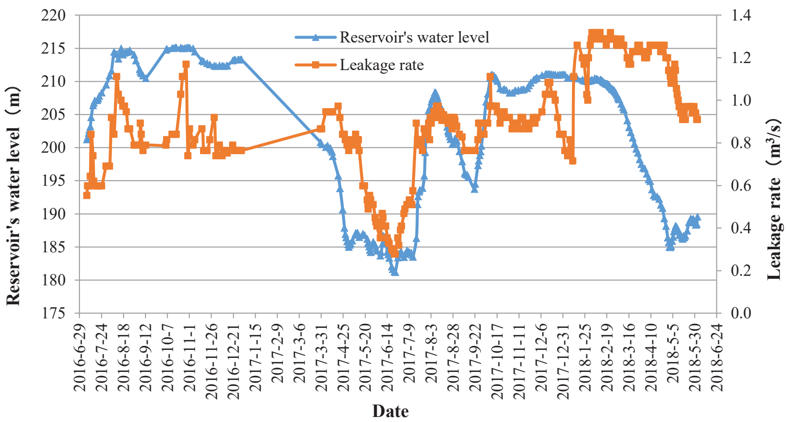

Fig. 2 : Evolution curves of reservoir's water level and leakage rate

4.2 Underwater sonar detection

The underwater sonar detection was carried out to measure the seepage velocities on the bed of the reservoir below the water level, including the areas of the upstream concrete slabs below the crest of the upstream blanket zone (at the elevation of 155.0m), the plinths and the bank slopes near the dam. For the Sonar detection, the test lines were arranged parallel and perpendicular to the dam axis to form a 4m×4m testing grid, and the sonar probe was dropt down to the bed of the reservoir at each point to measure the seepage velocity. For the anomaly leakage zones found during the detection process, the testing grid was then refined to 2m×2m. A concentrated leakage zone was found within the detection range. The leakage entrance was located at the peripheral joints of No. 29#~30# concrete slabs at the left side of the dam, with the maximum leakage velocity up to 1.04m/s. The leakage velocity contours map obtained by the underwater sonar detection is shown in Fig. 3.

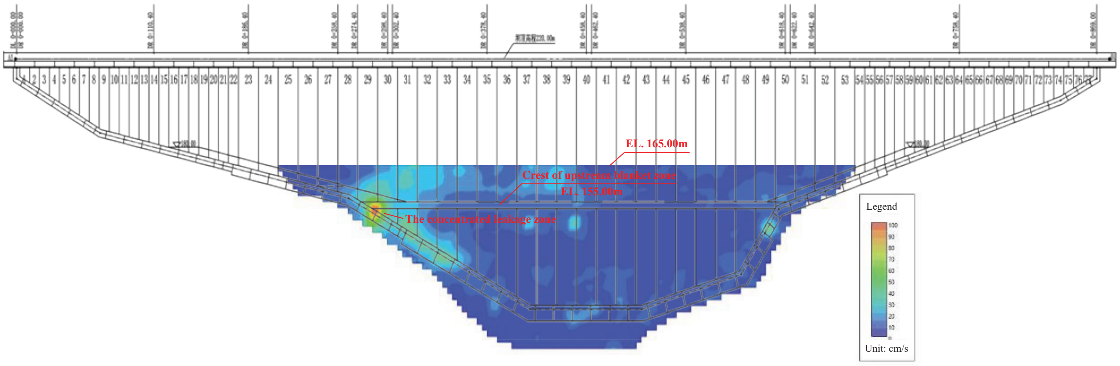

Fig. 3 : Leakage velocity contours map obtained by the underwater sonar detection

4.3 Underwater unmanned detection

Underwater ROVs were utilized to detect the concrete slabs and plinths above the elevation of 155.0m on the upstream face, and high resolution video was recorded around the concentrated leakage zone found by sonar detection. To confirm the leakage entrance and its location, tracer experiments were also undertaken along with the ROV video recording.

From the unmanned inspection, it was found that a leakage hole was formed on the No.38# concrete slab at an elevation of about 182.5m. The leakage hole was about 50cm in diameter (see Fig. 4), and the concrete near the hole was totally ruptured and brought away by the leakage water. The velocity at this hole was up to 0.92m/s.

When investigating the concentrated leakage zone found by sonar detection, image sonar was used to identify the details of the leakage entrance. It was found to be a large pit on the upstream blanket zone with about 10.8 m in length and 6 to 8 m in width (see Fig. 5). The leakage entrance located at the bottom of No. 29# concrete slab, near the elevation of 150.0~153.0m. The concrete slab was severely damaged and collapsed, and the clay materials of the upstream blanket zone were washed away by the inlet water, forming a funnel-shaped pit.

4.4 Hydraulic connectivity tests

Hydraulic connectivity tests were performed on the two detected leakage entrances (one is on the No.38# concrete slab, and another is at the bottom of No. 29# concrete slab). A large amount of pigments with different colors was released at these two leakage entrances. Respectively after about 5 to 6.4 hours, the out flow at the downstream measuring weir began to change color (see Fig. 6). The tests could provide evidence of hydraulic connectivity between the leakage entrances and the leaked water at the downstream side of the dam. It was also indicated that percolated leakage routes were formed inside the dam body.

Fig. 4 : Underwater high-definition photography of the leakage hole on No. 38# concrete slab

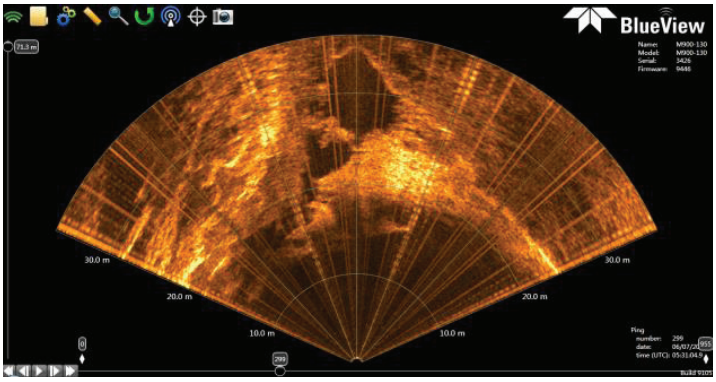

Fig. 5 : Image sonar detection results of the concentrated leakage zone on No. 29# concrete slab

Fig. 6 : Hydraulic connectivity test

4.5 Tested results

With the video-sonar integrated leakage detection method, two major leakage entrances (on the No.38# concrete slab and at the bottom of No. 29# concrete slab) at the upstream face of the dam were identified and precisely located. The leakage was caused by the damage and collapse of the concrete slabs, which destroyed the watertightness and integrity of the anti-seepage system. With different test means mutually verifying and complementing, the tested results are reasonable and convincible, which could meet the need of subsequent leakage treatment and rehabilitation of the dam.

5. CONCLUSION

Effective and precise detection of the leakage entrance is an important prerequisite for the evaluation of dam safety and the subsequent leakage repair. To meet the urgent need for quickly and accurately identifying the leakage entrance and leakage route, more comprehensive detection methods are required, and the existing technologies should be improved with strong adaptability to water depth, with high accuracy in locating, and the ability of high-resolution visualization. The present video-sonar integrated leakage detection method is a new and novel procedure which combines monitoring data analysis, underwater sonar detection, underwater high resolution video recording, tracer method, and hydraulic connectivity test, and is capable of detecting the underwater leakage efficiently and precisely. The present method was successfully applied in a 126m high CFRD whose leakage rate was up to 1300L/s, precisely locating the leakage entrances. The detection procedure in this study could provide practical references for similar projects.

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