Small temperature difference in the middle and later water cooling stages of RCC dam

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Abstract. Water cooling is the main measure to reduce temperature cracks in RCC dams. But later cooling usually means reducing water temperature rapidly after 120 days of the concrete age, which may cause larger self stress and tensile stress inside the concrete. The small temperature difference cooling can advance the starting time of middle and late cooling stages, and reduce the temperature stress effectively. However, the difference of temperature stress produced by different middle and late stages water cooling methods is large. It is necessary to analyse precisely how to use the small temperature difference methods in the middle and late cooling stages of dams properly. The cooling methods of RCC dam in the middle and late stages are studied by using the self-developed 3-D FEM floating mesh method temperature controlling simulation program. Result shows that when the small temperature difference is used to cool the dam in the middle and late stages, the temperature and temperature stress of the dam reduces obviously. When the age of the concrete is over, the dam should be cooled immediately, several levels of water temperature should be set in the middle and late cooling stages, the temperature of the water should be reduced slowly, which can reduce the temperature and temperature stress of the dam effectively. Study result will provide a favourable reference for practical projects.

1. Introduction
Water cooling is the main solution to reduce temperature cracking of roller compacted concrete dam (RCCD) [1][2][3]. But in actual practices, the defects of water cooling tend to be ignored. Generally, water begins to flow into the dam for water cooling 120 days after the concrete is in place. To reach the target temperature, water temperature needs to be lowered rapidly, which is likely to cause large spontaneous stress and tensile stress near the water pipe [4][5].

Liu Jun studied the long-term water cooling mechanism of large-volume concrete with small temperature difference, believed that this would reduce the tensile stress of concrete [6]. Zhu Bofang proposed the method of initial cooling with small temperature difference, and believed that the combination of middle and later stage cooling and initial cooling could prevent large tensile stress [7]-[12]. However, the planning of middle and later stage cooling and the proper application of initial cooling with small temperature difference in the latter two stages require careful analysis.

Chen Yaolong, Li Shouyi have been working on the finite element simulation analysis of thin-layer concrete temperature stress since 1989, and have put forward the three-dimensional finite element relocating mesh method [13], in which the relocated grids float into multiple large grids. The method has been put into practice in the temperature stress simulation of Longtan roller-compacted concrete gravity dam, which not only reduced the workload but also ensured the accuracy of calculation.
In this paper, based on the temperature calculation principle of RCCD, the floating grid method is adopted for the planning of RCCD water cooling in the middle and later stage of roller-compacted concrete gravity dam, where multiple-level water flow is adopted for middle and later stage to disperse temperature difference. In addition, RCC gravity dam is verified to provide scientific basis for the application of the method in real scenario.

2. Calculation Principle and Simulation Program of RCCD Temperature Field

2.1. Equation of water pipe cooling

The equation for the analysis of temperature field, i.e. the equation of heat conduction is as follows\textsuperscript{[14]}:

\[
\frac{\partial T}{\partial \tau} = a \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + \frac{\partial \theta}{\partial \tau}
\]  

(1)

where $a$ - Thermal diffusivity of concrete (m\(^2\)/h) ;

$\lambda$ - Heat conductivity of concrete in the unit of kJ/(m·h·℃);

$\rho$ - Density of concrete in the unit of kg/m\(^3\);

$c$ - Specific heat of concrete in the unit of kJ/(kg·℃);

$\tau$ - Time in the unit of h;

$\theta$ - Adiabatic temperature rise of concrete in the unit of ℃.

In this paper, the implicit method is adopted, which assumes that the strain increment under complex stresses takes a linear pattern. The assumed stress duration curve is a broken line, which is close to the actual stress duration curve, as shown in Figure 1.

Figure 1 Diagram of Stress Increment over Time

In a given period $\Delta\tau$, the total stress increment is calculated via the following equation:

\[
\{\Delta \varepsilon_n\} = \{\Delta \varepsilon_n^e\} + \{\Delta \varepsilon_n^c\} + \{\Delta \varepsilon_n^T\} + \{\Delta \varepsilon_n^0\}
\]  

(2)

Where $\{\Delta \varepsilon_n\}$-incremental array of total stress

$\{\Delta \varepsilon_n^e\}$-Incremental array of elastic stress

$\{\Delta \varepsilon_n^c\}$-Incremental array of creep stress

$\{\Delta \varepsilon_n^0\}$-Incremental array of spontaneous volume stress

$\{\Delta \varepsilon_n^T\}$-Incremental array of temperature stress

2.2. Three-dimensional finite element floating mesh method

Several small grid cells at a certain age were combined into one large grid cell, after which the cell body could be calculated as homogeneous. The layer thickness of RCC was generally set at 0.5m, with a wide range of temperature and stress variation in the vertical direction, where the dense grid was
needed for calculation. For each casting, the temperature field and stress field needed to be calculated correspondingly. The temperature, elasticity and creep stress would rarely vary when the age of the topmost layer reaches 28d during the construction, where individual layer could be compiled into a large cell and the newly poured thin upper layer is still calculated accurately according to the small step length. Therefore, continuous casting of thin layers was also considered in this method, allowing each cell to be calculated accurately despite the presence of multiple layers of RCC. A complete simulation program consists of pre-processing system, calculation program and post-processing system. The pre-processing system is written in Visual Basic, and the calculation program is written in Visual Fortran using the floating grid method. The post-processing system can process the temperature and stress changes.

3. Formatting the text

Zhu Bofang proposed that when concrete cools through water, it needs to disperse the temperature differences to reduce the gap between maximum and minimum temperature to 3-5 temperature differences. However, in the traditional process of secondary water cooling, the mechanism usually fails to meet demands on stress despite a decrease in temperature. In the middle and later stage of cooling, the water temperature can be gradually lowered, dividing the process into multiple stages so that the stress could be kept within the range, thus improving the anti-cracking property. Next, the paper will focus on how to carry out multi-level water cooling in the middle and later stages.

3.1. Numerical example

A non-overflow section of an RCC gravity dam was selected for the calculating model, which was 98 meters high and 294 meters long for the dam crest. The upstream, downstream and the bottom of the dam were extended twice the dam height as the foundation, which was set at 100 meters. The normal concrete cushion was 1.5 meters thick, and the RCC casting layer was 3 meters thick. The RCC casting was performed continuously until it reached 3 meters before there was an intermittent period of 10 days. The concreting project lasted for 395 days, with a total of 73250 nodes for the finite element model. The overall calculation model is shown in Figure 2.

![Figure 2 Overall Calculation Model](image)

The initial cooling measures of different plans were the same, including the cooling water pipe space of 1.5×1.5m, the flow rate of water at 1.0 m³/h, and the length of cooling water pipes at 250m. Initial water cooling was performed immediately after casting the large layer, lasting for 10 days at the temperature of 25℃. In the middle and later stage of water cooling, the following three plans were adopted for the research:

Plan 1: Set only one stage of water cooling, allowing the later-stage water cooling to start 90 days after casting. The cooling lasted for 60 days, with the temperature being kept at 9℃. The water cooling system went under normal procedures.

Plan 2: Divide the water cooling into two stages, which started 60 days after casting. In Stage One, the water supply lasted for 30 days at the temperature of 19℃. In the second stage, the water supply lasted for 40 days at the temperature of 9℃. Stage Two water cooling immediately followed Stage One.
Plan 3: Divide the water cooling into four stages, which started 30 days after casting (at the end of the concrete age). In Stage One, the water supply lasted for 30 days at the temperature of 24°C. Stage Two lasted for 30 days at the temperature of 19°C. Stage Three lasted for 30 days at the temperature of 14°C while Stage Four, lasting for 30 days, was set at the temperature of 9°C. The thermodynamic indexes of concrete are shown in Table 1.

| Concrete type | Unit weight (t/m³) | Elasticity modulus (10⁶ Mpā) | Linear expansion coefficient (10⁻⁶/°C) | Heat conductivity coefficient (KJ/m·h·°C) | Specific heat (KJ/Kg·°C) | Adiabatic temperature rise (°C) | Heat conductivity coefficient (m²/h) |
|---------------|-------------------|------------------------------|----------------------------------------|------------------------------------------|-------------------------|-------------------------------|----------------------------------|
| C20 | 2.40 | E=31.34(1-0.567e⁻⁰.⁰³⁶₇₅) | 0.85 | 9.905 | 0.992 | Tr = 23.695t / t + 3.92 | 0.0042 |
| C15 | 2.40 | E=28(⁰.⁷₅₇×)13.12×e⁻⁰.⁷₅₇ | 0.85 | 10.66 | 0.9773 | T = (19.085(1.151 - 1.388) / 3.957 + 1.151) | 0.0043 |

3.2. Simulation calculation and analysis of temperature field

The typical temperature nephogram shows the temperature variation at the end of construction and during the operation, which usually peaks at the end of construction and gradually decreases during the operation. The construction period features unstable temperature field, with main influencing
factors including the environmental temperature and concrete hydration heat. During the operation, ambient temperature is the main factor influencing the temperature.

According to the design specifications, the maximum temperature in the strong constraint zone (0m-14.5m) ranges between 38.5°C to 40.5 °C. In Plan 1, conventional secondary water cooling was adopted with a maximum temperature of 37.03 °C while in both Plan 2 and Plan 3, the temperature peaked at 35.49 °C and 29.8 °C respectively. In the middle and later stage water cooling, the temperature gradient near the water pipe was lower than that of the traditional secondary water pipe cooling system.

According to the specification, the maximum temperature in the weak constraint zone (14.5m-29.0m) ranges between 40.0°C-42.5°C. In Plan 1, the traditional secondary water cooling was adopted with the maximum temperature of 37.01°C. In Plan 2 and 3, the middle and later stage water cooling was adopted with the maximum temperature of 34.49°C and 31.8°C respectively, which met the requirements.

In the middle and later stage water cooling, the cooling method with small temperature difference was adopted, which significantly reduced the temperature of the dam body and the temperature gradient near the water pipe. However, the more divisions in the water-cooling plan for the middle and later stages, the lower the temperature, reflecting the advantage of cooling with small temperature difference.

### 3.3. Simulation calculations and analysis of stress field

Due to the large scale of typical points, only the main stress duration curve of typical points at the middle elevation of 415.50m and 469.5m was taken in this paper, along with the maximum temperature stress values during construction and operation, as shown in Table 2 and Table 3.

| Regional plan | Area of strong constraint (0-14.5m) | Area of weak constraint (14.5~29.0m) | Constraints area (29.0~98.0) |
|---------------|-------------------------------------|------------------------------------|-----------------------------|
|               | x stress | z stress | x stress | z stress | x stress | z stress |
| Plan 1        | 0.56     | 0.56     | 0.44     | 0.4      | 0.4     | 0.4      |
| Plan 2        | 0.42     | 0.36     | 0.35     | 0.3      | 0.35    | 0.3      |
| Plan 3        | 0.37     | 0.33     | 0.32     | 0.3      | 0.32    | 0.3      |

Table 2. The maximum temperature stress values in different zones during the construction of each plan (Unit: MPa)

| Regional plan | Area of strong constraint (0-14.5m) | Area of weak constraint (14.5~29.0m) | Constraints area (29.0~98.0) |
|---------------|-------------------------------------|------------------------------------|-----------------------------|
|               | x stress | z stress | x stress | z stress | x stress | z stress |
| Plan 1        | 0.54     | 1.34     | 0.54     | 1.34     | 0.54     | 1.34     |
| Plan 2        | 0.46     | 0.98     | 0.46     | 0.98     | 0.46     | 0.98     |
| Plan 3        | 0.40     | 0.98     | 0.40     | 0.98     | 0.40     | 0.98     |

Table 3. The maximum temperature stress values in different zones during the operation of each plan (Unit: MPa)

Note: Stress is positive in tension and negative in compression.

After the adoption of water cooling with small temperature difference, the temperature stress in different constraint zones of the dam has been reduced to some extent. The maximum temperature stress values in different zones during the construction of each plan are shown in Table 2, and the maximum temperature stress values during the operation are shown in Table 3.

In the later stage of water cooling, small temperature difference was adopted, significantly lowering the temperature stress of Plan 3, which was lower than that of Plan 2. After casting the strongly constrained zones, the first and third principal stresses of the dam were reduced by water...
cooling. The maximum temperature stress in Plan 1 was 0.56 MPA, while that of Plan 2 and Plan 3 was 0.42 MPA and 0.37 MPA respectively, with significant drop of temperature stress. In Plan 3, division of small temperature differences in the middle and later stage of water-cooling revealed that the temperature stress of Plan 3 was significantly lower than that of Plan 2. In Plan 2 and 3, where water cooling was performed at 60 days and 30 days of concrete age, earlier water cooling could significantly lower the temperature stress compared with Plan 1.

In the middle and later stage of water cooling, immediate water cooling at the end of concrete age could reduce the temperature stress. Meanwhile, the water temperature was divided into multiple levels to slow down the cooling process and reduce the temperature stress. The specification stipulates that the temperature difference between concrete and cooling water should not exceed 20℃\[^{[15]}\]. In this paper, the cooling water temperature was increased to narrow down the temperature difference between the two, proving the theory proposed by Zhu Bofang that the temperature difference shall not exceed the range of 8℃-10℃\[^{[9]}\].

4. Conclusion
(1) Compared with the water-cooling plan with small temperature difference, normal water cooling will lead to higher temperature gradient near the water pipe, resulting in excessive tensile stress and the generation of concrete cracks.
(2) In the middle and later stage of water cooling, water cooling should start immediately at the end of concrete age with multi-level water cooling stages to prolong the cooling duration, which is conducive to reducing temperature stress. Since the middle and later stage cooling is set at an earlier point, the construction progress will not be delayed. Changing the water temperature several times during the construction is highly significant to reduce the temperature stress and prevent cracks.

Acknowledgments
The research work was supported by the Natural Science Basic Research Program of Shaanxi (Program No. 2019JQ-577).

References
[1] Kang J.F., Zhao M.M., Jiang Y.C., et al. (2014) Study on the relationship between degree of constraint and temperature stress[J]. Journal of water conservancy and building engineering, 12(6): 21-25.
[2] Duan Y., Hu Z.P., Luo L.Z., et al. (2015) Study on temperature control and crack prevention of lining concrete of large underground cavern[J]. Journal of water conservancy and building engineering, (04): 107-110.
[3] Xiang K.S., Zhang H.Z., Ma Z.Y., et al. (2013) Study on temperature control and crack prevention of RCC gravity dam in cold area[J]. Journal of water conservancy and building engineering, (05): 200-203.
[4] Zhu B.F., Wang T.S., Ding B.Y., et al. (1976) The temperature stress and temperature control about hydraulic concrete structure[M]. Beijing: Water Resources and Electric Power Press.
[5] Zhu B.F. The temperature stress and temperature control about mass concrete[M]. (1999) Beijing: China Electric Power Press.
[6] Liu J., Huang Y., Zhou W., et al. (2011) Long-term water cooling with small temperature difference in large area concrete. Journal of Wuhan University(Engineering Edition), 44(5): 549-553.
[7] Zhu B.F., Zhang CH.R. (2010) Research on the key technology to safety of high arch dam[M]. Beijing: China Water Power Press.
[8] Zhu B.F. (2010) Water pipe cooling of concrete dam[J]. Journal of hydraulic, 39(5): 505-513.
[9] Zhu B.F., Wu L.K., Yang P., et al. (2008) Planning of water pipe cooling in later period of concrete dam[J]. Water Conservancy and Hydropower Technology, 39(7): 27-31.
[10] Zhu B.F., Li Y., Wu L.K., et al. (2008) Two principles about allowable temperature difference of concrete foundation for concrete dam[J]. Water Conservancy and Hydropower Technology, 39(7): 21-26.

[11] Zhu B.F., Wu L.K., Yang P., et al. (2008) Plastic water pipes are easy to encrypt to strengthen concrete cooling[J]. Water Conservancy and Hydropower Technology, 39(5): 36-39.

[12] Zhu B.F., Wu L.K., Zhang G.X. (2008) Advantages and disadvantages of water pipe cooling in concrete dam[J]. Water Conservancy and Hydropower Technology, 40(12): 26-30.

[13] Chen Y.L., Wang CH.J., Li SH.Y., et al. (2001) Simulation analysis of thermal stress of RCC dams using 3-D finite element relocating mesh method[J]. Advances in Engineering Software, 32(9):677-682.

[14] Li SH.Y., Zhang J.K., Zhang X.F. (2010) Study on simulation of temperature of RCC dam[M]. Beijing: China Water Power Press.

[15] National Energy Administration. (2017) NBT 35092-2017 Design specification for temperature control of concrete dams[S]. Beijing: Electric Power Press.