Application Research on the Fiber Bragg Grating Sensing Technology in Arch Dam Model Test

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Abstract. Fiber Bragg Grating (FBG) has the advantages of high sensitivity, high resolution, low cost and small volume. Therefore, FBG sensing technology is widely used in the monitoring of structural engineering. In this research, FBG sensing technology was applied in the geomechanical model test of arch dam for the first time. The geomechanical model of Lizhou arch dam was built, and the FBG sensors were arranged on the upstream dam surface, while the resistance strain gauges were arranged on the downstream dam surface. The model failure test was carried out to get the stress-strain state and its changing process of the dam body. The test results show that the monitoring results of the FBG sensors and the resistance strain gauges are basically consistent, and it is found that the initial cracking overloading safety coefficient is $K_1 = 1.4 \sim 2.2$, the nonlinear deformation overloading safety coefficient is $K_2 = 3.4 \sim 4.3$, the ultimate overloading safety coefficient is $K_3 = 6.0 \sim 6.6$. The application of FBG technology provides a method to solve the problem that the strain of the upstream surface of the arch dam model cannot be directly monitored due to the insufficient space caused by the installation and loading system, and also provides a new idea for the measurement technology in the geomechanical model test.

1. Introduction

The safety and reliability of the dam should be emphasized in the design, construction and operation of the dam. Only when the dam meets the requirements of overall safety can it perform its normal functions. As an important method to evaluate the safety and reliability of dams, geomechanical model test has been used to evaluate the safety of many hydraulic projects. Geomechanical model test is a method of scaling research on specific engineering geological problems according to certain similarity principles, and it is mainly used to study the deformation form, stability and failure mechanism of various buildings and their foundations, high slopes, underground cavern and other structures under external load [1]. For the geomechanical model of arch dam, the main purpose of the test is to analyze the stability of arch dam and the abutment and their failure mechanism, and to evaluate the safety of the project. Through the geomechanical model tests of Xiluodu arch dam[2], Lizhou arch dam[3] and Jinping-I arch dam[4], our research group simulated the failure process of the dam body and the rock mass on both sides of each project, and put forward substantial suggestions for improving the safety durability of the project, all of which obtained satisfactory results.

The purpose of the geomechanical model test is to measure the displacement and strain of the dam body, to monitor the displacement of the dam abutment resisting force body and the weak structural plane, and to obtain the failure and instability process of the model. But the test method still has its
limitations. Due to the loading system is equipped on the upstream of the model dam the displacement and strain monitoring system cannot be installed, and the displacement and strain of the upstream of the dam during the failure process cannot be clearly understood. In the process of arch dam cracking, the first crack usually occurs at the heel of the upstream dam, for that reason it is necessary to find a method to directly monitor the displacement and strain of the upstream face of the arch dam. What's more, the deformation instruments should have very high precision, which means they should also have small sizes and light weights, so that they can be easily installed in the model dams[5]. Optical fiber sensor technology has the advantages of high sensitivity, small size, corrosion resistance, strong anti-electromagnetic interference, and small impact on the structure when embedded in the structure, etc., and it can be used to monitor pressure, displacement, temperature, etc., so it has been widely used in the monitoring of structural engineering. The fiber Bragg grating sensing technology is one of the research hotspots in China. For example, Zhao Xingguang [6] applied the FBG sensing technology to tunnel monitoring, Wang Jinyu [7] use it to monitor the surface subsidence, Zhao Yang [8] applied it to the monitoring of structural health. Similarly, the FBG sensing technology can also be used in geomechanical models test. In the previous geomechanical model tests of arch dams, the strain monitoring of the dam body is mainly based on the resistance strain gauge installed on the downstream dam surface, and the strain of the upstream dam surface cannot be obtained directly. This limitation can be overcome by using FBG sensing technology. The application of FBG technology provides a new idea for the measurement technology in the geomechanical model test.

2. Fiber Bragg Grating sensing technology

Fiber Bragg Grating (FBG) is a kind of diffraction grating which is formed by making the refractive index of fiber core modulated axially periodically. The effective refractive index of fiber grating will be disturbed with the change of external physical quantity (temperature, pressure, etc.), and the disturbance of refractive index will result in the reflection of a spectrum. For the FBG sensor, the wavelength of incident light wave satisfying the Bragg condition of the FBG will reflect, and the remaining wavelength will continue to transmit through the FBG. Normally, the fiber gratings sensor monitors the strain by measuring the center wavelength of the reflected light wave. The center reflection wavelength of fiber grating can be expressed as:

$$\lambda = 2n_{eff}\Lambda$$

where, $\lambda$ is the central reflection wavelength; $n_{eff}$ is the effective refractive index of the fiber, and $\Lambda$ is the period of the fiber grating. By monitoring the change of wavelength, as shown in figure 1, the change of strain to be measured can be obtained [9].

![Figure 1. Working principle of FBG.](image)

In the geomechanical model test, FBG sensors are arranged on the upstream dam face and resistance strain gauges are arranged on the downstream dam face. According to the monitoring results, the failure mechanism and instability process of the model of the dam can be obtained.
3. Geomechanical model test

3.1. Test methods

Geomechanical model is usually used for rupture tests that are conducted under nonlinear conditions. Physical models must satisfy a series of similarity requirements [10], that is the requirements of the similarity principle. Similarity means that each element of the model must be similar to the corresponding element of the prototype, including geometric elements and physical elements. In order to achieve the purpose of the test and ensure the scientificity and accuracy of the test, it is necessary to ensure that the similarity coefficients of the model and the prototype meet the requirement of geometric similarity, constitutive relationship similarity, shear-friction resisting strength on geological structure plane similarity and loading similarity[11]. Firstly, the model should have a proper geometric similarity with the dam body, abutment rock mass and main geological structures; Secondly, the tensile strength, compressive strength and deformation modulus of the model material should be similar to the prototype. The dead weight and water-sand load acting on the model should also be similar to the prototype. The shear strength of the main geological structure should also be similar to the prototype. The main similarity relations is as follows: \( C_\gamma = 1, C_\text{e} = 1, C_\text{f} = 1, C_\mu = 1, C_\sigma = C_E, C_\alpha = C_c = C_E = C_\lambda, C_F = C_\gamma C_E^2 = C_\gamma^2 C_E^2 \), where \( C_\gamma, C_\text{e}, C_\text{f}, C_\mu, C_\sigma \) and \( C_E \) are the similarity factor of deformation modulus, unit weight, geometry, of stress and load; \( C_\mu, C_\gamma, C_\sigma, C_\alpha, C_\lambda \) and \( C_c \) are the similarity factor of Poisson's ratio, strain, friction coefficient and cohesion.

The method adopted in this test is overloading method. The loading method adopted is triangle overloading method. Considering that the instantaneous impact of flood on the dam during flood season will lead to the overload of the dam surface stress in the upstream, but the upstream water level cannot be increased indefinitely, the choice of triangular overload is more in line with the engineering practice and is also convenient for loading in the test.

3.2. Model dimensions and model similar materials

According to the topographic features of the valley in the dam site area, the main geological structure features of the dam, the layout features of the arch dam hub other factors, the geometric scale \( C_L = 150 \) was determined. The model size was 2.6m×2.8m×2m (along the river direction × transverse × height), equivalent to a range of 390m×420m×300m in the prototype project. According to the similarity principle of the model, the unit density ratio \( C_\gamma = 1 \) and the deformation modulus ratio \( C_E = 150 \) were determined.

The model similar materials can be divided into dam materials, rock mass materials and weak structure plane materials. According to the similarity ratio \( C_\gamma = 1, C_E = 150 \), it can be calculated that \( \gamma_m = 24 \text{kN/m}^3, E_m = 160 \text{MPa} \). The model material of Lizhou arch dam adopts barite powder as weighting material, a small amount of gypsum powder as cementing agent, water as diluent, and appropriate additives. The mixture ratio is selected according to the mechanical index of the model material to meet the requirements of physical and mechanical similarity. The rock mass materials are weighted with barite powder, high-grade oil as cementing agent, and fusible polymer materials as admixture. According to the rocks involved in the project, a certain amount of additives are added respectively to make the mixture according to different mixing ratios, and then y32-50 four-column press is used to press blocks of different sizes. It is necessary to do experimental research on materials according to the requirements of various mechanical indexes of materials [12]. The model materials of weak structural plane are selected according to the similarity of shear strength of structural plane. Through a large number of material experimental studies, barite powder, oil and polymer materials are mainly used, corresponding soft materials are prepared according to the required mechanical indexes, and different thin films are selected to cooperate with each other, so as to realize the similar simulation of shear strength of structural surface [13]. Mechanical parameters of each rock mass and weak structural plane model are shown in table 1 and table 2 below.
the deformation and overall stability of arch dam and foundation, such as fault the two abutment
A total of 64 surface displacement measurement points are arranged on the downstream face of the dam,
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3.3. Model loading and measurement system
During the test, load similar to the prototype should be applied to the model, including water pressure, silt pressure, temperature rise pressure, etc. The water pressure and silt pressure on the model are simulated by means of stratification and block loading of a small hydraulic jack on the upstream of the arch dam, the dead weight of the model is simulated by means of the unit weight of the model material is equal to that of the prototype material, and the temperature rise load is simulated by means of equivalent water load. The whole dam is divided into 13 sections, which are respectively loaded by 13 hydraulic jacks of different tonnage.

According to the test method, the model is firstly pre-loaded and the load is gradually loaded into the normal load to test the operation of the dam and foundation under normal working conditions. Then, the upstream water load was overloaded according to the step size of (0.2 ~ 0.3) \( P_0 \) (\( P_0 \) is the water load under normal working conditions), until the dam and foundation were greatly deformed and the overall trend of instability appeared, then the loading was stopped and the test was terminated. During the test, it is necessary to record the test data under different loads and observe the deformation and failure forms of the dam and foundation.

According to the test design, it is necessary to measure the surface displacement \( \delta \) of arch dam and abutment, the internal relative displacement \( \Delta \delta \) of structure plane and the strain \( \varepsilon \) of the downstream dam face. In the geological model test, three distributed sensing optical fibers are arranged along the foundation surface and the arch ring of the arch crown, which are used to monitor the strain of the dam body near the foundation surface and the corresponding change of the strain of the arch crown with the increase of the overloading multiple. Fiber \( C_1 \) is arranged along the foundation surface, and it is in series with nine FBG strain sensors. Two distributed sensing fiber optic \( C_4 \) and \( C_2 \) are arranged on the arch ring at the arch crown. \( C_4 \) is in series with three FBG sensors and \( C_2 \) is in series with six FBG sensors. A total of 64 surface displacement measurement points are arranged on the downstream face of the dam, the two abutments and the rock surface of the resistance body. In the main structural planes that affect the deformation and overall stability of arch dam and foundation, such as fault \( f_5, f_4 \), fracture \( L_4, L_2 \),

| Table 1. Mechanical parameters of rock mass of the model. |
|----------------------------------------------------------|
| Stratigraphic code | formation lithology | unit weight / (kN ∙ m³) | weathering degree of rock | \( \mu \) | \( E_m \) /MPa | rock - rock | rock - concrete |
|-------------------|---------------------|--------------------------|--------------------------|-------|--------------|-------------|----------------|
| \( Pk \)          | Thick layers of limestone, marbled limestone | 26.0 | The unloading rock mass | 20 | 0.033 53.33 | 0.55 0.8 4 0.80 4 |
|                   | Weakly weathered lower part | | The new | 2.02 | 80 0.65 1 2.667 1.05 6 |
| \( D_{1yy} \)     | Very thin, thin layer of carbonosilicate slate | 26.7 | The new | 0.30 | 27 — 0.8 4.667 — |
| Faults and impact | The left bank | 25.0 | The new | 0.20 | — 0.5 0.333 — |
| zones \( F_{10} \)| The right bank | | Weak weathering | 0.65 | — 0.5 0.333 — |

| Table 2. Mechanical parameters of structure planes of the model. |
|---------------------------------------------------------------|
| Structural plane type | Structural surface character | Shear strength | Deformation modulus |
|----------------------|--------------------------------|----------------|---------------------|
|                      | | \( f' \) /kPa | \( c' /kPa \) | /MPa |
| Interlayer shear zones \( f_{11}, f_{12} \) | Cuttings filling type | 0.65 | 0.533 | — |
| Interlayer shear zones \( f_{13}, f_{14} \) | Cuttings filling type | 0.45 | 0.2 | — |
| Steep crack \( L_{285} \) | Argillaceous filling | 0.20 | 0.0333 | — |
| Unloading fissure | Micro tensile fracture | 0.35~0.45 | 0 | — |
| Fissure zone \( L_1, L_2 \) | Fill with calcite flakes or mud film | 0.65 | 0.4 | 20~26.7 |
| Fault zone \( f_5, f_6 \) | Cuttings and calcite filled with mud | 0.45 | 0.333 | 20~26.7 |

3.3. Model loading and measurement system

Interlayer shear zone \( f_{1} \) to \( f_{4} \), etc., a total of 42 internal relative displacement meters are embedded to monitor its relative dislocation along the structural plane. A total of 12 strain measuring points were arranged at the arch crown and dam heel of four typical elevations of the downstream dam face. The resistance strain gauges were arranged at each measuring point in the horizontal direction, vertical direction and 45° direction, and a total of 36 resistance strain gauges were arranged to monitor the corresponding changes of strain on the downstream dam face with the increase of overload multiple. The measurement system is shown in figure 2 and figure 3 below.

4. Analysis of the test results
The strain of upstream surface is monitored by FBG sensors. C21, C22 monitor the strain of the arch crown, and C18 monitors the strain of the left abutment of the dam, and C15 monitors the strain of the dam heel. The distribution of the strain of the upstream dam surface under different overload multiples is shown in figure 4.
Figure 4. Relation of $\mu-\varepsilon$ at typical measuring points on the upstream surface of dam (Positive is tension, negative is pressure).

According to the monitoring results of FBG sensors, under normal working conditions, namely when the overloading coefficient $K_p=1.0$, the overall strain of the dam body is small. The strain of the dam increases with the increase of the overload coefficient. As $K_p=1.2 \sim 2.4$, the strain curve shows a turning point, indicating the initial crack at the heel of the face dam upstream. As $K_p=2.4 \sim 3.2$, the overall strain at the left arch fluctuates to a certain extent, and the strain curve shows a turning point and inflection point, which indicates that the rock mass of the left bank abutment has a large displacement under the influence of the internal structural plane. As $K_p=3.4 \sim 4.3$, the strain curve of the dam body fluctuates greatly, and the strain increases significantly. With the increase of $K_p$, the strain curve developed further, fluctuated and turned, indicating that cracks in the dam continued to expand. As $K_p=5.7 \sim 6.6$, the strain curve turns again, indicating stress release of the dam body and overall instability of the dam.

The strain of downstream dam surface is monitored by resistance strain gauges. In order to verify whether the monitoring results of fiber grating monitors and resistance strain gauges are consistent, the vertical and horizontal strains at the arch crown of the downstream were selected and analyzed. The distribution of the strain of downstream dam surface under different overload multiples is shown in figure 5.
According to the monitoring results of resistance strain gauges, under normal working conditions, namely \( K_p=1.0 \), the overall strain of the dam body is small. The strain of the dam increases with the increase of the overload coefficient. As \( K_p=1.4 \sim 2.2 \), the strain curve fluctuates, and the curve has a small turning point and inflection point, indicating that the initial crack appears near the heel of the upstream arch dam. As \( K_p=3.1 \sim 4.3 \), the overall strain of the dam body fluctuates greatly, forming a large inflection point, and the strain increases significantly, and the left half arch of the dam body cracks. With the increase of \( K_p \), the strain curve developed further, fluctuated and turned, indicating that cracks in the dam continued to expand. As \( K_p= 6.0 \sim 6.6 \), the cracks in the dam body extend to the top of the dam, and stress release occurs in the dam body, and the dam gradually losing the bearing capacity.

Combined with the upstream and downstream monitoring results, as \( K_p=1.0 \), the overall strain of the dam body is small, as \( K_p=1.4 \sim 2.2 \), the initial crack appears near the heel of the upstream arch dam; as \( K_p=3.4 \sim 4.3 \), the left half arch of the dam cracked; as \( K_p= 6.0 \sim 6.6 \), the cracks in the dam body extend to the top of the dam, and stress release occurs in the dam body, and the dam gradually losing the bearing capacity. The final failure pattern of the dam is shown in figure 6.

5. Conclusion

(1) FBG sensing technology was applied in the geomechanical model test of arch dam for the first time. The geomechanical model of Lizhou arch dam was built, and the FBG sensors were arranged on the upstream dam surface while the resistance strain gauges were arranged on the downstream dam surface. The test results show that the monitoring results of the FBG sensors and the resistance strain gauges are basically consistent at different overload stages.

(2) According to the test results of FBG sensors and resistance strain gauges, the overloading safety factor of each stage of the dam is obtained as follows: the initial cracking overloading safety coefficient is \( K_1 1.4 \sim 2.2 \), the nonlinear deformation overloading safety coefficient is \( K_2 3.4 \sim 4.3 \), the ultimate overloading safety coefficient is \( K_3 6.0 \sim 6.6 \).
According to the test results, during the process of dam cracking, the cracks first appeared near the right dam heel and left dam abutment, and large asymmetric strains appeared at the left and right abutments, which can provide scientific basis for engineering design and construction.

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