Finite element analysis of stress in the gallery of gravity dam on inclined bedrock based on ANSYS model

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Abstract. Taking a variety of galleries in a concrete gravity dam body as the research object, it analyzes the changing law of stress concentration phenomenon around the galleries in the dam body affected by the holes of the galleries. Use the large-scale finite element application software ANSYS to model the dam and the bedrock within a limited range, change the position of the gallery to obtain different solid models, and obtain the stress distribution map around the gallery after loading calculations. The results show that when the distance between the gallery and the upstream dam surface changes from 3.0 to 9.0m, the maximum principal stress of the gallery section gradually decreases and tends to remain unchanged; there is obvious stress concentration at the gallery and the dam heel. When the drainage gallery is arranged in the vertical direction, the change of the distance affects the stress distribution and state of the gallery. When the distance is changed from 15 to 25m, the stress changes from 0.106e7 to 0.088e7Pa, and tends to be stable, and the mutual influence gradually decreases. This provides guidance and suggestions for the design of the gravity dam gallery on the inclined bedrock.

1. Introduction
Concrete gravity dam is an important water conservancy project. In order to meet the needs of grouting, drainage, observation, inspection and transportation, there are often multiple galleries in the dam. Affected by the holes in the gallery, the stress distribution of the dam body changes, causing stress concentration around the gallery, cracks are easy to appear, and the safety of the dam is endangered. Therefore, analyzing the gallery holes of different positions and sizes to influence the law and process of the stress concentration phenomenon around the gallery in the dam body is of great significance to the design of the gravity dam gallery. This paper takes the design of the gallery in a concrete gravity dam as an example. Based on the finite element application software ANSYS [1], the dam and the bedrock within a limited range are modeled. The position of the gallery is changed to obtain different solid models, and the gallery is obtained after loading calculations. The surrounding stress distribution map, to evaluate the degree of influence on the safety of the dam [2-3].

2. Project Overview
A concrete gravity dam pivot project was built on a narrow and long river, with steep mountains on both banks, the river is rich in water, and the river slope is steep and current. The main part of the project is composed of non-overflow dam section, overflow dam section, bottom vent dam section, and ship lock. The left bank is used to build an underground powerhouse. Each non-overflow dam section is 20m long; the overflow dam section has a total length of 60m, divided into 3 dam sections, each section is 20m long, and is divided into 3 holes. The dam foundation is inclined upstream with an
inclination angle of 10 degrees. The bedrock elevation of the river bed is 30.00m, the dam crest elevation is 94.50m, the dam crest width is 10m, and the dam bottom width is 70m. The upstream dam slope rate $n=0.1$, the upper part is straight and the lower part is inclined upstream, and the break point elevation is 70.00m; the downstream dam slope rate $m=0.7$, and the downstream starting point elevation is 109.36m.

2.1. Hydrogeology

The area has abundant rainfall in spring and autumn, but less rainfall in winter; there are often heavy rains in summer, concentrated in June, July, and August, with greater intensity. The multi-year average value of the maximum wind speed during the 50-year return period of the corresponding flood season is 17.8m/s, the blowing range is 2.0km at the corresponding design flood level, and the blowing range is 2.2km at the corresponding flood level check. Determined by hydrology and water conservancy flood regulation calculations, the dead water level of the gravity dam is 96.00m; the design flood level is 120.00m, the corresponding storage capacity is 2.84 billion m$^3$, the corresponding downstream water level is 48.50m, and the discharge flow through the riverbed spillway is 5,964.42 m$^3$/s; check The flood level is 123.65m, the corresponding downstream water level is 51.74m, and the discharge flow through the riverbed spillway is 6871.53 m$^3$/s; the silt elevation at the bottom of the reservoir is 46.63m, the silt floating bulk density = 8.54 KN/m$^3$, the silt internal friction angle is 16°, and the coefficient of friction between the bulk concrete dam and bedrock is 0.65, the coefficient of shear strength is 1.04, and the shear cohesion is 0.93 MPa.

2.2. Dam load calculation

The load calculation includes self-weight, hydrostatic pressure, wave pressure, uplift pressure, sediment pressure, etc., and the 1m dam width is used for analysis. Selection of relevant parameters: C25 is selected for concrete, its weight is 24kN/m$^3$, water weight is 9.81KN/m$^3$, seepage pressure intensity coefficient $\alpha$ is 0.25, buoyancy weight of sediment is 8.54 KN/m$^3$, and the internal friction angle of silt is 16 degrees. The main hydraulic structures are designed according to level 1 buildings, and the buildings are also designed according to level 3 buildings. The structural safety level is III, the corresponding structural importance coefficient $\gamma_0$ is 1.1, the partial coefficient of hydrostatic pressure is 1.2, and the partial coefficient of floating force is 1.0. The contribution coefficient of sediment pressure is 1.2, and the contribution coefficient of wave pressure is 1.2. Among the material sub-factors, the shear friction coefficient of the concrete bedrock is 1.3, the cohesive force sub-factor is 3.0, the concrete compressive strength sub-factor is 1.5, and the basic combination and accidental combination in the anti-sliding stability limit state design formula The structural coefficients are all $\gamma_d=1.2$, and the structural coefficients of the basic and accidental combinations in the concrete compressive limit state design formula are $\gamma_d=1.8$. 

Figure 1. Basic profile of gravity dam

Figure 2. Load distribution diagram of dam body per unit width
3. Finite element optimization analysis of gravity dam profile

3.1. Introduction to ANSYS Software
As the first software in the FEA industry to pass the ISO 9001 quality certification, ANSYS leads the world's trend of finite element technology and is widely accepted by the global industry [2]. The software has powerful pre-processing and post-processing functions. Its graphical interface and interactive operation greatly simplifies the process of creating computer models. At the same time, before calculation, the geometry, materials and boundary conditions of the model can be verified through graphic display; In post-processing, the calculation results can be output in a variety of ways, such as sorting and retrieval of calculation results, color cloud graph, value line, animation display, etc. ANSYS is used to simulate the mechanical behavior of buildings such as dams, hydropower stations, aqueducts, conduit platforms and sluice gates. It has powerful advantages and can analyze and calculate the stability and stress state of these structures.

3.2. Finite element analysis of gravity dam profile
In this example, the concrete gravity dam H=94.5m. According to relevant regulations, the dam foundation is 1.5H for the upstream, 2H for the downstream, and 2H for the depth of the dam foundation. Set various parameters and values. According to ANSYS finite element modeling rules, it is assumed that the dam body and the dam foundation are continuous, that is, the dam body and the dam foundation are closely connected; the materials of the dam foundation and the dam body are uniform; the dam foundation and the bedrock model adopt linear elastic constitutive models. In order to create the physical environment, establish the model and divide the mesh, divide the dam element mesh, impose constraints and load during the construction period in the ANSYS software, perform static analysis of the dam, and through the static finite element analysis of the gravity dam, it is possible to know the displacement field and stress field of the dam under the action of static load, so as to understand the safety performance of the dam.

4. Gallery design and optimization
The research idea of the gallery system in this example is to determine the cross-section size of the grouting gallery and the drainage gallery according to the norms and empirical formulas, and change the position of the gallery on the basis of the cross-section size and form. The results of the stress in the gallery are the basis for optimization, and the optimal gallery position is selected to complete the design and optimization of the gallery [4-5].
4.1. Grouting gallery design
The section of the grouting gallery takes the shape of a city gate, with a bottom width of 3m, a total height of 3.5m, and a distance of 0.05 to 0.1 times the effective head from the upstream surface, with a maximum of 9.45m and no less than 4 to 5m. The distance between the bottom of the gallery and the bottom of the dam is 5m. Initially set the distance between the gallery and the upstream face of the dam X=3.0m. Build a dam model and subtract the section of the gallery from the model. The running results are shown in Figure 5 and Figure 6.

![Figure 5. Grid division of dam body gallery section](image1)

![Figure 6. The first principal stress cloud diagram of the gallery section](image2)

It can be seen from the above figure that when X=3.0m, the maximum principal stress at the bottom of the gallery is 0.239e7Pa, which is greater than the dam concrete tensile strength 0.127e7Pa, which does not meet the design requirements. Take X as the variable, and take X=3.0~9.0m in turn, and use the same method to perform finite element analysis. The results are shown in Table 1.

| X (m) | MAX (e7 Pa) |
|-------|-------------|
| 3.0   | 0.239       |
| 4.5   | 0.183       |
| 6.5   | 0.138       |
| 7.0   | 0.121       |
| 7.5   | 0.116       |
| 8.0   | **0.109**   |
| 8.5   | 0.108       |
| 9.0   | 0.108       |

According to the above table, when X≥8.0m, the maximum principal stress change at the gallery is already very small. Considering the installation of inspection and drainage galleries, try to make the gallery system in the vertical direction and on the same straight line. Take X=8.0m, that is, the gallery is 8.0m away from the upstream face of the dam.

4.2. Inspection and drainage gallery design and optimization
On the basis of the grouting gallery in the previous section, the inspection and drainage gallery is designed[6-7]. It is close to the upstream dam surface and on the same vertical line as the grouting gallery. Inspection and drainage galleries are set every 15~30m. The form of the cross-section takes the shape of a city gate cave, so that the cross-section of the gallery is 2m wide and 2.8m high. Initially set h=20m and use ANSYS finite element software to solve the analysis. The specific calculation results are shown in Figure 7 and Figure 8.
When $h=15$, there are a total of four galleries. The maximum stress on the dam surface appears at the bottom two galleries. The maximum tensile stress is $0.106\times10^7\text{ Pa}$, and no continuous tensile stress area is formed between the galleries. Stress concentration occurs around the respective sections of the gallery. Large areas of tensile stress appear on the bottom of the gallery and the arch of the gallery, and compressive stress areas appear on the bottom of the gallery. The numerical value meets the requirements of the specification. With the gallery spacing $h$ as the independent variable, the gallery system is optimized according to the stress conditions of the gallery system at different gallery spacings, and the most suitable vertical gallery spacing is finally selected. See Table 2 for specific results.

| $h$ (m) | 15 | 16 | 17 | 19 | 20 | 21 | **22** | 23 | 25 |
|--------|----|----|----|----|----|----|--------|----|----|
| MAX ($\times10^7\text{ Pa}$) | 0.106 | 0.105 | 0.105 | 0.104 | 0.102 | 0.101 | **0.086** | 0.089 | 0.089 |

According to the above table, when $h\geq22\text{ m}$, the maximum principal stress value reaches the minimum, and at the same time, considering that the gallery spacing cannot be too large, so as to avoid the uppermost gallery approaching the top of the dam, the optimal spacing is determined to be $h=22\text{ m}$.

5. Conclusion
The engineering geology is that the complete dam foundation is inclined upstream. Building a gravity dam on this kind of foundation rock is beneficial to the anti-sliding stability of the dam body and can reduce the amount of concrete pouring. In this example, the stress finite element analysis and gallery design of a gravity dam on an inclined bedrock are used to draw the following conclusions:

(1) For galleries whose form and size have been determined, when the location changes, the surrounding stress conditions will change significantly, which will also affect the stress distribution of the attached dam.

(2) When the distance $X$ between the gallery and the upstream dam surface changes from 3.0 to 9.0m, the maximum principal stress of the gallery section gradually decreases and tends to remain unchanged; there is obvious stress concentration at the gallery and the dam heel.

(3) When the drainage gallery is arranged in the vertical direction, the change of the distance $h$ affects the stress distribution and state of the gallery. When the distance $h$ changes from 15 to 25m, the stress changes from $0.106\times10^7$ to $0.088\times10^7\text{ Pa}$, and tends to be stable. The influence gradually diminishes.
Acknowledgments
This research was supported in part by the National Key R&D Program of China (2019YFC0408800), The Science and Technology Plan Project of Department of Water Resources of Zhejiang Province (RA1604).

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