Design and Application of a Flood Discharge Vibration Monitoring System for High Arch Dams

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Abstract. To understand the vibration characteristics of the dam body during flood discharge in high arch dams, including the acceleration and amplitude at different parts of the dam, an online vibration monitoring system for flood discharge was designed based on the operational characteristics of a specific double-curvature arch dam. By monitoring key effect data in real-time during flood discharge, the dynamic characteristics and operational behavior of the dam body were analyzed. This analysis identified the parts of the dam most significantly affected by flood discharge vibrations, providing technical support for assessing the impact of these vibrations on hydraulic structures.

Keywords: High arch dam; flood discharge vibration; monitoring system design; dynamic response analysis

1 Introduction

Concrete arch dams are a type of dam that is both safe and economical. Due to their ease of flood discharge and good seismic performance, they have been widely used both domestically and internationally. With the continuous development of dam construction technology, the height of arch dams has been steadily increasing. Currently, several high arch dams reaching 300 meters in height have been built and are operational in China. There have been frequent reports of incidents caused by flow-induced vibrations both at home and abroad, which has gradually drawn attention to the vibration issues of hydraulic structures under pulsating water flow loads. Given that the flood discharge structures in high arch dam hydropower projects often feature high heads, large flow rates, and extremely high flow velocities, while the dam structures themselves tend to be lightweight, the issue of dam vibrations induced by flood discharge has become increasingly prominent. In severe cases, this can affect the safe operation of the hydropower complex or even lead to structural damage. There have been several instances of structural damage due to improper flood discharge operations, such as the large-scale damage to the 1# flood discharge tunnel at the Ertan Hydropower Station

Y. Zhang et al. (eds.), *Proceedings of the 2024 10th International Conference on Architectural, Civil and Hydraulic Engineering (ICACHE 2024)*, Advances in Engineering Research 259,
https://doi.org/10.2991/978-94-6463-658-1_12

and the destruction of the energy dissipation pool bottom slab at the Wuqiangxi Hydropower Station hole.

In 2007, Kou et al. [1] conducted a comprehensive analysis of the vibration test results of 40 prototype arch dams at home and abroad, and concluded that there is a close relationship between dam height and the natural frequency of the dam body. In 2020, Wu [2] studied the vibration characteristics of the dam body of the Laxiwa arch dam through environmental vibration tests, and analyzed the spatiotemporal distribution law of the dam body vibration based on the vibration test results. In 2021, Mao et al. [3] used prototype vibration observation data of dams to systematically identify concrete dams and reveal the actual dynamic characteristic changes of structures under earthquake or environmental excitation. In 2022, Ouyang et al. [4] used their independently developed vibration testing system to analyze the vibration problems caused by deep hole overcurrent in the Xiluodu Hydropower Station dam. They found that the main frequency of the vibration response of the second dam gallery changed over time and there were intermittent low-frequency vibrations. Oliveira[5] is focused on the study of the dynamic behaviour of two large arch dams, and it presents some innovations for the improvement of seismic and structuralhealth monitoring systems for dams. In 2024, Tong[6] has been proven that the seismic wave analysis method considering radiation damping can reasonably reflect the seismic response of dams.Gao and Jiang[7,8] conducted time-domain and frequency-domain analysis on the strong earthquake monitoring data of the Luding earthquake based on the monitoring records of the strong earthquake monitoring system installed on the dam body and foundation of the Dagangshan arch dam, and summarized the dynamic response law of the Dagangshan high arch dam in the Luding earthquake. From the engineering practice results at home and abroad, it is feasible to use on-site prototype vibration monitoring technology to test the dynamic characteristics of dam structures and grasp their operating parameters. Based on the strong earthquake data recorded by the Guandi Dam strong earthquake monitoring array in Xichang, Liu[9] studied the response characteristics and laws by analyzing the time history characteristics and spectral response laws of each measuring point.Using the vibration table dynamic model test method, Xiong[10] studied the failure process and failure mode of Wudongde arch dam under strong earthquake conditions. The seismic failure mode of the dam body and the weak seismic areas of the structure were analyzed to evaluate the seismic safety of the dam.

Conventional dam safety monitoring systems, due to their sparse sampling frequency and limited measurable physical quantities, find it challenging to capture the dynamic-related characteristic parameters of the dam body under vibration conditions. Therefore, dynamic monitoring of high arch dams during flood discharge is necessary, and when combined with static monitoring data of the dam, it allows for more accurate analysis and assessment of the structural dynamic response under different operating conditions. This provides a reference for scientifically and rationally scheduling dam flood discharges. Since the discharge capacity and flood discharge power of high-arch dams abroad are not significant, there is a lack of mature operational experience for high-flow flood discharge in high-arch dams. Although China has conducted relevant theoretical analyses, experimental research, and some prototype observations on the issue of flood discharge vibrations in various high-arch dams in recent years, the differing operational environments and conditions of each high-arch dam have only yielded some preliminary qualitative analyses and monitoring results. Moreover, scale model tests face challenges in terms of comparability between the model and prototype and “scale effects.” At the same time, numerical simulations are limited by factors such as the difficulty in accurately obtaining computational parameters, the challenge of describing the mechanical characteristics of discontinuous surfaces, and the difficulty in matching computational boundary conditions with actual situations. These limitations affect the accuracy and reliability of the simulation results. Against this background, researching and designing a vibration monitoring system for high arch dams under flood discharge conditions has become an inevitable requirement.

To understand the vibration characteristics of the dam body during flood discharge in a high arch dam, including the acceleration and amplitude at different parts of the dam, this paper, based on the operational characteristics of a specific double-curvature arch dam, researches and designs an online monitoring system for flood discharge vibrations. By monitoring key effect data in real-time during flood discharge, the dynamic characteristics and operational behavior of the dam body are analyzed. This analysis identifies the parts of the dam significantly affected by flood discharge vibrations, providing technical support for assessing the impact of these vibrations on hydraulic structures.

2 Layout of Monitoring Sensors

A conventional hydropower station complex is composed of water-blocking structures, flood discharge structures, and water diversion and power generation structures. The water-blocking structure is a concrete double-curvature arch dam with a crest elevation of 610.0 meters and a maximum dam height of 285.5 meters. The flood discharge structures of the dam body include seven surface holes and eight deep holes, arranged with a cascading surface hole and an upturned deep hole. The flood discharge is managed through layered outflow, mid-air collision, and energy dissipation in a stilling basin, where two water jets collide mid-air before falling into the stilling basin for turbulent energy dissipation. Downstream of the dam, a stilling basin and a secondary dam are set up; the secondary dam is located at the end of the stilling basin to raise the water level within the basin. This hydropower station is characterized by a “narrow river valley, high arch dam, and large discharge capacity,” where the vibration caused by flood discharge through the outlets of the dam could potentially impact the structural safety of the dam and the stilling basin. On the one hand, the tensile strength of the concrete of the dam is low, and on the other hand, under the long-term effects of flood discharge vibrations, localized fatigue damage may occur in the dam.

To understand the structural dynamic response characteristics of high arch dam vibrations during flood discharge, we consider monitoring parameters such as acceleration, velocity, and joint dynamic displacement of the dam body in real time. Since the vibrations induced by flood discharge are low-frequency, random, and small in amplitude, the sensors need to have excellent low-frequency response capabilities. Therefore, the monitoring method employs velocity-type triaxial low-frequency vibration sensors to conduct real-time vibration monitoring of the dam body and dam abutment resistance structures, capturing data on vibration acceleration, velocity, amplitude, and frequency. Joint dynamic displacement sensors are used to monitor the opening and closing behavior of transverse joints in the dam body under different flood discharge conditions, analyzing and assessing the extent to which these joints are affected by flood discharge.

Vibration measurement points are selected at different elevations of typical dam sections, specifically sections 10#, 15#, and 22#, as well as at the horizontal tunnels on both sides of the dam crest. A total of 12 triaxial vibration monitoring points and four transverse joint dynamic displacement monitoring points are arranged (as shown in Figure 1). Additionally, a typical section is selected near the resistance structure tunnel of the dam shoulder (approximately 143 meters from the dam axis), where three triaxial vibration monitoring points are arranged at different elevations within the resistance structure tunnels on both the left and right banks.

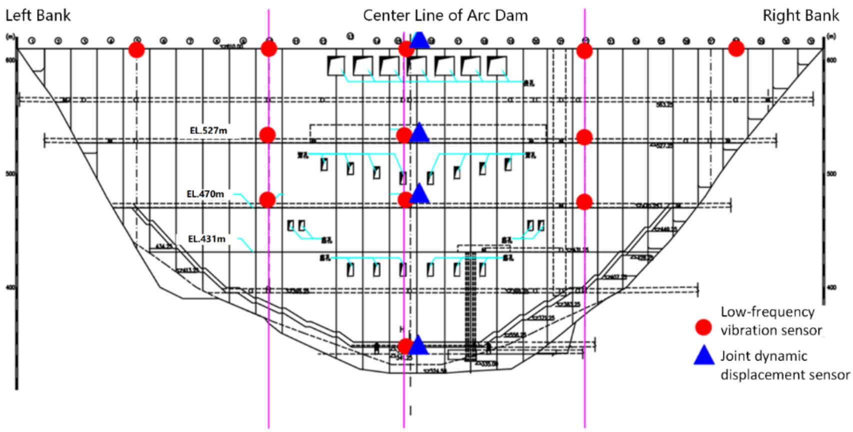

Fig. 1. Layout for dam flood discharge vibration monitoring

3 System Design

3.1 System Architecture

Since the vibration monitoring points for dam flood discharge are relatively dispersed, a distributed data acquisition system is employed to minimize interference introduced by long-distance signal transmission. Data acquisition devices are set up at different elevations, including the dam crest, the 527 gallery, the 470 gallery, and the 395 gallery, allowing sensor signals to be collected nearby, as shown in Fig. 2.

3.2 Data Acquisition and Communication

Due to the variety of sensor types in this system, the high sampling frequency, the large amount of data, and the need for synchronized data acquisition across sensors with consistent timestamps, the communication network requires high bandwidth and real-time performance. To ensure the reliability of the communication network, we construct a star-shaped fiber optic Ethernet structure based on the TCP/IP communication protocol. Depending on the distribution of the monitoring stations, new fiber optic cables are laid, or existing ones are utilized to establish communication lines for each station. Industrial Ethernet switches are installed at the data acquisition management station and each acquisition device node, providing RJ45 Ethernet access interfaces. The data acquisition devices themselves come with local area network (LAN) ports, allowing them to connect directly to the switch. The acquisition server of the management station also connects to the network via a LAN port, enabling high-speed communication with the data acquisition devices.

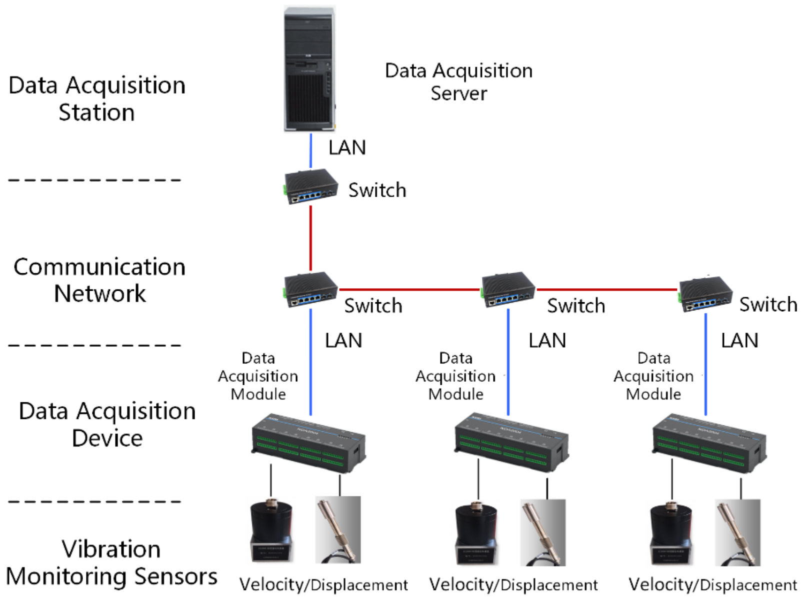

Fig. 2. Architecture of the dam flood discharge vibration monitoring system

3.3 System Power Supply

(1) Acquisition management station

The main power-consuming equipment at the acquisition management station includes the data server and network switch. The system requires an uninterrupted power supply during operation. The control room where the acquisition station is located has a relatively reliable mains power supply, which can be directly connected. Additionally, we provide an uninterruptible power supply (UPS) to prevent unexpected power outages.

(2) On-site data acquisition stations

The primary power-consuming equipment at the on-site data acquisition stations includes data acquisition devices and network switches. The system requires an uninterrupted power supply during operation. Since the mains power supply at the dam and gallery locations is generally reliable, there is no need to set up an independent power supply system at each monitoring station. Instead, the system can be connected to the nearby lighting or maintenance power supply system, with additional cables being installed as necessary.

To ensure continuous and uninterrupted system operation and to prevent network interruptions and data loss due to occasional tripping, each on-site monitoring station is equipped with maintenance-free batteries as a backup power source. These batteries are kept in a floating charge state using chargers to provide power to the data acquisition devices and communication equipment during temporary power outages.

4 Monitoring Results

4.1 Typical Flood Discharge Case

According to the scheduling plan and actual on-site hydrological conditions, the dam began its first flood discharge of the year at 10:29 AM on September 23. Before the discharge, the upstream water level was at 590.3 meters, and the downstream water level was at 382.8 meters. By midnight on October 7, two flood discharge events had occurred, primarily using the 3# and 6# deep holes. The first flood discharge took place from 10:29 AM on September 23 to 11:53 AM on October 3. Initially, the 3# deep hole was opened for discharge, and on September 27 at 4:35 PM, the 6# deep hole was also opened. The two holes were subsequently closed on October 2 and 3, respectively. The second flood discharge occurred from 5:32 PM on October 4 to 10:15 PM on October 7, during which only the 3# deep hole was opened. After the flood discharge ended, the upstream water level was 599.3 meters, and the downstream water level was 382.5 meters. The statistics of the monitoring data and the corresponding reservoir water level variations are shown in Table 1 and Fig. 3., respectively.

Table 1. Statistics on the opening and closing of deep holes during dam flood discharge (as of October 7, 2023)

Hole No.	Opening Time	Closing Time	Upstream Water Level (m)		Downstream Water Level (m)	
			Before Discharge	After Discharge	Before Discharge	After Discharge
6#	2023/9/27 16:35	2023/10/2 12:19	590.306	597.497	382.799	382.709
3#	2023/9/23 10:29	2023/10/3 11:53	590.306	598.028	382.799	381.489
3#	2023/10/4 17:32	2023/10/7 22:15	599.635	599.307	381.779	382.489

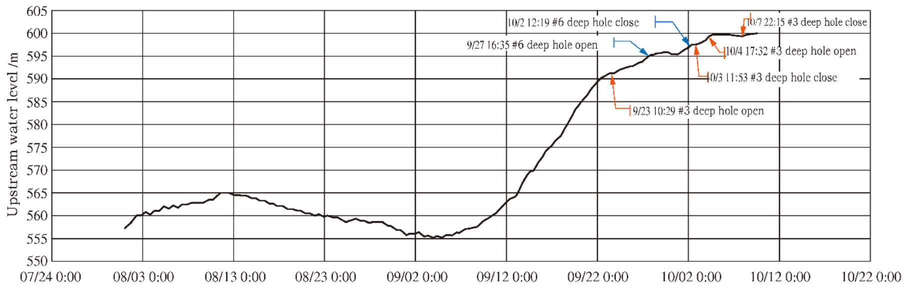

Fig. 3. Reservoir water level variations during the dam flood discharge

4.2 Monitoring Data Analysis

(1) Transverse Joint Dynamic Displacement

The joint displacement monitoring data from section 15# of the dam, during the typical period of September 24-25, was selected as a sample for analysis. The operational conditions included an upstream water level of 590.3 meters and discharge through the 3# deep hole alone. The monitoring data indicate that the magnitude of joint opening and closing at various typical elevations of section 15# during this discharge operation was minimal, with the maximum displacement being 0.796 μm and the maximum amplitude variation being 0.699 μm, observed at the elevation of 527.25 meters. From the time series data at each measurement point (as shown in Fig. 4), it is evident that the joint displacement exhibited rapid, narrow-range fluctuations during the flood discharge, with no significant abrupt changes or abnormal trends observed. The joints were generally in a dynamically stable state. In terms of displacement distribution patterns, the joint displacement amplitude was smallest at lower elevations, while the displacement at about two-thirds of the dam height showed relatively more significant changes, approximately three times that of the lower elevations. This phenomenon is related to the position of the deep holes and the restraint conditions of the crown beam dam section, and it generally aligns with expected patterns.

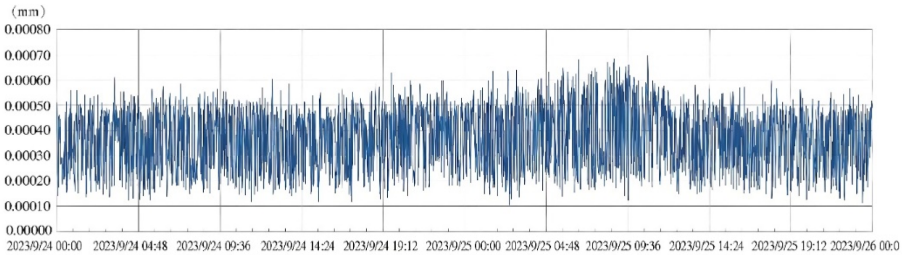

Fig. 4. Time series of joint displacement at the 527 m elevation of section 15#

(2) Dam body vibration velocity and dynamic displacement

Table 2. Statistical summary of dynamic response parameters at the dam crest elevation

Operating Condition	Monitoring Location	Radial Velocity (mm/s)	Tangential Velocity (mm/s)	Vertical Velocity (mm/s)	Radial Displacement (mm)	Tangential Displacement (mm)	Vertical Displacement (mm)
Before Discharge	Section 10#	0.003842	0.003604	0.003766	0.002021	0.001990	0.002167
	Section 15#	0.004165	0.003659	0.003418	0.002067	0.002066	0.001937
	Section 22#	0.004145	0.003871	0.003556	0.002182	0.002500	0.002026
Deep Hole 3# (Reservoir Water Level 590 m)	Section 10#	0.098693	0.020879	0.022733	0.009319	0.003037	0.002782
	Section 15#	0.066998	0.032853	0.026205	0.006639	0.004571	0.002338
	Section 22#	0.074458	0.020247	0.014518	0.007140	0.003128	0.002397
Deep Holes of sections 3# and 6# (Reservoir Water Level 590 m)	Section 10#	0.095463	0.025104	0.021459	0.008309	0.002069	0.001442
	Section 15#	0.073853	0.032742	0.031267	0.005505	0.003195	0.001563
	Section 22#	0.080085	0.020652	0.024637	0.007713	0.001670	0.001333
Deep Hole 3# (Reservoir Water Level 599 m)	Section 10#	0.108130	0.026261	0.029258	0.008862	0.003480	0.002853
	Section 15#	0.073865	0.034002	0.027047	0.006924	0.004103	0.002393
	Section 22#	0.073650	0.019060	0.016217	0.007046	0.002637	0.002256

Monitoring data (as shown in Table 2) indicate that at an elevation of 609 meters, the radial vibration energy is greatest in section 10#, followed by section 22# and then section 15# under different water levels. When both sections of the 3# and 6# deep holes were opened simultaneously, the average vibration velocity was greater than when only the 3# deep hole was opened (with an upstream water level of 590 meters). During flood discharge, the average vibration velocity was 5 to 20 times greater than when there was no discharge, with vibration displacement ranging between one μm and nine μm.

As shown in Figs. 5 and 6, during the flood discharge with an upstream water level of 590 meters, under the conditions of the 3# deep Hole alone being open and both the 3# and 6# deep holes being open simultaneously, significant vibrations were observed at the 609-meter elevation measurement points in various dam sections. The main radial and tangential frequencies of the double-curvature arch dam were around 1.56 Hz, while the vertical vibration energy was concentrated at 16.74 Hz. With an upstream water level of 599 meters and only the 3# deep hole open, the natural frequency of the dam was 1.53 Hz, and the main frequency of vibration energy was 15.45 Hz. Vibrations were more pronounced in sections 10#, 15#, and 22# at the dam crest, and these were greater than those observed when the water level was at 590 meters, indicating that the magnitude of dam vibration during flood discharge is related to the reservoir water level.

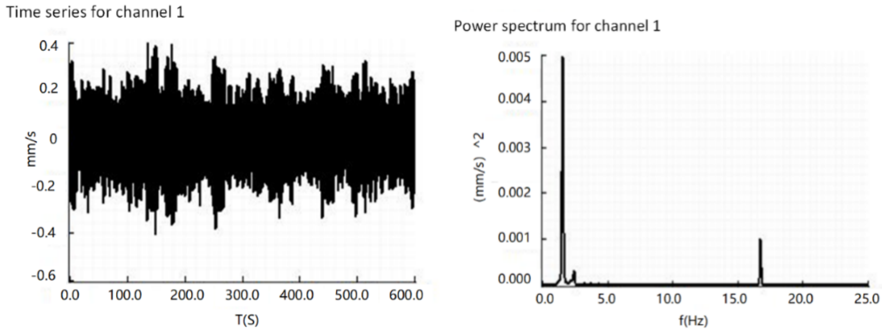

Fig. 5. Radial time series and power spectrum of section 10# dam crest with both sections of 3# and 6# deep holes open (Reservoir Water Level 590 m)

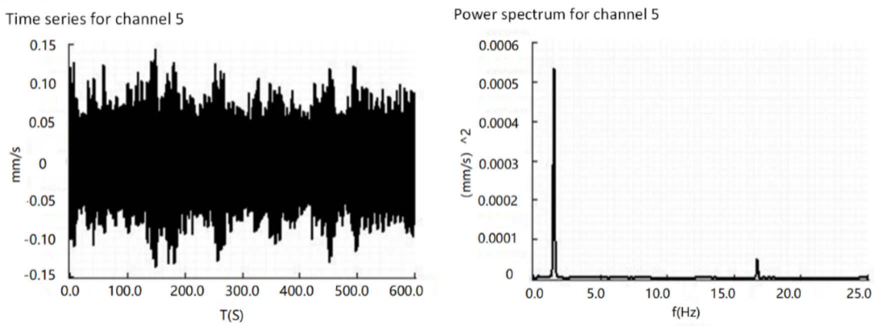

Fig. 6. Radial time series and power spectrum of section 15# dam crest with both sections of 3# and 6# deep holes open (Reservoir Water Level 590 m)

5 Conclusions

(1) For monitoring low-frequency, random, and minor vibration parameters of high arch dams under flood discharge conditions, sensors with excellent low-frequency response capabilities are required. By installing velocity-type triaxial low-frequency vibration sensors and displacement meters at key elevations of critical dam sections, real-time monitoring of the dam body and dam shoulder-resisting bodies can be achieved. This allows for the acquisition of essential effect quantities such as vibration acceleration, velocity, amplitude, vibration frequency, and joint opening and closing.

(2) The vibration monitoring of high arch dams utilizes a distributed automated monitoring system characterized by high sampling frequency, large data volume processing, and good data synchronization. This system is suitable for real-time monitoring of

structural vibrations under flood discharge conditions and can be integrated with conventional dam monitoring systems to facilitate comprehensive safety assessments of the dam.

(3) Monitoring results indicate that the changes in the joint opening and closing degree of the dam body during flood discharge are minimal, with no significant abnormal trends observed. The natural frequency associated with the dam is associated with low-frequency vibrations, and its vibration energy shows a clear correlation with reservoir water levels. Further sensitivity analysis of dam vibration response under different flood discharge conditions can be conducted in the future.

Acknowledgments

This study was supported by the research projects of China Three Gorges Corporation (202103469) and China Three Gorges Construction Engineering Corporation (JGAJ030222003).

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