Simulation and Research on Temperature Field of Taishan Roller Compacted Concrete Gravity Dam

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Abstract. Considering the design and layout features of Taishan RCC gravity dam, the concrete dam construction process was simulated and the three-dimensional finite element method was used to calculate the temperature field. The results showed that for the site of pouring in low temperature season, the method of natural warehousing watering was taken; whereas for the site of pouring in hot season, the method of control pouring temperature and the water cooling measures of the entire region were taken. In this way the maximum temperature could meet requirements of the design specifications of RCC gravity dam. The research results laid an essential basis for the RCC dam design and construction.

1. Introduction
The volume of concrete gravity dam section is huge and the amount of concrete poured for each time is large. The large temperature tension stress will be produced in dam body. When the tension stress exceeds the maximum allowable stress of concrete in dam section, temperature cracks may appear. Therefore, strict temperature control measures should be taken in the construction of the dam. In this paper, on the basis of controlling the pouring temperature at the pouring site in the high temperature season, the concrete in the whole area is cooled by natural river water. The temperature control scheme is simulated by finite element software. The maximum temperature can meet the design code of RCC gravity dam. The study result can provide a reference for the design and construction of the RCC gravity dam.

2. Project Overview
The fresh water resource project of Taishan nuclear power plant was located on Taishan City. The project consisted of the roller compacted concrete gravity dam, water cave and tunnel, access road, as well as other components. The dam crest length was 328m. The crest elevation was 53.6m, and the maximum dam height was 54m. The crest width was 7.0m. The upstream face of the dam was vertical, while the slope ratio of downstream was 1: 0.75. The overflow dam was arranged in the middle of the river bed and was divided into five holes. The net width of each hole was 10m. The top elevation of the weir was the normal water level of 48.4m. Because of the great concrete volume and high average temperature, the reasonable and feasible temperature control measures could be selected by means of simulation and calculation.
3. Principles and Methods of Calculation

At any point of R within the computational domain, the unstable temperature field must meet the heat conduction equation[1]

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

(1)

Where \( \alpha \) is conductivity temperature coefficient, and \( \theta \) is adiabatic temperature rise of concrete.

The strain increment of concrete under complex stress state includes an elastic strain increment, creep strain increment, temperature strain increment, shrinkage strain increments and autogenous volume deformation increment. Hence the relative equation[2] is

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

(2)

Wherein, \( \Delta \varepsilon_n^e \) is elastic strain increment; \( \Delta \varepsilon_n^c \) presents creep strain increment; \( \Delta \varepsilon_n^T \) is temperature strain increment; \( \Delta \varepsilon_n^s \) presents shrinkage strain increment; \( \Delta \varepsilon_n^0 \) is autogenous volume strain increment. The finite element method for stress field is seen in literature[3].

4. Calculation Parameter

The monthly average maximum temperature for many years is 28.2℃, the minimum temperature is 15.0℃ and the annual average temperature is 22.5℃. The monthly average temperatures for many years in the dam site is seen in table 1.

Table 1. The monthly average temperature for many years in the dam site (unit: ℃)

| Month | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
|       | 15.0| 15.7| 18.8| 22.6| 26.0| 27.5| 28.2| 27.9| 26.7| 24.3| 20.3| 16.5|

The second grading RCC was adopted in the dam upstream face, whereas the third grading RCC was adopted in the internal dam and the third grading normal concrete was adopted in the base cushion. The concrete thermal parameters was shown in Table 2.

Table 2. The thermal parameters of concrete

| Dam concrete | Thermal coefficient (m²/h) | Specific heat (kJ/kg·℃) | Thermal coefficient (kJ/m·h·℃) | Hydration heat rise equation (℃) |
|--------------|---------------------------|-------------------------|---------------------------------|--------------------------------|
| Dam upstream face | 0.003172 | 0.962 | 7.31 | T=23.00t/(2.29+t) |
| Dam interior | 0.003061 | 0.919 | 6.85 | T=19.83t/(2.75+t) |
| Dam base cushion | 0.003172 | 0.962 | 7.31 | T=23.55t/(1.15+t) |

The thickness of 1.5m in dam base cushion concrete was started pouring from November 21, 2009. The open casting time of RCC was December 20, 2009 and until June 20, 2010 the dam height reached the design elevation of 45.8m. The construction schedule was shown in table 3.

Table 3. The construction schedule of dam

| Number | Construction starting time | Initial height | Termination height | Number | Construction starting time | Initial height | Termination height |
|--------|---------------------------|----------------|-------------------|--------|---------------------------|----------------|-------------------|
| 1      | 2009.12.21                | 0              | 1.5               | 11     | 2010.05.11                | 24             | 27                |
| 2      | Consolidation grouting from December 25,2009 to February 20,2010 | 12              | 2010.05.21        | 27     | 30                         |
| 3      | 2010.02.21                | 1.5            | 3                 | 13     | 2010.06.01                | 30             | 33                |
5. Calculation model

In the computational model, the entire dam section between the transverse joints along the dam axis direction was selected. The direction of Pointing to the right bank of the dam axis is x -axis positive, the downstream direction is positive y-axis, vertically upward direction is the z-axis positive. Considering the effect of dam foundation on the temperature, the width of the horizontal (including upstream and downstream) and vertical foundations is 60.0m. The total elements of overall computation model are 8958 and nodes are 11312. The dam elements are 7740 and nodes are 9744. Boundary conditions are highly important in finite element calculation. The boundary conditions of the temperature field in this study are as follows[4]: the bottom of the foundation, its four side faces, and the transverse joint surfaces are treated as the thermal insulation boundary; the boundary conditions of the upstream and downstream directions are simulated using the solid–air convention before the reservoir is filled; the underwater boundary is the solid–water convention after water is filled, but the surface boundary above water still falls under the solid–air boundary condition. The solid–air boundary can be considered the third boundary, whilst the solid–water boundary can be regarded as the first boundary. The computational model is shown in Figure 1.

![Figure 1. Computation model of the dam](image)

6. Calculation scheme

Scheme 1: The pouring temperature of this scheme from November to April of the next year was natural temperature, and could adopt the monthly average temperature plus 2℃. The control pouring temperature measure from May to August was taken, and pouring temperature was less than or equal to 28℃. The construction schedule was shown in Table 3.

Scheme 2: The construction schedule and pouring temperature were the same as scheme 1. The concrete of the entire area from dam height 0.0m to 54.0m was cooled using natural water[5-6]. The cooling time was 15 days. The begin time of cooling was 12 hours after the large layer concrete was...
finished. The spacing of cooling water pipe was 1.5 × 1.5m and the length was 250m. The water flow was 1.0 cubic meter per hour.

7. Calculation results of temperature field

After the dam temperature reached stable value, the surface temperature changed with outside air temperature and water temperature. According to upstream and downstream water level of the reservoir, water temperature distribution and annual average temperature, the stable temperature was calculated about 20℃.

According to the thermal parameters and construction schedules, the temperature field was simulated. The temperature field cloud pictures of scheme 1 and scheme 2 in May 21, 2010 during construction period were shown in Figure 2 and Figure 3, and the cloud pictures in August 14, 2010 at the end of construction period were shown in Figure 4 and Figure 5. The maximum temperature, stable temperature, maximal temperature difference and specification permissible temperature difference in different position were shown in Table 4.
Table 4. The maximum temperature, stable temperature, maximal temperature difference and specification permissible temperature difference of scheme 1 and scheme 2 in different position

| Scheme | Area | RCC in Strong constraint region (Dam height 0.0~7.5m) | RCC in weak constraint region (Dam height 7.5m~15.0m) | RCC in Non-constraint region (Dam height 15.0m~51.0m) |
|--------|------|---------------------------------------------------|----------------------------------------------------|--------------------------------------------------|
|        |      | Maximum temperature(℃)                           | Stable temperature(℃)                              | Maximal temperature difference(℃)                 |
| Scheme 1 |      | 34.9                                              | 20.0                                               | 14.9                                             |
|         |      | 37.1                                              | 20.0                                               | 17.1                                             |
|         |      | 41.8                                              | 20.0                                               | 21.8                                             |
|         |      | 12~14.5                                           | 14.5~16.5                                         | \                                               |
| Scheme 2 |      | 30.5                                              | 20.0                                               | 10.5                                             |
|         |      | 32.8                                              | 20.0                                               | 12.8                                             |
|         |      | 37.1                                              | 20.0                                               | 17.1                                             |
|         |      | 12~14.5                                           | 14.5~16.5                                         | \                                               |

It could be seen from the results of temperature field:

1. In the RCC area of strong constraint position (dam height from 0.0m to 7.5m), the maximum temperature of Scheme 1 was 34.9℃, and the scheme 2 was 30.5℃. The specification permissible temperature difference of this position is from 12.0℃ to 14.5℃. The base temperature difference of scheme 1 was greater than specification permissible value while the scheme 2 was less than permissible value.

2. In the RCC area of weak constraint position (dam height from 7.5 to 15.0m), the maximum temperature of Scheme 1 was 37.1℃, and the scheme 2 was 32.8℃. The specification permissible temperature difference of this position is from 14.5℃ to 16.5℃. The base temperature difference of scheme 1 was greater than specification permissible value while the scheme 2 was less than permissible value.

3. In the RCC area of non-constraint position (dam height from 15.0 to 51.0m), the maximum temperature of Scheme 1 was 41.8℃, and the scheme 2 was 31.7℃ which was 4.7℃ less than scheme 1.

4. The cooling water pipes was embedded during construction period. The spacing was 1.5m × 1.5m. The cooling time was 15 days. The begin time of cooling was 12 hours after the large layer concrete was finished. The maximum temperature could reduce about 2~5℃. Hence, it was obvious that the cooling measures was effective to reduce the interior temperature.

5. It required a long process for the maximum temperature inside the dam reaching stable temperature. The temperature field results showed that the maximum temperature was appeared during construction period. The dam had a heat exchange with the surrounding environment during operation,
so the maximum temperature in the dam gradually decreased. The internal temperature was gradually close to stable temperature after 10 years.

(6) The scheme 2 was recommend which temperature control measures were reasonable and feasible.

8. Conclusion
The three-dimensional finite element method was adopted to simulate construction process of the Taishan RCC dam and compute temperature field. The distribution law of different schemes was analyzed. The results showed that the concrete pouring temperature from November to April of the next year was natural temperature, the control pouring temperature measure from May to August was taken, and the concrete of the entire area was cooled using natural water, thus the maximum temperature could meet the needs of design specifications of RCC gravity dam. The research results in this paper laid an essential basis for design and construction of the RCC dam.

References:
[1] Liu, X.H., Duan, Y., Zhou. W., Chang, X.L. (2013) Modeling the Piped Water Cooling of a Concrete Dam Using the Heat-Fluid Coupling Method. Journal of Engineering Mechanics., 139(9): 1278~1289.
[2] Zhu, B.F. (2012) Thermal stress and temperature control of mass concrete. China Electric Power Press, Beijing.
[3] Dong, F.P., Dong, Y. (2013) Select of Wall Rock Thickness for Thermal Stress Analysis of Circular Tunnel Concrete Lining. Journal of Engineering Mechanics., 139(7): 916~919.
[4] Liu, X.H., Zhang, C., Chang, X.L. (2015) Precise simulation analysis of the thermal field in mass concrete with a pipe water cooling system. APPLIED THERMAL ENGINEERING., 78(5): 449~459.
[5] Zhang, X.F., Li, S.Y., Chen, Y.L., Chai, J.R. (2009) The development and verification of relocating mesh method for the computation of temperature field of RCC dam. Advances in Engineering Software., 40(11): 1119–23.
[6] Zhu, Z.Y., Qiang, S., Chen, W.M. (2014) A model for temperature on concrete hydration exothermic rate (Part one: Theory and Experiment). Journal of Wuhan University of Technology-Mater., 29(3): 540–545.