Application of Micro Earth Pressure Cells to Geomechanical Model Tests of Arch Dams

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Abstract. Geomechanical model tests are important in the evaluation of the stability of engineering rock masses, and they play a key role in the stability studies on arch dam abutments. To further analyze the instability failure process and mechanical characteristics of dam abutment rock masses, this study employed a stress monitoring system in the traditional strain and displacement monitoring to improve the comprehensiveness of test results. With their advantageous properties, including their small volume, high sensitivity, and strong stability, micro earth pressure cells can directly monitor stress changes in arch abutment rock mass during geochemical model tests. On the basis of the overloading method, this study applied micro earth pressure cells to a 2D geomechanical model test on the Yebatan arch dam to investigate the working performance of the arch dam and arch abutment at EL.2 750 m. In the test, the surface displacement monitoring system and micro earth pressure cells on both sides of the deep unloading belts of the left and right dam abutments were arranged to study the pressure changes at the arch abutment and the influence of the geological structure. The results showed that the measured stress value near the arch abutment was large and that the measured stress value greatly decreased after passing through the deep unloading belt. Class IV, of strongly relaxed rock masses in the left abutment exerted an obvious attenuation effect on the arch thrust while fault f29 (f74) greatly influenced the right abutment. The results were verified by the displacement test data. The application of micro earth pressure cells facilitated the direct observation and analysis of dam abutment stress and improved the completeness of the test results. Thus, the proposed approach provides a new idea for geomechanical model tests.

1. Introduction
Arch dams are suitable for the construction of “U”-shaped and “V”-shaped valleys with superior economy and safety, but they are also the most complex dam type [1]. When retaining water, an arch dam mainly bears the upstream water pressure and sediment pressure and transmits the upstream load to the rock masses on both abutments through an arch action. A small part of the load is transmitted to the bedrock at the bottom of the dam through the action of a vertical beam. Therefore, the reaction of the rock masses on both sides of the abutments is the key to maintaining the stability of the arch dam. One of the major failure modes for high-arch dams is dam abutment rock instability [2]. The problem of arch dam abutment stability is especially prominent when the abutment rock mass contains fault, joints, deep unloading zones, and other unfavorable geological structures. Geomechanical model tests are one of the most effective methods to study this problem.
Many geomechanical model tests have been carried out on arch dams. Zhang [3] obtained the stress and displacement distribution of a dam and the failure mechanism and process of the abutment and dam body by carrying out a geomechanical model test on the Dagangshan arch dam. By employing the comprehensive method of overloading and strength reduction, Zhang [4] studied the deformation characteristics and failure conditions and mechanisms of the dam foundation and abutment of the Jingping arch dam. Tao [5] obtained data pertaining to displacement, stresses, acoustic emissions, and the entire failure process during an overloading test, along with the safety factors. These tests were mainly carried out to obtain the distribution and development of surface displacement and strain during the overloading process by arranging the surface points on the dam body and rock mass. Yang [6] and Yang [7] developed the structure inbuilt displacement measurement system, which can measure the relative displacement of weak structural planes in abutment rock masses. Through their study of surface displacement, strain, relative displacement of structural plane, and cracking and failure of the model, they comprehensively evaluated the overall stability and safety of the arch dam. They then proposed safety standards that may serve as basis for the safety evaluation and implementation of reinforcement measures for arch dams.

The results of displacement monitoring can reflect the distribution and variation of thrust at the dam abutment, but they do not provide the specific thrust value. Given the high bulk density and low modulus of the model material, strain gauges cannot be directly pasted on the model of rock mass for the strain test. Therefore, reflecting the influence of geological structures on the basis of the numerical value and variation of arch thrust in a geomechanical model test of an arch dam is impossible.

In this study, the strain-type micro earth pressure cell was applied to a geomechanical model test on the Yebatan arch dam with a deep unloading belt on both abutments. The overloading test of the geomechanical model plane was carried out at the typical elevation of 2,750 m of the arch dam. In the test, a surface displacement monitoring system and micro earth pressure cells were arranged in the model to study the pressure changes at the arch abutment and the influence of the geological structure. With their advantageous properties, including their small size, high sensitivity, and strong stability, the micro earth pressure cells could directly monitor the stress change of the rock mass on the abutment during the test. Through the results of the displacement and earth pressure cells, the process of failure and instability of the rock mass and the influence of the geological structure could be understood clearly. The application of micro earth pressure cells thus provides a new idea for geomechanical model tests.

2. Micro earth pressure cells

2.1. Working principle

The XY-TY02A series of earth pressure cells is specially tailored to model tests for measuring contact pressure. An earth pressure cell adopts the principle of strained full-bridge circuit. A high-precision full-bridge strain gauge is pasted inside the sensor sensing membrane. When external pressure acts on the surface of the sensing membrane, the membrane is deformed and transmitted to the strain gauge, thereby causing strain in the strain gauge. The corresponding external pressure can be obtained using the strain collection equipment for collecting strain change information and processing the calculation. A strain-type micro earth pressure cell is shown in Figure 1. Strain-type micro earth pressure cell. A large number of model tests in geotechnical engineering tests are related to the problem of earth pressure testing. An earth pressure cell is typically buried in the measured medium, and the strain signal is output on the basis of the deformation of the measured medium; then, the stress at the measuring point is determined by the calibration parameters of the earth pressure cell [8].
2.2. Main parameters of micro earth pressure cell

Dimensions: 28 mm × 10 mm
Measuring range: 0.1–50 MPa
Nonlinearity: ±0.5% F·S
Sensitivity: 0.1% F·S
Impedance: 350 Ω
Use of ambient temperature: −20±70 °C

2.3. Instrument installation

The earth pressure cell is embedded in the position where the earth pressure changes, that is, the pressure curve changes, to monitor the interface earth pressure. In principle, the horizontal embedding interval of the earth pressure cell is more than thrice the spacing of the cell body (≥0.6 m). The vertical spacing is the same as the horizontal spacing. The pressure surface of the earth pressure cell should face the earth to be measured. During embedding, the surface of the earth bearing the earth pressure cell should be strictly leveled, and the backfilled earth should be the same as the surrounding earth and carefully rammed by an artificial layer.

2.4. Calibration of earth pressure cell

The earth pressure cell is calibrated such that the value of the load coefficient K varies in different media. The typical calibration curve is shown in Figure 2.

![Figure 2](image)

**Figure 2.** Result of typical calibration test of micro earth pressure cell.

According to the calibration curve, the load coefficient K is 0.371692. The load factor K given by the merchant is 0.372629, and the comparison of the two values shows an error of 0.25%.

3. Application of arch dam model test

3.1. Project overview and geological conditions

The Yebatan Hydropower Station is located at the main stream of the Jinsha River in Baiyu County, Sichuan Province, and Gongjue County, Xizang Province. The normal water level of the station is 2,889 m, and the storage capacity is 1.08 billion m³. The concrete double-curved arch dam is 217 m high. The project has many characteristics, such as “narrow valley, high-arch dam, large discharge volume, high seismic intensity”; as well as special geological factors, such as deep unloading belts. The deep unloading belts on both sides of the dam area of the Yebatan Project are distributed in the conventional unloading area. Controlled faults, long fractures, or slow dip angle dislocation zones are
developed with large single gaps or dense local gaps. Tensile cracks in a slightly stretched state or broken zones filled with sugar-like fragments are usually slightly weathered, and they are locally affected by the later stage of groundwater with a strong degree of weathering. The dip angle of the deep unloading structure surface mainly ranges from moderate to steep, and the trend is almost parallel to the trend of the fault or slope of the dam area. A tensile void, no filling, and a few sugar-like debris can be seen. The degree of weathering is generally weak, ranging from weak weathering to light weathering. Strong local weathering is caused by the later groundwater transformation.

3.2. Simulation range and major similarity coefficients of the model
The allowable range of the test site conditions and the relative position and strength characteristics of the arch abutment rock mass (2,750 m elevation) and structural plane are considered in this work, along with the test requirements. On the basis of these factors, the actual simulation range is determined to be 786 m × 660 m (horizontal × vertical), the model size is 3.93 m × 3.30 m (horizontal × vertical), and the height direction is 10 cm thick.

The main similarity coefficients used in this model test are as follows:

Geometric similarity coefficient: $C_L = 200$
Bulk density similarity coefficient: $C_γ = 1$
Friction similarity coefficient: $C_f = 1$
Poisson’s ratio similarity coefficient: $C_μ = 1$

Modular similarity coefficient: $C_E = 200$
Load similarity coefficient: $C_F = 200$
Cohesion similarity coefficient: $C_c = 200$
Strain similarity coefficient: $C_ε = 1$

3.3. Simulation of deep unloading belts and faults
For the rock mass in the deep unloading relaxation zone, a small diamond-shaped block with a side length of 9 cm and a thickness of 5 cm is selected for simulation according to the rock fracture characteristics. According to the development position of the unloading rock zone on the left and right sides of the geological structure map, the masonry is built on the basis of the occurrence of the dominant cracks and connectivity rate. For the deep unloading III and IVs rock bodies developed on the left bank and the deep unloading IVs rock body developed on the right bank, they are strong deep unloading relaxation zones. Hence, in simulating their broken and relaxed states, each small diamond-shaped block is cut into four small blocks. The masonry of the deep unloading zone in the model is shown in Figure 3.

![Figure 3](image-url)

(a) (b)

Figure 3. Masonry of deep unloading zone. (a) Left bank and (b) right bank.

According to the geological structure simulation plan, the model simulates 11 main faults (left and right bank penetration faults f9, f23, and f21; left abutment faults f22 and f24; right abutment faults f29 and f74, f71, f28, f31, and f85). The model must meet the requirements of mechanical similarity and geometric similarity. Mechanical similarity is mainly achieved by developing similar materials on the structural plane. Geometric similarity requires the simulation of structural characteristics, such as occurrence and bandwidth, according to the geological structure map when the model is made. The masonry of fault f29 (f74) is shown in Figure 4.
3.4. Displacement measurement system
A total of 68 surface displacement measuring points are arranged on the left and right abutments and the rock mass of the resistant body (i.e., 33 measuring points on the left bank and 35 measuring points on the right bank). At each measuring point on the left and right banks, the displacements along the river and the cross river are obtained. A total of 133 surface displacement meters are arranged on the left bank, and 65 surface displacement meters are arranged on the right bank. The measuring points, such as the left bank faults f21, f22, a24, a23, and f9; and the right bank faults f29 (f74), f9, f28, f85, f31, f71, and f23, are mainly arranged near the abutment and the exposed area of the weak structural plane to monitor their surface and mutual displacements. The displacement measurement system is shown in Figure 5.

3.5. Micro earth pressure cell measurement system
Six strain-type micro earth pressure cells are arranged within a certain range of the left and right abutments (three earth pressure cells on the left bank and three on the right bank) to study the rule of force transmission of the arch thrust at the abutments of the dam and to test the stress of the resistance body of the abutments. The location of the earth pressure cells is shown in Figure 6.
3.6. Loading method of the model
In a geomechanical model test, hydraulic pressure and small jacks are usually used for loading. In this work, hydraulic jacks are used for loading in the test, and the number and specification of the jacks used are determined by load distribution and block calculation.

4. Analysis of test results

4.1. Results of micro earth pressure cells
The relationship curve between the internal stress \( \sigma \) and the overloading coefficient \( K_p \) of the resistance body on both abutments can be obtained according to the stress measured by the micro earth pressure cells (Figure 7).

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\begin{array}{c}
\text{Figure 7. Curve of earth pressure } \sigma \text{ vs. overloading coefficient } K_p. \text{ (a) Right bank and (b) left bank.} \\
\text{According to the curve, the internal stress of the resistance body of the left and right dam abutments shows an increasing trend as the overloading coefficient increases. Moreover, the distribution of stress in the resistance body of the two abutments is symmetrical with respect to the center line of the arch dam to some extent. Comparing the stresses of #502 and #503 on the right bank shows that when } K_p < 1.0, \text{ the stress of the two measurement points is small and presents small fluctuations. When } K_p > 1.0, \text{ the stress gradually increases as the overloading coefficient } K_p \text{ increases. The stress value of #502 is also greater than that of #503. The measuring points #505 and #506 on the right bank have the same stress variation law. The test results appear to indicate that stress is high near the abutment and that the stress value gradually decreases from the abutment to the downstream.} \\
\text{For the measuring point #502, when } K_p = 1.0–2.6, \text{ the pressure shows an increasing trend with the increase of the overloading multiple. When } K_p = 2.6–4.0, \text{ the stress shows a decreasing trend. When } K_p = 2.4–2.6, \text{ a large deformation occurs in the dam body and rock masses of the abutment, the number of cracks increases, and the cracks quickly expand, resulting in stress redistribution in the overall structure. As } K_p \text{ further increases, the stress value of #502 declines. When } K_p = 3.8–4.2, \text{ penetrating cracks appear in the dam body and rock masses of the abutment, the intersection of the cracks becomes increasingly dense, and the overall structure breaks, resulting in slight fluctuations in the stress value of the resistance body.} \\
\text{According to the test results, the stress value of #503 is much lower than that of #502. In addition to being farther away from the abutment, fault f29 (f74) is crucial in the reduction of stress. On the left bank, the stress value of #506 is smaller than that of #505, but the reduction is smaller than that on the right bank because of the absence of a fault or deep unloading zone between the two measuring points. The test results indicate that fault f29 (f74) and Class IV\textsubscript{s} of strongly relaxed rock masses on the right bank exert a great reduction effect on stress.}
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4.2. Results of surface displacement gauges
The curve between the typical surface displacement \( \delta \) in the deep unloading zone and the overloading coefficient \( K_p \) is shown in Figure 8.
The test result indicates that the overall displacement along the river is greater than the cross-river displacement and that the overall displacement on the right bank is smaller than that on the left bank. As the rock masses between the deep unloading zone and left abutment are hard and complete, arch thrust is mostly transmitted to the deep unloading zone. The rock masses between the deep unloading zone on the right bank and the right abutment are less rigid and incomplete, and fault f29 (f74) has a large width and low strength. The arch thrust is first transmitted to fault f29 (f74) and then to the deep unloading zone on the right bank.

The location of the measuring points is shown in Figure 9. The red measuring points marked in the figure represent the selected series of measuring points.

Figure 8. Curve of displacement $\delta$ vs. overloading coefficient $Kp$ in deep unloading zone. (a) Displacement along the river and (b) cross-river displacement.

Figure 9. Distribution of measuring points in arch thrust direction.

The curve of the displacement and overloading coefficient of the rock masses on the left and right banks is shown in Figure 10 and Figure 11.

Figure 10. Curve of displacement along river $\delta$ vs. overloading coefficient $Kp$. (a) On the right bank and (b) on the left bank.
Figure 11. Curve of cross-river displacement $\delta$ vs. overloading coefficient $K_p$. (a) On the right bank and (b) on the left bank.

According to the test results, the displacement of the measuring points near the left and right abutments is larger than that of the measuring points far from the abutments. The displacement of the abutment rock masses along the river and the cross-river displacement generally decrease gradually from the two abutments to the two banks.

Comparing the displacements of the rock masses in the direction of the arch thrust on the left and right banks reveals obvious differences in the displacement of the measuring points on both sides of the fault. For example, the displacement along the river measured by #91 and #93 and the cross-river displacement measured by #92 and #94 vary greatly, although they are on both sides of fault f29 (f74) on the right bank. On the left bank, the influence of the strong relaxation rock mass IVs and fault f9 results in the large difference in the displacements of #19, #21, and #23 along the river and in the cross-river displacements of #20, #22, and #24.

4.3. Influence of weak structure plane on the stress distribution of arch dam abutment

The stress and displacement of the abutment rock masses are correlated to some extent. For the rock masses of the abutment, the weak structural zone destroys the overall integrity of the rock masses, and the fractures and faults reduce the degree of compactness between the rocks, resulting in the obvious reduction of stress. In intact rocks, the reduction in stress is relatively small.

In the geomechanical model of the arch dam, surface displacement gauges are applied to monitor the displacement of the rock masses on both abutments. In addition, earth pressure cells are applied to the measurement of the stress of the rock masses. The stress data are obtained directly, and an intuitive stress distribution law is derived. Comparing the test results of the earth pressure cells and surface displacement gauges shows that the two methods are consistent. The stress and displacement of the area near the abutment are large, whereas those in the deep unloading zone and fault are significantly reduced. On the left bank, Class IV, of strongly relaxed rock masses and fault f9 exert great impact. On the right bank, Class IV, of strongly relaxed rock masses and fault f29 (f74) exert much influence. The test proves that earth pressure cells carry certain use value in geomechanical model tests.

5. Conclusion

(1) With their advantageous properties, including their small volume, high sensitivity, and strong stability, micro earth pressure cells can directly monitor the stress changes in rock masses on abutments during geomechanical model tests. The application of micro earth pressure cells to model tests enables the direct detection of the changes in rock mass stress and the identification of the stress distribution law. Combined with the application of earth pressure cells and displacement gauges, the proposed approach yields a highly accurate conclusion.

(2) According to the monitoring results of the earth pressure cells, the stress in the resistance body of the dam abutments on both sides is relatively high near the abutment and decreases as the distance increases. Moreover, the magnitude of the stress gradually decreases from the abutment to the downstream. The faults on both banks and Class IV, of strongly relaxed rock masses exert a significant effect on stress reduction. Class IV, of strongly relaxed rock masses show a significant
attenuation effect on the arch thrust on the left bank, and fault f29 (f74) exerts great impact on stress reduction on the right bank.

(3) According to the results of surface displacement monitoring, the displacements of the measuring points near the left and right abutments are relatively large. Moreover, the displacement of the measuring points far from the abutments is small. The displacements of the measuring points on both sides of the fault and strong relaxation rock mass are also different.

(4) The test results of the earth pressure cells are consistent with those of the surface displacement gauges, thereby indicating that earth pressure cells carry a certain use value in geomechanical model tests. However, the application of earth pressure cells to these tests has limitations. For example, the result can only provide a qualitative and general description of the stress distribution law in the test. In future experiments, measuring points may be added, or comparative tests may be conducted.

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