

Research on risk and measure of temperature control and crack prevention for foundation cushion of dam

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Abstract. In this paper, a three-dimensional finite element method was used to analyze the peak value of the foundation cushion of typical section of the Sanhekou dam, and the water cooling and pouring process were accordingly simulated. In order to meet the temperature control standards, three working conditions were analyzed. Results show that the use of refined water pipes and lower pouring temperature can make the maximum temperature of concrete lower than 30 °C. However, refined water pipes will lead to greater tensile stress at the end of second cooling stage and the strategy of "small temperature difference, slow cooling rate" should be adopted to further reduce the risk of cracking during later age.

Keywords: Simulation calculation; Water cooling; Cushion.

1. Introduction

Cracks in the dam foundation will bring problems of seepage, deformation and stability to the dam body. Dam foundation cushion concrete is a thin and large plate structure, and the large width to height ratio make it easy to produce cracks.

In the analysis of roller compacted concrete (RCC) gravity dam, Wang et al. [1] found that the causes of cracks in the foundation cushion can be classified into loading and non-loading factors, among which the non-loading factors are temperature change, concrete shrinkage and uneven settlement of foundation, etc. Jiang et al. [2] analyzed the causes of foundation cushion cracks of RCC gravity dam of Baishi reservoir, and found that cracks were mainly caused by the insufficient thickness of foundation cushion, the large temperature difference between inside and outside, and the large elastic modulus difference between bedrock and concrete. Feng [3] analyzed the cracks in the dam foundation concrete of Gouyutang reservoir, and found that the causes were the change of concrete gradation and lack of temperature control measures, as well as the establishment of longitudinal joints. Xue [4] analyzed the foundation cushion of Longhuakou RCC gravity dam by the simulation calculation and field monitoring data, and found that the internal and external temperature difference, the strong constraint of foundation, the large temperature variation and the tensile stress caused by the consolidated grouting led to the generation of cracks. The risk of concrete cracking can be lowered by reducing cement dosage, adding admixtures, and applying water cooling pipes and other temperature control measures [5]. Gu et al. [6] used a three-dimensional finite element method to calculate the temperature and stress field of a RCC arch dam. Cooling water and lower casting temperature can effectively reduce the thermal stress of foundation cushion. Fu [7] found that the concrete thickness, casting temperature and ambient temperature would have a great impact on the thermal stress when analyzing the long intermittent period of foundation cushion, and reasonable joint splitting measures could reduce the thermal stress.

The thermal stress of foundation cushion is affected by many factors such as external temperature, casting temperature, hydration heat of concrete and temperature control measures. In practical engineering, temperature field and stress field of foundation cushion can be analyzed by the three-dimensional finite element method, and water cooling and surface protection measures in the construction process should be considered in the analysis. Based on a typical section of Sanhekou dam, SAPTIS program [8] is used to calculate the temperature and stress field, and the temperature control measures of foundation cushion are analyzed.

2. Calculation theory

Temperature and stress field calculation theory can be found in ref. [9].

3. Project Overview

3.1 Sanhekou project

Sanhekou water conservancy project is one of the construction projects of Han-Ji-Wei River project. The RCC arch dam is with a height of 145m, normal water level of 643m, total storage capacity of 710 million m³.

3.2 Thermal and mechanical properties of concrete and bedrock

Tables 1, 2 and 3 show the thermal, deformation properties of concrete and thermal and mechanical properties of bedrock, respectively.

Table 1. Thermal properties of concrete

	Unit	C ₉₀ 25	C ₉₀ 25	C ₂₈ 25
Temperature conductivity coefficient	10 ⁻³ m ² /h	2.669	2.758	2.850
Heat conductivity coefficient	kJ/(m·h·°C)	6.51	6.39	6.71
Specific heat	kJ/(kg·°C)	0.997	0.963	0.971
Density	kg/m ³	2450	2420	2325
Poisson's ratio	/	0.167	0.167	0.167
Thermal expansion coefficient	10 ⁻⁶ /°C	9	9	9
Adiabatic temperature rise	°C	$\theta_0 = \frac{22.16t}{2+t}$	$\theta_0 = \frac{28.35t}{2+t}$	$\theta_0 = \frac{36.98t}{1.3+t}$

Table 2. Deformation properties of concrete

	Elastic modulus (GPa)			
	7d	28d	90d	180d
C ₉₀ 25	21.0	32.0	35.0	37.0
C ₉₀ 25	22.0	34.0	39.0	41.0
C ₂₈ 25	24.0	34.0	37.0	38.0

Table 3. Thermal and mechanical properties of bedrock

	Temperature conductivity coefficient	Heat conductivity coefficient	Specific heat	Thermal expansion coefficient	Density	Poisson's ratio	Elastic modulus
Unit	10 ⁻³ m ² /d	kJ/(m·d·°C)	kJ/(kg·°C)	10 ⁻⁶ /°C	kg/m ³	/	GPa
Bedrock			0.9	9	2600	0.25	30

4. Optimization analysis of cushion temperature control measures during

4.1 Computational models and boundary conditions

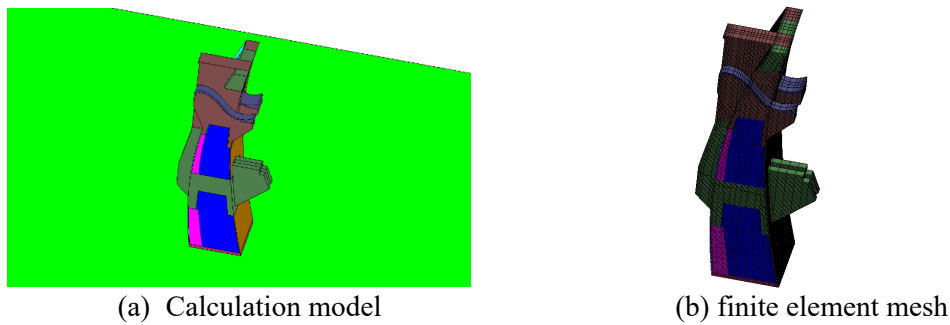


Figure 1. Calculation model and finite element mesh

Calculation model and finite element mesh of no.5 dam section of river bed are shown in Figure 1. The dam section has a bottom elevation of 501.0m and a top elevation of 646.0m. A total of 71122 units and 82767 nodes were divided. The transverse direction is Y direction, the downstream direction is X direction, and the vertical upward direction is Z direction. The boundary conditions of temperature field calculation are shown in Figure 2. The restraint boundary conditions of bedrock are shown in Figure 3.

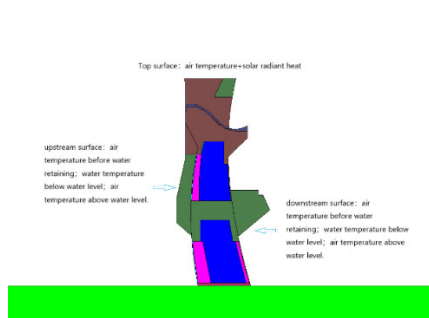


Figure 2. Temperature boundary

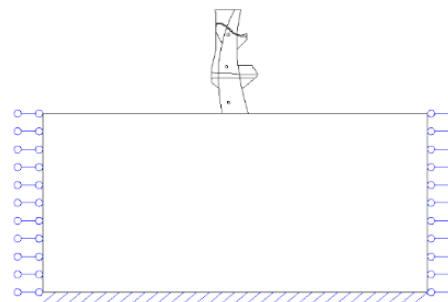


Figure 3. Restraint boundary

4.2 Calculate and working conditions

The calculation uses a three-dimensional finite element software to simulate the whole process of dam concrete construction period, including the casting process of dam, water cooling process. Under the design condition, the casting thickness of foundation cushion is 3.5m, the casting interval is 18 days, and the casting time is November 1, 2016. The allowable peak temperature of normal concrete at the cushion is 30°C. In order to analyze the risk of concrete cracking at foundation cushion and optimize the temperature control measures, this paper designed two working conditions on the basis of the basic working condition to achieve the temperature control standard, including refined water pipe and lower casting temperature. Detailed calculation conditions are shown in Table 4.

Table 4. Working condition

casting temperature (°C)	Water cooling				
	Time(d)	spacing (m × m)	Water temperature (°C)	Flow(m ³ /h)	
gk1	12	25	1.5×3.0	18	1.0
gk2	12	25	1.0×1.5	18	1.0
gk3	10	25	1.0×1.5	18	1.0

4.3 Results analysis

4.3.1. Maximum temperature and stress

Table 5 shows the calculation results of dam. Under the basic working condition (gk1), the maximum temperature inside the foundation cushion can reach 33.86°C, which exceeds the maximum allowable temperature of 30°C. The maximum stress in the transverse direction is 3.58MPa, which appears at the end of the second cooling stage. The safety factor calculated based on the tensile strength of 180d is 1.06. When the spacing between water pipes decreased from 1.5m × 3.0m to 1.0m × 1.5m, the maximum temperature of foundation cushion decreases from 33.86°C to 31.15°C, which decreases by about 2.7°C, but is still higher than the allowable maximum temperature. The maximum transverse stress increases from 3.58MPa to 4.12MPa, which appears at the end of the second cooling stage. The safety factor was reduced from 1.06 to 0.92. Under the condition of lowering casting temperature and refining water pipe (gk3), the maximum temperature in foundation cushion is reduced to 29.54°C, which meets the requirement of allowable maximum temperature, and the maximum stress in transverse direction is 3.82MPa, which is higher than the allowable tensile stress of concrete. The safety factor calculated based on 180d tensile strength is 0.99. According to gk1 and gk2, the infilled water pipe can reduce the maximum temperature to a certain extent, but the hydration heat of normal concrete rises too fast in the initial stage of casting, and the infilled water pipe is difficult to make concrete reach the temperature control standard. By lowering the casting temperature in gk3, the temperature control standard then can be achieved.

Table 5. Temperature and stress results of foundation cushion

	Maximum temperature (°C)	Maximum stress (MPa)	Safety factor
gk1	33.86	3.58	1.06
gk2	31.15	4.12	0.92
gk3	29.54	3.82	0.99

4.3.2. Evolution of temperature and stress

Figure 4 show the evolution of temperature and stress of concrete. In Figure 4(a), refined water pipes and lower casting temperature can significantly reduce the maximum temperature of concrete. In gk2 and gk3, due to the refined water pipes, there is a large temperature drop and a shorter cooling time for first and second cooling stage. In figure 4(b), the stress of gk1 is the largest during the first cooling stage due to the high temperature rise of concrete. During the second cooling stage, the stress of gk2 and gk3 is greater than that of gk1, mainly because the refined water pipe leads to a faster cooling rate at the second cooling stage. Compared with Figures 4(a) and 4(b), it can be seen that measures of gk3 should be adopted by refining water pipes and lower casting temperature. During the second cooling stage, the cooling flow rate or water temperature should be reduced to reduce the temperature drop, and the strategy of "small temperature difference, slow cooling rate" should be adopted to reduce the risk of cracking.

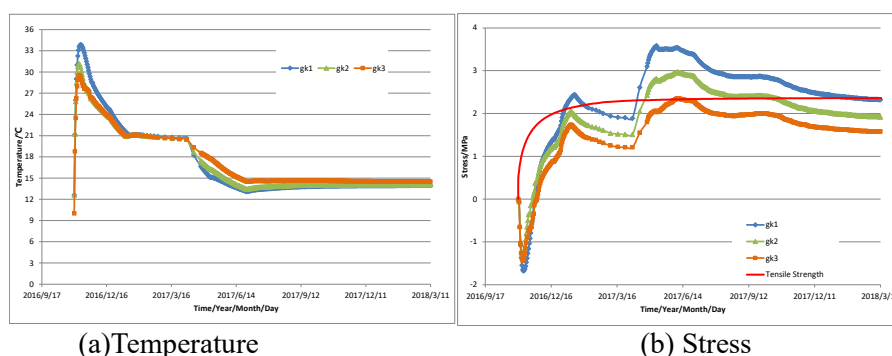


Figure 4. Evolution of temperature and stress of concrete

5. Conclusions

The normal concrete of foundation cushion is easy to crack due to the influence of constraint, hydration heat, temperature difference, rock foundation and other factors. In the analysis of the foundation cushion, attention should be paid to the maximum temperature, the maximum stress during the first cooling and the second cooling stage. Based on the analysis of a typical dam section of Sanhekou water reservoir, it is found that the maximum temperature is related to the maximum stress. Reducing the maximum temperature can effectively reduce the stress during the first cooling stage. The maximum stress of concrete is affected by the maximum temperature and cooling rate, and cooling too fast during the second cooling stage will cause the risk of cracking. Therefore, the casting temperature should be strictly controlled and the temperature control measures should be strengthened in the early stage, and the cooling rate should be slow in the later stage.

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