Optimization study on super-high arch dam temperature control standard and measure

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Abstract: Currently, for several super-high arch dams under construction which have caused a series of issues after being strict with temperature control standards, this paper has a sensitivity analysis through a variety of programs and a systematic study about the impact which the highest temperature, the cooling height, the same cooling zone height and other key factors have on the temperature stress of the construction period dam, and then proposes that the temperature control standard and the selection of measures of the ultra-high arch dam are relatively stricter than the regulatory requirements of the traditional dam as long as we have a reasonable control about the temperature drop on the time domain and the temperature gradient on the spatial domain. However we need not make all the dams as a constraint zone to have a temperature stress control. After separated from the basis constraints zone, the maximum temperature of the dam can increase 3-4°C at least. In addition, while the dam's same cooling zone height is controlled by the 0.2L (L for the bottom width), it can meet the requirements for filling and anti-cracking without using two cooling areas. This finding will help reduce the difficulty of height control of the cantilever when the dam is under construction.

1 Preface
With further development and utilization of water resources in the Western China, it’s expected that a batch of super-high arch dams whose height is from 200m to above 300m will be constructed in the Western China in the next ten to twenty years. Many new problems and challenges will be encountered during study, design and construction of dam with the increase of dam height, acceleration of construction progress and improvement of construction quality requirements [1]. Temperature control during construction period has been always one of the most important problems [2], because super-high arch dams generally adopt the construction method of continuous placement, low temperature arch closure, which requires dropping temperature of dam body to arch closure temperature in a short time. Hence, foundation restraint effect, and the mutual restraint effect between new and old concrete of dam body as well as the upper and lower cooling subarea with the increase of dam height and dam thickness, and thus temperature control difficulty will further increase and the conflict between selection of dam’s construction schedule arrangement, cantilever height control and concrete temperature control standard and measures will be more acrimonious. Reasonably and effectively solving the confliction between temperature stress control and crack prevention problem as well as other factors is often the key point of successful construction of dam [3, 4].

In recent years, scholars in China had comprehensively summarized the experiences and results of
concrete dam’s design, construction and scientific study, proposed the conception of “comprehensive temperature control and long-term heat insulation to terminate the history of crack dams” [5] and temperature control guiding thought of “small temperature difference, early cooling and slow cooling [5], to indicate directions for temperature control of future dam construction, and it also reflects application basic theoretical study and engineering technology of concrete dam crack prevention in China have made enormous progress. However, in the process of actual temperature cracking problem study, cracks are difficult to be avoided completely during construction period because of complex crack causes, existence of various uncertain (occasional) factors during construction, shallow concrete material feature recognition, incomprehensive crack cause factor considerations, insufficient design temperature control measure safety margin in actual engineering, blurred crack cause and mechanism analysis, design load can’t reflect actual load and other problems [6].

Because most of current specifications are based on former middle and small scale 100m level dams, so they have no specified provisions and normative guidance for currently constructed super-high arch dams, part construction requirements and standards of super-high arch dams are beyond the scope covered by traditional specifications. Therefore, specifications are continuously adjusted to satisfy the need of modern engineering construction, especially for super-high arch dams whose tendency is that the temperature control standards are more and more higher and measures are more and more stricter. Temperature control design of some super-high arch dams even controls the whole dam as confined zone. That is, the whole dam is not divided into foundation confined zone, weak confined zone and non-confined zone any more, but the whole is controlled as confined zone uniformly. For this reason, the highest temperature of Xiaowan arch dam elevation above the crack existence scope is controlled not higher than 27°C uniformly after cracks appear, which equals to its confined zone standard; confined zone temperature in Xiluoduo arch dam is not higher than 27°C in the Version I of its temperature control technical design scheme and the temperature of non-confined zone is adjusted to be 27°C in Version II from no higher than 31°C [7]; individual super-high arch dam even sets two simultaneous cooling zone on the whole dam in China. In fact, stricter temperature control measures are favorable from crack prevention aspect. However, it may bring a series of negative impact, such as problems of insufficient cross joint openness, increase of temperature control cost, difficult to coordinate the conflict between cantilever height with cooling schedule and joint grouting. Especially, crucial problems like whether super-high arch dam section really needs the whole dam as confined zone or to set 2 simultaneous cooling zones on the whole dam deserve further discussion.

Consequently, temperature control standards and measures of super-high arch dam still require deep and systematic study. This paper mainly discusses several key standard problems in relation to super-high arch dam, focuses on comparison and analysis of influence of the maximum temperature, cooling zone height and simultaneous cooling zone height on the temperature stress and safety of dam during construction period. Thus, the temperature control standards and temperature control measures suitable for super-high arch dam temperature control and crack prevention are put forward.

2 Analysis of the influence of the maximum temperature on arch dam temperature stress
Arch dam temperature stress is mainly from two factors, namely temperature difference and constraint. For foundation confined zone, the higher the temperature, the higher the foundation temperature difference, the stress is greater, while for non-confined zone, comprehensive impact of temperature drop process and upper and lower temperature gradient distribution shall also be taken into consideration except for the maximum temperature, inner and outer temperature difference.

| Parameter | Adiabatic temperature rise/°C | Elastic modulus/GPa | Linear expansion coefficient | Self-grown volume shrinkage and deformation | Allowable stress/MPa |
|-----------|-------------------------------|---------------------|-------------------------------|---------------------------------------------|----------------------|
| Parameter value | $27 \times (1 - \exp(-0.4e^{0.6}))$ | $44 \times (1 - \exp(-0.58e^{0.34}))$ | $6.5 \times 10^{-6}$ | -20 | 2.0 |
2.1 Maximum allowable temperature and stress comparison and analysis of foundation confined zone

Under the conditions with the same thermal and mechanical parameters as shown in Table 1, all arch closure temperatures are 13°C and the all of the first batch cooling heights are 0.4L (L is bottom width) in consideration of different dam bottom width and different allowable maximum temperature.

According the traditional cooling method, the crack prevention requirement can also be met when the maximum temperature rises to 29°C, even 35°C if assuming all of the first batch cooling heights are 0.4L and bottom widths are 25m; stress at the confined zone increases with the increase of bottom width, on the premise that the maximum temperature is controlled at 29°C, and the temperature stress just meets design requirements when bottom width is 60m. Safety coefficient gradually reduces with the increase of bottom width. The design crack prevention requirements can be met when the maximum temperature is lower than 29°C if bottom width is 80m. It indicates that it’s necessary to drop the maximum temperature and reduce foundation temperature difference for the high dam foundation confined zone with long bottom width. The specific parameters shall be determined via simulation calculation result according certain material features.

| Bottom width/m | Cooling zone height | Maximum temperature (°C) and secondary cooling end stress (MPa) | Allowable stress |
|----------------|---------------------|---------------------------------------------------------------|-----------------|
| 25             | 0.4L                | 27°C 29°C 31°C 35°C                                           | 2               |
| 40             | 0.4L                | 27°C 29°C 31°C 35°C                                           | 2               |
| 60             | 0.4L                | 27°C 29°C 31°C 35°C                                           | 2               |
| 80             | 0.4L                | 27°C 29°C 31°C 35°C                                           | 2               |

2.2 Maximum allowable temperature and stress comparison and analysis separating from foundation confined zone (above 0.4L)

The cooling zone height in Table 2 is 0.2L after separating from confined zone. Only set primary cooling and secondary cooling when conducting cooling. It can be seen from the stress calculation result that the stress can be controlled within allowable range when the maximum temperature is controlled under 35°C if cooling zone height at non-confined zone reaches to 0.2L for the dam body with 60m bottom width; the maximum temperature shall be at least controlled below 31°C when bottom width reaches to 80m.

Comparing the regular study results in Table 1 and Table 2, inner stress of dam is influenced comprehensively by many factors, such as the maximum temperature, dam bottom width, cooling process, cooling height, etc. after separating from constraint. For the dam section with bottom width below 60m, the maximum temperature can be 3~4°C higher than the concrete in confined zone after separating from constraint on the premise only two phase cooling is set. The maximum allowable temperature of concrete in confined zone can be further broadened after separating from constraint if further increase of midterm cooling or transition region and influences that the ordinary arch closure temperature in the non-confined zone is higher than confined zone. The standards used in different engineering shall be determined according to dam actual concrete material parameter features and relevant simulation calculation results.

| Bottom width/m | Cooling zone height | Maximum temperature /°C | Corresponding secondary cooling end maximum stresses of different maximum temperatures /MPa | Allowable stress /MPa |
|----------------|---------------------|--------------------------|------------------------------------------------------------------------------------------|----------------------|
| 25             | 0.2L                | 27°C 29°C 31°C 35°C     | 0.73-0.84 0.74-0.92 0.75-1.01 0.76-1.13                                                   | 2                    |
| 40             | 0.2L                | 27°C 29°C 31°C 35°C     | 1.24-1.33 1.26-1.34 1.28-1.36 1.35-1.39                                                   | 2                    |
3 Analysis of cooling zone height on arch dam temperature stress

Bottom width at crown cantilever section of high arch dam is generally around 40-70m. Arch dam bottom width is 60m, water pipe cooling includes primary and secondary cooling and the maximum temperature is controlled at 29°C, to conduct relevant sensitivity analysis.

3.1 Cooling zone height control in the confined zone

The stress is lower when the cooling zone is higher for the same temperature drop range and temperature drop rate in the foundation confined zone when cooling zone height is between 0.1L ~ 0.4L. Cooling zone height has stable influence on the maximum stress when cooling zone height is above 0.4L, as shown in Fig.1 (a)-(b).

3.2 Cooling zone height control in the non-confined zone

The maximum stress decreases to 1.85MPa from 3.2 MPa when the cooling zone height varies between 0.1L~0.3L in the non-confined zone and the maximum stress decrease to 1.75 MPa when cooling zone height is between 0.3L~0.4L. Cooling zone height has great influence on the stress and its influence degree gradually decreases with the decrease of height. As shown in Table 1 and Fig.2, cooling zone height has stable influence when the cooling zone height and width ratio reaches above 0.4L.

4 analysis of simultaneous cooling zone height on arch dam temperature stress and cantilever height control

Simultaneous cooling zone means a cooling zone set on the proposed grouted area and the temperature of simultaneous cooling zone is required to drop to the arch closure temperature when grouting in the proposed grouted zone (see Fig.3). This section mainly compares and analyzes the influence of simultaneous cooling zone height on the construction period temperature. Take an engineering as an example, suppose the distances of bottom of simultaneous cooling zone shown in Fig.3 from arch closure grouting elevation are respectively 0m, 9m, (1 simultaneous cooling zone) and 18m (2 simultaneous cooling zones).

Table 3 shows comparison of secondary cooling end dam axial stress and stress along river. It can be seen from the table that simultaneous cooling zone height has great influence on dam axial stress. Dam axial tensile stress without simultaneous cooling zone shall be 1.0MPa, while it decreases to
0.70MPa instantly after setting 9m simultaneous cooling zone, the tensile stress decreases slightly when simultaneous cooling zone increases to 18m from 9m, but the decrease range is just 0.06MPa. Simultaneous cooling zone height also has influence on stress along river, which is less than the dam axial stress. Tensile stress along river just decreases 0.1MPa when simultaneous cooling zone height increases to 9m from 0m and the stress along river has no change basically when it increases to 18m from 9m. Hence, being integration of the lower arch closure will increase constraint on the upper part, but this constraint increase impact is mainly on the dam axial, having little impact on the confined zone along river.

Therefore, two simultaneous cooling zones have limited improvement on the maximum stress of dam during construction period on the premise the upper and lower temperature gradients of the whole dam are well controlled. Thus, one simultaneous cooling zone can meet temperature control and crack prevention requirements.

Take actual control situation of one super-high arch dam as an example for impact of simultaneous cooling zone height on cantilever control. This dam has two simultaneous cooling zones. The maximum cantilever height of dam can reach to 75m theoretically, including 1 proposed grouted zone (9m), 2 simultaneous cooling zones (18m), 1 transitional region (9m), 1 overlaying zone (6-9m) and 30m height difference (height difference of allowable lowest pouring block and highest pouring block in design), plus influence of inconformity of cooling progress in different dam sections, the maximum cantilever height is easy to above 80m. Such high cantilever height undoubtedly is unfavorable for cantilever stress control during dam construction. Dam cantilever height can be effectively decreased if only one simultaneous cooling zone is adopted, the unfavorable crack risk caused by too high cantilever, and it also assists coordination control of dam construction schedule, joint grouting schedule and water pipe cooling schedule.

| Simultaneous cooling zone height | Stress along river (MPa) | Dam axial stress (MPa) |
|---------------------------------|--------------------------|-----------------------|
| 0m                              | 1.35                     | 1.0                   |
| 9m                              | 1.34                     | 0.7                   |
| 18m                             | 1.33                     | 0.69                  |

(a) Temperature drop process line  (b) Cooling division

**Fig.3** Typical temperature drop process and cooling division schematic diagram

5 Optimization and control of super-high arch dam temperature control thought

Presently, typical temperature drop process and division cooling scheme of super-high arch dam are shown in (a) and (b) of Fig.3. Its highlighted feature is that it complies with the “small temperature difference, early cooling and slow cooling” [5] guiding thoughts on temperature control. The temperature drop after temperature peak value is divided into several temperature drop and temperature control sections and proposed grouted zone, simultaneous cooling zone, transitional region and overlaying zone are set on the height direction, to form dynamic temperature gradient from top to bottom.

In the practical engineering, as shown in Fig.4, if the temperature gradient is reasonably controlled at the upper and lower layer height direction, the first batch cooling height in the foundation zone is 0.4L, cooling height is 0.2L from the second batch, one overlaying zone (also called simultaneous
cooling zone) is set for each batch and one transitional region is set on it. The mode that sets temperature gradient along height direction can better control the temperature stress of upper non-confined zone. The maximum stress decreases to 1.05MPa from 2.0MPa after separating from foundation under the same temperature drop range condition (assume maximum temperature is controlled at 29℃).

Therefore, it is not necessary to control the whole super-high arch dam as confined zone. In addition to increasing engineering capital investment, after dam separates from foundation constraint, dam construction safety can be guaranteed provided that temperature gradient is reasonably controlled, it’s cooled as per “small temperature difference, early cooling and slow cooling” measure and temperature and stress monitoring are strengthened. This temperature control thought has been successfully verified by Laxiwa Arch Dam.

Fig.4 Maximum stress distributions of different cooling batches

6 Conclusion
(1) Super-high arch dam bottom width is thick, it has strong foundation zone constraint, temperature control is difficult, so the maximum temperature shall be strictly controlled. The maximum temperature in the non-confined zone can be 3~4℃ higher than confined zone on equal conditions, no need to control the temperature by taking the whole dam as confined zone.

(2) The first batch cooling height of super-high arch dam foundation confined zone is controlled as 0.4L at best, while cooling height in the non-confined zone can be controlled no less than 0.2L, the temperature drop rate and temperature gradient can be controlled from time domain and spatial domain, and thus dam risk can be effectively controlled.

(3) It has little constraint effect on the upper concrete after simultaneous cooling zone height reaches to 0.2L because the constraint effect on upper concrete mainly reflects on the axial constraint after arch dam grouting arch closure and forming to be integration. On the premise of reasonably controlling upper and lower temperature gradient, simultaneous cooling zone height of super-high arch dam can be controlled at 0.2L after separating from foundation constraint, and just one simultaneous cooling zone is enough for arch dam simultaneous cooling zone height, and two simultaneous cooling zone scheme is not necessary.

(4) Though dam scale of super-high arch dam and temperature control difficulty is greater than traditional middle and low arch dam, and its temperature standards and measures are relatively strict, their temperature stress development and change law are consistent. Temperature cracks are avoidable provided to design dam reasonably, conduct construction carefully, strengthen monitoring and take the feedback and risk early warning work timely during construction, and the temperature standards and measures have no need to be excessively strict.

Acknowledgements
This paper was supported by China Three Gorges Corporation research project (BHT/0810、XLD/2114)，the Natural Science Foundation of China (No: 51779277, 51579252, 51439005), the National Key Research and Development Project of China (2016YFB0201000, 2018YFC0406700), the special fund(2016ZY10, SS0145B392016, SS0145B612017), of China Institute of Water Resources and Hydropower Research, State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin.
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