Simulation analysis on temperature rise during arch dam construction period

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Abstract. During the construction of a high arch dam, the concrete will have a certain temperature rise after being cooled by the external environment and the concrete's own hydration. As a high arch dam concrete temperature control stage, the temperature change generated outside the control, the impact on the actual project needs to be analyzed in conjunction with the specific project. This article focuses on the temperature rise phenomenon of an arch dam under construction in China, and analyzes the impact of the temperature rise phenomenon during the current arch dam construction period on the arch dam through monitoring data research and finite element simulation. The results show:(1)The arch dam has obvious temperature rise during the temperature control stage, which mainly occurs when the temperature rises after the cooling temperature is lower than the target temperature of the stage and after the large flow of water is stopped in the temperature control stage, and there is a short-term rise in temperature of 3°C;(2)According to the inversion results of the monitoring of the arch dam, there is a certain safety margin for the concrete stress level of the corresponding parts before and after the temperature rise phenomenon;(3)The temperature rise phenomenon can be controlled at the temperature. During the control period, the tensile stress level of the concrete is prevented from further increasing when the concrete strength is low.

1. Introduction

During the construction of the high arch dam, due to the continuous influence of the hydration heat of the concrete and the external temperature, the temperature of the concrete will rise rapidly in a short time after the large flow of water is cooled. The current phenomenon of the temperature rise of the concrete is common in the construction process of concrete dam projects that have been built or under construction at home and abroad. In the actual construction process, due to various reasons, 556 experienced a certain temperature rise during the construction period, especially the temperature control stage after the first phase of cooling. For example, in 2009, there were about 38 cracks in the Xiaowan Arch Dam during the construction period[1]. Combined with the temperature monitoring values during the construction period, it was found that many warehouses showed obvious temperature rise after the first cold stage, and some of the cracks were closely related to the early temperature rise phenomenon. Some domestic scholars have carried out some research on the phenomenon of temperature rise during the construction period. For example, academician Zhu Bofang’s research results show that the temperature difference between the upper and lower layers caused by the rise in the temperature of the
Concrete during the construction period of the Xiaowan Project is one of the important causes of concrete cracking[2]. The research results of Hua Youhe scholars show that when the early concrete temperature rises to 3 to 4.5 degrees Celsius, the generation of residual stress significantly reduces the safety margin of the arch dam pouring process[3]. It can be seen that the temperature rise as a temperature change outside the concrete temperature control plan is closely related to the construction quality of the arch dam.

At present, the main method to control the temperature of concrete during construction period is to control by erecting cooling water pipes inside the concrete[4]. With the optimization of water-passing temperature control schemes and technologies, as well as the development of construction technology and the accumulation of experience, the main temperature control schemes are constantly adjusted according to actual needs. Among them, the water-passing cooling strategy has gone through the "two phases and six phases" cooling The three stages of intermittent water stoppage, "three phases and nine phases" cooling, intermittent water stoppages, and "three phases and nine phases" cooling intermittently stop water. The typical temperature control curve evolution is shown in figure 1.

Figure 1. In this case simply justify the caption so that it is as the same width as the graphic.

At the beginning of the construction of domestic super high arch dams, such as Ertan Arch Dam and Xiaowan Arch Dam, the concrete in areas A and B adopted the "Phase Two and Six Phases" cooling scheme with intermittent water stoppage and stuffy temperature. In 2009, large-scale obvious concrete cracks were found in the Xiaowan Arch Dam. After the experts conducted investigation and analysis, a mid-term cooling phase was added to the temperature control plan, and the “three phases and nine phases” cooling intermittently stopped the water temperature. The plan obviously curbed the magnitude and duration of the temperature rise of the concrete during the construction period. After the crack arrest measures were implemented, the Xiaowan Arch Dam did not produce type IV temperature cracks in the subsequent[2]. Subsequent projects have adopted the temperature control standard of "three phases and nine phases". There is still a certain temperature rise in the completed projects so far. Although no large-scale cracks have occurred, it is still unavoidable that there will be no dams and no cracks. The status quo[5]. Several arch dams currently under construction have adopted the "three phases and nine phases" cooling and intermittent water shutdown scheme with the increase in technology level and investment, to further reduce the degree of additional temperature rise during the construction period[6]. This paper uses the finite element method to simulate the temperature rise phenomenon that has occurred during the construction period of a super high arch dam under construction in the southwest, and then study its temperature and stress field, and put forward some reasonable suggestions for the current and future temperature control and crack prevention of the arch dam.

2. Concrete temperature change process of an arch dam under construction in southwestern China

An arch dam under construction in Southwest China is built on the lower reaches of the Jinsha River, with a crest elevation of 834m and a maximum dam height of 289m. It is a super high arch dam project. The design arc length of the dam crest is 709.0m, the whole dam is divided into 30 transverse joints, a total of 31 dam sections, and the whole dam is poured with low-heat cement concrete. The arch dam began pouring in April 2017. As of May 2021, the highest elevation has been poured to an elevation of
825m. The temperature data of 80 internal permanent thermometers that have been buried in the dam sections 1 to 17 on the left bank have been compiled. According to statistics, the temperature trend of each thermometer is basically consistent with the design temperature curve of the "three phases and nine phases". A small number of warehouses have a temperature rise above 1.5°C during the two weeks of the construction period. The specific performance is the temperature rise after the cooling temperature is lower than the target temperature of the stage (hereinafter referred to as super-cooling) and the temperature rise after the large flow of water is stopped in the temperature control stage. The typical temperature monitoring timeline is as follows:

Through monitoring data sorting, it is found that most of the temperature rise phenomenon occurs at the end of the cold, and at the same time, compared with other stages of temperature changes, its fluctuation amplitude is expected to be larger, which is consistent with the development law of early hydration heat release of concrete. Since the early strength of concrete is low, and there is still a cooling stage after the end of a cold temperature control stage, if the temperature rises, it will have a greater impact on the safety of the concrete. Therefore, we will focus on the cold end due to ultra-cold The subsequent temperature rise phenomenon will be followed up. The following are the corresponding temperature rise monitoring statistics on the left bank of the arch dam:
Table 1. Statistics on the temperature rise in the early stage of the left bank of BHT.

| monolith number | Monitor name | date          | temperature rise | overcooling temperature value |
|-----------------|--------------|---------------|------------------|------------------------------|
| 4#              | T4-740-2     | 2020. 4. 19-4. 14 | 1.8℃             | 2℃                           |
| 6#              | T6-760-2     | 2020. 5. 15-5. 16 | 2℃               | 2℃                           |
| 7#              | T7-660-2     | 2019. 4. 13-4. 14 | 2.2℃             | 2℃                           |
| 9#              | T9-760-2     | 2020. 3. 31-4. 07 | 3.2℃             | 1.6℃                         |
| 9#              | T9-780-2     | 2020. 5. 18-5. 20 | 2.6℃             | 1.4℃                         |
| 10#             | T10-610-2    | 2018. 8. 29-9. 04 | 1.5℃             | 2.5℃                         |
| 10#             | T10-760-2    | 2020. 4. 27-5. 10 | 1.9℃             | 2.8℃                         |
| 11#             | T11-640-2    | 2018. 11. 6-11. 13 | 3℃               | 3.4℃                         |
| 11#             | T11-760-2    | 2020. 2. 19-2. 25 | 3℃               | 2.6℃                         |
| 12#             | T12-580-2    | 2018. 2. 5-2. 11  | 3.8℃             | 2.7℃                         |
| 14#             | T14-720-2    | 2019. 10. 26-10. 27 | 2℃             | 2.4℃                         |
| 15#             | T15-580-2    | 2018. 1. 1-1. 8    | 1.9℃             | 2.4℃                         |
| 15#             | T15-700-2    | 2019. 6. 19-6. 25 | 2.2℃             | 1.6℃                         |
| 15#             | T15-760-2    | 2020. 5. 30-5. 31 | 3.7℃             | 2.6℃                         |
| 17#             | T17-580-2    | 2018. 1. 15-1. 22 | 1.5℃             | 2.3℃                         |
| 17#             | T17-760-2    | 2018. 1. 15-1. 22 | 1.3℃             | 2.4℃                         |

According to the typical temperature rise timeline and corresponding statistical data, under the current cooling water system, the early temperature rise phenomenon of the arch dam is different from the current situation of the general rise at the end of the previous cooling stage, and its amplitude is often equal to the same. The cold stage is similar to the ultra-cold. Because the maximum rebound amplitude exceeds 3℃, the safety of concrete needs further evaluation. Therefore, this paper will conduct further research through finite element simulation.

3. Simulation of the influence of arch dam behavior under temperature rise

3.1. Simulation model
The calculation model in this paper selects the No. 17 monolith number model of an arch dam under construction in the southwest region for calculation. The specific behavior of the model is shown in figure below. The entire model is composed of 139, 045 units and 159, 968 nodes. In order to reflect the overall structural stress, the model is equipped with basic corridors, horizontal corridors, deep holes and diversion bottom holes according to the concrete arch dam design drawings provided by the design institute. According to the concrete partition provided by the design institute, the partition is set up, where the concrete from the dam foundation to the elevation of 585 is zone A, the elevation from 585m to 680m is zone B, and the elevation from 680 to the dam crest is zone C.
3.2. Boundary conditions and related parameters
In this paper, the 17# monolith number of the river bed is used as the finite element model for calculation. The gravity field and temperature field of the arch dam are coupled in the calculation process, and the creep of the concrete itself is also considered. It mainly considers the influence of concrete cooling and temperature reduction, self-hydration heat release, and external environmental influences on concrete temperature and temperature stress during the construction period. The project has not yet stored water during the calculation period, and the impact of water storage on the project is not considered.

Among them, the concrete hydration heat and water pipe cooling adopt the equivalent heat conduction equation[8].

\[
Q^{-}(\tau) = cp[T(\tau) - T_w] \phi_{\tau+2-1} 
\]

(1)

Where \(\phi\) is the hydration heat function, \(\phi\) is the cooling effect function, \(T_w\) is the water temperature, and \(\Delta\tau\) is the incremental step size.

Concrete creep calculation[8].

\[
C(t, \tau) = C_0(A_0 + A_1\tau^{-A_2})[1 - e^{-M_2(t-\tau)}] \\
+ C_0(B_0 + B_1\tau^{-B_2})[1 - e^{-M_3(t-\tau)}]
\]

(2)

Where \(C(t, \tau)\) is the concrete creep degree, that is, the creep produced under the action of unit stress, the dimension is MPa-1; \(\tau\) represents the loading time; \(C_0, A_0, A_1, A_2, M_1, B_0, B_1, B_2, D, M_2, M_3\) are the creep parameters determined by experiments.
Table 2. Thermodynamic parameters of various materials in the dam area.

| Materials                  | Bedrock | DamC30 | DamC35 | DamC40 |
|----------------------------|---------|--------|--------|--------|
| Modulus of Elasticity /GPa | 26      | 40.7   | 41.6   | 44.6   |
| Poisson's ratio            | 0.25    | 0.211  | 0.223  | 0.215  |
| Coefficient of linear expansion $\alpha$/(10^{-6}/°C) | 6.79    | 5.1    | 5.1    | 5.1    |
| Weight capacity /(kg/m³)   | 2500    | 2421   | 0.978  | 0.978  |
| Specific heat capacity / [kJ/(kg°C)] | 0.85    | 0.978  | 0.974  | 0.967  |
| Adiabatic temperature rise $\theta_a$(°C) | None    | 21.1   | 23.5   | 24.9   |
| Exothermic coefficient of heat of hydration | None    | 0.252  | 0.252  | 0.252  |
| Thermal conductivity / [kJ/(m²·°C)] | 185.04  | 160.56 | 159.84 | 164.16 |

In addition, the temperature and related data come from actual measurement data on the construction site.

3.3. Simulation result

In this paper, combined with the permanent monitoring meter deployed in the project and on-site scheduling, the actual monitoring on site is used as a reference to perform finite element simulation to simulate the current overall stress and strain state of the arch dam, and to calculate the concrete stress level at the location where the temperature rise phenomenon is located. Its influence on the behavior of the arch dam.

After the calculation is completed, compare the temperature values between the calculated results and the corresponding points of the actual monitor position. The temperature monitoring timeline of the T17-760-2 monitor is representative of the crowded temperature monitoring data, so this calculation Take the T17-760-2 monitor reading and the simulation calculation to read the result. The specific simulation value and the monitoring value trend and comparison are shown in figure 4:

![Comparison of simulation value and monitoring value of t17-760-2 thermometer.](image)

It can be seen from the results that the trend of the temperature curve is basically the same, and the range of temperature drop in each stage is the same, which proves that this calculation has certain reference value.
From the simulation results, the concrete stress level at the location where the temperature rise occurs develops with temperature changes, and the stress value at the most dangerous point is 0.48MPa, which is 0.45MPa away from the 2.0 safety curve during the same period. The whole is within the 2.0 safety curve range and still has a certain safety margin. At the end of the first stage of cooling, the tensile stress level rises rapidly due to the cooling temperature being lower than the cooling target temperature by a certain range. As the temperature rises, the tensile stress level decreases. At the same time, the tensile stress of the concrete is closer to the upstream surface. The value is 0.08MPa higher on average.

4. Conclusions
Footnotes should be avoided whenever possible. If required they should be used only for brief notes that do not fit conveniently into the text.

Combined with the finite element simulation analysis of the arch dam, the following conclusions are drawn:

- The arch dam has an obvious temperature rise in the temperature control stage, which mainly occurs when the temperature rises after the cooling temperature is lower than the target temperature of the stage and after the large flow of water is stopped in the temperature control stage, and there is a short-term rise of 3°C phenomenon;
- According to the inversion results of the arch dam monitoring, before and after the temperature rise phenomenon, the concrete stress level of the corresponding part has a certain safety margin, and the cracking risk caused by the temperature rise phenomenon is relatively low;
- The controllable temperature rise phenomenon can control the tensile stress of the concrete when the concrete elastic modulus is not fully developed during the temperature control period.

Arch dam construction has entered the 4.0 stage[10]. However, it is still a challenge to completely avoid temperature cracks in the ultra-high arch dams that have been built. To help the construction of seamless arch dams, if extreme weather is encountered during the concrete pouring during the construction period, it is possible to appropriately control a certain rise in concrete temperature through measures such as reducing the flow of water, which is conducive to the control of tensile stress and reduces the risk of concrete cracking.
Acknowledgement
The authors are grateful for the financial supports of National Natural Science Foundation of China (No. 51839007) and China Three Gorges Corporation Research Project (No. BHT/0809).

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