Research Article

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Analysis of the influence of asymmetric geological conditions on stability of high arch dam

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Abstract: Geological conditions play a decisive role in the stability of arch dam engineering, and the asymmetric geological conditions of the abutment have a very negative impact on the safety of the arch dam. This article takes Lizhou arch dam as the research object, and determines that the arch dam is preliminarily affected by the geological asymmetric characteristics. Through the geomechanical model test method, the overload failure test of the Lizhou arch dam was carried out, and the resistance body, the instability deformation of the structural plane of the two dam abutments, and the influence of each structural plane on the dam body are obtained, and the safety factor is determined. According to the test results under the condition of asymmetric foundation of arch dam, for the structural plane which affects the geological asymmetry of the arch dam, the corresponding reinforcement measures are carried out. The feasibility of the reinforcement scheme is verified by the finite element method, and the safety factor after reinforcement is obtained. According to the results, it is suggested that some engineering measures can be taken to reduce the geological asymmetry between the two banks and ensure the safe and stable operation of the arch dam in the future.

Keywords: arch dam, geological asymmetry, geomechanical model, stability analysis, ground stabilization

1 Introduction

With the development of hydropower technology, an increasing number of high arch dams have been built on foundations with complex geological structures, including double inclined complex foundation or soft base. In some arch dam projects, for example, Yebatan arch dam and Dagangshan arch dam [1–5], the abutments on both banks are asymmetric, which has an adverse effect on the safety and stability of the arch dam. This type of defect may cause the tensile stress on the downstream surface to be distributed along an oblique axis, and the compressive stress is skewed and asymmetric, resulting in reduced load carrying capacity. In the history of arch dam construction, due to the lack of attention to the impact of geological asymmetry, serious consequences had been caused [6]. For example, the break of the Malpasset arch dam (built in 1954) is caused by the weak left bank slope and the joints and fissures in the foundation [7]; the open transverse joints and increasing residual deformation of the Shevreira arch dam (completed in 1957) is due to the weak geological condition of the right bank [8]. To prevent the adverse effects of asymmetric foundation, concrete supporting piers, abutment anchoring treatment, and dam curve optimization are commonly used. For example, during the construction of Jiangping River Hydropower Station and Zhaolaihe River Hydropower Station [9,10], anchor holes and concrete plugs were used to reinforce the abutment, improving the stress condition and deformation distribution of the banks, which were critical to the successful completion and safe operation of these projects [11–13]. The overall stability and safety of the dam and foundation are particularly important in constructing high arch dams which often have asymmetric geological structures.

Geomechanical model testing is a method that studies the overall stability of a dam and its foundation. In this method, the physical and mechanical characteristics of a dam, abutment rock mass, and structural surfaces are simulated by using similar materials and applying

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normal and overloaded working conditions to obtain the deformation and instability process and the failure mechanism of the dam abutment resistance body and structural surfaces. In this article, the geological characteristics of the Lizhou arch dam were thoroughly analyzed using geomechanical model testing, and the influence of the asymmetric geological conditions on the safety and stability of the dam were investigated.

2 Analysis of the characteristics of geological asymmetry of Lizhou arch dam

The Lizhou Hydropower Station is the sixth cascade of a six-cascade hydropower station system in the mainstream of the Muli River. The dam is in Muli Tibetan Autonomous County, Liangshan Yi Autonomous Prefecture, Sichuan Province. The crest elevation of the dam is 2,092 m. The bottom elevation of the dam is 1,960 m, and the height of the dam (without the cushion) is 132 m. The design of the Lizhou roller compacted concrete (RCC) arch dam is a parabolic double curvature thin arch dam with equal thickness. The curves of upper and downstream surfaces of the crown cantilever are cubic parabolas, and the curves of upper and downstream surfaces of the horizontal arch ring are quadratic parabolas. The geometric shape of the dam is shown in Figure 1.

The geological condition of the Lizhou arch dam is complex and asymmetric. Although the rock strength is the same on both the banks, various weak structural surfaces have developed on both the abutments. Within the left dam abutment, the faults are F10, F4, and F5, and the long fissures are L1, L2, and LP285. Within the right bank,

the faults are F10 and F4. F4 is developed mainly within the left bank and partially within the right bank. L1 and L2 are fracture intensive zones, both of which are developed on the steep wall of the left bank. LP285 is a large fracture on the left bank. The strength parameters of the main fracture surfaces and weak structural surfaces are shown in Table 1, and the engineering geological cross section of the Lizhou hydropower station is shown in Figure 2. The development of structural surfaces on the left bank is more complex than that of the right bank. Most of the structural surfaces are at the abutment of the dam, and some of them are interlaced with each other to form potential slip channels. The structural surfaces of the right bank are relatively dispersed with a low hazard level. In summary, the geological condition of the left bank of the dam is more complex than that of the right bank, and the asymmetric geological conditions of the abutments on both the banks could pose threat to the safe operation of the dam.

3 Influence analysis of arch dam asymmetry in geomechanical model test

3.1 Model test method

In this article, the overall stability and safety of the Lizhou arch dam and its foundation are demonstrated through the geomechanical model test method. According to the engineering characteristics and test precision requirements, the geometric ratio of the model is $C_L = 150$. All the parameters are listed in Table 2. As shown in Figure 3, the simulation area extends 200 m to the upstream (about 1.5 times the height of the dam), 300 m to the downstream (about 2.3 times the height of the dam), and 300 m below the foundation surface (about 2.3 times the height of the dam) from the bottom center of the dam. The left and right bank abutments extend to the left and right directions by 150 m from the center line (about 1.1 times the height of the dam), respectively.

The load combination of upstream and downstream water pressure, silting pressure, deadweight, and temperature rise under normal conditions was selected as the test load. The test was carried out using jacks and the overload method. The measuring equipment mainly monitors the three parameters: the surface displacement of the dam body and abutment (δ), the internal relative

Figure 1: Geometric figure of Lizhou arch dam. (a) Plan of arch dam and (b) section view of crown cantilever.

Table 1: Geological recommended values of mechanical parameters of weak structural surfaces in dam site area

Type of structural surface	Structural plane character	Shear strength		Deformation modulus (GPa)	Distribution
		F'	C' (MPa)		
FJ1 and FJ2 interlaminar shear zones	Cuttings packing type	0.65	0.08	—	Right and left dam abutments
FJ3 and FJ4 interlaminar shear zones	Cuttings with mud type	0.45	0.03	—	Right and left dam abutments
L1 and L2 fracture zones	The fissures are more compact or filled with a small amount of calcite slices or mud film	0.65	0.06	3–4	The left dam abutment
F4 fault zone	Cuttings and calcite with mud filling type	0.45	0.05	3–4	Right and left dam abutments
F5 fault zone	Cuttings and calcite with mud filling type	0.45	0.05	3–4	Left dam abutment and foundation

Figure 2: Engineering geology section view of Lizhou hydropower station.

displacement of the structural surface ($\Delta\delta$), and the strain of the dam body (ε). The layout of the model surface displacement measuring system is shown in Figures 4 and 5. According to the geological characteristics of the abutment (foundation) of the Lizhou arch dam, the model mainly simulates the structural planes, including faults

Table 2: Similarity coefficient of geomechanical model test of Lizhou arch dam

Physical quantities	Similarity coefficient value	Physical quantities	Similarity coefficient value
C_L	150	C_F	After 150
C_γ	1.0	C_μ	1
C_ε	1.0	C_E	150
C_σ	150	C_f	1
C_δ	150	C_c	150

Figure 3: The model picture.

(F4 and F5), fissures (L1, L2, and LP285), and interlayer shear zones (FJ1–FJ4), in which 42 internal relative displacement meters were buried.

3.2 Analysis of deformation and instability of structural surface of dam abutment on both banks

According to the aforementioned discussion, the geological asymmetry of arch dam abutment is mainly affected

Figure 5: The layout of measuring points on the downstream surface of the dam.

by the structural surfaces of the two abutments. Therefore, in the geomechanical model, the main structural surfaces that affect the geological asymmetry are monitored, and the relative curves between the internal relative displacement of abutment structural surface and overload coefficient are obtained, as shown in Figures 6–8.

The main structural surfaces developed within the left dam abutment are faults (F4 and F5), fissures (L1, L2, and LP285), and interlayer shear zones (FJ1–FJ4). Under the action of arch thrust, relative dislocation occurs

Figure 4: The layout of displacement measurement points of two dam abutments and the surface of the resistance body in the model.

Figure 6: The relative displacement $\Delta\delta$ - K_p curve of F5 dam abutment position.

Figure 7: The relative displacement $\Delta\delta$ - K_p curve of Lp285.

in the downstream direction of structural surfaces. Hence, the fault F5 appears in the downstream direction as its relative displacement is multiple times of that of the other structural surfaces. Notably, a large displacement occurs in the middle of the dam abutment (2,020–2,040 m in elevation), where multiple intercutting fissures, including L1, L2, and LP285, have developed. The poor integrity of rock mass at this area leads to a low load carrying capacity and a large displacement and fissure carrying capacity of the abutment. The relative displacement curves of the interlayer shear zones, including FJ2–FJ4, have large fluctuations and inflection points, and through fissures along the structural surface have developed at the outcrops of FJ3 and FJ4. The above structural surfaces have a great influence on the deformation and stability of the left dam abutment and resistance body.

The main structural surfaces developed within the right dam abutment include a fault (F4), an unloaded fracture (LP4-x), and interlayer shear zones (FJ1–FJ4). Among them, F4 has a large impact on the deformation and stability of the right dam. It is located in the downstream slope of the arch of the dam crest, where the

Figure 8: (a) The relative displacement $\Delta\delta$ - K_p curve of FJ3 on the right bank. (b) The relative displacement $\Delta\delta$ - K_p curve of FJ3 on the left bank.

relative displacement of the structural surface is larger and the inflection point of its displacement curve appears earlier. The unloading fissure LP4-x was not destroyed in the test. Obvious fluctuations and inflection points in the relative displacement curves of the interlayer shear zones, FJ3 and FJ4, were observed. Through fissures were produced along the structural surface at the outcrop of FJ3. The above structural surfaces all contribute to the deformation and stability of the right dam abutment and resistance body.

According to the relationship curve between the relative displacement of the structural surface and the overload coefficient, the failure process and the failure mode of the model and the overload safety factors of weak structural surfaces at different positions are determined as follows (Table 3).

Based on the relationship between the relative displacement of the structural surface and the overload coefficient, the failure process and the failure mode of the model as well as the overload safety factors of weak structural surfaces are summarized as follows: The influence of overload on the relative displacement amplitude and the abutment structural surfaces of the left dam is greater than that of the right dam; The damage on the exposed structural surfaces of the left dam abutment is more severe than that of the right dam abutment; The overload safety factors of the

Table 3: The overload safety factors of structural surface

Structural surface	Section	Overload safety factors	Structural surface	Section	Overload safety factors
F4	The left bank	$K = 3.0\text{--}3.6$	FJ2	The left bank	$K = 2.4\text{--}3.0$
	The right bank	$K = 2.4\text{--}3.0$		The right bank	$K = 3.2\text{--}3.6$
F5	The dam abutment of left bank	$K = 3.0\text{--}3.6$	FJ3	The left bank	$K = 3.4\text{--}3.8$
	The dam foundation of left bank	$K = 3.6\text{--}4.0$		The right bank	$K = 3.0\text{--}3.4$
L2	The left bank	$K = 3.0\text{--}3.6$	FJ4	The left bank	$K = 3.4\text{--}4.0$
Lp285	The left bank	$K = 3.4\text{--}3.8$		The right bank	$K = 4.0\text{--}4.3$
FJ1	The left bank	$K = 4.0\text{--}4.6$	F10	The left bank	—
	The right bank	$K = 4.3\text{--}4.6$		The right bank	—

structural surfaces within the abutment and the foundation of the left bank are 3.0–4.0, while the overload safety factors of the right bank are 4.0–4.6; The failures of the left bank abutment and dam foundation appear earlier than those of the right bank abutment and dam foundation.

3.3 Influence of geological asymmetry on dam abutment and resistance body

The influence of the instability deformation of the structural surface on the dam abutment resistance body can be assessed by the displacement of the left and right dam abutments along the river, the measuring points on the surface of the resistance body, and the failure of dam abutment rock mass. As shown in Figure 9, on the surface of the left dam abutment, the degree of surface displacement of the rock mass near FJ3 and between FJ2 and FJ3 is the highest, followed by that of the rock mass near FJ4 within the upper part of the dam abutment. The fault F5, near the arch end, has a relatively large displacement on its exposed part. Another displacement on the right dam abutment surface along the river is located near FJ3 and FJ4 and at the outcropping of the unloading fissure LP4-x of the boundary layer. It has an elevation of 2,150 m. Based on the data obtained from the measuring points A–A and a–a on the left and right dam abutments, respectively, displacements along the river were observed on both the dam abutments, and the left abutment has a larger degree of displacement compared with the right abutment suggesting that the left abutment has more damage.

In the process of overload, the rock mass on both the dam abutments was damaged. The damage at the left dam abutment, especially at the outcrop and nearby rock mass of each structural surface, is more severe than that at the

right dam abutment, as shown in Figure 10(a). The outcrop area of the fault F5 was seriously damaged. The fracture is completely through the structural surface at an elevation from 2,050 to 1,990 m, and it extends upward to the dam crest and converges with the interlayer shear zones, FJ3 and FJ4. The interlayer shear zones, FJ3 and FJ4, have severe damage in their outcrops. The fissure extends about 75 m downstream from the arch end and 40 m upstream along the structural surface. A large number of fractures appear on the surface of the rock mass between FJ2 and

Figure 9: (a) The relative displacement δy – K_p curve of left bank A–A along river. (b) The relative displacement δy – K_p curve of right bank a–a along river.

Figure 10: (a) Slip failure mode of left bank dam abutment. (b) Slip failure mode of right bank dam abutment.

FJ4. At the upstream side of the arch dam, fissures, including L2, LP285, and L1, have severe cracks in the outcrop area. These fissure cracks expand and connect along the structural surface. They cover the entire dam surface and intersect with FJ3 and FJ4.

The range and degree of the damage on the right bank are smaller than that of the left bank, as shown in Figure 10(b). The outcrop of the interlayer shear zone, FJ3, was severely damaged, and the fissures extend 32 m upstream and 57 m downstream along the structural surface from the arch end. The fissures at the outcrop of FJ4 on the dam abutment extend upward to an elevation of 2,120 m. There are several fissures on the surface of rock mass near FJ3 and FJ4. A large number of fractures developed along the joint direction appear near the dam heel in the upstream side of the arch dam, and they spread from the dam bottom upward to the dam crest and interlace with each other.

Figure 11: (a) Radial displacement δr change process of the downstream surface of the arch ring at an elevation of 2,050 m. (b) Radial displacement δr change process of the downstream surface of the arch ring at an elevation of 2,000 m.

3.4 Analysis of the influence of geological asymmetry on dam safety

Under the action of arch thrust, the dislocation deformation of the structural surface induces the displacement within the abutment resistance body along the river. As the overall displacement trend of the left dam abutment is larger than that of the right dam abutment, an asymmetric deformation of the arch dam was observed during the test, as shown in Figure 11. Under normal working conditions, the displacement of the dam body is symmetrical. While in the overload stage, with the increase in the overload coefficient, the displacement of the left half arch, especially the middle and upper parts, gradually exceeds that of the right half arch. The displacement characteristics are related to the interlaced fault F5, the fissure dense zones L1 and L2, and the long fissure LP285 distributed in the resistance body of the middle and upper parts of the left dam abutment.

With the increase in the overload, two fissures appear successively in the arch dam body, and the final failure mode is shown in Figures 12 and 13. The first fissure initially appeared in the left half arch at an elevation of 2,040 m of the downstream dam surface and then spread

Figure 12: The final failure mode of the dam.

to about half of arch length at the top of the left half arch dam, running through the upstream and downstream dam surfaces. This fissure is mainly caused by the complicated geological conditions at this part of the left dam abutment, where F5, L2, and LP285 are interlaced, resulting in the stress concentration phenomenon at the arch end. The second fissure appeared in the right half arch near the foundation surface (the toe of the dam), where F5 intersects the dam body. The fissure gradually extended to an elevation of 2,043 m but did not reach the upstream dam surface. The formation of this fracture is mainly caused by the mutual dislocation of the hanging wall and the foot wall of the fault F5.

The influence of the external load on the dam displacement is summarized as follows: When $K_p = 1.0$, the displacement of the dam body is small; When $K_p > 2.2$, the overall displacement curve fluctuates to a certain extent; When $K_p = 4-4.0$, the fluctuation of the dam displacement increases and the displacement growth speed accelerates; When $K_p = 6.3-6.6$, the dam body presents a large deformation and shows a trend of instability. Hence, the overload safety factors for the overall stability of the arch dam and foundation, K , is 6.3–6.6.

4 Analysis of reinforcement treatment effect of dam abutment

4.1 Finite element modeling and reinforcement scheme

To further explore the influence of the asymmetric geological conditions on the dam body, this article refers to the reinforcement schemes for the dam abutment of high

Figure 13: Schematic diagram of failure mode of downstream arch dam surface.

arch dams, such as Jinping I arch dam, Xiaowan arch dam, and Baihetan arch dam [14,15]. Combined with the geological conditions of Lizhou arch dam, concrete displacement and reinforcement measures are adopted for the weak structural surface of the dam abutment of Lizhou arch dam to improve the overall stability of the dam and abutment. The reinforcement scheme is shown in Figure 16. The main reinforced structural planes are F5, L2, and LP285 in the left bank and F4 in the right bank. The processing range is as follows: for the right bank, 1.5–2.0 times arch end thickness at the upstream, 2.0–3.5 times arch end thickness at the downstream, and 0.6–1.1 times arch end thickness embedded in the mountain; for the left bank, 0.6–1.0 times arch end thickness at the

Figure 14: Finite element mesh map of Lizhou arch dam.

Figure 15: Finite element mesh map of dam body.

Figure 16: Schematic diagram of the reinforcement part.

Figure 17: Radial displacement distribution of the downstream surface of the dam when $K_p = 1$.

upstream, 2–4 times arch end thickness at the downstream, and 3.5–5.0 times arch end thickness embedded in the mountain.

The reinforcement scheme was simulated by ANSYS software, and the numerical simulation range of the reinforcement scheme and the discrete method of unit division structure were the same as the numerical simulation scheme of the natural foundation. The three-dimensional finite element model is shown in Figures 14–16.

4.2 Analysis of reinforcement effect

The displacement cloud diagrams of the downstream surface of the arch dam under normal working conditions and overload conditions are shown in Figures 17 and 18. The displacement at the lower part of the arch dam body is smaller than that at the upper part, and the displacement at the arch end is smaller than that at the arch crown. The displacement of the left and right half arches is generally symmetrical and the trend of the displacement variation of the dam body in the reinforcement scheme is the same as that in the natural foundation. While, with the reinforcement scheme, the displacement of the left and right half arches is symmetrical and the degree of the displacement is smaller.

Combined with the trend of the displacement variation of the dam body and abutment and the section diagram of the abutment failure at different elevations under various overload coefficients, it can be seen that: When K_p reaches 4.0–4.5, the plastic zones of the left and right dam abutments expand further to the downstream, connecting the structural surfaces of the downstream, and the plastic strain value continues to increase; When K_p is

Figure 18: Radial displacement distribution of downstream surface at dam elevation of 2,059 m.

Figure 19: (a) Plane section diagram of plastic zone ($K_p = 4.0 \nabla 2,030$ m). (b) Plane section diagram of plastic zone ($K_p = 8.0 \nabla 2,030$ m).

raised to 7.0–8.0, the plastic zones continue to expand, and the plastic zones of the dam abutment and foundation are fully connected, and the plastic zone of the rock mass in each elevation plane is connected with the structural surfaces, and the dam and foundation lost their load carrying capacity. Besides, the plastic failure zone of the left bank is slightly larger than that of the right bank (Figure 19).

The overall stability safety factor of the arch dam and foundation with the reinforcement scheme is 7.0–8.0, which is an increase of 16.67% compared with the natural foundation state. With foundation reinforcement, the asymmetry of the foundation is alleviated, and the deformation of the dam is decreased. Hence, the overall safety degree of the dam and foundation are improved.

5 Conclusion

The geological condition of the dam abutment of Lizhou arch dam is complex. The weak structural surfaces such as faults, joints, and fissures intersect with each other and are asymmetrical, which lead to serious damages of the dam abutment and affect the stability and safe operation of the dam. In this article, a three-dimensional geomechanical model test and finite element calculation are employed to study the overall stability of the dam body and abutment of Lizhou arch dam, and the influence of the reinforcement scheme on the stability of the dam is analyzed and discussed, which provides a reference for constructing arch dams under the asymmetric geological conditions. The main conclusions are as follows:

- (1) In the process of the geomechanical model test, large relative displacements occurred at the fault (F4), the fractures (L1, L2, and LP285), and the interlayer shear zones (FJ2–FJ4) of the left dam abutment. The degree of deformation of the resistance body in the left dam abutment is greater than that of the fault F4 and the interlayer shear zones FJ3 and FJ4 in the right dam abutment. The overload safety factor of the structural surface of the left bank dam abutment and dam foundation is between 3.0 and 4.0. The overload safety factor of the structural surface of the right bank dam abutment and dam foundation is between 4.0 and 4.6. The structural surfaces of the dam abutment and dam foundation on the left bank are less stable than that of the right bank.
- (2) In the geomechanical model test, the damage on the left abutment is more severe than that on the right bank. The damage on the left abutment is mainly on the upper and middle parts, especially the structural plans in the outcrop and nearby rock of each structural surface, while the damage on the right bank is largely on the middle and lower parts. The geological asymmetry formed within the structural surfaces and weak zones is the main cause of dam failure.
- (3) Due to the instability and deformation of the structural surface, the displacement range and failure status of the left dam abutment resistance body are more serious than that of the right dam abutment. Under the action of the arch thrust, the dam abutment resistance body shifts along the river due to the dislocation deformation of the structural surface. The overall displacement trend of the left dam abutment is greater than that of the right dam abutment, which leads to asymmetric deformation. The overall stability safety factor of the arch dam and foundation, K , is 6.3–6.6. After the reinforcement, the displacement

of the left and right half arches is symmetrical and the displacement value decreases. The K value after being reinforced is 7.0–8.0, which increases by about 16.67%. This shows that the reinforcement scheme effectively reduces the asymmetry and improves the overall stability and safety of the dam body.

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