Research on Key Technology of Temperature Stress and Temperature Control of Arch Dam in Cold Area

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Abstract: Generally, the arch dam is thin, and the temperature stress has a significant impact on the safety of the arch dam, which will be more prominent in cold areas. By taking the arch crown section of a high arch dam as an example, this study aims to optimize the measures and indicators of temperature control of dam concrete during the construction process in different months so as to prevent cracks during the construction period of the dam.

1. Introduction

A normal concrete double-curved arch dam in western China has a dam elevation of 649 m, a foundation surface elevation of 555 m, a maximum dam height of 94 m. There is a multi-year average temperature of 5 °C, an extreme maximum temperature of 39.4 °C, and an extreme minimum temperature of \(-41.2\) °C. The building task of concrete arch dams in this area is arduous. The difficulties in crack prevention are mainly concentrated on the following points: The foundation 3 m thick concrete cover plate is easy to occur penetrating cracks in the long interval; This area is very cold in winter, the cold wave is frequent throughout the year, and temperature varies widely from day to night, which makes it difficult to control the internal and external temperature difference of the upstream and downstream surface concrete of the dam to prevent surface cracks; The annual construction period of the dam is from April to October, and from November to the following March, construction suspend to pass the winter. It is also difficult to prevent cracks in the overwinter horizontal plane and control the temperature difference between the upstream and downstream layers of old and new concrete; The stable temperature of the dam is low, and the dam body needed to be water cooling to achieve the temperature of arch sealing before joint grouting, which is likely to occur greater temperature stress, and is bad for dam crack prevention. This paper takes the arch crown section of a high arch dam as an example, aims to optimize the measures and indicators of temperature control of dam concrete during construction process in different months to achieve the purpose of crack prevention during dam concrete construction.

2. Simulation model and calculation data

2.1. Construction conditions and material parameters

The construction progress is arranged according to the height of 3 m each floor, and the height of last floor is 4 m. On June 20, 2010, a 3 m thick concrete cover plate had been finished pouring, and the
main body was poured after 56 days. At the end of October, owing to the temperature dropped to a lower level, the pouring was stopped. At that time, the elevation of the dam was 576 m. From April to September of 2011, the pouring elevation was 576 m–612 m. From April to mid-September of 2012, the pouring elevation was 612 m–645 m, and the pouring was completed in late September. The concrete elevation was 649 m. The relevant thermal performance parameters are shown in Table 1.

| Concrete strength grade | Corresponding elevation (m) | Adiabatic temperature rise (℃) | Specific heat (kJ/kg·℃) | Thermal diffusivity (m²/h) | Thermal expansion coefficient (10⁻⁶/℃) |
|-------------------------|----------------------------|--------------------------------|-------------------------|---------------------------|--------------------------------------|
| Three-graded concrete A(Ⅰ): C₉₀₃₀W₁₀F₄₀₀ | 555–567 600–649 | T=26.66d/(2.22+d) | 0.951 | 0.0038 | 9.25 |
| 4-graded concrete A(Ⅱ): C₉₀₃₀W₁₀F₄₀₀ | 567–600 | T=28.97d/(2.88+d) | 0.897 | 0.0035 | 9.98 |

2.2. Calculation model and boundary conditions
Considering the influence of joint grouting on the dam body, the calculation model uses three adjacent arch crown sections 1. The coordinate system origin of the whole coordinate system is located at the dam heel of the dam upstream. The X direction is the direction of the water flow, the positive direction is the upstream to the downstream. The Y direction is the vertical flow direction, the positive direction is the right bank to the left bank, the Z direction is the vertical direction, and the positive direction is vertically upwards. In order to ensure the calculation accuracy, the dam body is divided into 8 parts in the upstream and downstream direction, and the height direction is divided into layers with 0.5 m height. The three-dimensional finite element calculation model is shown in Figure 1, and the 8 nodes isoparametric space unit is used. There are totaling 15036 units, and 17876 nodes.

In the calculation of the temperature field, the adiabatic boundaries include the foundation bottom surface, the four sides of the foundation and the transverse joint of the dam section. The surfaces of the upstream and downstream dam are treated according to the third type of boundary (the dam surface is in contact with the air) before the water storage; After the water storage, the third type boundary is
above the water surface, and the insulation board below the water surface is also treated as the third type boundary.

In the calculation of the stress field: the ground surface is treated as a fixed support, the foundation is treated as a simple x-direction supported in the upstream-to-downstream direction, and the two boundaries of the foundation are treated as simple y-direction supported along the dam axis direction. The side of the dam body is subjected to Y-direction normal constraint after joint grouting, and the rest are free boundaries.

2.3. Temperature control boundary condition

(1) Temperature control of warehousing: During the construction period, the pouring temperature of concrete in different months is controlled as follows: the pouring temperature is controlled to 12 °C from May to September, and in April and October, the concrete is naturally placed in the warehouse and the pouring temperature is 10 °C and 8 °C.

(2) Temporary thermal insulation scheme: After pouring, the upstream and downstream faces are covered with 2 cm thick polyurethane foam for temporary thermal insulation, which are treated according to the third type of boundary conditions. The pouring layer is temporarily thermally insulated with 2 cm thick polyurethane foam, and the concrete poured from May to September is maintained by “spraying”. The “spraying” water temperature is about 18 °C in May, about 24 °C in June-August, and about 18 °C in September.

(3) Water supply requirements for cooling water pipes: 1.5 m×1.5 m water pipes are laid in each layer of concrete for first-stage water cooling. Before 0.5 h of the concrete is poured, the water pipes are laid for water supply and pre-cooled. The water supply ended in 15 days after pouring. The cooling water pipe is made by high-strength polyethylene pipe, each roll has a 200 m length, and the water flow rate is about 20~25 L/min. The water passing direction is changed once a day, and the cooling water come from river. The concrete poured from June to August each year will be second-stage cooled from October 1st to October 15th of the year to reduce the inner and outer temperature difference of the upstream and downstream surface concrete during wintering. Before the arch grouting, the water temperature in the cooling water pipe is 4 °C.

(4) Overwinter top surface thermal insulation: The thermal insulation is insulated with a 26 cm thick quilt, and the equivalent heat release coefficient is 15.37 kJ/(m²•d•℃); the overwinter thermal insulation quilt is uncovered in mid-April of the following year to start new concrete pouring.

(5) Permanent thermal insulation on the upstream and downstream surfaces: The thermal insulation insulated is with 10cm thick sprayed polyurethane, and the equivalent heat release coefficient is 23.90 kJ/(m²•d•℃). The concrete poured in 2010 began to be sprayed at the beginning of October of that year, and the concrete poured in 2011 and later was sprayed after the mold was removed.

(6) Closure time of arch: According to different pouring months, the arch closure time is determined separately. The concrete pouring before October 2010, the closure of arch will be on May 15, 2011. The concrete pouring in October 2010, the closure of arch will be on August 15th, 2011; Among the concrete poured in 2011 and 2012, the concrete pouring in April and May, the closure of arch will be on May 15 of the following year. The concrete pouring in June and July, the closure of arch will be on August 15 of the following year. The concrete pouring in August and later, the closure of arch will be on November 15 of the following year.

3. Simulation results

3.1. Basic consolidation grouting cover plate

Due to the installation of the cooling water pipe, although the cover plate is poured in the summer with high temperature, the maximum temperature is only about 25 °C. After the concrete reaches the maximum temperature, the temperature continues to decrease due to the cooling of the water. After the second stage of water cooling, the concrete is cooled for 15 days. The temperature is lowered by about 5 °C; The third-stage cooling is 4 °C cold water for one month. However, after May, the outside
temperature rises. Under the combined effect of external temperature rise and water cooling, the concrete temperature at the end of the water cooling is reduced to 8.6 °C, and then this part is jointed with grout.

Although the cover plate concrete is poured in the summer and is located in the strong constraint area of the foundation, which is strongly restrained by the foundation. However, due to the multi-stage cooling method before the joint grouting, the creep of the concrete is fully exerted, resulting in greater stress relaxation. So, the stress on the front cover of the joint grouting is not exceeded the prescribed limits. In the operation period after water storage, the stress of the cover plate rises slowly with time, but does not exceed 2.0 MPa, which meets the crack prevention requirements of concrete.

3.2. Concrete in summer pouring area
Due to the control of the summer concrete pouring temperature of 12 °C, and the first stage of water cooling, the maximum temperature of the pouring block is about 26 °C. After the concrete reaches the maximum temperature, the temperature continues to decrease due to the cooling of the water. The concrete temperature drops by about 4~6 °C after 15 days of the second stage of the river water inlet; The third stage cooling inlets the cold water of 4 °C for 1 month, and the concrete temperature drops to 8.5 °C, and then this part is jointed with grout.

In addition, after entering the operating period, the temperature of the upstream and downstream faces of the dam is mainly affected by the cyclical changes in ambient temperature or water temperature. Located on the upstream surface of the underwater part, the lowest temperature is about 4 °C; and the concrete surface in contact with the atmosphere, the lowest temperature is about 1.2 °C ~ 2.0 °C. That is, after taking 10cm thick polyurethane on the upstream and downstream surfaces, there is no subzero temperature on the surface of the dam.

During the construction period, the maximum stress in the middle part of the summer pouring block occurs after the end of the third stage cooling (before the joint grouting), at which time the concrete temperature in this part basically reaches the stable temperature, and the stress does not exceed 1.5 MPa; However, the maximum stress on the upper and downstream surface occurs in the middle of February next year, and the stress is about 2.0 MPa, which mainly due to the lowest outside temperature at this period. At the joint operation of the dam after joint grouting, under the joint action of outside temperature and water temperature, the stress of concrete shows a significant cyclical change with temperature.

3.3. Concrete on overwinter surface
After the concrete in the layer of the overwinter surface is cooled and covered with a 26 cm thick quilt in the first stage, the lowest temperature of the upstream and downstream surface concrete appears at the end of February of the following year, and the lowest temperature is about 3.0 °C; while the lowest temperature of the concrete in the middle of the overwinter surface appears at the end of the month, the minimum temperature is about 10.0 °C.

During the wintering period, the moment of maximum stress on the overwinter surface appears in the end of January of the following year, and the maximum stress is about 0.8 MPa. In the vicinity of the upstream and downstream faces, the horizontal stress σ_y of the vertical water flow direction is larger, and in the middle of the overwinter surface, the horizontal stress σ_x of the parallel water flow direction is larger. After entering the operation period, the concrete stress on the surface of the overwinter surface is relatively large, which is mainly caused by the change of outside air temperature and water temperature. Its maximum stress is about 1.9 MPa, which basically meets the requirements of concrete crack prevention.

3.4. Summer joint grouting area concrete
In cold regions, the summer temperature is high and the arch sealing temperature is low. The temperature difference between these two is large. The surface concrete is higher than the arching temperature due to the external heat in the summer arching, which will lead to the large temperature
difference of the surface concrete after entering the winter. And the temperature difference is larger along the dam thickness direction, so that the concrete produces high surface stress.

The temperature calculations show that although the casting block was subjected to fourth stages cooling, the concrete temperature was cooled to a stable temperature for joint grouting. The effect of cooling in the first, second and fourth stages is remarkable. The effect of the third stage cooling is not significant, and during the third cooling stage, the temperature of the upstream concrete surface increases slightly. The main reason is that the cooling time of the third cooling stage is in the summer of 2012, the river water cooled, and the river water temperature and the outside air temperature were both high, which resulted in the third stage cooling effect is not obvious. At the end of the fourth-stage cooling of the upstream surface, it can only be reduced to about 10.5 °C. The main reason is that the fourth-stage cooling time is in summer, and the concrete surface is more seriously affected by the external temperature.

From the change of stress, for the concrete at the upstream surface and near the upstream, owing to the joint grouting time is in summer, the maximum stress does not appear at the end of the fourth-stage cooling, but appears in March of 2013. This is mainly because the temperature of the concrete surface before the joint grouting is higher than the stable temperature. When the temperature is low in winter, the temperature difference of the surface layer of the concrete is large, resulting in a large stress. After taking measures such as permanent thermal insulation on the surface of the dam and strengthening the cooling of the surface concrete, although the surface stress of the summer joint grouting concrete pouring block will be larger during the winter of the construction period, which can still meet the crack prevention requirements. The process line of typical point temperature and stress change on the upstream side of the joint grouting block in summer is shown in Figure 2.

**Figure 2.** Typical point temperature and stress change process line on the upstream side of summer joint grouting block.

4. Conclusion
The dam foundation consolidation grouting cover plate was completed in June, and then a two-month consolidation grout was processed. During this period, the surface cracks were easily produced by the cold wave and developed into deep cracks. Therefore, it is necessary to control the pouring temperature of the cover plate and strengthen the temporary insulation during the consolidation grout. The concrete is poured in summer, the pouring temperature is controlled to 12 °C, and after the surface "spraying", internal water cooling and other measures, the maximum temperature is about 26 °C. In
February, the maximum tensile stress of concrete on the upstream and downstream surfaces is about 2 MPa, which is less than the allowable tensile strength of concrete.

After 10cm thick polyurethane is sprayed on the upstream and downstream sides of the dam for permanent insulation, in the winter, the lowest temperature on the upstream surface of the dam is about 4 ℃, there is no subzero temperature on the dam surface, and the dam temperature gradient and temperature stress on the upstream and downstream surfaces can be effectively controlled, then the purpose of crack prevention of the upstream and downstream surfaces is achieved.

The annual wintering surface of the dam covers 26 cm quilts. The most stressful time on the wintering surface appears in the late January of next year. The maximum stress is about 0.8 MPa, which can satisfy the anti-crack requirement during the winter and winter, and effectively control the upper and lower temperature difference between the concrete in the nearby winter surface, and prevent the cracks in the vicinity of the overwinter surface.

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