Test and Analysis of Flood Discharge Vibration Characteristics of Beams on Surface Orifice Gate Piers of Xiluodu Dam

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Abstract. During the flood discharge period when the deep-hole gates of Xiluodu dam were opened, obvious vibration occurred in the beams on surface orifice gate piers. In order to find the cause of vibration, in this paper, the natural vibration characteristics and vibration source characteristics of beams on surface orifice gate pier were studied by field test and numerical simulation. The research showed that when the Xiluodu dam opened multiple deep-hole gates for flood discharge, the main frequencies of the flood discharge vibration excitation of the dam body were closed to the local natural frequencies of beams on surface orifice gate piers, which was the main reason for the obvious forced vibration of beams on surface orifice gate piers. It is suggested that by reducing the number of deep-hole opening gates, the flood discharge vibration amplitude of beams on surface orifice gate piers can be significantly reduced.

Keywords: Xiluodu dam, gate pier of surface orifice, flood discharge vibration, frequency characteristic.

1 Introduction

The dam crest elevation of Xiluodu Hydropower Station is 610.0 m, and the maximum dam height is 285.5 m. The structure is characterized by "narrow valley and high arch dam". The flood discharge facilities of the hub are 7 surface orifices, 8 deep holes and 4 flood discharge holes on both sides of the dam body. Among them, 7 surface holes and 8 deep holes form a double-layer discharge orifice layout (See Fig.1). The outlets of the surface orifices are the energy dissipation of the large differential toothed bucket, and the outlets of deep-holes are the energy dissipation of the flip flow. The maximum total discharge of the dam body is 32278m^3/s.

Xiluodu Dam was officially impounded in May 2013, and the deep-hole gate was opened for flow. With the increase of deep-hole flood discharge, the flood discharge led to obvious vibration of buildings such as ice-making building and mixing building

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on the right bank of the dam[1]. The dam itself and the plunge pool also produced vibration during flood discharge[2].

With the completion of surface orifice gate piers and the completion of the beams laying on surface orifice gate piers, it was found that during the flood discharge period when multiple deep- hole gates were opened, the vibration of beams on surface orifice gate piers and the gantry crane was obvious, and the staff generally felt obvious vibration. Since no one has proposed the problem of flood discharge vibration of beams on surface orifice gate piers in the past, it has not been found that other scholars pay attention to and study the problem. In order to study the vibration source and vibration characteristics of beams on surface orifice gate piers under the flood discharge condition, and analyze the safety state of the structure, the flood discharge vibration test and the natural vibration characteristics test of beams on surface orifice gate piers were carried out.

2 Introduction of beams on surface orifice gate piers

The beams on surface orifice gate piers are reinforced concrete prefabricated beams laid between the two gate piers, which are used for the operation of the portal crane and the passage of personnel, including track beams and traffic beams. The beam on which the track is laid is called the track beam. and the rest is called traffic beam. The beams are composed of prefabricated T-shaped reinforced concrete beams. The size and shape of beams were varied according to the different placement positions. The adjacent beams were connected by welded steel plates. The two ends of the beams were placed on surface orifice gate piers through chloroprene rubber bearings. After All T-beam were installed, a layer of concrete pavement was poured on the surface. The specific structural section view is shown in Fig.2, and the top view is shown in Fig.3.

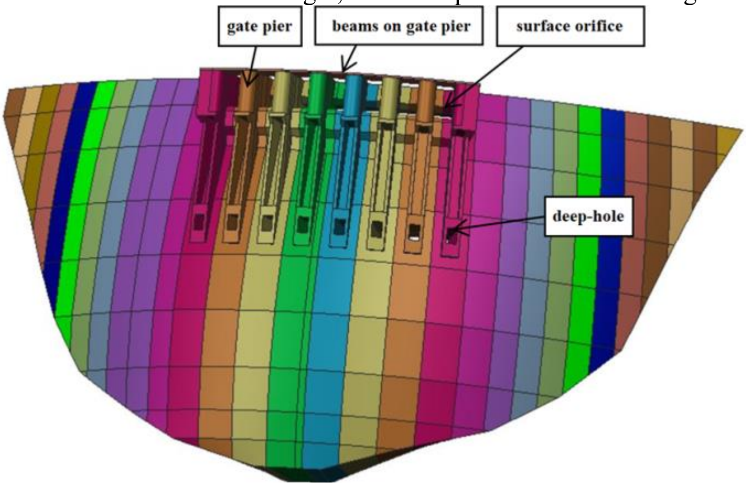


Fig. 1. Structure diagram of Xiluodu Dam

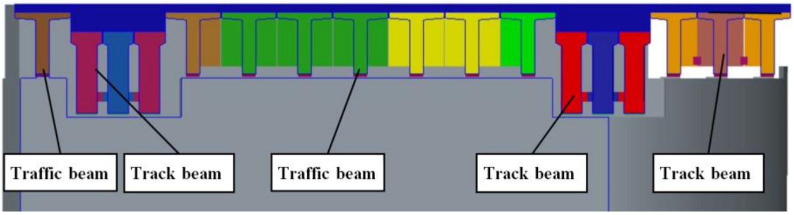


Fig. 2. Cross-section view of beams on surface orifice gate pier

3 Test analysis of natural vibration characteristics of beams on surface orifice gate piers

In order to study the cause of flood discharge vibration of beams on surface orifice gate piers, it is necessary to analyze the beams' natural vibration characteristics first. This paper mainly used the following three methods to analyze:

(1) Pulsation method: The pulsation method is often used to measure the dynamic characteristics of the structure[3-4]. This method does not require artificial excitation, but only needs to monitor, collect and analyze the response of the structure under natural excitation, which is very economical and feasible. The response of the structure under natural excitation is also called pulsating response. It is generally believed that this natural excitation is a kind of white noise input, and the pulsating response's frequency spectrum of the structure directly reflects the frequency characteristics of the structure. Because the pulsation response of the structure is relatively weak, it is necessary to use a high-sensitivity sensor for acquisition, and it needs to be collected for a long time to improve the recognition accuracy of the frequency characteristics of the structure. The frequency characteristics of large structures are often obtained by this method. Sensors were arranged at the typical positions of beams, and the local natural vibration characteristics of beams were tested and analyzed by using the pulsation response of beams. The pulsation time history test of each measuring point was recorded for 15 minutes.

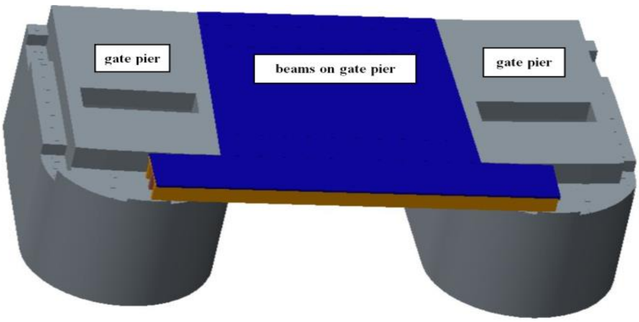


Fig. 3. Schematic diagram of local structure of gate pier

(2) Hammering method: Hammering method is also a common method to test the dynamic characteristics of structures[5-7]. This method is to stimulate the impulse response of the structure by hammering the structure. Through the spectral analysis of the impulse response, the frequency characteristics of the structure can be obtained. The excitation point on the beam was hammered by force hammer, and the impulse responses generated by hammering were monitored and recorded. The impulse responses were used to analyze the natural vibration characteristics of beams. Each excitation point was hammered about 10 times.

(3) Simulation analysis method: Simulation analysis method is a very popular frequency characteristic analysis method at present. It is necessary to establish the simulation model of the structure. The frequency characteristics of the structure can be obtained by the modal analysis of the simulation model. This method requires accurate simulation of structural size and material properties to obtain reliable results. The simulation models of beams and surface orifice gate piers were established, and the mode characteristics of beams were obtained by simulation analysis.

The field tests were carried out when the dam had no flood discharge, and there were no other vibration and noise interference sources around the measuring points during the tests.

3.1 Measuring point arrangement

Under the same flood discharge condition, the vibration response of different beam on surface orifice gate piers was obviously different, indicating that the vibration characteristics of each beam were significantly different. For this reason, the various beams on surface orifice gate piers were tested in detail, and the layout of the measuring points is shown in Fig.4.

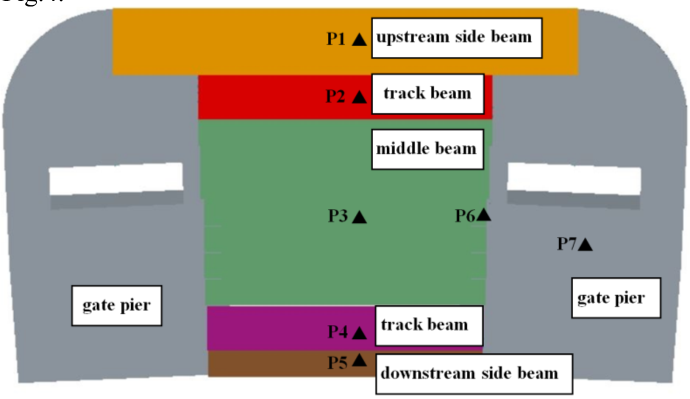
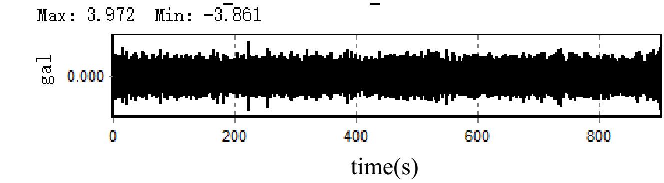


Fig. 4. Schematic diagram of measuring points arrangement

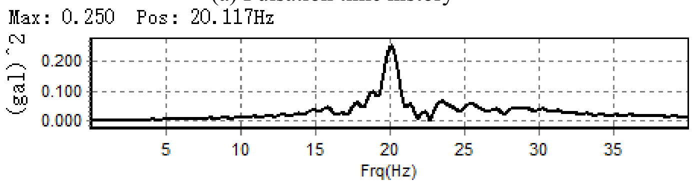
3.2 Analysis of natural frequency characteristics

Spectrum analysis of the time histories obtained by the tests could obtain frequency characteristics of each beam, see Fig 5 and Fig 6. The mode characteristics of the corresponding position is also obtained by simulation analysis, see Fig 7. The frequency characteristics of each beam obtained by the hammering method were shown in Fig 8 ~ Fig 11. The natural frequency of each measuring point of the beams on 6# surface orifice gate pier obtained by the three methods are shown in table 1.

The results of the frequency characteristics of the field test analysis were basically the same, and the natural frequencies obtained by the simulation method were slightly different, indicating that the simulation model was reasonable. The overall results show that the natural frequencies of beams on different surface orifice gate piers are different. The nature frequency of the upstream side beam is between 7Hz ~ 12Hz, the nature frequency of the upstream track beam is between 23Hz ~ 28Hz, the nature frequency of the middle beam is between 16Hz~18Hz, and the nature frequency of the downstream side beam is between 19Hz~21Hz.

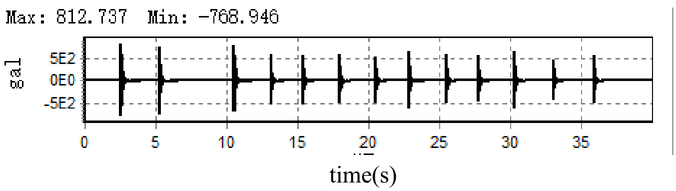


(a) Pulsation time history

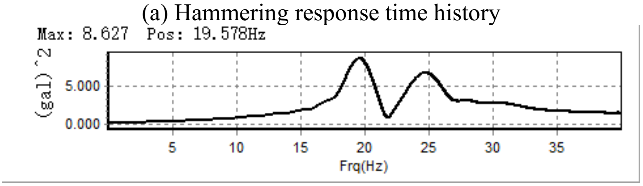


(b) Vibration frequency spectrum

Fig. 5. Pulsation time history (a) and its frequency spectrum (b) of one measuring point



(a) Hammering response time history

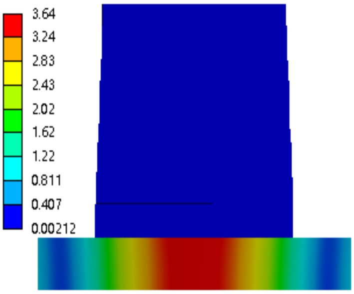


(b) Vibration frequency spectrum

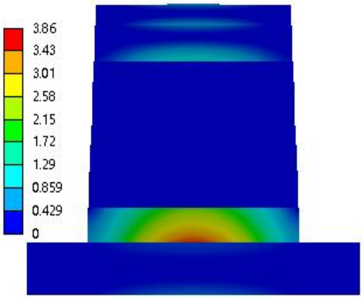
Fig. 6. Hammering response time history (a) and its frequency spectrum (b) of one measuring point

Table 1. Frequency characteristic results of different methods

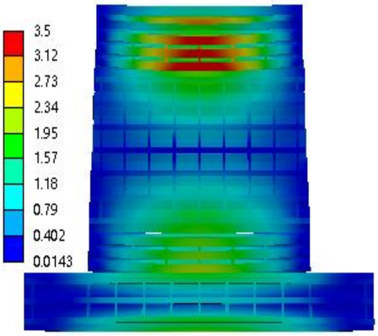
measuring point position	Results of natural vibration frequency(Hz)		
	Pulsation method	**Hammering method**	**Simulation analysis method**
P1 (at upstream side beam)	7.67	7.58	8.02
P2 (at track beam)	23.63	23.51	24.19
P3 (at middle beam)	16.01	15.67	16.9
P4 (at track beam)	23.58	23.68	22.10
P5 (at downstream side beam)	20.07	19.58	20.62



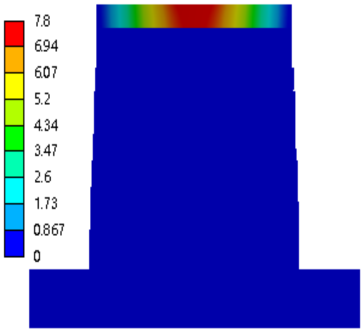
(a) Modal vibration patterns of 8.02Hz



(b) Modal vibration patterns of 24.19Hz

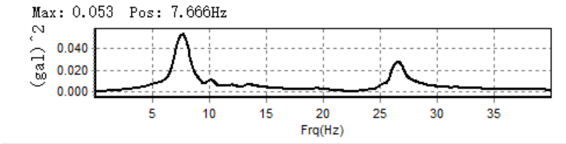


(c) Modal vibration patterns of 22.10Hz

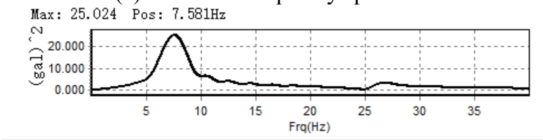


(d) Modal vibration patterns of 20.62Hz

Fig. 7. Modal responses of simulation analysis

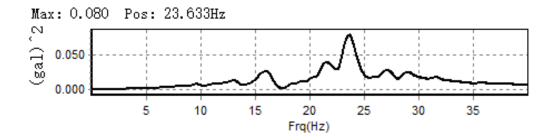


(a) Pulsation frequency spectrum

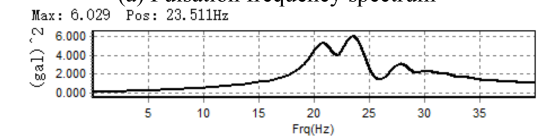


(b) Hammering frequency spectrum

Fig. 8. Pulsation frequency spectrum (a)and hammering frequency spectrum (b) of vertical direction at P1

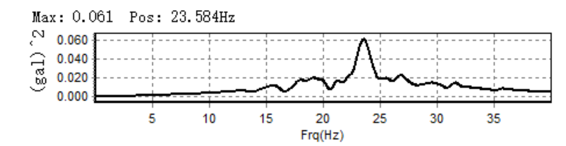


(a) Pulsation frequency spectrum

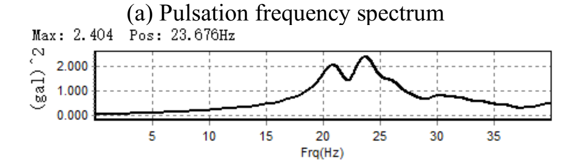


(b) Hammering frequency spectrum

Fig. 9. Pulsation frequency spectrum (a)and hammering frequency spectrum (b) of vertical direction at P2

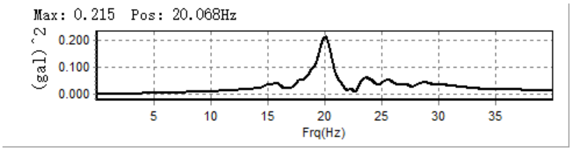


(a) Pulsation frequency spectrum

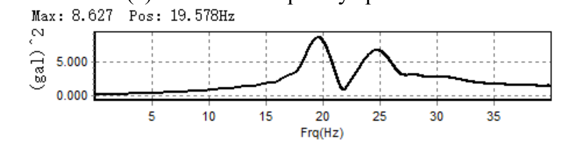


(b) Hammering frequency spectrum

Fig. 10. pulsation frequency spectrum (a)and hammering frequency spectrum (b) of vertical direction at P4



(a) Pulsation frequency spectrum



(b) Hammering frequency spectrum

Fig. 11. pulsation frequency spectrum (a)and hammering frequency spectrum (b) of vertical direction at P5

4 Analysis of flood discharge vibration characteristics

During the multi deep-holes flood discharge of Xiluodu Dam, monitoring points were always placed on gate pier (P7), the left end of beam (P6) and the middle of beam (P3), See Fig 4. The vibration of the flood discharge conditions of four deep-holes and three deep-holes and the transition condition when one gate was closed, were monitored and recorded. According to the monitoring data of the above working conditions, the vibration characteristics of different working conditions were analyzed and compared as follows.

4.1 Vibration amplitude comparison

The measuring points' root mean square values of vibration acceleration under two working conditions are shown in table 2.

Through the statistical Table 2, we can summarize some conclusions as follows.

Under the condition of four (2#, 3#, 6#, 7#) deep-hole gate flood discharge: the vibration of the middle measuring point of the beam, compared with the pier measuring point, the vibration of the middle measuring point was obviously enlarged in the vertical direction and along-river direction, and slightly changed in the cross-river direction (see table 2). Vibration was transmitted from the gate pier to the middle of the beam. In the middle of the beam, the vibration was obviously amplified in the vertical direction(See Fig.12) and the along-river direction(See Fig.13), and the vibration change in the cross-river direction is not large(See Fig.14).

Table 2. Statistical table of root mean square values of vibration acceleration under two working conditions

monitoring position	monitoring direction	flood discharge condition	
		three deep-holes (gal)	four deep-holes (gal)
P7 (at pier position)	vertical	0.70	3.70
	along-river	0.70	1.40
	cross-river	1.20	11.00
P6 (at Left side)	vertical	1.90	7.00
	along-river	1.00	2.50
	cross-river	1.40	11.80
p3 (at middle position)	vertical	4.60	49.80
	along-river	2.00	52.50
	cross-river	1.60	13.30

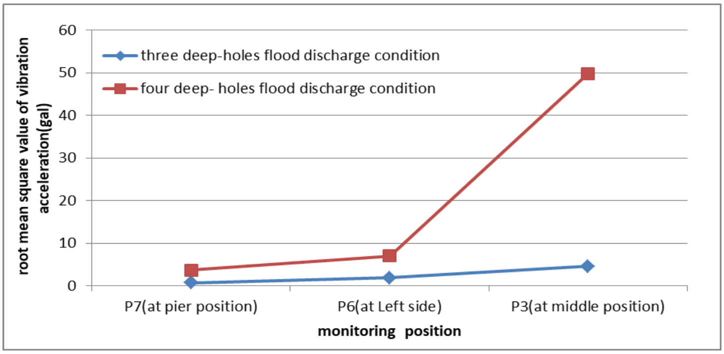


Fig. 12. Vertical vibration amplitude comparison curve

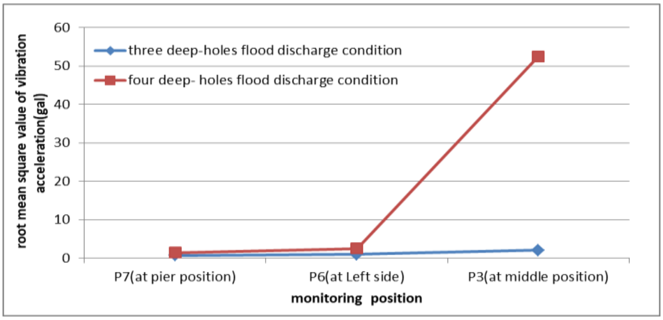


Fig. 13. Along-river vibration amplitude comparison curve

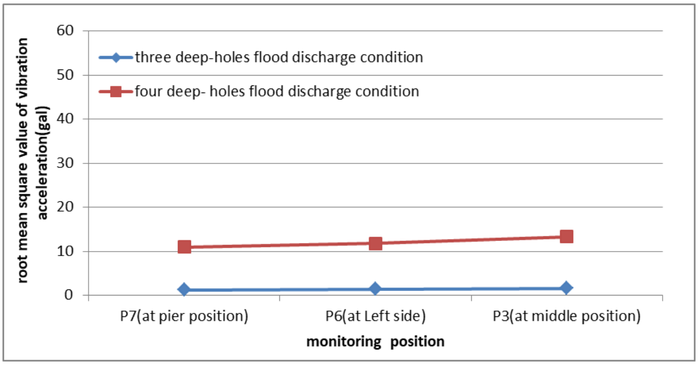


Fig. 14. Cross-river vibration amplitude comparison curve

Three (2#, 3#, 6#) deep-hole gates flood discharge condition: the vibration of the middle measuring point of the beam, relative to the pier measuring point, the vibration of the middle measuring point increased slightly. Compared with the four deep-hole flood discharge condition, the vibration amplification effect was obviously weakened.

Tests and statistics showed that four deep-holes flood discharge condition could stimulate the vibration of beams on surface orifice gate pier, and there was an obvious forced resonance phenomenon in the middle of beams.

4.2 Frequency spectrum comparison

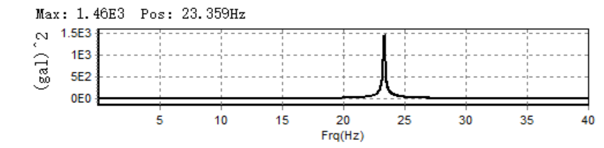
According to the spectrum diagram and statistical table (see Table 3), the dominant frequency (23.4Hz) amplitude of the vibration spectrum was very obvious (see Fig 15 (a)~ Fig 17 (a)) under the four (2 #, 3 #, 6 #, 7 #) deep-hole gates flood discharge condition, and the main frequency amplitude of the vibration spectrum of the measuring point was not very significant (see Fig 15 (b)~ Fig 17 (b)) under the three (2 #, 3 #, 6 #) deep-hole gates flood discharge.

4.3 Transition process analysis

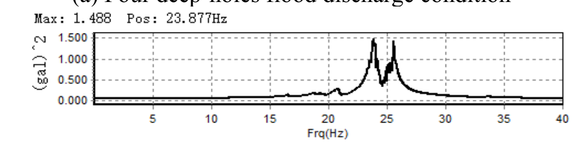
From the four (2#, 3#, 6#, 7#) deep-holes flood discharge condition, and 7# deep-hole gate closed, adjusted to the three (2#, 3#, 6#) deep-holes flood discharge condition, the measuring points monitored and recorded the whole process' vibration time history (See Fig18). Before and after the 7# deep-hole gate was closed, the vibration acceleration value of the measuring point at the middle of beam changes significantly, and it's vertical vibration acceleration peak value decreases from 150.2gal to 23.1gal immediately, it's along-river vibration acceleration peak value decreases from 152.1gal to 9.3gal immediately, its cross-river vibration acceleration peak value decreased from 49.4 gal to 9.3 gal immediately. It showed that magnitude of flood discharge and different gate dispatching operation conditions have a significant impact on the vibration of beams on surface orifice gate piers.

Table 3. Statistical table of main frequency under two working conditions

monitoring position	monitoring direction	flood discharge condition	
		three deep-holes (Hz)	four deep-holes (Hz)
P7 (at pier position)	vertical	43.2	23.4
	along-river	24.4	23.4
	cross-river	24.0	23.4
P6 (at Left side)	vertical	43.5	23.4
	along-river	24.0	23.4
	cross-river	24.0	23.4
P3 (at middle position)	vertical	23.8	23.4
	along-river	23.8	23.3
	cross-river	24.0	23.4

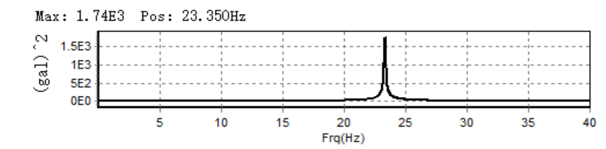


(a) Four deep-holes flood discharge condition

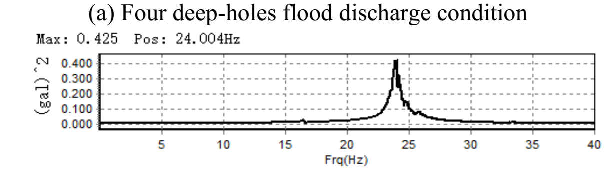


(b) Three deep-holes flood discharge condition

Fig. 15. vertical frequency spectrum of P3

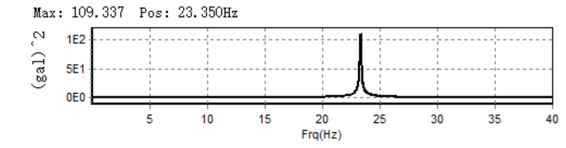


(a) Four deep-holes flood discharge condition

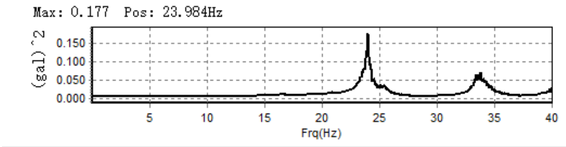


(b) Three deep-holes flood discharge condition

Fig. 16. Along-river direction frequency spectrum of P3



(a) Four deep-holes flood discharge condition



(b) Three deep-holes flood discharge condition

Fig. 17. Cross-river direction frequency spectrum of P3

5 Vibration source analysis

It is considered that there are four kinds of potential vibration sources around gate piers that could lead to the vibration of beams on surface orifice gate piers, namely, the vibration of the units in the powerhouse of the hydropower station, the flood discharge vibration of the dam body, the pulsation of the plunge pool and the pressure pulsation caused by the flood discharge.

Through this study, the unit vibration (main frequency 31.25Hz), plunge pool pulsation (0 Hz~11Hz) and flood discharge pressure pulsation (0.5Hz~ 2Hz) in the powerhouse of hydropower station were excluded. It was determined that the vibration source of beams on surface orifice gate piers was the flood discharge vibration of the dam body (The monitoring data analysis results of Dam Flood Discharge Vibration Monitoring System[8] showed that the main frequencies of the dam body vibration caused by multi-deep holes flood discharge condition were 17Hz ~ 23Hz, See Fig 19 for an example, and they were closely related to the water level).

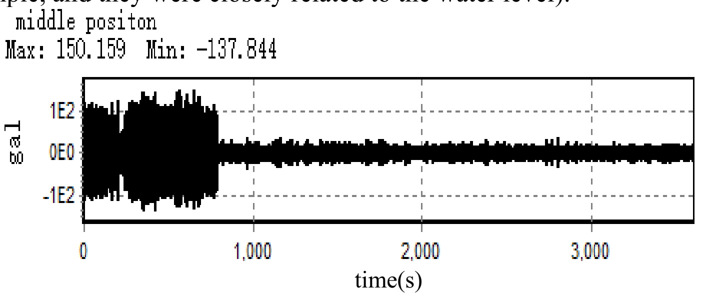
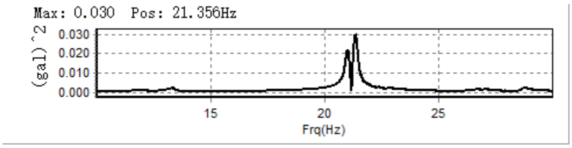
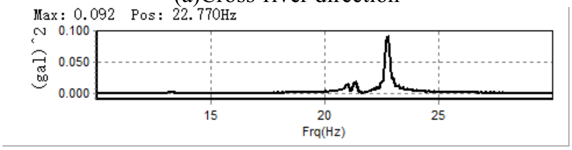


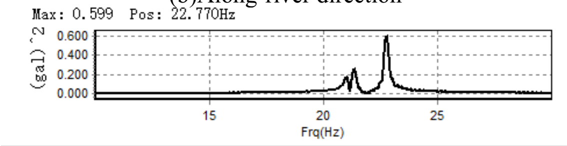
Fig. 18. vibration time history of one deep-hole gate closing process at middle position of beam



(a)Cross-river direction



(b)Along-river direction



(c)Vertical direction

Fig. 19. Flood discharge vibration frequency spectrum (three directions) of dam crest measuring point

It could cause the vibration of the dam body under deep-hole flood discharge condition. The vibration of the dam body drived the vibration of surface orifice gate pier, and the flood discharge vibration of the dam body was transmitted to beams on surface orifice gate piers. When the water level was 576.7m, the main frequency of the dam body vibration was about 22.7Hz, which was close to the natural frequency of beams on surface orifice gate pier, which could cause the obvious forced vibration of beams on surface orifice gate pier under deep-hole flood discharge condition. The staff standing on the beam could feel the obvious vibration, and the obvious vibration was mainly reflected in the vertical and along the river. The simulation analysis also showed that the forced vibration under the flood discharge condition did not threaten structure safety of beams on surface orifice gate piers.

6 Conclusion

The vibration of beams on surface orifice gate piers of Xiluodu dam was obvious when deep-hole gate was opened for flood discharge, especially when four deep-hole gates were opened. Through the field vibration test analysis and simulation analysis, it was shown that the main frequencies (mainly between 17Hz~23Hz) of the flood discharge vibration of dam body, during deep-holes flood discharge of Xiluodu dam, were close to the natural frequencies(mainly between 7Hz~28Hz, especially the local natural frequency of the track beam was about 23Hz) of beams on surface orifice gate piers, which was easy to excite forced vibration of beams, and leaded to significant vibration of beams on surface orifice gate piers, but the forced vibration would not affect the safety of the structure itself.

The field test showed that compared with four deep-holes flood discharge condition, the vibration amplitude of beams on surface orifice gate piers was greatly reduced under three deep-holes flood discharge condition, indicating that the adjustment of the number of deep-hole flood discharge gates could significantly change the structural vibration. If it is not necessary for discharge more flood of dam, it is recommended to minimize the number of deep hole gates to open. It is possible to open three or less deep-hole gates for flood discharge, which is beneficial to the vibration control of beams on surface orifice gate piers.

This study also shows that the structural frequency characteristics can be effectively obtained by the pulsation method, hammering method and simulation analysis method. The pulsation method and hammering method can accurately obtain the frequency characteristics of the prototype structure and can be used to verify the accuracy of the simulation model. The effective combination of the test method and the simulation analysis method can accurately and deeply study the vibration characteristics of the structure.

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References

1. Jinhui Ouyang, Hongtao Shi, Guangping Zhou. (2022) Dam deep hole flow vibration test analysis of Xiluodu hydropower station in Jinsha River. Journal of China Academy of Water Resources and Hydropower Research, 20 (01): 57-63.
2. Jingjie Tian, Yanpian Mao. (2021) Study on the flood discharge vibration characteristics of the bottom plate of Xiluodu plunge pool. Electromechanical technology of hydropower station, 44 (11): 71-76 + 109.
3. BROWNJOHN J M W. (2003) Ambient vibration studies for system identification of tall buildings. Earthquake Engineering Structural Dynamics, 32(1):71-95.
4. Peilei Yan, Endong Guo,Houli Wu, etc. (2021) Basic natural vibration period test and analysis of RC shear wall structure in Shanghai based on pulsation method [J].Vibration and impact,40 (17) : 146-151 + 188.DOI : 10.13465 / j.cnki.jvs.2021.17.020.
5. LU E O, ZAIDI M R. (2011) Dynamic stiffness and loss factormeasurement of engine rubber mount by impact test. Materials and Design, 32(4):1880-1887.
6. Zhang Guogang, Tang Shenghua, Fang Zhi, Jin Yao. (2023) Experimental study on uncertainty of modal parameter identification of cable-stayed bridge by hammering method. Highway, 68 (11): 139-147.
7. Yang Chen, Gao Jianyong, Wang Maohua. (2023) Estimation of high-precision transfer function of variable time-base sampling hammering method. Noise and vibration control, 43 (02): 292-297.
8. Qi Ling, Yanpang Mao, Wenfeng Ma, etc. (2020) Design and application of flood discharge vibration monitoring system for Xiluodu high arch dam. Hydropower and pumped storage, 6 (05): 1-5 + 10.