UNDERWATER LEAKAGE DETECTION AND REHABILITATION FOR CONCRETE FACED ROCKFILL DAMS

JIANHUA LU, YI XU, XIAOMING ZHOU AND JINZHANG TIAN
Changjiang Survey, Planning, Design and Research Co., Ltd., Wuhan, China And National Dam Safety Research Center, Wuhan, China

ABSTRACT

Modern concrete faced rockfill dam (CFRD) has been remarkably developed and widely practiced around the world, due to its adequate safety, economic efficiency and good foundation adaptability. However, the design and construction of CFRD still rely largely on engineering experience, resulting in frequent occurrence of various engineering problems during service time. In recent years, many CFRDs have experienced serious leakage, which not only affects the normal operation and performance efficiency of the project, but also jeopardizes the dam safety. Therefore, the detection and rehabilitation techniques for leakage of CFRDs are urgently demanded. With respect to the leakage problem in Liaoye CFRD in Chongqing, China, the video-sonar integrated method for leakage detection is successfully applied to precisely locate the leakage pathways, and the underwater rehabilitation techniques are adopted for repairing the leakage. After rehabilitation, the leakage of the dam is considerably reduced and the accident hazards have been eliminated. The underwater leakage detection and rehabilitation techniques for CFRDs presented in this study could provide practical references for similar projects.

Keywords *: CFRD; leakage; leakage detection; leakage treatment*

1. INTRODUCTION

The concrete faced rockfill dam (CFRD) is an important type of dam that has developed rapidly in the past three decades, due to its adequate safety, economy efficiency and good foundation adaptability, which has been widely constructed and practiced around the word [1]. Since the modern CFRD construction technology was introduced into China from 1985, it has experienced three stages as introduction and assimilation, endogenous innovation, and breakthrough development, respectively represented by the Xibeikou, Tianshengqiao I, and Shuibuya (the world's highest CFRD) Dams. At present, there are more than 600 CFRDs around the world, including constructed, under-construction, and proposed dams, while China possesses nearly 50% of the total number [2].

Different kinds of defects in CFRD have also been exposed in the construction or operating period for a large number of CFRDs in China, such as slab extrusion damage, structural cracks, excessive leakage and hydraulic erosion, even collapse accident. Particularly, leakage has become a common deficiency for CFRDs. For example, the Aguamilpa Dam (187 m in height, 257.7 L/s in leakage rate) in Mexico, the Campos Novos Dam (202 m in height, 1300 L/s in leakage rate) and the Barra Grande Dam (185 m in height, 1284 L/s in leakage rate) in Brazil have experienced excessive leakage problems[1]. The Gouhou CFRD in Qinghai Province in China collapsed in 1993, which was caused by the seepage failure of impervious body[3]. There are also a considerable number of CFRDs that have to empty the reservoir for repair and rehabilitation due to massive leakage in China, such as the Zhushuqiao Dam[4], Baiyun Dam[5] in Hunan Province, and Mopan Dam[6] in Guangxi Province, etc., due to excessive leakage. The leakage of CFRD will inevitably affect the normal performance. Seepage failure always occurs in cushion and transition layers of CFRDs under long-term excessive leakage conditions, leading to the continuing loss of fine particles under hydraulic gradient. The loss of fine particles in cushion and transition layers would even enlarge the leakage rate, which would enlarge the deformation of rockfill dam body and cause severe damage to the face slab, jeopardizing the safety of the dam.

For the CFRD, an impervious concrete slab is utilized on the upstream face of underlying rockfill body to provide watertightness. Most cases for the leakage of CFRDs occur on the concrete slab. It is still challenging for detecting and remedying of the leakage [7], since that the leakage is always beneath in deep water, the velocity is extremely low and the leakage paths are unconcentrated. Underwater leakage detection and rehabilitation for CFRDs has become an urgent and key issue in the field of dam safety and engineering [8]. This paper introduces several new methods regarding the detection and rehabilitation of the leakage problems suitable for CFRDs. The video-sonar integrated leakage detection combines monitoring data analysis, sonar detection, underwater high resolution video, tracer method, and hydraulic connectivity test, which could detect the underwater leakage efficiently and precisely. To reliably repair the leakage on the concrete slab, the underwater rehabilitation techniques including underwater crack filling, underwater grunting, and surface sealing with geomembrane, are proposed. Take the Liaoye CFRD for instance, the leakage point and damaged zone on the concrete slab was precisely detected by the video-sonar integrated leakage detection method, and the underwater rehabilitation techniques were subsequently applied to repair the leakage. After rehabilitation, the leakage of the dam is considerably reduced and the accident hazards have been eliminated. The underwater leakage detection and rehabilitation techniques for CFRDs presented in this study could provide practical references for similar projects.

2. PROJECT PROFILE

Liaoye Reservoir is located in Liangping County, Chongqing City, China, and is an important water supply project. The normal water level of the reservoir is 500.0m and the total storage capacity is 16.29 million m3, which is a medium-scale project. The reservoir's water-control project includes main dam, auxiliary dam, spillway, water intake tower and water intake tunnel. The main dam is a CFRD with a maximum dam height of 66.2m, crest elevation of 502.2m, crest length of 371.67m, and crest width of 7.0m. The downstream dam slope is 1:1.4. The dam body adopts conventional material zoning profile, including the cushion layer, the transition layer, the main rockfill zone, the downstream rockfill zone, the weighted cover zone and upstream blanket zone on the concrete face slab. The cushion and transition layers are filled with limestone, the main rockfill and the downstream rockfill zone are composed of hard sandstone, the weighted cover zone is filled with excavated and abandoned rocks, and the upstream blanket zone is filled with clay. A typical profile of the dam is shown in Fig. 1.

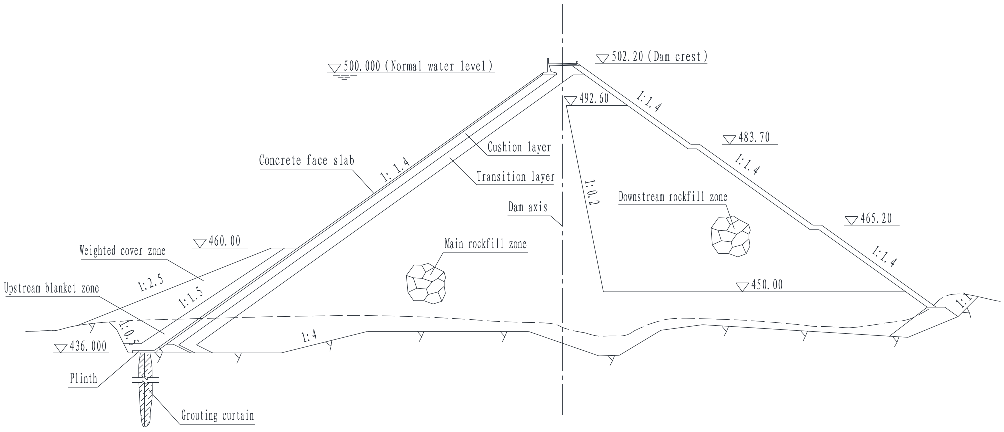

Fig. 1 : Typical profile of the main dam of Liaoye Reservoir

The Liaoye Reservoir commenced impounding in December 2011. During the first few years of operation, the leakage rate of the main dam has basically remained at 30~40 L/s at high water level, and the seepage monitoring instruments in the dam body are basically normal. When the water level reached above 493.88m in December 8, 2015, several leakage points were observed along the downstream of the dam toe, and the leakage rate increased to 84.4 L/s. When the water level of the reservoir was lowered down, the leakage rate showed a slight decrease. After a total rainfall of 100 mm at the dam site area in May 6, 2016, the reservoir's water level rose rapidly, and the leakage rate at the dam toe had a sudden increase again. After the rainy season began around June 2016, the reservoir's water level reached above 492.78m, and the maximum leakage rate was estimated approximately to 381 L/s. Subsequently, it is maintained at about 330 L/s. Fig. 2 shows the evolution curves of reservoir's water level and leakage rate from December 2015 to July 2016.

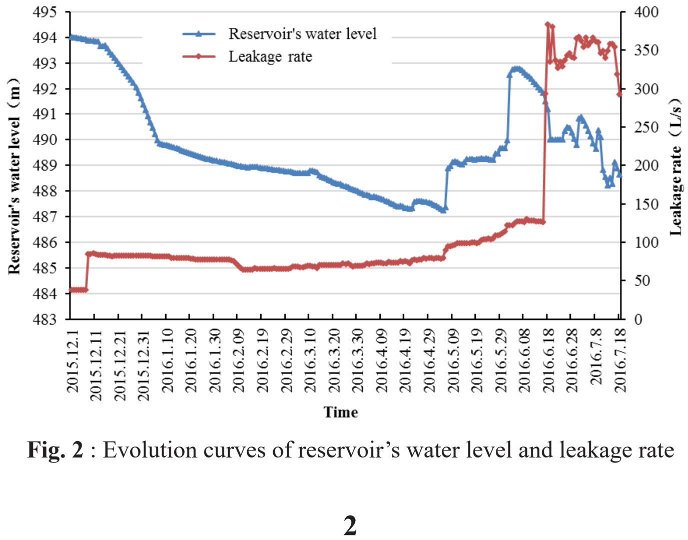

Fig. 2 : Evolution curves of reservoir's water level and leakage rate

3. UNDERWATER LEAK DETECTION

The maximum leakage rate of Liaoye Dam has reached 381L/s, accounting for 72.3% of annual average runoff of the reservoir (527L/s), which remarkably affected the reservoir's storage capacity and water supply. Among the dams of the same kind and the similar scale, such leakage rate was considerably large. When the water level of the reservoir was lowered down, the leakage rate showed a slight decrease. According to the experience in several CFRDs that leaked excessively, the leakage of Liaoye Dam is likely to be caused by the damage or failure of watertightness of the upstream concrete slab. In order to repair and rehabilitate the dam as soon as possible for safely operation, the video-sonar integrated leakage detection method was employed for detecting the leakage of the dam.

3.1 The video-sonar integrated leakage detection method

Leakage problems of CFRDs 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. At these circumstances, leakage detection faces the difficulties in low efficiency, limitative precision and poor implementation in practice. The video-sonar integrated leakage detection method is a comprehensive combination of different means which includes monitoring data analysis, sonar detection, underwater high resolution video, tracer method, and hydraulic connectivity test [9]. 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. The different test means could mutually verify and complement each other. The flow velocity detection accuracy of this method is 10^{-3} cm/s, which is 100 times higher than the existing methods, and the detection water depth exceeds more than 150m. The new leakage detection method shows high efficiency and adequate precision, and has been successfully applied in a large number of CFRDs in China and around the word.

3.2 Test results of Liaoye CFRD

(1) Analysis of monitoring data

As a medium-scale reservoir, the main dam of Liaoye Reservoir has installed the necessary safety monitoring instruments in accordance with the requirements of the regulations, with osmometers embedded in the dam foundation and dam abutments, triaxial joint meters and thermometers installed at the face slabs and joints, and measuring weir built afterwards the dam toe. The monitoring data show that the measured values of the four joint meters on the right side of the dam were obviously abnormal, and the maximum displacement at the same locations was larger than 15cm. The measured pressure value of osmometer PB3-1 at the 0+280 section on the right side of the dam body is relatively large. After a preliminary analysis, the peripheral joints and face slabs around the right bank of the dam might have defects in watertightness that were caused by cracking or damaging, which may be one of the important pathways for the leakage.

(2) Sonar detection

The sonar detection technology was used to detect the areas below the reservoir water level, including the face slabs, sealing structures in the joints, 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 the water level 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. The detected results show that there was a concentrated leakage point on the No. MB33 face slab on the right side of the dam, with the elevation of 462.5m. The velocities at this concentrated leakage site was larger than 0.1cm/s, with a maximum value of 0.82m/s. The leakage velocity contours map obtained by sonar detection is shown in Fig. 3.

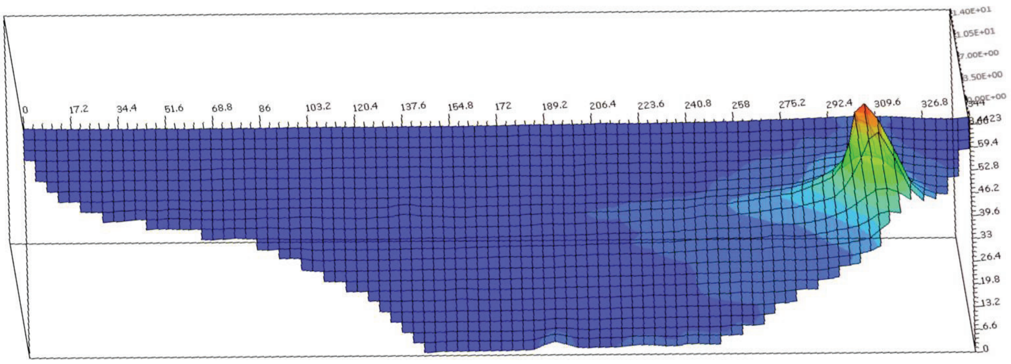

Fig. 3 : Leakage velocity contours map obtained by sonar detection

(3) Underwater high resolution video with tracer method

Underwater ROV with high resolution cameras, image sonar and an inkjet device, was utilized to take an inspection the face slabs and joints located above the crest of the upstream blanket zone, and to take high resolution video around the anomaly leakage zones found by sonar detection. To confirm the leakage and its location, tracer experiments were also undertaken along with the ROV video recording. It was found that the concentrated leakage site turned out to be several large cracks in length of over 5m on the face slab. The largest shear displacement between the two sides of the cracks was observed to be more than 5cm. The ROV inspection and tracer experiments around the concentrated leakage site can be found in Fig. 4.

Fig. 4 : The ROV inspection and tracer experiments around the concentrated leakage site

(4) Hydraulic connectivity test

Hydraulic connectivity test was conducted to validate the presence of the leakage path. The concentrated leakage site was found on the concrete face slab with elevation around 462.5m at the right side of the dam. A large amount of pigments was injected and absorbed in to the cracks around the concentrated leakage site. After about 6 hours, the outflow from the measuring weir afterwards the dam toe changed its color as the released pigments (see Fig. 5), and the color got darken with increasing time. This test provides evidence of hydraulic connectivity between the concentrated leakage site and the leaked water at the downstream side of the dam. From the travelling time of the released pigments, it was found that a concentrated and connected leakage path has been formed inside the dam body.

Fig. 5 : Hydraulic connectivity test

Underwater leakage detection found that there was a concentrated leakage path caused by the shear cracks on the face slab near the elevation of 462.5m at the right side of the dam. According to the experience of Zhushuqiao Dam, Baiyun Dam and other similar projects, the excessive leakage caused by the failure of the anti-seepage body (face slabs, joints and sealing structures, etc.) would lead to the continuing loss of fine particles of the fine particles in the cushion and transition layers under hydraulic gradient. A long time leakage might even cause the seepage failure of cushion and transition layers, which will bring about further damage and deterioration to the face slabs, raising safety risks of the dam. In order to ensure the safety operation of the dam, it is necessary to carry out emergency treatment and repair of the dam leakage as soon as possible.

4. UNDERWATER LEAKAGE REHABILITATION

4.1 Preliminary design

According to previous engineering experience, the leakage treatment methods of CFRD are mainly divided into three categories: emptying the reservoir to repair the dam on dry land, scattering clay materials on water to cover the leakage site, and underwater leakage rehabilitation. The leakage of the main dam of the Liaoye Reservoir was predominantly caused by the shear cracks on the face slab. The treatment object has been clearly located by the aforementioned underwater leakage detection. Repair the dam on dry land is relatively simple and convenient, while emptying the reservoir would affect the performance and benefits of water supply, and the reservoir is difficult to be emptied due to the lack of emptying facilities. Scattering treatment with clay material usually works on the cases of widespread leakage with low velocities, which is not suitable for a concentrated leakage path. Therefore, the underwater leakage treatment method was selected for repairing the Liaoye Dam. The underwater leakage treatment method combines the measures of filling, grouting, sealing, and covering to efficiently reduce the leakage rate, fill the infiltration point and the leakage channel, and rehabilitate the watertightness of the anti-seepage system [10]. First, diving operations were carried out more than 20 m below the water level to clean up and inspect the cracked and damaged face slabs, and then inject the silt material into the crack. Underwater sealing material was used for filling the cracks and repairing the damaged slabs. Underwater grouting with cement and fly ash slurry was conducted in the cushion layer to rebuild its supporting effect near the damage slabs. Finally, the concentrated leakage site and the damage face slab were tightly sealed by pasting an impervious SR cover sheet and the geomembrane entirely covering.

4.2 Rehabilitation measures

(1) Underwater cleaning and inspection

Diving operations were carried out more than 20 m below the water level, to clean the damaged slab by highly pressurized water within a certain range area, and take a detailed and careful inspection to check the damage and cracks of the slab. The inspection found that: (1) Crack I was located on No. MB33 slab, at the elevation of 463.7~466.1m, with crack length of 4.0m and crack width of 2~3mm; (2) Crack II was located at the bottom of No. MB33 slab (near the peripheral joint), at the elevation of 461.5~464.1m, with crack length more than 5.3m and crack width about 3~5cm. Concrete around the cracks was severely damaged and shedding. The Crack II has been proved to be the main entrance of the leakage, and the infiltration velocities near this crack were considerably large. Illustration of the crack distribution on No. MB33 slab is shown in Fig. 6.

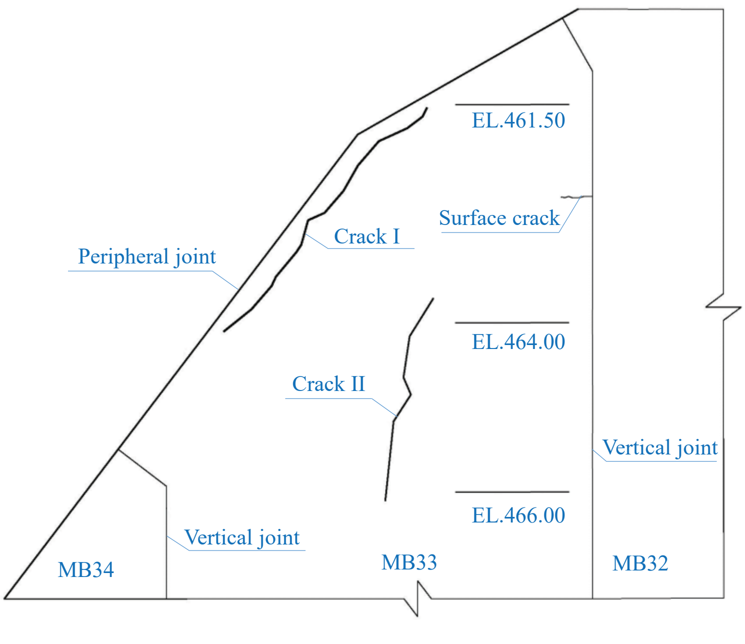

Fig. 6 : Illustration of the crack distribution on No. MB33 slab

(2) Silt materials injection

The flow velocities in the concentrated leakage site at No. MB33 slab were considerably large. In order to reduce the flow velocities, a large amounts of silt materials mixed with fly ash and fine sand is injected into the cracks through a conduit. The silt materials were composed of coarse and fine particles and easy to be driven by water flow. As a result, the silt materials were brought into the cushion layers under the slab to produce the supporting effect to the above slab, reducing the flow velocities at the leakage site. During the injection process, the particle gradation of the silt materials was adjusted according to the absorbing rate due to the fact that the flow velocities were reduced gradually as the increase of injection amount. Finer particle should be utilized and injected when the flow velocities were reduced obviously, until the silt materials were no longer absorbed by the infiltration water.

(3) Crack filling and face slab repairing

After the injection of silt materials was completed, the flow velocities have been considerably reduced around the concentrated leakage site. Underwater sealing material (i.e., underwater cementitious material) was then used for filling the cracks and repairing the damaged slabs.

(4) Underwater grouting

Underwater grouting treatment methods usually include cement and fly ash slurry grouting and chemical slurry grouting. Cement and fly ash slurry grouting was conducted in the cushion layer around the cracks and the damaged slab. The grouting treatment could rebuild the cushion layer's supporting effect near the damage slabs, and rehabilitate the anti-seepage performance of the damaged face slab.

(5) Impervious covering on the surface

After the underwater grouting, the concentrated leakage site and the damage face slab were tightly sealed by pasting an impervious SR cover sheet. The impervious SR cover sheet extended larger than the area of the damaged slab, and was held on the slab by bolts. A geomembrane was finally used to cover the concentrated leakage site entirely, provides additional watertightness.

4.3 Rehabilitation results

The leakage repair and rehabilitation of Liaoye CFRD began in mid-August 2016. With the gradual implementation of various treatment measures in respect to the cracks and damaged slabs, the leakage rate of the dam has progressively decreased. After the completion of the underwater injection of silt materials, the leakage rate at the measuring weir was observed to decrease to below 7L/s. After the underwater grouting, the leakage rate was reduced to 2.5L/s; In mid-September, 2016, all of the treatment measures has been accomplished, and the leakage rate was lowered to 1.8L/s. So far, the leakage of the dam has been quite stable within the rate of 5L/s. The comparison of the leakage at the measuring weir before and after the treatment is shown in Fig. 7. The leakage rate of the dam has been significantly reduced, and the damaged face slab has been fully rehabilitated, largely migrating the risk of dam safety.

(a) Before the treatment (b) After the treatment

Fig. 7 : Comparison of the leakage at the measuring weir before and after the treatment

5. SUMMARY

The CFRD has been widely constructed in water conservancy and hydropower projects all over the world, and many successful experience many successful experiences have been gained. However, several different kinds of defects have also been exposed in the construction or operating period for a large number of CFRDs, such as slab extrusion damage, structural cracks, and excessive leakage. Underwater leakage detection and rehabilitation for CFRDs has become an urgent and key issue in the field of dam safety and engineering. With respect to the leakage problem of Liaoye CFRD, the concentrated leakage site and damaged zone on the concrete slab was precisely detected by the video-sonar integrated leakage detection method, and the underwater rehabilitation techniques were subsequently applied to repair the leakage. After rehabilitation, the leakage of the dam is considerably reduced and the accident hazards have been eliminated. The underwater leakage detection and rehabilitation techniques for CFRDs presented in this study could provide practical references for similar projects.

REFERENCES

[1] Hongqi Ma, Fudong Chi. Technical Progress on Researches for the Safety of High Concrete-Faced Rockfill Dams. Engineering, 2016, 2(3):332-339.

[2] Zeyan Yang, Jianping Zhou, Fuqiang Wang, et al. The 30 Years' Development of Concrete Face Rockfill Dam in China. Hydropower and Pumped Storage, 2017, 3(1):1-5. (In Chinese)

[3] Junchun Li. Gouhou Dam and Analysis for Causes of the Dam Failure. Chinese Journal of Geotechnical Engineering, 1994, 16(6): 1-14.

[4] Xueqin Zheng, Erfeng Zhao, and Chenfei Shao. Cause and Stability Analysis of Cracks in Concrete Slab of Rockfill Dam under High Temperature Difference Condition. IOP Conference Series: Earth and Environmental Science. IOP Publishing, 2019, 304(5): 052075.

[5] Jiexiong Tan, Dashui Gao, Mixue Wang, et al. Seepage treatment technology for RCC dam of Baiyun Hydropower Station. Yangtze River, 2016, 47(2):62-66. (In Chinese)

[6] Jianhua Lu, Bo Tian, Yuanliang Gu. Research and innovation of reinforcement technology of composite rockfill dam. Yangtze River, 2011, 42(12):60-62. (In Chinese)

[7] Jinsheng Jia, Yao Xu, Jutao Hao, et al. Localizing and quantifying leakage through CFRDs. Journal of Geotechnical and Geoenvironmental Engineering, 2016, 142(9): 06016007.

[8] Lifeng Wen, Junrui Chai, Zengguang Xu, et al. A statistical review of the behaviour of concrete-face rockfill dams based on case histories. Géotechnique, 2018, 68(9): 749-771.

[9] Jinzhang Tian, Zhicheng Zha, Mixue Wang, et al. Application of Video and Sonar Integrated Leakage Detection Technology in Concrete Faced Dam Leakage Detection. Water Resources and Power, 2019, 37(1):88-90. (In Chinese)

[10] Xiaoming Zhou, Jinzhang Tian, Zhicheng Zha. Underwater emergency treatment methods for the CFRD and its application. Yangtze River, 2018, 49(s1):189-191. (In Chinese)