Research on reinforcement at the RCC dam toe of a hydropower station

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Abstract. The dam of a hydropower station is a RCC arch dam. Based on relevant tests and monitoring data, the compression strength of the dam concrete and the temperature of grouting of the transverse joints in some areas do not meet the design standard. To solve those quality problems, this paper evaluated the stress and deformation of the present dam and checked the safety of the dam. In addition, by analyzing the reinforcement body of the dam, the paper assessed the safety of the reinforced dam. According to the calculating results by FEM, the maximum equivalent tensile stress exceeds the allowable tensile stress and the exceeding area mainly locates on the dam heel of upstream face, which extends about 5.20 meters upward from the foundation. The effect of the reinforcement at the dam toe is obvious and the tensile stress after reinforcement meets the standard under the condition that the shear strength between the reinforcement and the dam body is not reduced or is reduced by less than 30%.

1. Background

Influenced by temperature change, deterioration of concrete quality of dam body and geological conditions, as well as earthquake, the dangers of concrete dam such as cracking and leakage is likely to occur during the process of construction and operation [1-3]. At those situations, the dam needs reinforcing and repairing, thus improving its work behavior. And the most common used reinforcement measures is to establish reinforcement body downstream the dam, which has enhanced overall stability and safety of dam. There are many dams in good operation in China and abroad after constructing reinforcement body at the dam toe [4-9].

The dam of a hydropower station is a RCC double-curvature arch dam. The normal water level of the reservoir is 650 meters; the elevation of the crest is 653 meters; the elevation of the bottom of the dam is 558 meters; the width of dam crest is 5 meters; the bottom width of crown cantilever is 22.0 meters; the arc length of the center line of the dam crest is 299.54 meters; the center angle of top arch is 80.624°. Based on the related tests and monitoring data, the compression strength in some areas of the arch dam do not meet the design standard. The strength of the concrete in EL.590m~EL.611m area is particularly low. Moreover, the measured exit temperature exceeds the design value (below 18℃). At the same time, the cooling water pipes below EL.578.5 meters and some cooling water pipes in EL.578.5 meter~EL.612 meter were damaged during the process of strengthening grouting and curtain grouting of dam foundation, which makes the pipes could not carry out the second stage cooling. The grouting temperature of the transverse joints in the above area cannot meet the design requirements (within 14℃~16℃.)

Considering the existent quality problems of the dam that affects the safety of engineering, it is necessary to make the overall evaluation of the stress and deformation of the dam and check the safety
conditions of the dam. At the same time, the reinforcement body established at the dam toe was considered and the safety condition of the dam after reinforcement was assessed.

2. Stress safety assessment of the present dam

2.1. Finite element model and calculation conditions
The finite element model of the dam and foundation is shown in Figure 2 including 167092 elements and 175078 nodes. The constraints of the model are that the base rock of the model is added fixed constraints and the other boundaries are added normal constraints.

![Figure 1. 3-D finite element model](image)

Based on the geological material combined with the on-site situation of dam foundation after excavating, the mechanical parameters of rock mass adopted in the calculation are shown in Table 1.

| Deformation modulus (GPa) | Riverbed, left bank below EL.580 and right bank below EL.600 | Left bank above EL.580 | Right bank above EL.600 |
|---------------------------|-------------------------------------------------------------|------------------------|-------------------------|
| Poisson's ratios          | 0.24                                                        | 0.24                   | 0.24                    |

According to the statistical data during construction and the test results of core samples, the proposed standard value of dam concrete strength is shown in Table 2. For C30 normal concrete, the standard value of compressive strength is 26.2MPa. The unit weight of dam concrete, γ is 24.0kN/m3. Elasticity modulus of C15 concrete is 16GPa and its Poisson’s ratio is 0.21. The elasticity modulus of C20 concrete is 22GPa and its Poisson’s ratio is 0.19. The sealing temperatures below and above 612 meter elevation are 21℃ and 16℃ respectively.

| Deformation modulus (MPa) | Below EL.578.5 | EL.578.5~EL.612.0 | Above EL.612.0 |
|---------------------------|----------------|-------------------|----------------|
| RCC                       | 20.0           | 20.0              | 25.0           |
| Metamorphic Concrete      | 20.0           | 15.0              | 25.0           |

2.2. Stress of present dam
The calculation results of finite element equivalent stress of the present dam show that the maximum tensile stress (2.24MPa) of upstream surface of the dam in temperature drop condition occurs in the heel of the dam. The maximum tensile stress of downstream surface is 0.85MPa. The maximum compression stress (-4.43MPa) occurs at the end of the downstream arch. The maximum compression stress in upstream surface is -3.87MPa. In temperature rise condition, the maximum tensile stress of upstream surface is still in the heel of dam with the value of 2.13MPa. The maximum tensile stress of downstream surface is 0.65Mpa. The maximum compression stress in arch end of downstream surface is -4.64MPa while the maximum compression stress in upstream surface is -3.45MPa. Therefore the maximum
tensile stress of current dam body is 2.24MPa, occurring in the heel of upstream surface of the dam under the condition of temperature drop as shown in Figure 2. It can be seen that the maximum tensile stress value exceeds the allowable tensile stress and the scope in which tensile stress exceeding the standard in the elevation direction extends about 5.2 meter upward from the foundation surface. The maximum compression stress is -4.64MPa, appearing at arch end of downstream surface under the temperature rise condition as shown in Figure 3, which meets the standard requirement.

![Figure 2. The equivalent first principal stress of the dam before reinforced under temperature drop condition](image)

![Figure 3. The equivalent third principal stress of the dam before reinforced under temperature rise condition](image)

3. Study of reinforcement scheme of dam

3.1. Reinforcement scheme

To increase the limitation to the arch end and reduce the stress level of the dam body, the reinforcement measure was considered as shown in Figure 4, that is, excavation gap below EL. 630 between the two arch ends and the excavated rock wall was filled with concrete.

![Figure 4. The reinforcement at the dam toe](image)

3.2. Comparison analysis of reinforcement

The classical stress values of the dam before and after being reinforced are compared shown in Table 3. The distribution of equivalent principal stress after being reinforced under typical working conditions is shown in Figure 5 and Figure 6.
Table 3. The classical stress values of the dam before and after being reinforced (MPa)

|                     | Temperature drop condition | Temperature rise condition |
|---------------------|-----------------------------|----------------------------|
|                     | Before reinforced           | After reinforced           | Before reinforced | After reinforced |
| First principal stress | 11.30                       | 6.08                       | 9.90             | 4.45             |
| Third principal stress | 8.17                        | 17.50                      | 10.50            | 17.90            |
| Equivalent first principal stress | 2.24                       | 1.04                       | 2.13             | \               |
| Equivalent third principal stress | 4.43                       | \                          | 4.64             | 5.38             |

Figure 5. The equivalent first principal stress of the dam after reinforced under temperature drop condition

Figure 6. The equivalent third principal stress of the dam after reinforced under temperature rise condition

From the calculation results above, it can be found that: (1) The maximum tensile stress of dam before and after reinforced occurs in the upstream surface of the bottom of dam riverbed. The maximum tensile stress of dam after reinforced reduces from 11.30MPa to 6.08MPa and the equivalent maximum tensile stress of dam reduces from 2.24MPa to 1.04MPa, both of which meet the standard requirements. (2) The maximum compressive stress of dam before and after reinforced occurs under the temperature rise condition. The value of the maximum compressive stress before reinforced is 10.50MPa which appears at the arch end of the lower elevation of the dam. After being reinforced, the compressive stress in this area is reduced to 7.33 MPa. And the equivalent compressive stress in the area decreases from 4.64MPa to 3.14MPa after the dam being reinforced. (3) Due to the stress concentration at the bottom of the joint, the maximum compressive stress of dam after reinforced occurs near EL. 612 of the left bank dam toe. The value of maximum compressive stress is 17.90MPa and the corresponding equivalent value is 5.38MPa, both of which meet the standard requirements.

4. Analysis of the influence of variation of shear strength between the reinforcement and the dam

For the proposed reinforcement measure, the bonding between the dam and the reinforcement affects the transmission force between them. However, the bonding between the dam and the reinforcement is influenced by many factors, such as the connection mode between seams, construction quality, the stress state of the joint surface under the action of external temperature during operation, temperature deformation during construction, and the quality of the joint grouting. Therefore, there is some
uncertainty between the dam and the reinforcement. To analyze the influence of variation of shear strength between the reinforcement and the dam on reinforcement effect, the stress and displacement of the dam under the reduction of the shear strength by 30%, 50% and 70% are calculated. The typical stress of dam is shown in Figure 7 and Figure 8.

From the calculation results, it is found that: (1) Compared with the situation that the shear strength of the dam body and the reinforcement is not reduced, the maximum tensile stress of the upstream surface has an upward trend when the shear strength is reduced by 30%, 50% and 70%. The maximum tensile stress increases obviously after equivalent treatment. When the shear strength is reduced by 70%, the maximum tensile stress is increased from 1.04MPa (without discount) to 1.90MPa. (2) After the shear strength between the dam and the reinforcement is reduced by 30%, 50% and 70% respectively, the maximum compressive stress in the downstream surface is reduced due to the weakened stress concentration effect at the bottom of the joint. Among them, the maximum compressive stress is the smallest when the shear strength is reduced by 50%, which is reduced from 5.38MPa (without discount) to 4.35MPa.

5. Conclusions and suggestions
Based on the actual situation that the strength of dam concrete and the grouting temperature of dam arch cannot meet the design requirements, the paper first determined corresponding calculation parameters based on the results of drilling and coring of dam concrete, geophysical detection and indoor test. Then
the effectiveness and feasibility of the reinforcement were analyzed. Additionally, the influence of variation of shear strength between the dam and the reinforcement on the stress and displacement of the dam was studied.

Via calculation and analysis, it is known that the maximum finite element equivalent tensile stress of the dam exceeds the allowable tensile stress when the grouting temperature of the transverse joints below EL.612 is 21℃ and that above EL.612 is 16℃. The area exceeding the standard range mainly locates on the upstream surface of the dam, which extends about 5.20 meters upward from the foundation surface. The reinforcement effect studied in this paper is fairly well and the stress of dam body after reinforcement meets the standard requirement when the shear strength between the reinforcement and the dam body has no reduction or its reduction is less than 30%. However, the interaction between the reinforcement and the dam under the effect of temperature deformation during the process of construction is complex. Therefore, it is necessary to adapt measures to control the highest temperature and the temperature rise of the reinforcement concrete. Moreover, proper joint should be carried out to reduce the restraint between the dam body and the reinforcement, and the appropriate joint grouting work is required after the cooling of the reinforcement concrete.

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