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

X W Wang¹, J R Xu², L J Xue³, M J He³, W D Zhang², Y R Liu³*, D N Zhong², J J Gu², Q Yang¹

¹State Key Laboratory of Hydrosience and Hydraulic Engineering, Tsinghua University, Beijing 100084, China
²PowerChina Huadong Engineering Corporation Limited, Hangzhou, 311122, China
³PowerChina Chengdu Engineering Corporation Limited, Chengdu 610072, China

Corresponding author ‘s e-mail: liuyaru@tsinghua.edu.cn

Abstract. High arch dams in China have been impounded and entered the operation stage in succession. The value and law of deformation during impoundment are different, which brings a great challenge to the performance and long-term safety of the arch dam. Based on the analysis of monitoring data of Jinping No.1 arch dam and Xiluodu arch dam, it is pointed out that the valley width deformation is irreversible plastic deformation, and there are two modes of valley width deformation of dam foundation: bank slope deformation mode and overall deformation mode. The bank slope deformation mode shows that the valley width of the upstream is significantly larger than that of the downstream, and the chord length of the dam is not large. Based on the principle of effective stress, the deformation mechanism of bank slope deformation mode is discussed. The overall deformation mode shows that the valley width of the upper and lower reaches is similar and the magnitude is large, and the chord length of the dam is large. The boundary displacement method is used to simulate the overall deformation mode. The model of Baihetan arch dam is established, and the structural model and geological conditions of the dam site are simulated in detail. Based on 3D nonlinear finite element calculation, the effects of two valley width deformation modes on the displacement, stress and local cracking of Baihetan arch dam are analyzed, and the calculated results are compared. The results show that the overall deformation mode can cause infinite valley width deformation, while the bank slope deformation mode can only cause limited valley width deformation. When the same valley shrinkage value is produced, the bank slope deformation mode can make the dam produce new stress concentration area, and the overall deformation mode has little effect on the dam stress, which indicates that the non-uniform deformation of the dam foundation is the key to affect the stress in the dam.

1. Introduction

In China’s southwest, northwest and other areas, water conservancy and hydropower construction has achieved vigorous development. At present, four 300m-grade high arch dams have been put into operation in China, namely Xiaowan(295m high), Jinping No.1(305m high), Xiluodu(285.5m high) and Baihetan(289m high), which indicates that the construction of high arch dams is gradually transforming from the construction period to the operation period. The different slope deformation modes caused by impoundment bring great challenges to the performance and long-term safety of the arch dam.

Arch dam is a high order statically indeterminate structure, which is sensitive to the deformation of dam foundation, especially the non-uniform deformation of dam foundation. The Kolnbrien arch dam in Austria is 200 meters high. Under the action of high water pressure at the early stage of
impoundment, shear and tensile cracks appear at the bottom of the dam heel [1,2]. The Malpasset arch dam in France broke after five years of impoundment. The change of stress state in the contact area between the dam and the foundation and the redistribution of load transmitted by the dam to the foundation should be the fundamental reason to affect the change of foundation strength [3,4]. After impoundment, Xiluodu arch dam in China has a certain degree of valley shrinkage, and the dam deforms upstream. Affected by this, the auxiliary weir corridor and water cushion pond appear compression cracking [5]. The abnormal deformation of the slope caused by impoundment seriously threatens the safety of the arch dam. It is of great significance to study the influence of slope deformation mode on the arch dam to ensure the long-term stability and safe operation of high arch dams.

Many scholars have studied the mechanism of slope deformation and the influence of slope deformation on dam, but there is no unified understanding yet. As for the mechanism of the valley width deformation of Xiluodu, through the regression analysis of monitoring data, it is pointed out that the valley width deformation process had a weak correlation with the change process of reservoir water level [5]. Zhang et al. studied the deformation and stress characteristics of Xiluodu arch dam by taking the reservoir water action as the reservoir pressure and osmotic pressure respectively [6]. Frigerio and Mazza analyzed the effect of sliding deformation of the left bank of Beauregard arch dam on the dam based on boundary displacement method [7]. Yang et al. proposed the effective stress principle to explain the mechanism of slope deformation and analyze the influence on arch dam [8].

In this study, based on the reservoir storage and slope monitoring data, the deformation mode of the dam foundation slope is analyzed. Based on the principle of effective stress and boundary displacement method, the deformation mode of slope is discussed. The 3D nonlinear finite element model of dam-foundation system is established, and the effects of two deformation modes on the displacement, stress and local cracking of the dam are studied.

2. Monitoring data of the deformation of arch dam

2.1. Jinping No.1 arch dam

Jinping No.1 arch dam [9], with a height of 305m, officially entered the impoundment period in November 2012. Figure 1 shows the position of valley width survey line and chord length survey line. Figure 2 shows the time-history curve of deformation and reservoir water level, and the negative value means contraction. As can be seen from the figure 2, valley width deformation is an irreversible plastic deformation that does not decrease with the drop of water level, but the rate of valley deformation gradually slows down. In the whole process of water storage, the deformation of the upstream survey line is greater than that of the downstream. The chord length deformation is an irreversible plastic deformation and its magnitude is between the valley width deformation of the upper and lower reaches.

![Figure 1. Valley width survey lines of Jinping No.1.](image)

![Figure 2. Curves of deformation value with the impounding process.](image)
Figure 4 shows the time-history curve of deformation and reservoir water level, and the negative value means contraction. Similar to the law of Jinping No.1 arch dam, the valley width deformation is an irreversible plastic deformation that does not decrease with the drop of water level, and the rate of valley shrinkage is gradually slowing down. During the whole process of impoundment, the deformation of the upstream valley width is basically similar to that of the downstream. The variation law of chord length deformation and valley width deformation is basically the same, but the magnitude of chord length deformation is slightly smaller than valley width deformation due to the effect of arch thrust.

2.3. Summarization of deformation modes

The valley width deformation can be divided into two modes by comparing the monitoring results of Jinping No.1 arch dam and Xiluodu arch dam:

1) Bank slope deformation mode: the valley width deformation value of the upstream is significantly greater than that of the downstream. The deformation of chord length of dam is not large and between the valley width deformation of upstream and downstream. The typical project is Jinping No.1 arch dam.

2) The overall deformation mode: the valley width deformation of the upper and lower reaches are similar and the magnitude is large. The chord length deformation of the dam is large but less than the valley width deformation of the upstream and downstream. The typical project is Xiluodu arch dam.

3. Analysis of deformation mechanism during impounding

3.1. Drucker-Prager yield criterion considering effective stress principle

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

\[ f(\sigma) = \alpha I_1 + \sqrt{J_2} - H \]  \hspace{1cm} (1)

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

The effective stress principle is extended to D-P criterion. We can get:

\[ f(\sigma) = \alpha (I_1 - 3\beta p_0) + \sqrt{J_2} - H \]  \hspace{1cm} (2)

Where \( \beta \) is Biot coefficient [10], and

\[ I_1 = \sigma_1 + \sigma_2 + \sigma_3 \]  \hspace{1cm} (3)

\[ p_0 = -\gamma h \]  \hspace{1cm} (4)
According to the above equation, the effect of effective stress change on the yield state can be simulated. In this study, D-P criterion considering the principle of effective stress [11] was used to analyze the influence of rising water level on slope deformation during the impounding period.

3.2. Boundary displacement method

After the long-term deformation of the slope is obtained, the effect of the slope deformation on the arch dam can be analyzed by the boundary displacement method [12]. As shown in figure 5, the simple support constraint of the boundary part of the finite element model is removed, and the fixed displacement condition of a specific mode is applied to cause the corresponding deformation of the slope, and the influence of long-term deformation of the slope on the arch dam is analyzed. At the same time, the sensitivity analysis can be carried out by the overloading boundary displacement.

4. Numerical verification of deformation mechanism

4.1. Calculation Model

The simulation range of this model is 7.5km×5.3m×1.7km. The grid model adopts eight-node hexahedron and six-node pentahedron elements, and the total number of nodes is 336102, the total number of elements is 315201 and the total number of the dam elements is 21104. The calculation model and the overall computing grid are shown in figure 6. Figure 7 shows the positions of valley width and chord length survey lines arranged in Baihetan arch dam.

4.2. Results by effective stress method

Table 1 shows the shrinkage values of five survey lines under the action of effective stress, and the negative value means contraction. It can be seen that the effect of effective stress on the upstream is
greater than that on the downstream. With the increase of the water level, the range of effective stress and the water head also increased gradually, and the valley shrinkage value increased in both upstream and downstream, but the increase rate in upstream is greater than that in downstream. The deformation of chord length of dam is not large and between the valley width deformation of upstream and downstream. Therefore, the effective stress can simulate the bank slope deformation mode.

Table 1. Incremental value of valley width caused by change of effective stress (mm).

| Measuring Line | Location     | Elevation | 765m | 785m | 800m | 825m |
|----------------|--------------|-----------|------|------|------|------|
| 1              | Upstream     | 834m      | -15.54 | -20.65 | -25.53 | -36.55 |
| 2              | Upstream     | 834m      | -12.15 | -17.01 | -21.52 | -31.41 |
| 3              | Chord Length | 834m      | -2.83  | -3.57  | -4.20  | -5.63  |
| 4              | Downstream   | 834m      | -2.16  | -2.73  | -3.21  | -4.31  |
| 5              | Downstream   | 834m      | -1.55  | -1.97  | -2.33  | -3.10  |

4.3. Results by boundary displacement method

As shown in figure 5, the geological conditions of Baihetan are complex and asymmetrical, and the geological conditions of the left bank are worse than that of the right bank, after the displacement ‘a’ of the left bank slope is given, the right bank displacement is simulated as ‘a/2’. Table 2 shows the shrinkage values of five survey lines under the action of boundary displacement, and the negative value means contraction. The valley width deformation of the upper and lower reaches are similar and the magnitude is large. The chord length deformation of the dam is large but less than the valley width deformation of the upstream and downstream. Therefore, the method based on boundary displacement can simulate the overall deformation mode.

Table 2. Incremental value of valley width caused by boundary displacement (mm).

| Measuring Line | Location     | Elevation | a=180mm | a=360mm | a=540mm | a=900mm |
|----------------|--------------|-----------|---------|---------|---------|---------|
| 1              | Upstream     | 834m      | -23.60  | -47.57  | -72.28  | -123.62 |
| 2              | Upstream     | 834m      | -25.19  | -50.59  | -76.66  | -130.51 |
| 3              | Chord Length | 834m      | -25.34  | -50.60  | -76.18  | -127.97 |
| 4              | Downstream   | 834m      | -26.53  | -53.03  | -79.89  | -134.40 |
| 5              | Downstream   | 834m      | -28.42  | -56.82  | -85.63  | -144.16 |

5. Influence of slope deformation on arch dam

This section calculates the displacement, stress and local cracking of the dam caused by the bank slope deformation mode and the overall slope deformation mode. On the basis of considering the dead weight, temperature field and dam surface water load, the effective stress and boundary displacement are calculated respectively.

5.1. Influence on arch dam displacement

The displacement at the junction of the downstream dam surface and foundation surface is selected to represent the deformation of the dam foundation. Figure 8 shows the displacement caused by effective stress under the water level of 825m, and figure 9 shows the displacement caused by boundary displacement under the water level of 825m. It can be seen that the bank slope deformation mode based on the effective stress can cause the non-uniform deformation of the dam foundation, while the slope deformation mode based on the boundary displacement can hardly cause the non-uniform deformation.

5.2. Influence on arch dam stress

Figure 10 shows the range where the tensile stress on the dam foundation surface is greater than 1.5MPa under the action of effective stress, ‘a=180mm’ and ‘a=5400mm’. It can be seen that the
Effective stress change can make the dam produce new stress concentration area, but the boundary displacement has very little influence on the stress. Only when the boundary displacement is large enough will a range of tensile stresses occur. The change of effective stress can lead to the concentration of tensile stress at the downstream arch, while the boundary displacement mainly compresses the arch dam, showing a large compressive stress.

![Figure 8. Displacement caused by change of effective stress](image)

![Figure 9. Displacement caused by boundary displacement (a=180mm).](image)

![Figure 10. The range of tensile stress greater than 1.5MPa: (a) effective stress; (b) a=180mm; (c) a=5400mm.](image)

### 5.3. Influence on local cracking of arch dam
Figure 11 shows the distribution range of the yield zone on the foundation surface under the action of effective stress, ‘a=180mm’ and ‘a=5400mm’. The change of effective stress can cause a certain range of yield zone, but yield zone will appear only when the boundary displacement is large enough. The yield caused by effective stress change is mainly tensile failure and tension-shear failure, while the yield caused by boundary displacement is mainly shear failure.

![Figure 11. The distribution range of the yield zone: (a) effective stress; (b) a=180mm; (c) a=5400mm.](image)

### 6. Conclusion
In this paper, the monitoring data of Jinping No.1 and Xiluodu are analyzed. Based on the principle of effective stress and boundary displacement method, the slope deformation mode is discussed. Based on numerical analysis, the effect of effective stress and boundary displacement method on dam-foundation system is studied, and the influence of slope deformation mode on arch dam is analyzed. The main conclusions are as follows:

1. Based on the monitoring data, slope deformation is divided into two modes. One is the bank slope deformation mode. The valley width deformation of the upstream is significantly greater than that of the downstream, and the chord length deformation value of the dam body is little. The typical project is Jinping No.1 arch dam. Another is the overall deformation mode. The valley width deformation of the upper and lower reaches is similar and the magnitude is large. The chord length deformation of the dam is large but less than the valley width deformation of the upstream and downstream. The typical project is Xiluodu arch dam.
(2) The bank slope deformation mode can be simulated by effective stress principle and the overall deformation mode can be simulated by boundary displacement method. The overall deformation mode can cause infinite valley width deformation of the dam foundation, while the bank slope deformation mode can only cause limited valley width deformation.

(3) When the same valley shrinkage value is produced, the bank slope deformation mode can make the dam produce new stress concentration area, and the overall deformation mode has little effect on the dam stress, which indicates that the non-uniform deformation of the dam foundation is the key to affect the stress in the dam body.

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