Finite Element Calculation and Analysis of Stress and Deformation Characteristics of Arch Dam

Ping Wei¹*, Liuchuang Wei²

¹Faculty of Architectural Engineering, Kunming University, Yunnan Kunming 650214, China
²Faculty of Mechanical and Electrical Engineering, Kunming University, Yunnan Kunming 650214, China
*Corresponding author's e-mail: weiping1123@126.com

Abstract. The arch dam is a high-order and ultra-static overall space shell structure on the consolidation and bedrock, and its geometry, boundary conditions and stress state are complex. The three-dimensional finite element solid model of arch dam is established, and the stress and deformation characteristics of the actual dam project are calculated. It is concluded that there is a large tensile stress at the dam at the arch crown section and a large compressive stress at the dam site. The transverse displacement of the body occurs at the abutment of the upstream and downstream faces. The calculation results are in accordance with the stress and deformation characteristics of the arch dam, and the maximum stress and maximum displacement meet the design requirements of the arch dam.

1. Introduction
The arch dam is a statically indeterminate space shell structure fixed to the bedrock. The arch on the plane is convex upward, and the section of the crown beam is a vertical curve. The external load of the arch dam is transmitted to the rock mass of the dam by the action of the arch of the dam. The stress state of the dam is mainly stressed. The arch dam has good dam body and basic working conditions, strong overload capacity, good seismic performance, low dam accident and good durability. It has high comprehensive safety and gives full play to the advantages of high compressive strength of concrete. Larger economy, but the design of arch dams is relatively complex compared to other dam types.

2. Analysis of deformation characteristics of arch dam
When the external load increases and a part of the dam body is partially cracked due to excessive tensile stress, the arch dam can automatically adjust the role of the arch and the role of the beam and the distribution of the load to redistribute the internal stress. In this way, the load carrying capacity and overall stability of the dam can be maintained.

3. Finite element calculation and analysis of engineering examples
In the design and selection of a power station, a parabolic double-curved arch dam model is proposed; the dam crest elevation is 2460.0m, the base surface is 2210.0m, and the maximum dam height is 250.0m. It is a large-scale high arch dam dominated by power generation; The valley is narrow and the bank slope is steep and V-shaped; the river valleys on both banks are basically symmetrical, with an
average slope of 40° to 45°; the arch dam is shown in Figure 1. In the finite element analysis, the bedrock takes 1.5 times the dam height upstream, 2.5 times the dam height to the downstream, and 1 times the dam height to the left and right banks and the foundation depth. The working condition is: the upstream normal water level is 2452.0m. The downstream water level is 2243.5m; the upstream silt elevation is 2230.0m, the sediment float weight is 7.5kN/m³, and the internal friction angle is 12°; the dam body weight is considered according to the overall weight. The concrete strength of the dam is mainly C30 and C35, and the elastic modulus value of C30 is adopted. Considering the influence of continuous load, the calculation takes 2/3; the material parameters of the dam and dam foundation are shown in Table 1.

![Figure 1. Schematic diagram of double arch dam](image)

| Table 1. Arch dam material parameters |
|--------------------------------------|
| position                            | material parameters |
|                                      | density /kg/m³ | elastic modulus /MPa | poisson's ratio |
| dam body                            | 2400           | 20000               | 0.17            |
| dam foundation                      | 2200           | 23000               | 0.25            |

3.1. Hydrostatic pressure formula

\[ p = \gamma H \]  

Where: \( H \)—the water level from the upstream water level of the dam to the base surface of the dam; \( \gamma \)—The bulk weight of water.

In this analysis, water pressure loads were applied to the surface according to different water levels with a gradient of 9800 N/kg. The upstream and downstream water pressures are added to the upstream and downstream faces of the dam according to the water head. The weight of the arch dam body material is only considered by its own weight, and it is calculated by numerical integration method, and the influence of staged construction is not considered.

According to the Code for Design of Masonry Arch Dam, the sediment pressure is calculated according to the following formula.

\[ p_n = \frac{\gamma_r' h_n}{2} \tan^2 \left( \frac{45° - \Phi_n}{2} \right) \]  

\[ r'_n = r_1 - (1 - n) \gamma \]  

Where, \( h_n \)—Sediment deposition height in front of the dam; \( \Phi_n \)—The internal friction angle of the sediment; \( \gamma'_n \)—The floating capacity of the sediment is heavy; \( \gamma' \)—The dry bulk weight of the sediment; \( \gamma \)—The severity of water; \( n \)—The porosity of the sediment.
3.2. **SOLID95 unit modeling**

SOLID95 defines 20 nodes, each with 3 degrees of freedom in the X, Y, and Z directions. The SOLID95 unit has any orientation in space, and the unit has the ability of creep, radiation expansion, plasticity, stress stiffness, large strain and large deformation. Establish a SOLID95 unit analysis diagram, as shown in Figure 2.

![Figure 2. SOLID95 unit analysis](image)

3.3. **Solid modeling**

Apply SOLID95 to model the actual engineering dam body. The specific process: building the line-building surface-forming the dam foundation model-meshing, see Figure 3, Figure 4. After pre-processing, the cell type definition, material definition, section definition, and real constant definition of each unit are sequentially performed.

![Figure 3. Construction line, construction drawing](image)

![Figure 4. Dam foundation model and mesh map](image)

The arch dam structure is selected as the research object, and the interaction between the dam body, the water body and the foundation is considered. Calculation range: the bedrock takes 1.5 times the dam height upstream, 2.5 times the dam height to the downstream, and 1 times the dam height to the left and right banks and the foundation depth, regardless of all grouting and drainage in the dam. The dam and the foundation are divided into a finite element mesh as a whole structure. The hexahedral eight-node isoparametric element SOLID95 is used for analysis. When meshing the model, the method of dividing the mesh by sub-region is adopted. This method is beneficial to control the number of meshes and the accuracy of the calculation results.

When dividing the grid, the grids are divided into six different control elevations. Using the solid modeling tool, the structural model is divided by the SOLID95 unit (see Figure 5 for the dam finite element calculation model). Directional regulation: The X direction is positive to the right bank, the Y direction is positive to the downstream, the Z direction is positive to the vertical, and the coordinate system satisfies the right hand spiral rule. The basic constraint case: the left and right sides are bounded by the X direction, the upper and lower boundaries are bounded by the Y direction, and the bottom boundary is the fixed end constraint.
4. Dam stress analysis
The SOLID95 is used to calculate and analyze the stress in the x, y, and z directions of the dam and the first and third principal stress cloud diagrams, as shown in Figures 6 and 7.

![Figure 6. X, Y, Z direction stress cloud](image)

![Figure 7. First and third principal stress clouds](image)

The calculation results show that from Fig. 6 and 7, the maximum stress in all directions occurs near the dam site. The maximum stress occurring in the X direction is 0.520 MPa, and the minimum stress is -0.742 MPa. The maximum stress occurring in the Y direction is 0.258 MPa, and the minimum stress is -0.665 MPa. The maximum stress occurring in the Z direction is 0.459 MPa, and the minimum stress is -0.856 MPa. The maximum stress occurring in the first principal stress is 0.680 MPa, and the minimum stress is -0.186 MPa. The maximum stress at which the third principal stress occurs is 0.103 MPa, and the minimum stress is -0.111 MPa.

The analysis shows that the maximum displacement of the dam body occurs at the top of the arch crown beam, and the displacement along the river gradually increases with the increase of the elevation. At the same elevation, the displacement direction decreases from the arch crown to the two banks. The compressive stress at the crown of the upper part of the dam is larger and gradually decreases toward the two banks. The compressive stress at the arch end is the largest at the downstream end and gradually decreases toward the arch. On the arch crown section, large tensile stress occurs at the dam, and the compressive stress at the dam site is large.

5. Dam displacement analysis
The SOLID95 is used to calculate and analyze the displacement and displacement vector of the dam in the x, y, and z directions and as shown in Figures 8 and 9.

![Figure 8. X, Y, Z direction displacement map](image)
The calculation results show that in the case of normal water storage level, the maximum displacement occurring in the X direction in Figure 8 is 0.01665m, the minimum displacement is -0.0134m; the maximum displacement occurring in the Y direction is 0.0813m, and the minimum displacement is -0.00133m; the maximum displacement occurring in the Z direction is 0.0182m, and the minimum displacement is -0.224m. In Figure 9, the maximum displacement is 0.083m and the minimum displacement is 0.00233m.

The analysis shows that the maximum displacement and total displacement in the Y direction occur at the center of the upper part of the dam, and the maximum displacement decreases in a circular direction, which is consistent with the deformation characteristics of the arch dam. The maximum displacement value satisfies the normative design value.

6. Conclusion

The ANSYS software parametric design language was used to establish a three-dimensional finite element calculation model for an arch dam project. The finite element stress and displacement calculations were carried out under the action of water load, silt load and self-weight of the arch dam. The main research results are as follows:

(1) The results calculated by finite element are in accordance with the stress and deformation characteristics of the arch dam, and the maximum stress and maximum displacement meet the design requirements of the arch dam.

(2) The transverse displacement of the dam body occurs at the upstream and downstream abutment shoulders. On the arch section, large tensile stresses appear at the dam, and the compressive stress at the dam site is large.

(3) Due to the stress concentration caused by the sudden change of the geometry of the calculation model, the maximum tensile stress and maximum compressive stress of the dam body appear at the base surface of the dam body due to the finite element calculation results of the arch dam under complex loads. In addition to the stress concentration area, the stress state of the dam meets the arch dam stress control standard.

Acknowledgements

This paper has been supported with the science & technology plan item found from Yunnan Provincial Department of Science and Technology-university joint fund surface item (2018FH001-048) and the scientific research item found from Yunnan Provincial Department of Education (2014Y386).

References

[1] Wang H., (2006) Three-dimensional finite element static and dynamic analysis of masonry continuous arch dam based on ANSYS. Hehai University.

[2] Wei L., (2009) Research on Key Technologies of 3D Modeling Software for Arch Dam Structure. University of Electronic Science and Technology of China.

[3] Du Q., (2012) Modeling and Finite Element Analysis of Variable Diameter Involute Double Curved Arch Dam. Chongqing Jiaotong University.