Three-dimensional Simulation Analysis of Overflow Section of Slurry Stone Wide-slit Gravity Dam

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1. Introduction
The masonry dam type is often used in some small and medium-sized projects, especially those built by the prefectures and counties. It is a very realistic subject to seek effective stress analysis methods to analyze whether the dam is stable and safe, and whether the stresses meet the specification requirements[3].

In this paper, a reservoir of East China is taken as an example for finite element analysis. The overflow dam section of the reservoir is a slurry stone wide-slit gravity dam with obvious three-dimensional features. In order to better analyze its stresses and strains, the three-dimensional finite element analysis of the overflow dam section is carried out, along with the comparative calculation of the dam section before and after reinforcement. The calculation and analysis are mainly focused on the masonry part of the wide-slit overflow dam section. Analyze the stress and strain distribution to obtain a satisfactory dam body stress and strain effect for a concise discussion[4].

2. Project Overview
With a total storage capacity of 64.53 million m³, the reservoir is a medium-sized project based on irrigation, combined with flood control, water supply, power generation, etc. The overflow dam section of the reservoir is a slurry stone wide-slit gravity dam, which is 61m long. The dam foundation elevation is 113.8m, and the dam crest elevation is 156.20m, as well as the dome elevation is 148.5m, and the maximum dam height is 42.40m. The concrete anti-seepage panel is located upstream of the dam, with a horizontal width of about 1m, which is a sloping wall (its slope is 1:0.6). The masonry stones are distributed downstream and on both sides of the anti-seepage panel, with a horizontal width of about 2m. The thickness of the stones on both banks is about 4.9m-6.5m, and its diameter is
generally 40cm-100cm. The surface of the bedrock is generally weakly weathered, and the lithology is dominated by flesh-red rhyolite-fused tuff which is relatively hard. The core is relatively intact, and the quality is good.

3. Numerical Model

3.1 Computing Scheme
This paper mainly takes a 9.0m wide typical wide-slit overflow dam section as a calculation model the model (including the left and right symmetry planes, each with half of the pier). Model calculation boundary is extended to the 1.5 times dam height in the upper, lower and depth directions of the overflow dam section foundation, in order to reduce the impact of boundary conditions on the calculation results. Boundary constraints imposed during finite element calculation analysis include: fixed constraints at the bottom of the bedrock, constraints applied upstream and downstream direction on the upper and lower faces of the bedrock, and symmetry plane constraints on the left and right banks of the dam and pier (i.e., on the Z=±4.5m plane). Other loads are applied separately according to different calculation conditions. Compared with several unit types, the three-dimensional 10-node tetrahedron and 20-node hexahedral quadratic units are selected for calculation and analysis (Figure 1), which have high calculation accuracy[5][6].

3.2 Three-dimensional Finite Element Calculation Model
The three-dimensional model and mesh division of the wide-slit overflow dam section before and after reinforcement are shown in Figure 2. Coordinate system compositions of 3D computing model are as follows: select the middle section of the wide-slit dam section (the middle of the hollow section) as the x-y plane of the coordinate system, the x-axis points to the downstream of the reservoir, the y-axis is vertically upward (the overflow dome position is equivalent to x=0, y represents the actual elevation), and the z-axis points to the right bank.

| Computing scheme       | Number of units | Number of nodes |
|------------------------|-----------------|-----------------|
| Pre-reinforcement model| 85936           | 145614          |
| Reinforced model       | 103023          | 182989          |

Figure 1. 3D 20-node unit

Figure 2. Middle profile of overflow dam section
3.3 Calculation Condition
The upstream and lower water levels of each calculation condition are shown in Table 2.

| Item                        | Upstream water level (m) | Downstream corresponding water level (m) |
|-----------------------------|--------------------------|------------------------------------------|
| Basic combination           | Water storage condition  | 153.80                                   |
|                             | design flood level (p=1%)| 154.73                                   |
| Special combination         | Check flood level (p=0.05%) | 156.09                                   |
|                             |                          | 122.3                                    |
|                             |                          | 123.9                                    |
|                             |                          | 125.5                                    |

Load combination is as follows: self-weight + pier load + upstream hydrostatic pressure + dam foundation uplift pressure + overflow surface dynamic water load.

Especially for the dam foundation uplift pressure calculation, Considering the "Design Specification for Concrete Gravity Dam" (SL 319-2018) and "Design Specification for Stone Masonry Dam" (SL 25-2006), the strength reduction factor of the uplift pressure α equals 0.6[7].

3.4 Material Parameters
After referring to the relevant data and "Design Specification for Stone Masonry Dam", comprehensively considering the creep of concrete and the weathering of masonry, Correct the material parameters of the calculation model[8]. The material parameters selected in the calculation analysis finally are as follows:

| Material         | Bulk weight (γ) (kN/m³) | Elastic modulus (E) (10⁴MPa) | Poisson's ratio (μ) |
|------------------|-------------------------|-----------------------------|---------------------|
| Bedrock          | 26.0                    | 1.70                        | 0.26                |
| Concrete panel   | 24.0                    | 1.91                        | 0.167               |
| Slurry stones     | 23.5                    | 1.00                        | 0.20                |
| Rock blocks       | 20.4                    | 1.00                        | 0.20                |

4. Stress Analysis
The stress distribution and variation law of the overflow section of the wide-slit gravity dam under the design and check conditions are similar. This paper focuses on the analysis of the stress distribution under the check condition of special combination.

4.1 Calculation and Analysis on Displacement of Overflow Dam Section
It can be figured out from the distribution cloud diagrams in Figure 3-4 that the maximum upstream and downstream horizontal and vertical displacements of the overflow dam section are in the upper part of the pier and the dam. Under the load of the check condition, the upstream and downstream horizontal displacement is within 0.2cm, and the vertical displacement is within 0.3cm. From the analysis of the calculation result chart, it is considered that the calculated values of stress and deformation of the dam before and after reinforcement are not large, and there is no local instability and shear failure in the dam.
After reinforcement.
check conditions

After reinforcement.
check conditions

Figure 3. Upstream and downstream displacement distribution cloud map

Figure 4. Vertical displacement distribution cloud map

4.2 Calculation and Analysis of Masonry Stress in Wide-silt Dam Section

It can be found out from Figure 5-8 that:

(1) Principal tensile stress on the masonry hollow surface in overflow dam section

Before reinforcement, the principal tensile stress values and distribution areas of the masonry are small overall. The maximum principal tensile stress is 0.24MPa at the bottom of the dam body corridor, and the others are within 0.05MPa.

After the implementation of the reinforcement scheme, the principal tensile stress distribution area and stress values of the open side wall of the overflow dam section are small. The maximum principal tensile stress at the bottom of the masonry dam body corridor is 0.22 MPa.

(2) The principal compressive stress of the masonry stone surface in overflow dam section

Before the reinforcement, the maximum principal compressive stress appeared in the small range near the bottom corner of the downstream hollow exit hole, resulting in stress concentration. Its value is 3.8MPa, and then the stress values are reduced to 1.2MPa within a small range around the maximum stress position (about 1.0m). The local maximum compressive stress at the bottom of the dam body corridor is 2.3 MPa. Below 127.0m elevation, the principal compressive stress is about 0.6-1.4MPa in the intersection of the upstream waterfront and the hollow side. The principal compressive stress value is 0.8-1.2MPa in the area that is below 127.0m elevation upstream, below 120m elevation at the central, and below 123m elevation downstream of hollow side in slurry stone dam, where the principal compressive stress value at the bottom of the dam section is between 0.9 MPa to 1.4MPa.

After the implementation of the reinforcement scheme, the maximum principal compressive stress is also at the bottom corner of the hollow downstream outlet hole, which is 3.4 MPa, about 15% lower than before. Then it is reduced to 1.1 MPa in a small range around the maximum stress position. The local principal compressive stress at the bottom of the dam body corridor is 2.1 MPa, where the elevation is below 127.0 m, and its stress is obviously reduced. The principal compressive stress value is 0.6-0.8MPa in the area that is below 127.0m elevation upstream, below 120m elevation at the central, and below 123m elevation downstream of hollow side in slurry stone dam, which is about 20% lower than before. The principal compressive stress at the bottom of the dam section is 0.6-1.1MPa, which is about 10% lower than before. After reinforcement, the values of the principal compressive stress on the three different elevations (elevation 117.5m, 112.0m, 126.5m) on the hollow side are correspondingly reduced.

Considering the comparison of the calculated stress results, under the basic and special combinations, the key parts of the overflow dam section after reinforcement, especially the intersection area of upstream side inside and beside the hollow, the stress of the dam body masonry stones is significantly improved. At the same time, the tensile and compressive stress of the overflow masonry section meets the design specifications.
Figure 5. Schematic diagram of the coordinates and positions of the key points on the hollow side of the overflow dam section.

Before reinforcement check conditions

After reinforcement check conditions

Figure 6. Principal tensile stress distribution of hollow inner wall.

Before reinforcement check conditions

After reinforcement check conditions

Figure 7. Principal Compressive stress distribution of masonry.

Elevation 117.5m

Elevation 122.0m

Elevation 126.5m

Figure 8. Principal compressive stress curve.
4.3 Masonry Shear Stress Analysis
In terms of the calculation results, the horizontal shear stress on the hollow upper side and side face of the overflow dam section is significantly improved after reinforcement. Under check condition, the elevation is below 127.0m, the stress in the intersection area of upstream side inside and beside the hollow decreased from 0.32-0.36MPa to 0.12-0.18MPa, which was more than half lower than that before. The stress of the upstream hollow side is reduced from 0.22-0.26MPa to 0.12-0.14MPa. After reinforcement, the horizontal shear stress values on the three different elevations of the hollow side are correspondingly reduced, and the distribution of shear stress values in the reinforcing area on the side of the pavement is reduced significantly.

![Before reinforcement. check conditions](image1)
![After reinforcement. check conditions](image2)

Figure 9. Horizontal shear Stress distribution of the hollow inner wall

![Before reinforcement. check conditions](image3)
![After reinforcement. check conditions](image4)

Figure 10. Horizontal shear stress distribution of the 117.5m elevation profile

![Shear stress curve](image5)

Figure 11. Hollow side shear stress curve

5. Conclusion
From the calculation analysis, we can conclude that:

(1) Under load affecting, there is a stress concentration at the bottom corner of the downstream
hollow outlet hole. Under the check water level, the maximum principal compressive stress of the masonry after reinforcement is 3.4 MPa, which is about 15% lower than that before. The principal compressive stresses of upstream facing and side of the hollow are below 2.1MPa. In the reinforced area below 127.0m, the value of the principal compressive stress is significantly improved compared with that before reinforcement, which is reduced by 10%-20%;

(2) After reinforcement, the principal compressive stress of the top stone masonry arch in the overflow dam section is not large. The principal compressive stress is about 0.6MPa at upstream facing and side of the hollow below 127.0m, and the principal compressive stress is significantly reduced compared with that before consolidation;

(3) After reinforcement, the horizontal shear stress of the upstream facing and side in the hollow overflow dam section is significantly improved, and the horizontal shear stress values on the three different elevations of the hollow side are correspondingly reduced. The distributed of shear stress values in the reinforced area is significantly reduced.

(4) After reinforcement, the dam body masonry in the overflow dam section, under basic and special combinations, the key part stress of the dam body masonry is obviously improved, also, the stress intensity can meet the design specifications. The dam body stress and deformation values are not large. There is no local instability and shear failure.

(5) The maximum up and downstream and vertical displacements of the overflow dam section are all in the upper part of the pier and the dam. The dam stress and deformation values before and after reinforcement are not large, and there is no local instability and shear failure.

(6) From the analysis of the stress and local stability of the dam body masonry in the overflow dam section before and after reinforcement, it can be seen that after reinforcement, the overall stability of the overflow dam section is improved.

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