Experimental Study on the Global Stability of the Xiaowan Arch Dam Using a 3D Geo-Mechanical Model Test

Jianhua Dong¹, Xianlian Wang², Jianye Chen¹*, Yuan Chen¹, Baoquan Yang and Lin Zhang¹

¹ State Key Laboratory of Hydraulics and Mountain River Engineering, School of Water Resources and Hydropower, Sichuan University, Chengdu, Sichuan, 610065, China
² Sichuan Electric Power Design Consulting Co., Ltd., Chengdu, Sichuan, 610041, China
*Corresponding author’s e-mail: jianyechen@163.com

Abstract. In this paper, a three-dimensional geo-mechanical model test for the Xiaowan high arch dam was studied and the topographical and geological features, the distribution of weak structural planes, the shallow relaxation unloading phenomena were simulated. Furthermore, a type of model material known as the temperature analogous material, whose strength varies with temperature throughout the experiment, was used to simulate the decrease in shear strength of the weak structural planes. The deformation characteristics and failure mechanism of the dam foundation and abutments were obtained by using comprehensive test method, which considered both the overloading and strength-reduction techniques. Through data analysis, the strength reserve coefficient, the overloading and the global safety factor were obtained. Synthetic analysis of the test results indicates that the displacement of the mid-upper abutment was reduced and the failure zone become smaller due to the significant reinforcement effects of concrete displacement plugs on the faults and alteration zones. The failure pattern shown in the model test indicates that reinforcements should be installed at faults F11 and F10 above an elevation of 1245 m in the right abutment and the rock above the thrust block in the left abutment.

1. Introduction

With the rapid developments in the construction of hydropower projects, several high dams and large reservoirs are being built or are planned to be built in China[1]. Many of those projects are massive and located besides large rivers and deep mountain valleys in Western China, most of which have complicated geological conditions and high earthquake intensity. Some recent examples are the Xiaowan arch dam (294.5 m high), which is located on the LanCang River, the Jinping-I arch dam (305 m high), which is located on the Yalong River, the Xi Luo-du arch dam (278 m high), the Bai Hetan arch dam (284 m high), and the DaGangshan arch dam (210 m high), which is located on the Dadu River. Many academic studies are now investigating the most appropriate method for analysing and evaluating the stability and safety of these high dams [2-3]. Geo-mechanical model testing is proved to be one of the important methods to analyse and evaluate such structures.

Geo-mechanical model testing is based on a certain similarity principle and can be used to simulate the dam body and its geological structures, such as faults, fractured zones, weak intercalation surfaces, and joint fissures [4-6]. The primary purposes of the test are to obtain the deformation distribution...
characteristics of the dam body and foundation, and to reveal the failure patterns and failure mechanisms of the entire structure under different loading conditions. This global stability safety factor of the dam and foundation can be determined [7-8]. The strength-reduction method considers the safety reserve capacity of the dam abutment and foundation rock mass and attempts to reduce the mechanical parameters of the rock mass gradually until the failure of the foundation [9-14].

This study constructed a three-dimensional (3D) geo-mechanical model for the Xiaowan high arch dam, which simulated the topographical and geological features, the distribution of weak structural planes, the shallow relaxation unloading phenomena, and the dam reinforcement scheme. During the test, traditional model materials were used to simulate the dam body, the concrete reinforcement plug, and the mail rock mass of the abutment and foundation, whereas temperature-analogue materials were used to simulate faults F11, F10, F5, F12, F19, and F20. A small specially prepared rhombic block and thin block were used to simulate the shallow layer of the unloading rock body. The failure test was performed using the comprehensive method, which considers both the overloading and strength-reduction techniques. The deformation characteristics of the dam foundation and abutment, failure process, failure modes, and failure mechanism were obtained. The global safety factor for the dam foundation and abutment was determined, and the dam stability was evaluated by synthetically analysing the test data. Finally, reinforcement measures for the weak zones of the dam abutment were recommended.

2. Project background and geology conditions

2.1. Project background
The Xiaowan Hydropower Station is located in the middle reaches of the Lancang River in Dali Prefecture in the western region of Yunnan Province, China. The project is composed of a barrage, a flood discharge hole of the dam body, a plunge pool behind the dam, a left-bank spillway tunnel, and a right-bank water diversion and power generation system. Among them, the barrage is a concrete parabolic variable-thickness hyperbolic arch dam, which reaches a maximum height of 294.5 m. The total installed capacity of the hydropower station is 4,200,000 KW.

2.2. Geology conditions
The geological structure in the dam site has the following characteristics: (1) There are a wide variety of rocks, which have varying properties, together with significant inhomogeneity; (2) Class II, Class III, and Class IV faults in the abutments, along with five alteration zones, are crossed in length and width; (3) The rocks in the superficial area of the dam foundation indicate a clear relaxation and unloaded appearance after the dam foundation was excavated; (4) A Class V tectonic structural plane cuts various rocks in 3D space into varied inclination angles, joint fissure sets along different elevations.

3. Model design and manufacture

3.1. Determination of the simulation range
In this test, the geometric proportion of the model is determined to be \( C_L = 300 \) based on the comprehensive analysis of the scale of the test site, The model simulation range of the Xiaowan Arch Dam is determined to be as follows: the model size is \( 3.61 \times 4.80 \times 2.23 \) m (length\times width\times height), which is equivalent to the dimensions of the prototype, \( 1083 \times 1440 \times 669.5 \) m. The simulation domain is sufficiently large to meet the requirements of the destructive test and can fully represent the actual conditions of the study.
3.2. Similarity simulation of the rock mass material and structural plane

According to the physico-mechanical parameters of the prototype rock mass and main structural plane, the corresponding parameters of the model materials can be obtained using the similarity principle, as shown in Table 1.

| Categorization | Prototype | Model |
|----------------|-----------|-------|
|                | E (GPa)   | f'    | c' (MPa) | E (MPa) | f'    | c' (MPa) |
| I              | 25.0      | 1.50  | 2.2      | 83.3    | 1.5   | 0.0073   |
| II             | 22.0      | 1.50  | 2.0      | 73.3    | 1.5   | 0.0067   |
| IIIa           | 14.0      | 1.20  | 1.2      | 46.6    | 1.2   | 0.004    |
| IIIb           | 10.0      | 1.15  | 1.0      | 33.3    | 1.1   | 0.0033   |
| F11            | 1.5       | 0.80  | 0.4      | 5.0     | 0.8   | 1.33     |
| F10            | 1.0       | 0.90  | 0.4      | 3.3     | 0.9   | 1.330    |
| F5             | 1.5       | 0.85  | 0.3      | 5.00    | 0.8   | 1.25     |
| F20            | 1.5       | 0.80  | 0.3      | 5.0     | 0.8   | 1.08     |
| F19            | 1.5       | 0.90  | 0.4      | 5.0     | 0.9   | 1.33     |
| E8             | 2.5       | 0.40  | 0.03     | 8.3     | 0.4   | 0.12     |
| F4, E5         | 3.5       | 0.70  | 0.2      | 11.6    | 0.7   | 0.67     |

In the geo-mechanical mode test, the material used to simulate the rock mass should have high density, low strength, and low deformation modulus. A series of model material tests on various material components and proportions were performed. The experimental results showed that the similar material of rock mass should be primarily composed of barite powder, cement, water, paraffin, and hydraulic press oil. Furthermore, the relationships between the deformation properties and the content of different components were obtained. Therefore, according to the physico-mechanical parameters in Table 1, different types of rock mass materials to be used in the model test were prepared successfully.

3.3. Load types and loading system

The water pressure and earth pressure were simulated in this test. According to the similarity theory, the water pressure was calculated using an elevation of 1,240 m, which is the normal water level of the upstream. The earth pressure was calculated using an elevation of 1,097 m. The loads were applied using hydraulic jacks distributed at different elevations of the upstream surface of the dam, as shown in Fig. 1. The number and type of the jacks were determined by the load distribution.

Figure 1. Loading system on the upstream surface of the dam
3.4. Model measuring system
In order to monitor the radial, tangential, and chordwise displacements of the downstream face of the dam body under different loading conditions, the displacements in the transverse and parallel river directions, and the displacements of the dam abutment and resistance body, 69 surface displacement measuring points were arranged and 133 surface displacement gauges were installed. No monitoring instruments were arranged on the upstream face of the dam body in this test because the jack loading system were installed here. In order to obtain the relative displacement trend of structural planes under different loading conditions, 121 self-made strain internal displacement testing instruments were arranged in faults and alteration zones which have great influence on abutment stability.

3.5. Test procedure
The combined overloading and strength reduction methods were applied in this test. The model failure test procedure is as follows. First, the model was pre-loaded and then the normal load level was applied. Afterward, the shear strength of the abutment rock faults, such as F11, F10, and F5, were reduced by approximately 20% by heating up the model materials. Finally, the overloading test was implemented until the dam instability caused the destruction of the dam abutment. The loads were applied successively in the following order as factors of the normal working load, P0: 1.2, 1.4, 1.6, 1.8, 2.0, 2.2, 2.4, 2.6, 2.8, 3.0, 3.3, and 3.5. The whole progress of deformation and failure of the dam body, abutments, and foundation under all loading conditions was observed using different types of instruments.

4. Results and discussions
A photograph of the geo-mechanical model test is shown in Fig. 2. The test results of the relationship curves between the displacements $\delta_p$ of the measuring points on the downstream face of the dam body and the overloading coefficient $K_p$ are shown in Fig. 3. The variation of relative displacement $\Delta\delta$ of typical measuring points in the structural plane with overloading coefficient $K_p$ are shown in Fig. 4.

![Figure 2. Photograph of the geo-mechanical model](image)

4.1. Displacement distribution regularity of the dam body
The asymmetry of the two-bank terrain and the geological condition of the dam abutments created an asymmetric trend of the displacement of the dam body. Under normal working conditions, the displacement of the dam body was quite small, and the radial displacement was primarily symmetrical. In the strength reduction range, the change rate of the dam body displacement was not large. In the overloading stage, with an increase in overloading multiples, the displacement of the dam body continuously increased and had an asymmetric trend, which indicates that the displacement of the right arch abutment was slightly larger than that of the left arch abutment. When the overloading coefficient exceeded 3.0, an increase in the displacement amplitude of the dam body was accelerated, which
indicates that the dam body had deformed significantly and entered the process of deformation and instability.

4.2. Surface displacement distribution characteristics of the abutment and resistance body
Under normal working conditions, the surface displacement of the abutments and resistance blocks of both the left and right banks was minimal, and there was no abnormal phenomenon. The surface displacement had minimal change in the strength reduction phase. When \( K_p = 1.2~1.4 \), the displacement curves of most measuring points had small fluctuations, which was similar to the curve variation in the strain process of the dam body. With an increase in loading, the displacement of the measuring points increased gradually, and the displacement curves along the river had large changes in amplitude, whereas the displacement curves in the transverse river direction had only slight changes. The displacement curves of both abutments, which were near the arch abutment, had large-amplitude variations, such as measuring points 42, 44, 52, 60, and 62 of the right abutment and measuring points 94, 98, and 100 of the left abutment. The displacement curves at the outcropped points of the fault surface of both abutments increased rapidly, such as faults F11 and F12 of the right abutment and faults F19, F12, and F11 of the left abutment. The displacement of the right bank was slightly larger than that of the left bank. After \( K_p \) was increased to over 3.0, the surface displacements of both abutments increased rapidly and the change amplitude of the displacement curve increased. Furthermore, the measuring points near and around the arch abutment and at the fault outcropped points had abruptly increasing displacement and fluctuating displacement curves. The abutment rock mass deformed considerably, and the rock fissures expand and connect with each other.

4.3. Distribution characteristics of the relative displacement of faults
The variation relationship of the relative displacement of each measuring point with the overloading safety factor was obtained with the internal displacement meter pre-buried in the structural plane. The experimental data analysis results provided the distribution characteristics of the relative displacement of the structural planes of both abutments. Fault F11 in the right abutment is closest to the arch abutment, its relative displacement is large because of the influence in strength reduction, especially from elevations of 965 m to 1,090 m in the middle-lower part. The relative displacement of the elevations in the middle-upper part is short because fault F11 and the alteration are reinforced. Fault F11 is greatly deformed, particularly because it is influenced by Alteration Zones E4 and E5. E1, which is at an elevation of approximately 1,150 m, has a large relative displacement. Fault F10 of the elevation in the middle-upper part is near the arch abutment, however, once F11 is replaced with a concrete plug, its relative displacement becomes short, and the cracking phenomenon occurs above an elevation of 1,245 m. The relative displacement of fault F12 is large at an elevation of 1,090 m because F12 is near the right arch abutment at elevations of 1,070-1,110 m. The relative displacement
of fault F5 is large at elevations of 965-1,150 m in the middle-lower part under the influence of strength reduction. Therefore, the faults and alteration zones that primarily influence the stability of the right dam abutment are F11, F10, F11, F12, E4, and E5.

The relative displacement of fault F11 in the left dam abutment is large, especially at the measuring points in the middle-lower part. The second largest displacement is at fault F12, and the relative displacement of fault F19 is large because it is near the arch abutment. The displacement of fault F20 (E8) is small at the elevations of the middle-lower part, whereas the displacement is large at the elevation of 1,210 m in the upper part. Therefore, the faults and alteration zones that primarily influence the stability of the left dam abutment are F11, F12, F19, and F20 (E8).

The distribution characteristics of the overload curves of the relative displacement of each measuring point in the structural planes indicates that the relative displacement inside each fault is small under normal working conditions; in the strength reduction stage, the shear strength of faults F12, F11, F19, F10, F5, and F20 is reduced by 20%, i.e., the strength-reduction coefficient $K_T$ is 1.20. Under the influence of strength reduction, the relative displacement of each fault is sensitive, and the increment of the relative displacement is small, with small ranges of adjustment. The curves do not indicate a trend of abrupt increases, and the dam abutment operates normally. The displacement of the fault clearly increases in the overloading test stage, when $K_p>1.8$; when $K_p=3.3-3.5$, the deformation curves have clear inflection points or turning points and have large fluctuations, which indicates that a large displacement has occurred in the fault.

4.4. Failure pattern and characteristics

The failure patterns of the left and right dam abutments are shown in Fig. 5.

The primary failure areas of the left dam abutment are as follows: (1) There were significant cracks in the rocks neighbouring an elevation of 1,245 m; rocks in the upper part of the arch abutment had fractures along the moderately gentle dip angle of 40°. (2) Because rocks in the middle-lower part on the downstream face were influenced by fault F11, the rocks around the outcropped points of fault F11 at an elevation of 1,130 m had fractures. (3) Rocks around the concrete reinforcement at the elevation of the lower part had significant failure and experienced cracking failure along the interface of the bucket and rock mass.

The extent of failure and the failure degree of the right dam abutment were more significant than those of the left dam abutment. The main failure areas are as follows: (1) The rocks between faults F11 and F10 at elevations of 1,245-1,310 m had serious failure; (2) because the rocks in the middle-upper part of the right dam abutment are influenced by three categories of rocks and alteration zone E1, the extent of cracking of the rocks near an elevation of 1,170 m is slightly larger; (3) the rocks in the middle-lower part of the downstream face have serious failure at elevations of 975~1,090 m, and the primary failures occur along the interface between the downstream bucket and rock mass.

The arch dam and upstream side of the dam foundation plane had significant cracking failures, and inter-connective cracks from the left bank to right bank appeared around the dam feet on the upstream
side. Two fissures appeared at the left and right semi-arches on the lower stream face of the arch dam. The fissure of the left semi-arch cracked at an elevation of 1,110 m at the bottom of the left arch dam up to the dam crest, approximately 240 m away from the arc length of the left arch dam. Furthermore, the resistance bodies of the two abutments had inhomogeneous deformation.

4.5. Evaluation of the global safety factor of the arch dam and foundation

Based on the geological characteristics of the Xiaowan Arch Dam project, the failure test was performed by using a comprehensive method combining the overload and strength reduction techniques, and the similar experimental procedures under normal working conditions were conducted. Based on the analysis of the experimental data and results, the strength reserve coefficient \( K_1 \) is 1.2 and the overloading safety factor \( K_2 \) was estimated to be 3.3-3.5, respectively, that is,

\[
K_c = K_1 \times K_2 = 1.2 \times (3.3 - 3.5) = 3.96 - 4.2
\]

Thus, the global safety factor \( K_c \) for the Xiaowan Arch Dam and foundation should be 3.96-4.2, which meets the present design requirement.

5. Conclusions

The deformation characteristics and failure mechanism of the dam foundation and abutments were obtained in the test. A stability evaluation of the model test indicates that the strength reserve coefficient is 1.2, the overloading safety factor is 3.3-3.5, and the global safety factor for the dam foundation and abutment is 3.96-4.20. The dam stability meets the requirements for the stability of the dam abutment and foundations while not considering the influence of seepage pressure and seismic loads.

Because of the asymmetry of the geological conditions, the failure patterns of the two abutments are asymmetric, which indicates that the failure pattern of the right abutment is more significant than that of the left abutment. The failure regions appear primarily around the faults and alteration zones where the dam abutments are not reinforced and in areas where the downstream bucket and bedrock come into contact. A certain degree of failure has appeared in the shallow-layer of the unloading relaxed rock mass at the middle-lower elevation. The reinforcement to the main faults and alteration zones has clear results, and the areas that are not reinforced exhibit sliding and failure phenomena.

Synthetic analysis of the test data indicates that the displacements of the mid-upper abutment are smaller, and the failure zone are smaller due to the excellent reinforcement effects of concrete displacement plugs on the faults and alteration zones. The demonstrated failure pattern in the model test indicates that reinforcements should be installed at faults F11 and F10 above an elevation of 1,245 m in the right abutment and the rock above the thrust block in the left abutment.

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