Study on Influences of Water Temperature on Stress Distribution for High Arch Dam in Impounding Period

Shunwen Ji1*, Minsheng Zheng1, Zhifang Zhao2

1Zhejiang Institute of Hydraulics & Estuary, Key Laboratory of Water Disaster Prevention and Reduction of Zhejiang Province, Hangzhou 310000, China
2Zhejiang University of Technology, Hangzhou 325000, China
*jishunwen@zjwater.gov.cn

Abstract. Water temperature affects not only the water quality and ecological balance of the reservoir, but the temperature and stress field distribution of the high arch dam during water storage and operation management. During low water storage and initial operation, the concrete in reservoirs over 100 m deep in particular can easily crack or expand because of low temperature reservoir water. This paper studies the water temperature distribution law of the reservoir during initial storage by establishing a three-dimensional fluid dynamics model. Based on this, this paper explores the three-dimensional temperature field and stress field of the dam body during the storage period, the causes of cracking, and stress distribution in key parts of the arch dam.

1. Introduction
The arch dam is a statically indeterminate structure with relatively strong self-regulating ability. However, due to the limitation of the characteristics of concrete, it is easy to crack under the influence of temperature stress, cold water strike and water load during construction, thus affecting the overall stability of the dam. For example, Xiaowan and Ertan arch dams have cracks during construction [1-2], and Side and Shangbiao arch dams have cracks after long-term operation [3-4].

Cold water strike and the huge water pressure during storage are the main cause for the high arch dam to crack near the upstream surface. Therefore, accurate prediction of the water temperature distribution in the reservoir is of great significance for improving the simulation and calculation accuracy of the dam body temperature and stress field during storage and initial operation period. This paper analyses the overall stress distribution and causes of dam cracking during water storage by studying the fluid-solid coupling issues including water temperature, dam temperature, and stress field, aiming to improve the reliability of safety operation by optimizing stage cooling, closure grouting, and water storage plans.

2. Causes of cracking
After the completion of the arch dam, the integrity of the dam body is enhanced after joint grouting. Without in-time water storage, the surface temperature of the dam will increase due to solar radiation and high temperature. The arch ring will expand and deform towards the upstream, resulting in a large tensile stress near the abutment downstream. Self-weight also leads to deformation towards the upstream, making the downstream surface of the dam body easy to crack. The cases are Shuanghe and
Fengle arch dams [5]. Therefore, it is necessary to store water as soon as possible after joint grouting to avoid empty-storage operation of the dam.

During water storage process, the low-temperature water causes the increase of tensile stress near the upstream surface of the arch dam. Coupled with the temperature stress during construction, the upstream dam surface is likely to crack or expand. In addition, large water load and sand load are also possible reasons for large tensile stress areas near the foundation of the dam upstream, as shown in Figure 1. Therefore, it is suggested to place peripheral seams in the high tensile stress zones of the dam on the riverbed to avoid such cracks.

![Figure 1. Stress distribution of arch dam under water pressure.](image)

3. Simulation of water temperature

3.1. Method and simulation program

The Environmental Fluid Dynamics Model (EFDC) is mainly applied for the simulation of flow fields such as reservoirs and rivers, temperature fields, and water quality. The stimulation should take into consideration the structure, the effects of solar radiation, atmospheric environment, waves, tides, etc.[6]. This paper adopts a discrete numerical method on a staggered grid for the water temperature model and applies step-by-step method to solve the temperature transport equation. Since the temperature field distribution is directly related to the variation of pressure gradient force and turbulent kinetic energy in the calculation domain, coupled solution is applied to the temperature equation, hydrodynamic equation, and turbulence model.

3.2. Simulation model and parameter

Water temperature in the deep reservoir changes little in the direction along the width but much along the depth direction. This paper establishes a two-dimensional temperature model of the reservoir facade for research. The reservoir inflow and outflow is shown in Figure 2, in which the water supply period is from January to May and the storage period is from May to September. Assume that the initial water temperature is equal to the initial inflow water temperature of 11.6℃, and the water temperatures in different months are shown in Figure 3.

![Figure 2. The inflow and outflow series of reservoir.](image)

![Figure 3. The temperature of inflow.](image)

3.3. Simulation results

Take into consideration the initial inflow and outflow, temperature, and solar radiation, this paper predicts the change of water temperature in the reservoir. Simulation calculation shows that the surface water temperature of the reservoir is higher due to the influence of temperature and solar radiation with the highest temperature similar to the air temperature. The convection of the water body
is obvious in the middle layer of the reservoir, and the water temperature fluctuates greatly when the
water is warming. The deeper the water, the lower maximum water temperature, and longer time lag
of the highest temperature. At the bottom of the reservoir, the water temperature varies slightly, about
12~14℃.

The water temperature distribution in typical months is shown in Figure 4. In April, the surface
water body forms an upper thermocline with a high temperature and low density and the surface
temperature of about 17℃ due to solar radiation. The water with low temperature and high density is
at the bottom with bottom temperature of about 12℃. In August, the temperature in the external
environment and the solar short-wave radiation both increase, thus the surface water forms a
continuous thermocline that is thicker in the deeper water. Since the vertical velocity of the water body
is relatively small, the heat is mainly diffused, leading to smaller increase of the temperature of the
lower water. In December, the heat is mainly transferred on the surface of the reservoir. The
thermocline in the middle of the water still exists, but moves down as the water temperature gradually
decreases, so the water temperature at the bottom gradually increases to 15℃. During the cooling
process, the water temperature in the front of the dam generally decreases and the temperature
difference also decreases in the vertical direction.

4. Simulation of thermal and stress fields in impounding period

4.1. Method and simulation program
This paper accurately simulates construction, water pipe cooling, joint grouting and staged water
storage of the high arch dam by adopting the three-dimensional temperature field and stress field finite
element calculation model. During construction, the precise iterative algorithm of water pipe cooling
is used to simulate the water pipe cooling process inside the concrete [7]. During the water storage
period, considering the coupling effect of the reservoir water temperature, the water temperature is
applied to the dam as a third type of boundary.

As the hydration reaction and temperature field change, the concrete produces complex strains with
various factors influencing each other. In stress field simulation calculation, based on the elastic creep
theory, considering such factors as concrete temperature deformation, autogenous volume deformation,
and creep, the variation process of each strain component and their respective influence on the dam
stress are studied.

4.2. Simulation model and parameter

Figure 5. 3D finite element model
This paper takes Jinping I High Arch Dam as the research object, whose finite element calculation model and grid, and the concrete thermodynamic parameters are shown in Figure 5 and Table 1 respectively. The dam is 305 m high and runs from No. 1 to No. 26 from the left to the right bank. The construction design divides the dam body into 2164 casting blocks in order to accurately stimulate staged cooling, joint grouting, and staged water storage.

| Concrete Mark | $a$ | $\lambda$ | $c$ | $\alpha$ | $\theta_0$ | $E_0$ |
|---------------|-----|---------|-----|--------|---------|------|
| C40           | 0.0042 | 10.12   | 0.96 | 10.33  | 26.6    | 33.35|
| C35           | 0.0041 | 9.86    | 0.94 | 10.16  | 25.8    | 31.9 |
| C30           | 0.0041 | 9.15    | 0.90 | 9.87   | 24.4    | 30.74|
| C25           | 0.0040 | 9.12    | 0.88 | 9.54   | 24.0    | 30.45|

4.3. Simulation results

Before water storage, the internal temperature of the dam is reduced to $14^\circ C$ through the second-stage water pipe. At this point, the air temperature is higher and the surface temperature of the dam is about $21^\circ C$. Since the temperature is higher outside and lower inside, the dam surface is pressed and internally pulled with the stress value of 0.5~1.0MPa (positive for pulling). In the first water storage, the upstream water depth reaches 104.5m with and the surface water temperature ranging between $12.0^\circ C$ and $14.0^\circ C$. Due to the short storage time, water temperature has no significant effect on the concrete temperature inside the dam (Figure 6).

In the fourth water storage, the upstream water depth reaches 300.0m. The dam surface temperature below the upper 1/2 dam basically stands at $12^\circ C$ while that of above the 1/2 dam height affected by the water temperature stands between 14.0 and 18.0$^\circ C$ (Figure 7). Near the deep hole, the temperature of the upstream surface of the dam is $17.0^\circ C$, the internal sealing temperature is $12.0^\circ C$, and the temperature of the downstream dam surface is $21.0^\circ C$. The temperature difference between the upper and lower of the dam body is relatively large. In the hot season, due to direct sunlight and hot ambient temperature, the temperature difference can reach 20$^\circ C$, leading to that the downstream concrete is relatively compressed and the upstream concrete is relatively pulled. Coupled with the residual temperature stress during construction and the tensile stress generated by the water load, the upstream surface of the dam body is likely to crack.
The arch dam is a statically indeterminate structure. As the internal water pipe cools and staged water storage continues, the dam stress is also constantly adjusted and redistributed. During construction, internal water pipe cooling leads to higher temperature outside and lower inside, and the interior of the dam body is relatively pulled. After water storage, the tensile stress inside the dam is reduced because of water load and the temperature difference. The tensile stress near the upstream abutment and the base gradually increase with the maximum local tensile of 4.0 MPa. As the water continues to rise, the tensile stress zone of the abutment gradually extends upward but is relatively lower in depth. The downstream of the dam is mainly subjected to compression with the compressive stress of concrete near the base being about -10.0 MPa while the downstream dam has lower central compressive stress or is even pulled.

5. Conclusion
For arch dams, especially high ones, under the influence of construction residual stress, water cooling, water load, cold wave, and solar radiation are the main causes of concrete cracks during the water storage period, thus making temperature control and crack prevention a comprehensive topic for study.

(1) During construction, the cooling water pipes upstream are partitioned along the upstream and downstream directions with different arching temperatures so as to reduce the temperature difference between the concrete and the water on the upstream dam surface, which can reduce cracks.

(2) In the hot season, the temperature of concrete surface is high. When it encounters the low-temperature water, the tensile stress on the upstream surface soars. Combined with the residual temperature stress after construction, the upstream surface concrete is easy to crack.

(3) Simulation calculation and analysis are needed in reducing the stress of the arch dam. Only by adopting staged cooling, setting reasonable filling temperature, and optimizing the staged water storage plan, can the stress in the key parts of the dam be effectively controlled for safety.

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