Study on the working performance of Wudongde Arch Dam during the first impounding period

Weisheng Du\textsuperscript{1,2,*}, Peng Lin\textsuperscript{2}, Ning Yang\textsuperscript{3}, Jianshu Ouyang\textsuperscript{2}

\textsuperscript{1}Deep Mining and Rock Burst Research Institute, China Coal Research Academy, Beijing 100013, China, duweisheng1225@126.com
\textsuperscript{2} State Key Laboratory of Hydroscience and Engineering, Tsinghua University, Beijing, China, 100084
\textsuperscript{3} China Three Gorges Corporation, Beijing, China, 100038

Abstract: The first impounding process in the foundation pit of an arch dam will lead to stress redistribution, and the working state of the dam needs to be reanalyzed. Taking the Wudongde Arch Dam under construction in China as the engineering background, ABAQUS finite element analysis software simulates the dam stress distribution and transverse seam opening of Wudongde Dam under four different impounding elevations. According to stress distribution and the opening degree of transverse seams, the optimal impounding elevation with the most negligible influence on the joint grouting process is determined. The simulation results indicate that the pressure generated by impounding will increase the dam deformation to the downstream river and banks. The maximum compressive stress of the upstream dam heel and the maximum tensile stress of the left and right arch abutments would decrease to some extent after impounding. The transverse seams have a tight compression tendency after impounding, and this tendency increases as the water level rises. According to the simulation results, the working performance of the dam is the best when the elevation difference between the impounding elevation and the joint grouting elevation is 36 m. Timely impounding is beneficial to the stress state of the dam and joint grouting process during the construction period.

Keywords: Impounding; Dam deformation; Stress distribution; Transverse seam opening

1. Introduction
Developing hydropower is of great significance for reducing carbon emissions and promoting sustainable energy development. There are abundant hydropower resources in Southwest China, and several super-high arch dams are under construction. The first impounding process has a negligible impact on the stability of dams (Akhtarpour and Salari, 2018). Whether the dam can keep a stable working state and the dam construction process can be fully controlled are closely related to the construction quality and safety of the dam. Therefore, the research on the actual working state of the dam during the impounding process of the foundation pit has essential engineering significance (Zhang et al., 2019). Many scholars have studied the working behavior of the dam during the first impounding period.

During the impounding process of the dam foundation pit, the upstream and downstream water levels vary frequently. The gravity effect, hydrostatic pressure effect and uplift pressure effect caused by the additional reservoir water load would affect the horizontal and vertical deformation of the dam body and foundation. The research on specific effects has achieved preliminary results. Monitoring methods are used in most of these studies. In terms of the deformation of dams, the displacement of Xiluodu Dam (Zhang et al., 2015), Xiaowan Dam (Han et al., 2010), Lijiaxia Dam (Yang et al., 2006), Goupitan Dam (Wang et al., 2010) during the first impounding period are analyzed. The analysis results show that the displacement of the dam body during the impounding process is mainly affected by the reservoir water level and temperature. Guan et al. (2006) pointed out that the deformation of the dam top is affected by
the temperature. The effect of impounding on the stress distribution of dams cannot be ignored. Scholars mainly use field monitoring and finite element analysis to study this problem. Fu et al. (1998) used the strain gauges, non-stress gauges and thermometers embedded to monitor the stress of the dam body during the first storage period of Tiantangshan Arch Dam, and pointed out that the stress was mainly controlled by the external temperature and water storage level. Sun et al. (2006) used the data from the gravity monitoring network of Three Gorges Dam to analyze the gravity effect of the dam area before and after impounding process.

The impounding process also affects the opening and closing of the transverse joint. When the foundation pit is filled with water, the concrete grouting process on the upper part of the dam is still ongoing, and the pressure of the reservoir water compacts the cross-section surface. Exploring the effect of water storage on the opening of the upper transverse joint is of great significance for the reasonable control of impounding to ensure the grouting effect. Han (2003) proposed a formula for calculating the change in width of transverse joints under hydraulic pressure based on the arch beam splitting method. Li et al. (2008) also researched arch sealing and grouting during the impounding process in Jinping Dam and obtained similar conclusions.

Wudongde Dam is located on the Jinsha River at the junction of Luquan County, Yunnan Province, and Huidong County, Sichuan Province, China. The dam is currently in the critical period of initial impounding, and the choice of impounding elevation is crucial. Wudongde Dam is a double-curved arch dam with a design elevation of 718 m at the base level, a 988 m elevation at the top of the dam, and a maximum 270 m dam height. Studying the actual working state of the dam during the impounding process of the dam foundation pit is of great significance to ensure the standard construction progress and control the construction quality.

2. Analysis method and Model

2.1 Yield criterion of the analysis

The three-dimensional finite element analysis method is adopted in this study, and the yield criterion is the Drucker-Prager (D-P) criterion, as shown in Eq. (1).

\[ f = \alpha I_1 + J_2^{\phi} - H = 0 \]  

where \( I_1 \) is the first invariant of stress, and \( J_2 \) is the second invariant of stress. The expressions of \( \alpha \) and \( H \) are shown in Eqs. (2) and (3).

\[ \alpha = \frac{3c\phi}{\sqrt{9 + 12c^2\phi}} \]  

\[ H = \frac{3c}{\sqrt{9 + 12c^2\phi}} \]  

where \( c \) is the cohesion and \( \phi \) is the friction angle.

The D-P criterion is consistent with the Mohr-Coulomb (M-C) yield criterion under plane strain conditions. It represents the D-P circle that takes the middle value of the circumscribed and inscribed M-C hexagon. Non-linear iteration is performed according to the elastoplastic fracture method, and the contours of the unbalanced force upstream and downstream of the dam such as plastic yield, subcritical fracture, buckling expansion, and point safety and overload are calculated.

2.2 Simulation method of transverse joint

The concrete arch dam is gradually formed as a whole by stage sealing and grouting. Simulating the opening, closing and dislocation behaviour of transverse joints under external load is an essential aspect
of evaluating the initial stress, deformation and overall stability of the storage dam. The contact surface theory and Newton-Raphason method are used to define the transverse joint. In the Newton-Raphason method, the first few terms of the Taylor series of the function \( f(x) \) are used to find the root of the equation \( f(x) = 0 \). The advantage of this method is that the square converges near the single root of the equation \( f(x) = 0 \). It can also be used to find multiple roots and complex roots of equations.

During the simulation process, the contact is defined by surface-surface, the contact attribute is taken as the friction type of the penalty function. The grouted transverse joint surface is set as non-contact in the calculation. The non-grouted transverse joint surface is set as the contact surface, and the initial state of the transverse joint opening is simplified to zero. This study focuses on examining the law of the influence of water impounding and increasing water load on the opening of transverse joints.

### 2.3 simulation model

The finite element software ABAQUS is used for model analysis. A three-dimensional model is used for analysis. The analysis range is nearly 1 time the dam height in the upstream, nearly 2 times the dam height in the downstream, and nearly 2 times the dam height on the left and right sides. The simulation depth is 1 time the height of the dam. The total simulation range is 1500 m × 1000 m × 660 m. The grid uses eight-node hexahedron and six-node pentahedron elements. The calculation grid is shown in Figure 1.

![Figure 1 Analytical model of a dam](image)

#### Table 1 Mechanical parameters of various materials

| Materials      | Density (g/cm³) | Deformation modulus (GPa) | Poisson's ratio | friction coefficient | cohesion (MPa) |
|----------------|-----------------|---------------------------|-----------------|----------------------|----------------|
| Dam            | 2.4             | 43.2                      | 0.170           | 1.7                  | 5.0            |
| Power house    | 2.4             | 43.2                      | 0.170           | 1.7                  | 5.0            |
| II₁            | 2.69            | 35                        | 0.22            | 1.5                  | 1.9            |
| II₂            | 2.69            | 20                        | 0.24            | 1.3                  | 1.6            |
| III₁           | 2.70            | 18                        | 0.25            | 1.1                  | 1.3            |
| III₂           | 2.70            | 10                        | 0.28            | 0.95                 | 1.0            |
| F₄₂ Fault      | 2.4             | 0.4                       | 0.3             | 0.4                  | 0.07           |

Various rock masses and faults are simulated in the model. In the simulation process, the ABAQUS built-in life and death unit technology simulates the image at different time nodes. The parameter values of the materials in the model are shown in Table 1. All the mechanical parameters of the materials are obtained based on the on-site geological survey. The materials have been marked in Figure 1. As Fault F₄₂ and powerhouse are inside the model, the fault and powerhouse are listed separately in Figure 1(b).

### 3. Simulation results of dam performance

The dam’s performance under 4 different working conditions is simulated in this section. In the four simulation cases, the elevations of the first impounding are 0 m, 808m, 817m, and 826m, respectively. The stress distribution of the dam and the displacement of the transverse joints are exhibited and analyzed below.
3.1 Transverse joints deformation analysis

Figure 2 shows the results of transverse joints deformation opening under different conditions. It can be seen from the simulation results:

(1) Comparing the working condition without water pressure and the working condition after impounding, it can be seen that the upstream water filling has a restraining effect on the transverse joints, which makes the transverse joints tend to close.

(2) Under the same working conditions, the deformation laws of the transverse joints of the dam sections are the same. The transverse seam opening of the bank slope dam section on both sides is obvious, and the maximum opening value of the transverse seam is located on both sides of the bank slope dam section. Taking Case 2 as an example, the tops of the 2 # and 13 # transverse joints on both sides of the bank slope dam open 4.25 mm and 2.65 mm, respectively.

(3) For the same horizontal seam, the top opening is the most obvious, and the bottom opening is the least obvious. Taking Dam Section 2 of Case 3 as an example, the opening degree of the horizontal seam gradually decreases from 4.05 mm to 0.51 mm from top to bottom.

(4) For different impounding conditions simultaneously, as the water-filled elevation increases, the opening of the transverse joint gradually decreases.

![Figure 2](image)

**Figure 2** Opening degree of transverse joints in all dam sections (unit: m)

3.2 Stress state of the dam
The first and third characteristic stress distribution of the foundation surface under each case condition is shown in Figs. 3~6.

1. The upstream dam heel is under pressure no matter under what conditions. Under the impact of impounding conditions, the maximum compressive stress of the upstream dam heel in each case decreases with the increase of the impounding height. The maximum compressive stress is 4.32 MPa, 4.19 MPa, 4.05 MPa.

2. As the difference between the impounding elevation and the grouting elevation increases, the decrease in the maximum compressive stress of the upstream dam heel gradually increases. In cases 1-4, the difference between the impounding elevation and the grouting elevation is 27 m, 36 m, and 45 m, the compressive stress reductions of upstream dam heel are 0.60 MPa, 0.73 MPa, and 0.87 MPa, respectively.

3. The downstream toe is under pressure in all cases. Under the impact of impounding, the maximum compressive stress downstream of the dam toe in each case increases with the increase of the impounding elevation; from cases 2 to 4, the maximum compressive stress is 2.84 MPa, 2.97 MPa, 3.10 MPa, respectively.

4. As the elevation difference between impounding and grouting increases, the maximum compressive stress at the downstream dam toe gradually increases. When the filling water elevation and grouting elevation differ by 27 m, 36 m, and 45 m, respectively, the increase in compressive stress at the downstream dam toe is 0.60 MPa, 0.73 MPa, and 0.86 MPa.

![Figure 3](image-url)
Figure 4 Distribution of the first and third principal stress on the foundation under the working case 2 (unit: Pa)

Figure 5 Distribution of the first and third principal stress on the foundation under the working case 3 (unit: Pa)
3.3 Comparison of calculation and monitoring results

The real-time monitoring system is installed on Wudongde Arch Dam to monitor the working performance of the dam accurately. Considering the water impounding conditions of the Wudongde Arch Dam, a comparative and analysis is carried out on the deformation of the transverse joints and the stress of the dam. In terms of stress, the calculated stress value is close to the monitored value in terms of magnitude, which is consistent with the behaviour of the arch dam. In terms of the deformation of the transverse joint, the calculated deformation of the transverse joint is slightly smaller than the actually monitored deformation, which may be caused by the grouting process. Although there are specific numerical differences between the calculation and real monitoring results of the stress and deformation of the dam, the essential characteristics are in good agreement, which conforms to the typical working performance of Wudongde Arch Dam.

4. Conclusions

By carrying out the overall working performance of Wudongde Arch Dam at different impounding elevations, the following conclusions were obtained:

(1) The upstream impounding has a restraining effect on the transverse joints, which causes the transverse joints to have a tight closing tendency. This constraint increases as the water level rises. After reaching a certain height, the hydraulic pressure has a significant effect on the joint width. The lower the impounding elevation, the more conducive to the grouting work.

(2) The maximum compressive stress of the upstream dam heel decreases with the increase of the impounding height under each working case, and the maximum compressive stress of the downstream dam toe increases with the increase of the impounding elevation. After impounding, the maximum tensile stress at the left and right arch ends decreases under the water pressure, and the decreased value increases with the filling height. The increase of impounding elevation is beneficial to the improvement of the dam body’s tensile performance.

(3) To facilitate the smooth implementation of joint grouting, while considering the improvement of the stress state of the dam, case 3 is regarded as the best impounding scheme, and the difference between the filling water elevation and the grouting elevation is 36 m.

Acknowledgments

The authors acknowledge the assistance from Wudongde Construction Department.

References

[1] Akhtarpour, A., Salari, M. (2018). The Deformation Mechanism of a High Rockfill Dam during the Construction and First Impounding. Scientia Iranica, 27(2): 566-587.
[2] Zhang G., Liu Y., Zhang L., Liu, Y., Li, S. (2019). The true working performance inversion simulation analysis of Jinping level-I arch dam. IOP Conference Series Materials Science and Engineering, 657:012001.
[3] Zhang, C., Wang, R., Tang, X. (2016). Safety evaluation of Xiluodu ultra-high arch dam during the initial impoundment period. Journal of Hydraulic Engineering, 47(1): 85-93.
[4] Han, S., Zhao, B., Liao, Z., Xia, J. (2010). On monitoring data by plumb lines in early impoundment period of Xiaowan dam. Dam and Safety, 03:38-41.
[5] Yang, J., Chen, D., Wang, J. (2006). Analysis of deflection displacement of Lijiaxia arch dam and abutment during water storage period. Yellow River, 05: 67-68+70.
[6] Wang, Z., Hu, Q., Yu, X., Duan, G. (2010). Analysis of operation condition of Goupitan Hydropower Station arch dam in initial impoundment period. Yangtze River,41(22):29-31.
[7] Guan, W. (2006). Study and application of safety monitoring models on concrete arch dam deformation analysis (Thesis). Xi’an University of Technology.

[8] Fu, W., Huang, P. (1998). Monitoring and stress analysis of the Tiantang Mountain Arch Dam during its water storage term. Journal of South China University of Technology, 06:103-109.

[9] Sun, S., Xiang, A., Zhu, P., Shen, C. (2006). Gravity change and its mechanism after the first water impoundment in Three Gorges Project. Acta Seismologica Sinica, 2006, 19(5): 522-529.

[10] Chen, Y. (1987). Effects of staged construction and staged water storage on dam body stress of Baishan Arch Dam. Northeast Water Resources and Hydropower, 02:17-22.

[11] Han, X. (2003). Study on working condition during construction period and integral degree of safety on Jinping Arch Dam (thesis). Guangxi University.

[12] Li, Z., Gu, Y., Zhang, L. (2008). MSC.Mar-based deformation analysis of high arch dam in water storage period. Advances in science and technology of water resources, 04:15-19.