Study on the deformation mechanism of abutment slope and its influence on the dam during the impoundment of high arch dam

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Abstract. The deformation of abutment slope during impoundment poses great challenges to the working behavior and long-term safety of the arch dam. According to the monitoring data of impoundment and slope, slope deformation, valley width change, and arch dam chord length change are systematically analyzed and studied. It is pointed out that the deformation of the dam body and foundation is an irreversible plastic deformation and is evidently correlated with impoundment. Based on the unsaturated effective stress principle of fractured rock mass and the action mode of the reservoir basin pressure, the deformation mechanism of abutment slope has been discussed. The large-scale 3D nonlinear finite element model is established based on numerical analysis, and the deformation mechanism during impoundment and the effect of the effective stress change on the displacement and stress of the dam body are analyzed. The results indicate that effective stress can elucidate the valley contraction to some extent and that the contribution of the reservoir basin pressure is small. Slope deformation is beneficial to the dam displacement to some extent. Moreover, it has a negligible influence on the dam surface stress. However, the junction of the dam and foundation needs to be given special attention.

1. Introduction
After the Ertan (240-m high) arch dam has started its operation, numerous extra-high arch dams have been built in southwest China, which include Jinping No. 1 (305-m high), Xiluodu (285.5-m high), and Xiaowan (295-m high). Until now, Xiaowan has been normally operating for 9 years, and Jinping No. 1 has undergone impoundment process for 8 years. River valley contraction and slope deformation caused by impoundment have become hot issues in the engineering research of high arch dams [1]. The arch dam-foundation system is a high-order statically indeterminate structure. The deformation of dam foundation, especially the non-uniform deformation, seriously affects the safety of the arch dam. In the 1960s, the left slope of the Beauregard arch dam in Italy underwent a deep-seated gravitational slope deformation (DSGSD), and the sliding speed was directly proportional to the increase in the water level of the reservoir. The left bank foundation slide caused the arch dam to be squeezed, the dam body tended to be deformed upstream, and the bottom of the downstream surface cracked horizontally [2]. The excavation of the surveying level hole of the Zeuzier arch dam in Switzerland changed the rock mass drainage, which resulted in uneven subsidence of the dam foundation. Moreover, the dam body was repaired and strengthened before normal operation was resumed [3,4]. With a height of 305 m, Jinping No. 1 arch dam is the world’s highest double-curved arch dam. In the
early stage of impoundment, the valley continues to contract with the increase in the water level of the reservoir. Moreover, it is greatly affected by impoundment, and so far, slope deformation has not fully converged [5,6]. Abnormal slope deformation caused by impoundment seriously threatens the safety of the arch dam. Thus, it is important to study the deformation mechanism of the slope to ensure the long-term stability and safe operation of extra-high arch dam. Currently, the mechanism explanation and quantitative analysis of slope deformation and valley contraction are seriously insufficient. In the past 50 years, it has been thought that the DSGSD in the Beauregard arch dam is caused by a reduction in the shear strength of the sliding surface of the left bank slope [2]. In China, numerous scholars have put forward their own views on this issue. Most studies on high slope deformation are based on numerical analysis. The causes of valley contraction include creep deformation [7, 8], change in pore water pressure, osmotic pressure increment, and softening of bubbly rock mass [9]. To study the decrease in valley width, the effective stress principle of unsaturated fractured rock mass is proposed, and it is considered that the decrease in valley width indicates the irreversible plastic deformation of the slope caused by the change in the effective stress due to impoundment [1].

In this study, based on the data of impoundment and slope monitoring, the deformation of abutment slope, change in valley width, and change in arch dam chord length are systematically analyzed. Then, the deformation mechanism of the slope is discussed based on the unsaturated effective stress principle of fractured rock mass, as well as the action mode of the reservoir basin pressure. A 3D nonlinear finite element model of the large-scale dam-foundation system is established to investigate the contribution of the effective stress principle of unsaturated fractured rock mass and the reservoir basin pressure to valley contraction. Based on numerical analysis, the effect of slope deformation on the dam body is analyzed.

2. Monitoring data of the deformation of Jinping No. 1 arch dam

The Jinping No. 1 reservoir, with a crest height of 1885 m, officially entered the impoundment period on November 30, 2012. By March 2018, it had undergone seven impoundment processes. The surface deformation measurement points are utilized to observe the surface rock mass deformation of the slope and monitor the overall macroscopic deformation of the slope. Figure 1 presents the horizontal displacement distribution diagram of the measured points of the left bank slope. The deformation characteristics of the dam and foundation are analyzed based on the following three aspects: slope deformation, valley width change, and arch dam chord length change.
Figure 1. Distribution of measuring points on the left bank slope

2.1. Slope deformation
The lower part of the dam crest elevation is greatly affected by impoundment. Thus, the lateral and vertical displacements of a typical measuring point of 1855 m elevation in the upstream region are selected for analysis, as can be seen from Figure 2. The positive lateral displacement indicates pointing to the riverbed, whereas the positive vertical displacement indicates lifting of the foundation. From Figure 2, it can be seen that the lateral and vertical displacements increase monotonously with the impoundment process and that the two are somewhat correlated. The displacement change rate and water level change also exhibit a certain correlation.

Figure 2. Variation curve of the lateral and vertical displacements of a measuring point at an elevation of 1855 m with the impoundment process: (a) displacement; (b) displacement change rate

2.2. Valley width change
A total of 20 measuring lines of river valley width are arranged in Jinping No. 1. In this paper, five representative lines are selected for analysis. As can be seen from Figure 3, the two valley width measuring lines (1–2) are located upstream, whereas the three valley width measuring lines (3–5) are located downstream. Figure 4 presents the curve of valley width change and water level change over time. Analysis of the monitoring data of the valley width reveals that the continuous contraction of the valley is an irreversible plastic deformation, without the alterations of contraction and expansion with the water level fluctuation.

Figure 3. Valley width measuring lines of Jinping No. 1

2.3. Arch dam chord length change

Figure 4. Curves of valley width change with the impoundment process
Figure 5 presents the distribution diagram of the chord length measuring lines of the dam body. The deformation of the chord length in April, August, and December of each year of each measuring line is selected. Moreover, the curve of the variation process of chord length deformation with time is illustrated in Figure 6. As can be seen from the figure, the line above the water level changes periodically due to the periodic change in the water level. The chord length below the water level continues to decrease, which is an irreversible plastic deformation. Finally, the chord length deformation tends to converge and starts to change periodically with the water level.

Figure 5. Schematic diagram of the monitoring arrangement of the dam chord length

Figure 6. Deformation process of the dam chord length

3. Analysis of the deformation mechanism during impoundment

3.1. Drucker–Prager criterion considering the effective stress principle

The Drucker–Prager (D-P) yield criterion is widely used in geotechnical engineering. It is expressed as follows:

\[ f(\sigma) = \alpha I_1 + \sqrt{J_2} - H \]  

where \( \alpha \) and \( H \) can be uniquely determined by the friction angle (\( \varphi \)) and cohesion (\( c \)) of the material by fitting the Mohr–Coulomb criterion.

Terzaghi proposed the concept of effective stress, which is applicable to porous media, such as soil, to analyze the influence of fluid in porous media on the deformation strength of geotechnical materials [10, 11]. The effective stress principle is based on saturated porous media. However, the actual rock mass is a heterogeneous material composed of rock blocks, faults, and cracks. In the initial stage of impoundment, the water rapidly flows along the main fissure, which is filled with water but not connected. The fracture is affected by self-balanced water pressure; thus, no seepage force or floating supporting force can be formed. For the rock mass fracture, the micro effect is hydraulic fracturing, whereas the macro effect is the strength reduction of the rock mass. The reduction is related to the fracture water pressure. The fracture water pressure changes its stable state only by means of effective stress. The effective stress principle is extended to the D-P yield criterion. Given that the pore pressure \( \sigma_0 \) is a spherical tensor, it only affects the size of \( I_1 \) and has nothing to do with that of \( J_2 \). Replace the \( \sigma \) in \( I_0 = \sigma_\mu \) with \( \sigma_\nu \) to obtain the D-P yield criterion, taking into account the effective stress principle:

\[ f(\sigma) = \alpha I_1 - 3\beta p_0 + \sqrt{J_2} - H \]  

where \( \beta \) is the Biot coefficient [12], and

\[ I_1 = \sigma_1 + \sigma_2 + \sigma_3 \]
\[ p_0 = -\gamma h \]
\[ J_z = \frac{S_y S_y}{2} = \frac{(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2}{6} \]  

(5)

The Biot coefficient of fractured rock mass reflects the saturation degree of the rock mass. At the initial stage of impoundment, the rock mass fracture is in an unsaturated state, and the Biot coefficient tends to 1.0; it is when the arch dam structure is the most dangerous. After long-term impoundment, once the rock mass fracture is fully saturated, the Biot coefficient tends to 0, and formula (2) degenerates into formula (1). Subsequently, it returns to the conventional pore seepage model. In this study, the D-P yield criterion considering the effective stress principle [13] was adopted to analyze the influence of the rising water level on slope deformation during the impoundment period.

3.2. Reservoir basin pressure

The reservoir basin pressure may cause the valley to contract or expand. As can be seen from Figure 7, one mode is that the bottom of the valley is subjected to reservoir basin pressure, and the bottom and top of the valley expand at the same time. Another is that the application of reservoir basin pressure at the bottom of the valley leads to bottom valley expansion and upper valley contraction. In this paper, to verify the action mode of the reservoir basin pressure, when calculating the action effect of the reservoir basin pressure, the surface of foundation is assumed to be an impermeable medium, and surface water load is applied on the surface element.

4. Numerical verification of the deformation mechanism

4.1. Model introduction

The simulation range of this model is 5000 × 5750 × 1520 m. The grid model uses eight-node hexahedron and six-node pentahedron elements. Moreover, the total number of nodes is 484167, the total number of elements is 461521, and the total number of the dam elements is 10360. In Figure 8, the calculation model and the overall computing grid are presented. The parameters of the calculation model are provided by the design institute, and the material parameters are obtained by inversion.

**Figure 7.** The action modes of the reservoir basin pressure: (a) expansion at the bottom and contraction at the top; (b) expansion at the bottom and top
4.2. Calculation results of effective stress

Based on the D-P yield criterion, considering the effective stress principle in Section 3.1, the river valley width deformation increment due to impoundment in the third (1800–1840 m) and fourth (1840–1880 m) stages of Jinping No. 1 arch dam is simulated and calculated. To facilitate comparison with the monitoring data, the valley width measuring lines consistent with Figure 2 are selected. As can be seen from Table 1, for the upstream valley width measuring lines 1 and 2, the calculated value after using the effective stress is in good agreement with the measured value. Conversely, the downstream valley measuring lines 3, 4, and 5 are not in good agreement, which may be due to the effect range of the effective stress mainly upstream. In the analysis of impoundment in the fourth stage, the calculated value and monitored value are in the same deformation direction toward the valley, which can explain the contraction of the valley to some extent.

Table 1. Incremental value of the valley width caused by the change in the effective stress for impoundment in the third and fourth stages (mm)

| Measuring line | Location   | Elevation | The third stage | Monitoring value | The fourth stage | Monitoring value |
|----------------|------------|-----------|-----------------|------------------|------------------|------------------|
| 1              | Upstream   | 1917 m    | −3.95           | −5.51            | −4.14            | −10.7            |
| 2              | Upstream   | 1930 m    | −1.33           | −3.44            | −1.51            | −6.15            |
| 3              | Downstream | 1930 m    | −9.52           | −1.62            | −1.27            | −6.00            |
| 4              | Downstream | 1829 m    | 0.72            | −1.85            | −0.96            | −1.30            |
| 5              | Downstream | 1829 m    | 0.73            | −0.55            | −0.93            | −3.05            |

4.3. Calculation results of the reservoir basin pressure

To study the contribution of basin pressure to valley contraction and the range of its influence in the third and fourth stages of impoundment, reservoir basin pressure is first applied in the range of 0–4000 m upstream of the dam. Then, the reservoir basin is divided into two areas: 0–1700 m and 1700–4000 m, respectively, as can be seen from Figure 9. The variation values of the river valley width change under the water pressure of the three kinds of range are presented in Figure 10. The results indicate that the river valley above the dam crest contracts to some extent by reservoir basin pressure. However, its magnitude is small, and it is not the main factor for the river valley contraction. The reservoir basin pressure far away from the dam site has negligible effect on valley contraction.
4.4. Summary of deformation mechanism

The increase in the reservoir basin pressure and the change in the effective stress due to the increase in the water level lead to the decrease in the width of the high elevation part of the valley upstream. The water pressure on the reservoir basin has negligible contribution to valley contraction, which leads to bottom valley expansion and upper valley contraction to some extent. The change in the effective stress significantly contributes to valley contraction and may be the main factor leading to valley contraction.

5. Influence of slope deformation on arch dam

This section calculates the displacement and stress of the dam caused by the change in the effective stress in the third stage. Considering the dead weight, temperature field, and dam surface water load, the effect of the effective stress change caused by the upstream water level increasing from 1800 to 1840 m is taken into account.

5.1. Influence on arch dam displacement

As the water level increases from 1800 to 1840 m, the effective stress in the foundation changes, and the displacement increment of the arch crown and two arch abutments is presented in Figure 11. The change in the effective stress has a certain effect on the displacement of crown cantilever and arch abutments. The left and right arch abutments are deformed toward the riverbed, causing a slight squeezing effect on the arch dam. The displacement of crown cantilever along the river decreases, which offsets part of the water load of the upstream dam surface and is beneficial to the dam body.
5.2. Influence on arch dam stress

Figure 12 presents the vector diagram of stress increment in the upstream and downstream dam surface caused by the change in effective stress. Effective stress has a negligible influence on the dam surface stress, and its influence area is mainly located at the junction of the dam and foundation.

6. Conclusions

In this paper, the monitoring data of Jinping No. 1 are systematically analyzed. On the basis of the principle of unsaturated effective stress of fractured rock mass and the action mode of the reservoir basin pressure, the deformation mechanism of the bank slope is discussed. Based on numerical analysis, the contribution of the effective stress of the rock mass and reservoir basin pressure to valley contraction is investigated. Moreover, the influence of slope deformation on arch dam body is analyzed. The main conclusions drawn from this study are as follows:

1. Based on the systematic collation and analysis of the monitoring data, it is pointed out that an obvious correlation exists between reservoir impoundment and dam body deformation and foundation, the change in valley width and chord length all have a large degree of irreversible plastic deformation.

2. The mechanism analysis and numerical verification demonstrate that the effective stress principle of the rock mass can elucidate the valley contraction phenomenon to some extent, and the reservoir basin pressure can cause the deformation of the slope near the dam area to the riverbed.

3. Slope deformation caused by the change in the effective stress is beneficial to dam displacement to some extent. However, the stress concentration in the local area of the interface between the dam and foundation caused by the change in the effective stress of the foundation has a significant influence on the local failure and long-term stability of the arch dam.

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