Optimization and control strategy of ideal temperature control curve for super-high arch dam

Liu Youzhi 1*, Liu Chunfeng 2, Tan Yaosheng 2, Li Jintao 1
1. State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin Beijing, 100038
2. China Three Gorges Projects Development Co. Ltd., Chengdu, 610041
Youzl@iwhr.com; 1205354232@qq.com; 1244292229@qq.com; 411461036@qq.com

Abstract: During the construction period, the super-high arch dam is poured monolithically, and the temperature stress level is high. The key to ensure the overall safety of the dam is to do a good job of temperature control and crack prevention during the construction period, and the formulation and optimization of temperature drop curve during the construction period is an important prerequisite for ensuring the temperature control. In addition to the conventional indexes such as the maximum temperature, temperature gradient, cooling range, cooling rate and final combined stress, the transverse joint aperture of the dam should be taken into consideration for the determination of temperature drop curve during dam construction. In this paper, Baihetan super-high arch dam project was taken as an example to study this problem, and the influence of different maximum temperature, target temperature and different cooling process on dam temperature stress, safety factor and transverse joint aperture was systematically analyzed. The results showed that different cooling processes and the setting of stage target temperature have obvious effects on the temperature stress, transverse joint aperture and safety factor during dam construction, and the coupling relation between these factors should be considered comprehensively in formulating the ideal cooling curve, so as to realize the optimization of the overall safety risk of the dam.

1. Introduction
Temperature control and crack prevention during the construction of high arch dam has always been the key content in the industry, and after years of accumulation, many gratifying achievements have been made [1]. The temperature control and crack prevention work of high arch dam involves materials, structure and construction, etc. Low-heat cement has been fully applied in high arch dam [2, 3]. In addition, the dam monitoring means has gradually changed from “digital monitoring” to “intelligent monitoring”, and “low-temperature pouring, comprehensive insulation and water pipe cooling” have become the three main measures of high arch dam. The temperature control concept of “small temperature difference, slow cooling, early cooling and early protection” has become a consensus in the industry [4].

With the development of modern information technology, the temperature control is becoming more and more intelligent, and the temperature control of dam has entered the stage of intelligent control from traditional manual control [5-7]. Its core is to cool the dam completely according to the designed cooling curve through intelligent control means. Obviously, it is the proper setting of the cooling curve that matters. For dam temperature control, if an ideal cooling curve is found on the
premise of determining concrete material properties, which makes the temperature, stress and deformation process of concrete match the development and growth process of concrete material properties, the dam cracking risk will be better controlled. This is also the core of temperature control and crack prevention.

For this reason, many scholars have carried out related research, such as ZHANG Guoxin[8] and others have systematically discussed on the temperature control and crack prevention for super-high arch dams, and proposed that the problem of spatio-temporal gradient control should be taken into account in the temperature control. In terms of temperature control standards and measures for super-high arch dams, they put forward that the super-high arch dams need not be controlled by two same cooling zones. In addition, the research group also proposed the Nine-Three-One temperature control mode[9], which provided a systematic control method for how to effectively realize the cooling of dam concrete. ZHU put forward the feasibility of building high quality arch dams without cracking and the relevant techniques[10]. LIN[7] put forward the intelligent cooling control method and system for mass concrete. HU et al.[11] put forward the gradient control theory for cracking of arch dams. JING, CHANG[12] et al. put forward the spatio-temporal dynamic control measures for temperature control and crack prevention during construction of high arch dam. FAN et al.[13] put forward the construction intelligent control packaged technology and its application for a large hydropower project. Most of the above-mentioned research focuses on the recheck and optimization of temperature control standards and measures for dam concrete design, the theoretical analysis of temperature control and the intelligent control of the given design cooling curve in the construction process, which is inadequate in considering how to coordinate the dam cooling process as a whole, how to realize the coupling control among indexes such as the cooling range, cooling rate and final combined stress beyond the maximum temperature, basic temperature difference, temperature difference between internal and external and temperature difference between storeys, and how to realize the global optimization of safety factor in dam cooling. The optimization and formulation of ideal temperature curve still need further analysis.

Combined with the Baihetan project, the coupling effects of different maximum temperatures, target temperatures and different cooling processes on the dam temperature stress and the transverse joint aperture was systematically analyzed, based on which the coupling relation between these factors should be considered comprehensively when formulating the ideal cooling curve, so as to realize the optimization of the overall safety risk of the dam. The research has provided important technical support for the safety control of the cooling curve during the construction period.

2. Optimization of ideal temperature control curve for high arch dam

Several super-high arch dams built in recent years are basically controlled according to the temperature control idea of “low-temperature pouring, comprehensive insulation and water pipe cooling”. Due to the adoption of comprehensive thermal insulation measures, the temperature difference between internal and external during the construction period was relatively weakened. Relatively speaking, the control of cooling process has become the focus of optimization, and most of them followed the characteristic temperature control curve as shown in Fig. 1 (step type) or Fig. 2 (continuous type). Different projects have slightly different key control indexes due to different geographical and meteorological conditions. As can be seen from Fig. 1, for arch dams, several main temperature control indexes during construction include pouring temperature, maximum temperature, cooling range or target temperature (including Phase I, Mid-term and Phase II), and cooling rate (including Phase I, Mid-term and Phase II). The determination of these temperature control indexes will directly affect the safety factor of the dam, and will also have an impact on the actual transverse joint aperture of the dam. Limited by the compilation, this paper took Baihetan arch dam as an example and selected several key main influencing factors and parameters for demonstration and analysis. Related basic calculation parameters are shown in Table 1.
Fig. 1 Scheme 1: Cooling scheme in the same grouting area with same gradient

Fig. 2 Scheme 2: Continuous cooling scheme in the same grouting area with different gradient

Table 1 Thermal and mechanical parameters of sensitivity analysis

| Index parameter | Adiabatic temperature rise/℃ | Elastic modulus /GPa | Linear expansion coefficient | Deformation in itself volume/μm | Allowable stress /MPa |
|-----------------|-------------------------------|----------------------|-------------------------------|---------------------------------|----------------------|
| Parameter value | $23 \times t/(3.6-t)$ | $44 \times (1 - \exp(-0.58^{0.16}))$ | $5.0 \times 10^{-6}$ | $-15 \times 10^{-6}$ | $2.0$ |
| Parameter value | Arch sealing temperature | | | | |

2.1. The influence of the maximum temperature

As shown in scheme 1 in Fig. 3, when the maximum temperature was different, the temperature drop in first stage cooling was different, and the corresponding stress change process was obviously different. In the later stage, because the whole cooling process was completely the same for a long time, the final stress difference was not significant. From the maximum opening value, the higher the maximum temperature is, the greater the transverse joint aperture is, but the overall difference is small. The results of scheme 2 in Fig. 4 indicated that the stress level grew with the increase of the maximum temperature. The stress level at the age of 21 days in scheme 2 was lower than that of scheme 1 due to the slow cooling during the first stage cooling (the first 21 days). However, due to the unsynchronized temperature control measures, the temperature gradient between upper and lower layers was relatively large, and the stress level was higher than that of scheme 1. The results of the transverse joint aperture showed that the transverse joint aperture of the asynchronous temperature control scheme was larger than that of the synchronous temperature control scheme. The reason is that the synchronous cooling range of adjacent dam sections in the later stage of scheme 2 was larger than that of scheme 1. Generally speaking, both the stress and the final transverse joint aperture are related to the cooling process as well as the maximum temperature, so the ideal temperature control curve should be comprehensively analyzed according to different situations.
2.2. The influence of first stage cooling on stress and transverse joint aperture

According to the calculation results in Fig. 6, as the cooling range in first stage cooling increased, the early stress was getting larger and the safety factor smaller, and the later stress level was getting lower. On the contrary, as the cooling range in first stage cooling decreased, the early stress was getting smaller. At the later stage, the cooling range was large, and the later stress was also large. It can be seen from the transverse joint aperture hydrograph that the larger cooling range in the early stage means the smaller synchronous cooling range and the transverse joint aperture in the later stage. Otherwise, the smaller cooling range in the early stage means the larger transverse joint aperture in the later stage. Therefore, in order to simultaneously ensure that the early and later stresses have more reasonable safety and the transverse joints have better grouting, the early and later cooling ranges should be considered in coordination.

Relatively speaking, as shown in Fig. 7, the stress level during the cooling process of the concrete in the unconstrained zone was kept at a relatively low level, and the safety degree was relatively high, indicating that the concrete in the unconstrained zone has more adjustable room in terms of stress control and transverse joint aperture control.

**Fig. 3** Comparison of temperature and stress at different maximum temperatures (cooling scheme 1)

**Fig. 4** Comparison of temperature and stress at different maximum temperatures (cooling scheme 2)

**Fig. 5** Comparison of temperature and stress processes in different cooling process
2.3. The influence of intermediate cooling on stress and transverse joint aperture

According to the calculation results in Fig. 8, when the start time of intermediate cooling was the same, the greater the cooling range in intermediate cooling was, the greater the stress was. The temperature difference was directly proportional to the stress, but has relatively little influence on the final stress and final transverse joint aperture. Fig. 9 showed the variation in temperature stresses when the intermediate cooling and second-stage cooling were advanced. It can be seen that when the intermediate cooling and second-stage cooling advanced, the safety factor of the constraint zone was obviously reduced, and the risk was higher and the transverse joint aperture was smaller. The calculation results in Fig. 10 showed that after leaving the constrained zone, whether it was normal cooling or proper advance cooling, the overall temperature stress of the dam was relatively low, and the influence on the final transverse joint aperture was relatively small, indicating that there is more adjustable room in the cooling process and transverse joint control of the dam in the unconstrained zone.
2.4. The influence of second-stage cooling target temperature on stress and transverse joint aperture

As shown in Fig. 11, the change of the target temperature of the second-stage cooling directly affected the cooling range in the later stage and the basic temperature difference. Obviously, the higher second-stage cooling target temperature means the higher stress and the smaller transverse joint aperture, and vice versa. Since the closure grouting temperature in the second-stage cooling directly affects the key factors of the overall stress state of the dam, the index should be comprehensively determined in combination with the overall stress state of the dam.

3. Optimization and control strategy of ideal temperature control curve for high arch dam

3.1. Optimization ideas and strategies

Based on the above analysis results, it can be seen that for high arch dams, the stress inside the dam changed dynamically with the temperature, and the stress levels and safety factors in different parts and regions were quite different. The whole safety factor of the dam could be optimized by dynamically adjusting the whole process of cooling curve inside the dam. The optimization of the overall safety factor of the dam should consider the coordination between temperature stress and the transverse joint aperture, and take into account the project grouting when the safety factor of
temperature stress is optimal. As far as scheme 1 and scheme 2 mentioned in this paper are concerned, the adjustability of scheme 1 is relatively better.

3.2. Engineering application
Baihetan arch dam is located in Ningnan County, Sichuan Province and Qiaojia County, Yunnan Province in the lower reaches of Jinsha River. The maximum dam height is 289 m and the maximum bottom width is 93 m. The whole dam is made of low-heat cement concrete. Up to the deadline of this paper, nearly 2/3 of the dam pouring has been completed, and the whole process follows the temperature drop and control scheme proposed in this paper, without cracks. The average transverse joint aperture is above 1.0mm, and the grouting is good. The effectiveness and feasibility of the scheme one have been proved by the engineering practice results.

4. Conclusion and suggestion
Through the research of this paper, the main conclusions are as follows:

(1) The optimization of ideal temperature control curve for super-high arch dam should consider the coordination between temperature stress and transverse joint aperture, and take into account the project grouting when the safety factor of temperature stress is optimal;

(2) Different cooling processes and the target temperature at different stages have obvious influence on the temperature stress, transverse joint aperture and safety factor during dam construction, and the coupling relation between these influencing factors should be considered comprehensively when formulating the ideal cooling curve, so as to realize the optimization of the overall safety risk of the dam.

Acknowledgements
This paper was supported by China Three Gorges Corporation research project (BHT/0810, XLD/2114), the special fund of China Institute of Water Resources and Hydropower Research, State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin.

Reference
[1] ZHU Bofang, ZHANG Chaoran. Research on the structural safety of high concrete arch dams [M]. China Water & Power Press, February 2010 (in Chinese).
[2] YANG Huajin, LI Wenwei. The research and application of hydraulic concrete [M]. China Water & Power Press, February 2005 (in Chinese).
[3] WANG Pengfei, LIU Youzhi, FAN Yilin, et al. Analysis on feasibility of application of low-heat cement concrete to construction of ultra-high arch dam [J]. Water Resources and Hydropower Engineering, 2018, 49(9): 191-198 (in Chinese).
[4] ZHU Bofang. Pipe cooling of concrete dam from earlier age with smaller temperature difference and longer time [J]. Water Resources and Hydropower Engineering, 2009, 40(1): 44-50 (in Chinese).
[5] ZHU Bofang, ZHANG Guoxin, XU Ping. Decision making support system for temperature and stress control of high concrete dams in construction period [J]. Journal of Hydraulic Engineering, No.1, 2008: 23-28 (in Chinese).
[6] ZHANG Guoxin, LIU Youzhi, LIU Yi. Transformation from “digital dam” to “intelligent dam”—research progress on temperature control and crack prevention of high dam [C]. Proceedings of Annual Meeting of Chinese National Committee On Large Dams, 2012 (in Chinese).
[7] LIN Peng, LI Qingbin, ZHOU Shaowu, et al. Intelligent cooling control method and system for mass concrete [J]. Journal of Hydraulic Engineering, 2013, 44(8): 950-957 (in Chinese).
[8] ZHANG Guoxin, AI Yongping, LIU Youzhi, et al. Discussion on temperature control and crack prevention for super-high arch dams [J]. Journal of Hydroelectric Engineering, Vol.29, No.5, 2010: 125-130 (in Chinese).
[9] ZHANG Guoxin, LIU Yi, LI Songhui, ZHU Bofang. Research and practice of Nine-Three-One temperature control mode [J]. Journal of Hydroelectric Engineering, 2014, 33(2): 179-184 (in Chinese).

[10] ZHU Bofang. On the feasibility of building high quality arch dams without cracking and the relevant techniques [J]. Journal of Hydraulic Engineering, 2006, 37(10): 1155-1162 (in Chinese).

[11] HU Yu, LIN Peng, et al. Gradient control theory for cracking of arch dams. Journal of Hydroelectric Engineering, No.11, 2017, 102-110 (in Chinese).

[12] JING Xiangyang, CHANG Xiaolin, ZHOU Wei, LIU Xinghong. Spatio-temporal dynamic control measures for temperature control and crack prevention during construction of high arch dam and its engineering application [J]. Journal of Tianjin University, No.8, 2013: 705-712 (in Chinese).

[13] FAN Qixiang, ZHOU Shaowu, LIN Peng, YANG Ning. Construction intelligent control packaged technology and its application for a large hydropower project [J]. Journal of Hydraulic Engineering, July 2016, 916-923 (in Chinese).