Study on Temperature Control and Crack Prevention Scheme for Lining Concrete Construction of Spillway Tunnel in Summer

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Abstract. In view of the characteristics of high strength and thin thickness of spillway tunnel lining concrete, the temperature field and stress field of spillway tunnel lining concrete during summer construction are simulated by using large-scale finite element software SAPTIS, and the risk assessment of lining concrete surface flow maintenance time and internal water passage time on its own cracking during summer construction is analyzed. For a project, the simulation calculation is carried out, and the results show that under the given working conditions, compared with non-flow curing, the surface point stress of surface flow curing for 28 d decreases by 1.34 MPa, and the minimum crack safety factor increases by 0.79; the internal middle point stress decreases by 0.75 MPa, and the safety factor increases by 0.31. The cooling time of internal water in lining concrete is longer than the time when the maximum temperature of concrete occurs, which cannot effectively reduce the maximum temperature of internal temperature, but it can reduce the internal tensile stress to a small extent and improve the safety factor. The research results have guiding value for thermal control and crack prevention of lining concrete.

1. Introduction
With the rapid development of hydropower engineering construction, the scale and section size of hydraulic tunnel are increasing. Hydraulic tunnel belongs to underground engineering, which is difficult to repair. If harmful cracks occur, the integrity and durability of the structure will be affected. In addition, as long as improper maintenance, not taking effective water cooling and thermal insulation measures in the construction process, the tensile stress caused by temperature drop and temperature difference will be fully exerted, resulting in the occurrence of cracks. Dry shrinkage, self-volume deformation and autogenous shrinkage of aggregate can all cause shallow cracks in lining concrete at early stage. Geological faults, uneven lithology, bolt constraint, and uneven thickness caused by over-excavation all make lining concrete generate cracks at any position randomly. Temperature control of lining concrete to prevent cracks during construction is an important task for lining construction of spillway tunnel.

The above analysis expounds the complexity of the formation mechanism of tunnel lining concrete
cracks [1]. The lining concrete side wall and vault were poured by stages, the low-heat cement was used, the mortar cushion between lining and surrounding rock was sprayed [2], the flow water maintenance in high temperature season, and the water cooling parameters were optimized [3]. The water cooling can take away the heat generated in the concrete. In order to reduce the internal and external temperature difference and cooling amplitude, the water duration, water temperature and water flow should also be set reasonably and effectively [4]. Reducing pouring temperature is also an effective measure for temperature control and crack prevention of lining concrete [5]. In this paper, the spillway tunnel of a project is taken as the research object. The simulation analysis method of the whole process of concrete and the SAPTIS platform [6] are used to analyze the temperature control effect of concrete. The reasonable and effective temperature control and crack prevention scheme is selected to guide the field construction. Provide technical support for temperature control design of the project.

2. Basic principle

2.1. Basic Theory of Temperature Field Calculation [7]

The temperature field satisfies the heat conduction equation:

$$\frac{\partial T}{\partial t} = a \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + \frac{\partial \theta}{\partial t}$$  (1)

Where: $T$——°C; $a$——the thermal conductivity, m$^2$/h; $\theta$——adiabatic temperature rise of concrete, °C; $t$——time, d; $\tau$——the age, d.

2.2 Equivalent heat conduction equation of water pipe cooling

The equivalent heat conduction equation of concrete is as follows:

$$\frac{\partial T}{\partial t} = \nabla^2 T + (T_0 - T_W) \frac{\partial \Phi}{\partial t} + \theta_0 \frac{\partial \psi}{\partial t}$$  (2)

Where: $\nabla^2 T$——Laplace operator; $a$——the thermal conductivity of concrete, m$^2$/h; $T_0$——the initial temperature of concrete, °C; $T_W$——the initial temperature of cooling water, namely the inlet water temperature, °C; $\theta_0$——the final adiabatic temperature rise, °C; $\Phi$ and $\psi$——functions considering the cooling effect of water pipe.

2.3 Basic Theory of Stress Field Calculation

$$\{\Delta \varepsilon_n\} = \{\Delta \varepsilon_n^e\} + \{\Delta \varepsilon_n^c\} + \{\Delta \varepsilon_n^T\} + \{\Delta \varepsilon_n^S\} + \{\Delta \varepsilon_n^0\}$$  (3)

Where: $\{\Delta \varepsilon_n\}$——the concrete strain increment, $\{\Delta \varepsilon_n^e\}$——the elastic strain increment, $\{\Delta \varepsilon_n^c\}$ is the creep strain increment, $\{\Delta \varepsilon_n^T\}$——the temperature strain increment, $\{\Delta \varepsilon_n^S\}$——the shrinkage strain increment, $\{\Delta \varepsilon_n^0\}$——the autogenous volume strain increment.

3. Study on Temperature Control and Crack Prevention Scheme

3.1. Engineering overview

A project is a first class (1) project, the main building of the hub is a level 1 building, and the secondary building is a level 3 building. The deep-hole spillway tunnel is arranged on the right bank, which is composed of shore-tower inlet, free level tunnel and outlet flip bucket. The average annual temperature in the cave is 14°C, and the annual variation of temperature is 8°C. The thermal and mechanical parameters of lining concrete of flood discharge tunnel are shown in table 1 to table 2.

| Table 1. Thermodynamic parameters of concrete. |
|-----------------------------------------------|
| | Unit | $C_{90\ 40}$ |
| Temperature conductivity coefficient | $10^{-3} m^2/h$ | 2.669 |
| Thermal conductivity coefficient | kJ/ (m·h·°C) | 8.723 |
| Specific heat | kJ/ (kg·°C) | 0.92 |
Density $\text{kg/m}^3$ 2450
Poisson's ratio $/$ 0.167
Thermal expansion coefficient $10^{-6}/\text{°C}$ 10
Adiabatic temperature rise $\text{°C}$ $\theta_0 = \frac{46.948t}{1 + 1.1845/t}$

Table 2. Thermodynamic parameters of bed rock.

| Temperature conductivity coefficient | Thermal conductivity coefficient | Specific heat | Thermal expansion coefficient | Specific heat | Poisson's ratio | Elastic modulus |
|-------------------------------------|---------------------------------|--------------|-------------------------------|--------------|----------------|----------------|
| Unit Value                          | $10^{-3}$m$^2$/h                 | kJ/(m·h·°C) | kJ/(kg·°C)                   | $10^{-6}/\text{°C}$ | kg/m$^3$       | /              | GPa            |
|                                     | 2.533                           | 6.46         | 0.838                         | 8.5          | 2600           | 0.22           | 21             |

3.2 Calculation Model and Basic Data

When calculating the temperature field, the surrounding and bottom surface of bedrock and specimen are adiabatic boundary, the top surface is heat exchange boundary, and the ambient temperature is multi-year average temperature. When cooling through water, the equivalent algorithm is used. When calculating the stress field, the left and right sides of the bedrock are normal constraints, and the bottom is three-dimensional constraints. The model is 9m long, 11.2m high and 1m thick. The computational grid and feature point layout are shown in figure 1.

3.3 temperature control and crack program

Scheme 1: Casting in July, demolding after pouring 3d, C40 anti-abrasion concrete pouring temperature 18°C, water 7d, water pipe spacing 1.0×1.0m, water temperature 14°C, flow 1.0m$^3$/h, surface without insulation, no water conservation.

Scheme 2: Casting in July, demoulding after pouring 3d, C40 anti-wear concrete pouring temperature 18°C, water 7d, water pipe spacing 1.0×1.0m, water temperature 14°C, flow 1.0m$^3$/h, surface without insulation, flow maintenance 3d/7d/14d.

3.4 Result analysis

3.4.1 Simulation Analysis of high temperature season. From figure 2 to figure 3, it can be seen that the maximum temperature inside the scouring concrete of the spillway tunnel can reach about 35 °C under the condition of 3 days after pouring, 7 days of water flowing and no water curing. According to the temperature process line of the characteristic point of the bottom slab of the spillway tunnel, the maximum temperature is 34.6°C on 1.5 d, and it drops to 22°C on 7 d. Then the temperature of the lining concrete changes with the temperature, and the temperature decreases continuously. Until the first winter (February), the temperature of the concrete decreases to the lowest, from the highest temperature of 34.6°C to the lowest temperature of 7.6°C, and the cooling range is above 26°C. Then the temperature
of lining concrete fluctuates periodically with the ambient temperature, and the fluctuation range is about 13°C. The maximum temperature difference between inside and outside was 6.24°C, which occurred in 1.5 d.

Corresponding to the above temperature law of concrete, concrete stress also shows obvious regularity change. Because the bottom slab, side wall lining and top arch of the spillway tunnel belong to the thin-walled structure in a strong constraint state, the stress caused by temperature drop increases rapidly. Taking the bottom slab as an example, when the maximum temperature of concrete is reduced from 34.6°C to 7.6°C, the stress of concrete has exceeded the allowable stress, and when the minimum temperature in winter ( January next year ) is reduced to 7.6°C, the tensile stress of concrete reaches the maximum value of 2.84 MPa, which is far more than the allowable stress of concrete. The safety factor of the virtual tensile strength according to the maximum tensile stress corresponding to the age is 0.99.

![Temperature envelope diagram](image1.png)

![Stress envelope diagram](image2.png)

**Figure 2.** Temperature and Stress envelope diagram.

![Temperature process line](image3.png)

![Stress process line](image4.png)

**Figure 3.** Temperature and Stress line.

### 3.4.2 Analysis of Influence of Surface Water Maintenance Age

In order to change the time of water curing, the simulation schemes of 0d, 3d, 7d and 14d are carried out on the basis of scheme 1. The characteristic values of the maximum temperature difference between inside and outside, the maximum tensile stress and the minimum anti-cracking safety factor of the concrete of the bottom plate of the flood discharge tunnel are shown in table 3 to table 4 respectively. And the relationship between the characteristic values and the curing time is shown in figure 4 to figure 5.

According to the characteristic values and relationship curves of the following flow curing ages on the bottom concrete of the spillway tunnel, it can be seen that the maximum temperature cannot be effectively reduced because the internal water cooling time of the concrete is longer than the time of the internal maximum temperature. However, the surface flow curing has a significant influence on the temperature stress of the lining of the spillway tunnel. Compared with the results of 0 d ( no water conservation ) and 3 d of water conservation, the maximum internal temperature decreased by 2.69°C, the maximum internal and external temperature difference increased by 9.14°C, the maximum internal temperature of the lining concrete fluctuates periodically with the ambient temperature, and the fluctuation range is about 13°C. The maximum temperature difference between inside and outside was 6.24°C, which occurred in 1.5 d.

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tensile stress decreased by 0.23 MPa, and the minimum crack safety factor increased by 0.08. With the increase of curing age from 3 d to 28 d, the internal maximum tensile stress decreased from 2.68 MPa to 2.16 MPa, which decreased by 0.5 MPa, and the safety factor increased from 0.99 to 1.22. When the surface is maintained without flowing water or the maintenance time is less than 3 d, the minimum crack safety factor of the surface point and the middle point is less than 1, which is bound to produce cracks. According to the simulation calculation, the water flow maintenance of spillway tunnel lining is essential.

According to the above analysis, under the condition of other cooling parameters unchanged, the surface water flow maintenance is at least 28 days under the pouring temperature of 18℃ in summer.

**Table 3. Maximum temperature of characteristic points.**

| Time/d | Surface point | Middle point | Temperature difference |
|--------|---------------|--------------|------------------------|
|        | $T_{\text{max}}$/℃ | $T_{\text{max}}$/℃ | $\Delta T_{\text{max}}$/℃ |
| 0      | 26.5          | 32.85        | 6.24                   |
| 3      | 23.97         | 30.16        | 15.38                  |
| 7      | 23.76         | 30.16        | 15.38                  |
| 14     | 23            | 30.16        | 15.38                  |
| 28     | 21.64         | 30.16        | 20.08                  |

**Table 4. Maximum tensile stress and minimum safety factor of characteristic points.**

| Time/d | Surface point | Middle point |
|--------|---------------|--------------|
|        | $\sigma_{\text{max}}$/Mpa | $K_{\text{min}}$ | $\sigma_{\text{max}}$/Mpa | $K_{\text{min}}$ |
| 0      | 2.8           | 0.91         | 2.91         | 0.91          |
| 3      | 2.28          | 1.13         | 2.68         | 0.99          |
| 7      | 2.05          | 1.25         | 2.59         | 1.02          |
| 14     | 1.73          | 1.49         | 2.37         | 1.11          |
| 28     | 1.46          | 1.76         | 2.16         | 1.22          |

**Figure 4.** Relationship curve between temperature and flow age.
4. Conclusions
According to the simulation results, when pouring the lining concrete of the spillway tunnel in the high temperature season, it is necessary to cool the lining with water at the same time, and to cool the lining with water after removing the mould at the early age. It not only reduces the maximum internal temperature of the lining concrete, but also effectively reduces the temperature difference between the inside and outside of the lining, effectively reduces the tensile stress on the lining surface, and effectively reduces the risk of cracks.

For the lining concrete pouring in the high temperature season (July), the maximum tensile stress on the surface and internal occurs in the winter of the first year, so after October, the lining concrete should be well insulated and covered. Therefore, for thin-walled lining concrete, water cooling and surface flow maintenance, winter cover insulation, can effectively reduce the internal and external temperature difference of concrete structure, in a reasonable time for timely surface flow, surface insulation, internal water cooling, can obtain good temperature control and crack prevention effect.

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