Study on Method for Controlling Opening and Closing Mechanism of Transverse Joint of Super-high Arch Dam

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Abstract: the high-efficiency transverse joint simulation and analysis technique was developed based on the discontinuous deformation theory. This technique developed was used to realize the simulation of the overall construction and concreting process of the 300m super-high arch dam by the 3D finite element method, simulate the actual dam inside and transverse joint working behaviors throughout the process, analyze the temperature, stress and aperture change process in the inside and transverse joint face of the dam, discuss the opening and closing mechanism and crucial influencing factors of the transverse joint of super-high arch dam. Based on the feedback and analysis of field monitored data, the causes for the relatively small aperture in the foundation restraint zone of the arch dam were further analyzed, and the later aperture was predicted. The measures and proposals for effectively increasing transverse joint aperture and enhancing the groutability were further put forward, to provide important guarantee for ensuring the transverse grouting effect of the arch dam and the overall safety of the dam.

1 Introduction

In recent years, crack prevention by temperature control for super-high arch dams during construction is the study focus of many engineers and scientific researchers all the time [1~4].

Enhancement of the temperature control measures for the super-high arch dam is the effective guarantee for dam construction and operation safety, but causes some new problems, especially relatively small transverse joint aperture resulting from relatively low maximum temperature. Opening of transverse joint requires at first the compressive stress in the earlier temperature rise stage to be countervailed and at the same time the joint face tensile stress to exceed transverse joint bonding strength. Only these two conditions can ensure smooth opening of transverse joint [5]. So, in order to ensure smooth opening of transverse joint, the temperature drop range must be adequate. The maximum temperature of the super-high arch dam is kept relatively low, the temperature drop ranges of later intercooling and secondary cooling are limited relatively, and the actual maximum temperature is usually kept lower than the maximal permissible temperature. So, the aperture and opening time are affected to some extent. Besides temperature, dam cantilevers, concrete coping height, altitude difference between two adjacent dam blocks, autogenous volumetric deformation, cooling process, etc. also affect opening of transverse joint in actual construction. So, simulation and control of transverse joint aperture and actual working behaviors are very complicated actually. Considering that aperture and working behavior of model joint will directly affect the grouting effect and overall safety of the
dam, the simulation of arch dam transverse joint aperture and working behavior is very crucial. In recent years, Hou Chaosheng [6], Li Jianxin [7], Zhou Wei[8] et al. have made some beneficial contributions to this aspect, but none of them have put up any effective proposal for how to ensuring the transverse joint aperture and grouting effect under the condition of relatively low maximum temperature of super-high arch dam.

By taking an arch dam as an example, this paper explores the effective method and measures for controlling the transverse joint aperture of super-high arch dam, simulates the actual transverse joint opening and closing iteration process of dam during construction by the transverse joint opening and closing simulation technique based on the manifold discontinuous deformation theory[5,9], predicts and forecasts the future transverse joint aperture based on feedback and analysis of the transverse joint aperture, and puts forward the measures and proposals for effectively increasing transverse joint aperture and enhancing groutability according to the feature of small transverse joint aperture of the dam, and thus provides an important guarantee for increasing the transverse joint aperture, ensuring the grouting effect and overall safety of the dam during the dam construction.

2. Method for simulating transverse joint of super-high arch dam

During construction of arch dam, transverse joints are set at some intervals along the dam axis. Transverse joints are reserved for cutting the temperature tensile stress along the dam axis. The construction method of the arch dam makes the transverse joint stress very complicated. At the beginning of construction, due to influences by concrete temperature rise and dead weight, transverse joint faces bear compressive stresses; as the temperature drops, such compressive stresses fall gradually later and disappear, until the transverse joints open; after grouting and water retaining, the transverse joint faces may be stressed again, but the face near the upstream may open. Temperature changes in the four seasons also affect the opening and closing of joint faces. So, in the course of construction and operation, the working statuses of transverse joints are very complicated.

The transverse joint calculation model must simulates the above-said behaviors, and must be of relatively fast and good convergence for simultaneously computing tens of thousands of transverse joint units. The joints encountered in hydraulic structure analysis can be classified into three categories, structural joints (transverse joints and longitudinal joint), cracks, and rock joint fissures. The basic considerations for the transverse joint calculation model are shown as below: ① transverse joint behaviors are simulated by thickness-free transverse joint contact element; ② a compression spring with very high rigidity is set between transverse joints, to ensure the right and nodes of the transverse joints are not implanted or implanted within the allowable extent; ③ two transverse joint unit intensities are set before and after grouting, the intensity before grouting is lower than that after the grouting; and two failure modes are considered for transverse joints, namely tensile failure with the criterion that the tensile stress exceeds the set tensile strength and shear failure with Mohr-Culomb failure criterion; ④ pre-failure transverse joint units transmit forces like a continuum, while post-failure transverse joint units can resist against compression, and can resist against shear (without cohesive force) after compression but cannot resistant against tension; ⑤ the contact elements for simulating actual joints are calculated by the nonlinear iterative method, namely the distances between the two sides of joints are calculated continuously, and it shall be deemed that the joint is open and the two sides of the joint can independently deform when the result is higher than 0, and the joint is closed, the two sides of the joint is compressed and nothing can be injected into the joint when the result is 0.⑥ The joint closing and opening involve geometric nonlinearity, while shear and yielding involve material nonlinearity, thus the joint iterative computation include iterations of two nonlinear processes, namely geometric nonlinear and material nonlinear processes.

In the above-said considerations, the nonlinear iterative method proposed by Shi Genhua [5]is used to solve the joint opening and closing and sliding problems, the incremental method [10]is used to simulate loads because temperature and water level change processes need to be simulated, and the superposition method is adopted for simulating joint opening, closing and sliding statuses.
Joint status change and calculation method between the two calculation steps I and \( i+1 \) are shown as below:

1. From closing to closing without sliding and yielding: stiffness matrix is not modified at all and it is not necessary to release unbalanced force;
2. From closing to closing without sliding and yielding, namely joint face shear stress: \( |\tau| > c + \sigma, \tan \phi \)
   Stiffness coefficient: \( \alpha_n^i \rightarrow \alpha_n^{i+1}, \alpha_b^i \rightarrow \alpha_b^{i+1} = 0 \), the stress exceeding the shear strength is released, where, \( \alpha_n^i \) and \( \alpha_b^i \) are normal and shear stuffiness correction factors in step \( i \);
3. From closing to opening of common joint:
   Stiffness coefficient: \( \alpha_n^i \rightarrow \alpha_n^{i+1} = 0, \alpha_b^i \rightarrow \alpha_b^{i+1} = 0 \), all the joint face stresses in step \( i \) are released;
4. From opening to closing:
   The normal aperture of the last calculation step is “+”, and that of current calculation step is “−”, the tangential insertion proportion needs to be calculated to determine the tangential force required to be compensated.
   Stiffness coefficient: \( \alpha_b^i \rightarrow \alpha_b^{i+1}, \alpha_n^i \rightarrow \alpha_n^{i+1} \), the stress required to be compensated:
   \[
   [\sigma] = [D] \begin{bmatrix} \delta_x^i \\ \delta_y^i \\ \delta_z^i \end{bmatrix},
   \]
   \( \delta_z^i \) is normal penetration quantity, \( \delta_x^i \) and \( \delta_y^i \) respectively represents the displacement quantities along the local coordinate axes \( x^i \) and \( y^i \) after penetration of the contract points. Iterate statuses from ① ~ ④ of all joint units within a load time step until convergence, and then the calculation of the next load time step may be performed.

Due to the above-said transverse joint simulation technique, it is possible to realize dynamic simulation and analysis of construction temperature stresses of the whole arch dam throughout the construction.

3 Analysis on transverse joint opening and closing mechanism and law of the arch dam during construction

3.1 Calculation model
The overall simulation calculation model and transverse joint model as shown in Fig.1 and Fig.2 respectively were used for analysis.

![Fig.1 arch dam calculation model](image1)

![Fig.2 transverse joint model of the dam](image2)

3.2 Analysis on transverse joint opening and closing mechanism and law
Fig. 3 shows the typical relationship between transverse joint apertures and temperatures of the dam, and shows the following features of the transverse joint opening and closing process of an arch dam.

1. In the early temperature rise and fall stages, transverse joints were closed in most cases mainly because the compressive stress became dominant during the temperature rise. As the temperature fell,
the temperature rise compressive stress of the early stage was countervailed, and the transverse joint bonding strength needed to be countervailed if the transverse joint was of bonding strength. So, under the premise that temperature drop range was low and the transverse joint was of relatively higher bonding strength, the transverse joint would be closed or of very small aperture relatively for a long time;

(2) Most concrete was not open until the inter-cooling or the secondary cooling stage, which indicates that the tensile stress caused by temperature drop at this time exceeded the transverse joint bonding strength;

(3) most transverse joints were closed at the beginning. However, as the temperature fell later, most transverse joints would smoothly become open with a transverse joint aperture exceeding 1.0mm and relatively high grouting ability in most cases.

**Table 1. Transverse joints aperture average of different grouting compartment**

| Grouting area | joint aperture at the end of primary cooling /mm | joint aperture at the end of middle cooling /mm | joint aperture at the end of second cooling /mm |
|--------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|
|              | Predictive value | Predictive value | Monitored value | Predictive value | Monitored value | Predictive value | Monitored value |
| 1            | 0.16             | 0.39             | 0.34             | 0.78             | 0.69             |
| 2            | 0.00             | 0.22             | 0.18             | 0.74             | 0.61             |
| 3            | 0.05             | 0.40             | \No instrument  | 0.93             | \No instrument  |
| 4            | 0.09             | 0.31             | 0.17             | 0.82             | 0.73             |

**Fig. 3 Typical schematic diagram on transverse joint aperture vs temperature in non-restraint area of dam**

4. **Feedback analysis on monitoring results of transverse joint apertures**

Based on the temperature of the arch dam before the intercooling and actually measured transverse joint apertures, we performed simulation feedback and predictive analysis on transverse joint apertures. Table 1 and Fig. 4 show simulation calculation results vs actually measured results. The predictive values of all the grouting compartments were basically the same as the finally monitored values at the end of intercooling and at the end of secondary cooling, which further the effectiveness and reliability of transverse joint simulation calculation results.
5. Analysis on effective measures for enlarging transverse joint apertures and ensuring groutability of super-high arch dam

Ensuring transverse joint aperture always goes against the measures for temperature control. Considering the first lot of cooled transverse joint apertures of the arch dam is small, the following measures and methods are proposed for ensuring the dam transverse joints are open and of relatively good groutability in the later cooling period:

① The target temperature of the primary cooling period should be increased from 20℃ to 22℃;
② The maximum temperature in the non-restraint area should be increased to 29℃, and the target temperature of the primary cooling period should be 24℃;
③ Ultra cooling temperature should be 1~3℃;

The finite element simulation calculation results of the above-said measures are shown in Fig. 5~Fig. 6, and the effectiveness of enlarging later transverse joint apertures by the related measures are shown as the followings: ① 2℃ higher target temperature in the primary cooling period can effectively enlarge transverse joint aperture by about 0.2mm; ② Increasing the restraint area maximum temperature from 27℃ to 29℃, and at the same time raising the target temperature of the primary cooling period to 24℃ can enlarge transverse joint aperture by about 0.5-0.6mm; ③ the water pipe cooling temperature 3℃ can enlarge later transverse joint aperture by about 0.3mm, but at the same time increase the restraint area stress by 0.3-0.4MPa and non-restraint area stress by 0.1-0.2MPa;

In conclusion, the apertures of the transverse joints in the foundation restraint area should be enlarged by raising the target temperature of the primary cooling period and increase temperature drop ranges in the synchronical intercooling and secondary cooling period, rather than raising the maximum temperature or adopting the water pipe cooling method; while those in the non-restraint area can be enlarged by properly raising the maximum temperature and the target temperature of the primary cooling period; at the same time, the surface finishing technology of the transverse joints should be improved, excessive finishing should be avoided and only furs need to be removed, in order to avoid too high transverse joint bonding strength which causes transverse joints to open at the best time; in
addition, surface heat preservation must be well performed for the upstream and downstream in case of grouting in high-temperature season.

Figure 5. Influence on transverse joints due to different maximum temperature and target primary temperature cooling mode.

Figure 6. Influence on transverse joints apertures due to the super-cooling mode.

6. Conclusions

The following conclusions and advices are presented according to all the above analysis:

(1) Relatively temperature control measures for the super-high arch dam, controlling especially the “maximum temperature” for the whole dam uniformly as per the temperature requirement for the strong restraint area may affect apertures of transverse joints, and the transverse joint bonding strength may affect the best opening time of transverse joints. Under such conditions, preliminary experiment and study needs to be well performed, including the relationship between transverse joint apertures and maximum temperature & transverse joint bonding strength, surface finishing technology selection, etc., in order to guide the construction better.

(2) The real working behaviors and transverse joint opening and closing processes of the dam can be presented relatively really by the feedback simulation and analysis, and the dam groutability of transverse joints of super-high arch can be effectively guaranteed by rationally optimizing construction, cooling and temperature control schemes in the construction period.

(3) The transverse joint simulation technique in this study can faithfully reflect the opening and closing iterative process of the dam transverse joints under the effects of comprehensive loads, like temperature, dead weight, hydraulic pressure, etc. Up to now, this technique has been widely adopted and applied to several domestic super-high arch dams, and is worthy of further generalization.

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