Selection and optimization of water filling scheme in front of super-high arch dam

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Abstract: During the construction of super-high arch dam, the timing of water filling in front of the dam is the key link in the safety management and control of arch dam. Besides the cantilever of dam and the transverse joint aperture of concrete arch dam, the stress in the corridor area at the bottom of the dam should be considered for the timing of water filling in the dam. In this paper, Baihetan super-high arch dam project was taken as an example to study this problem, and the risk of overall dam overhang under gravity load and the influence of different water levels on the transverse joint aperture and stress in the corridor area was systematically analyzed. The research results showed that different water level elevations have obvious influence on the transverse joint aperture and stress state in corridor area, and the selection of water level elevations needs to comprehensively consider the mutual coupling relationship among these influencing factors, so as to realize the effective control of dam safety risk.

1. Introduction

In recent years, many super-high arch dams have been built or are under construction in China. During the construction of arch dams, the dam will gradually form a whole with the increase of dam pouring height and closure grouting11. In this process, due to the dam protection during flood season, diversion tunnels on both sides of the river are often used for a long time, and no water will flow into the foundation pit in front of the dam for a long time. Therefore, no water retaining measures are taken in front of the dam. However, with the increase of dam height and the completion of closure grouting step by step, the dam will overhang on the whole. Engineering practice experience showed that when the overhang of arch dam cannot be controlled properly, it is possible to produce excessive stress at dam abutments, dam toes and dam fillet on both banks below, resulting in cracks2-4. In addition, with the elevation of the dam body, the tensile stress of the top and bottom plates of the corridor will increase under the action of gravity load, which will increase the cracking risk of the top plate of the corridor. In order to effectively control these problems, it is often necessary to solve or alleviate these problems by water filling the foundation pit in advance. This method can not only alleviate the overhang of arch dam, but also effectively improve the stress level of the dam foundation corridor and increase the water temperature of the reservoir in the foundation constrained area, thus being beneficial to the safety control during whole process of dam construction and operation. Therefore, for super-high arch dams, it is necessary to carry out similar research at the initial stage of pouring, and reasonably optimize the timing and elevation of water filling the foundation pit, which provides very
important support for effectively controlling the dam working behavior and avoiding possible cracking risks\textsuperscript{[5]}. Therefore, taking Baihetan arch dam under construction in China as an example, this paper studies the timing and elevation of foundation pit water filling in the process of dam construction, and focuses on the overhang of arch dam and the risk of stress cracking of the dam corridor under the gravity function. In addition, the ideas and measures conducive to stress state control under the condition of dam overhang were put forward, which provides support for the safe construction of the project.

2. Risk analysis of cracking caused by gravity load of super-high arch dam
Baihetan double-curvature arch dam belongs to 300 m super-high arch dam, with the maximum dam height of 289 m, the foundation elevation of 545 m and the concrete volume of the dam body of about 8.03 million m\textsuperscript{3}. The dam is divided into 31 dam sections, and the two sides of the dam are asymmetrically arranged. The layout of arch dam plane and crown cantilever is shown in Fig. 1.

2.1. Risk analysis of dam overhang under gravity load
In order to reflect the risk of the dam overhang, the simulation method for the construction process of the dam was adopted to simulate the superposition process of the dam’s gravity load in the whole process, and the basic law and change trend of the overhang stress under the dam’s gravity load were analyzed. In the calculation, only the gravity load was considered, and other loads such as temperature, water pressure and creep were not considered. The grouting was carried out according to the actual closure grouting progress of the dam. It can be seen from Fig. 1 that, under the premise of not retaining water in front of the dam, the overhang stress caused by gravity load was mainly in the left and right banks of the downstream surface and the expanded foundation area of the riverbed, which were also two areas that need to be paid attention to during the construction of arch dam. With the increase of dam height, obvious tensile stress was increasingly obvious on the left and right banks of the downstream surface of the dam. By the end of June, 2019, the maximum dam height was close to about 150m. If there is no water storage in the upstream, the tensile stress of about 0.6–0.8 MPa may appear locally, and the vertical tensile stress of about 0.8–1.0 MPa may appear at the expanded foundation area in the downstream, which will gradually increase with the increase of dam height.
2.2. Risk analysis of corridor cracking under dam gravity load

According to the hole theory, as shown in the photoelastic test diagram of standard corridor in Fig. 4, when the vertical compressive stress of 1 MPa is generated theoretically inside the dam without holes, the tensile stress of 1 MPa will be generated on the corridor roof (point A); when the tensile stress of 1 MPa is generated along the river, the tensile stress \((\sigma_y, \sigma_x, \tau_{xy})\) along the river on the roof of the hole area will reach 3 MPa, showing obvious stress concentration at the edge of the hole.

It can be seen from the stress hydrograph of the corridor area in the dam shown in Fig. 5 that with the increase of dam height, the compressive stress on the corridor area, especially the grouting corridor, has been increasing (which means that the tensile stress on the top and bottom of the corridor has been increasing), while the stress along the river presented a certain tensile stress in the cooling stage, which was converted into a smaller compressive stress under the action of temperature rise and remained relatively stable. It was not reflected as a larger compressive stress with the increase of water level until the dam was blocked by water. It can be seen that the tensile stress level of the internal corridor will be in a state of increasing all the time before the dam damming.
3. Analysis of the influence of different water filling heights on the stress state of the dam

Generally speaking, in order to effectively reduce the unfavorable tensile stress on the downstream surface and corridor area caused by the overall rise and overhang of the dam, water filling in front of the dam is generally adopted to relieve it. However, the timing and elevation need to be rechecked and analyzed, because this kind of water retaining scheme in front of the dam has both advantages and disadvantages. Its advantages mainly include: first, it can alleviate the adverse effects caused by the dam overhang; second, it can increase the thrust along the river, thus reducing the risk of corridor cracking. The disadvantages mainly include two aspects: first, attention should be paid to reducing the transverse joint aperture, thus affecting the transverse joint grouting; second, the upstream water pressure produces tensile stress at the dam heel.

Fig. 1 shows the influence of different dam filling heights on the transverse joint aperture. It can be seen from the table that when the grouting elevation of dam joints was 574 m and the upstream water retaining levels reached 575 m~600 m respectively, the 15#-23# transverse joints were all under compression. The higher the water level was, the greater the compression of transverse joints would be. The maximum compression was 0.11 mm. Obviously, the water filling in front of dam at this stage has an impact on the transverse joint aperture. The main reason is that when the elevation of arch dam is low, the stress of the arch dam is mainly the stress along the beam direction and the effect at the direction of the arch is not significant.

Fig. 2 shows that after the dam was grouted to the elevation of 637 m, if the upstream foundation pit was filled with water to reach the elevation of 630 m, the maximum transverse joint compression was 0.17 mm. Considering that the average maximum transverse joint aperture of this project was about 1.0 mm, the influence of this compression on the transverse joint grouting was still controllable. However, when the water level reached 660 m, the compression of the transverse joint will approach 0.5 mm, which will affect transverse joint grouting.

Therefore, if the impounded level reached 660 m, the grouting elevation in front of the dam needs to exceed 660 m, otherwise it may affect transverse joint grouting.
Table 1  Transverse joint compression at different water filling levels at the end of July 2018  
(grouting elevation 574 m)

| Water level | Grouting area | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 |
|-------------|---------------|----|----|----|----|----|----|----|----|----|
| 575         | 4             | 0.01 | 0.02 | 0.02 | 0.02 | 0.01 | 0.02 | 0.01 | 0.01 | 0.04 |
|             | 5             | 0.01 | 0.02 | 0.04 | 0.03 | 0.02 | 0.02 | 0.02 | 0.03 | 0.07 |
|             | 6             | 0.01 | 0.03 | 0.05 | 0.03 | 0.03 | 0.02 | 0.03 | 0.03 | 0.09 |
|             | 7             | 0.02 | 0.04 | 0.05 | 0.04 | 0.03 | 0.03 | 0.03 | 0.04 | 0.11 |
| 585         | 4             | 0.01 | 0.02 | 0.03 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.05 |
|             | 5             | 0.02 | 0.04 | 0.05 | 0.03 | 0.02 | 0.02 | 0.03 | 0.04 | 0.07 |
|             | 6             | 0.02 | 0.05 | 0.06 | 0.04 | 0.03 | 0.02 | 0.04 | 0.05 | 0.09 |
|             | 7             | 0.04 | 0.06 | 0.06 | 0.04 | 0.03 | 0.03 | 0.05 | 0.06 | 0.11 |
| 600         | 4             | 0.04 | 0.05 | 0.04 | 0.03 | 0.03 | 0.03 | 0.04 | 0.04 | 0.01 |
|             | 5             | 0.06 | 0.07 | 0.07 | 0.05 | 0.03 | 0.03 | 0.06 | 0.06 | 0.02 |
|             | 6             | 0.07 | 0.09 | 0.08 | 0.05 | 0.03 | 0.04 | 0.07 | 0.08 | 0.03 |
|             | 7             | 0.08 | 0.10 | 0.08 | 0.05 | 0.03 | 0.04 | 0.08 | 0.10 | 0.04 |

Table 2  Transverse joint compression at different water filling levels at the end of June 2019  
(grouting elevation 637 m)

| Water level | Grouting area | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
|-------------|---------------|----|----|----|----|----|----|----|----|----|----|
| 630         | 11            | 0.13 | 0.13 | 0.13 | 0.11 | 0.11 | 0.12 | 0.11 | 0.12 | 0.11 | 0.08 |
|             | 12            | 0.16 | 0.16 | 0.14 | 0.12 | 0.12 | 0.13 | 0.13 | 0.14 | 0.12 | 0.09 |
|             | 13            | 0.17 | 0.17 | 0.15 | 0.13 | 0.12 | 0.13 | 0.14 | 0.15 | 0.14 | 0.1 |
|             | 14            | 0.19 | 0.18 | 0.16 | 0.14 | 0.13 | 0.14 | 0.15 | 0.17 | 0.15 | 0.12 |
| 660         | 11            | 0.36 | 0.34 | 0.32 | 0.3 | 0.29 | 0.32 | 0.31 | 0.34 | 0.31 | 0.27 |
|             | 12            | 0.41 | 0.37 | 0.34 | 0.33 | 0.35 | 0.35 | 0.35 | 0.38 | 0.35 | 0.29 |
|             | 13            | 0.44 | 0.43 | 0.39 | 0.35 | 0.35 | 0.36 | 0.38 | 0.42 | 0.39 | 0.3 |
|             | 14            | 0.47 | 0.46 | 0.41 | 0.36 | 0.36 | 0.38 | 0.40 | 0.46 | 0.42 | 0.32 |

3.1. Influence of different water retaining height on stress in dam corridor area

It can be seen from Fig. 6 and Fig. 7 that, when the upstream of the dam starts to retain water, the compressive stress level along the river in the corridor of the dam body was obviously improved, and the improvement of the compressive stress along the river would effectively reduce the stress level on the top and bottom plates of the corridor caused by gravity load, improve the stress distribution in the corridor area as a whole, and reduce the cracking risk in the corridor area.

It can be seen from the above that the water retaining in front of the dam would obviously improve the stress in the upstream corridor, which is beneficial to improve the stress in the corridor area. Therefore, water filling should be carried out as soon as possible if conditions permit. The higher the water level is, the more favorable the stress improvement in the corridor area will be. Therefore, comprehensive consideration should be given to transverse joint grouting of the dam and the stress in the corridor.
4. Conclusion and suggestion

Through this study, the main conclusions are as follows:

1) The unfavorable tensile stress caused by the gravity load of arch dam mainly concentrated on the downstream surface of dam body, including the left and right banks, the downstream expanded foundation area and the corridor area with bottom elevation. Under pure gravity load, obvious tensile stress gradually generated on the left and right banks of the downstream surface of the dam, which will increase the risk of cracking on the downstream surface.

2) When the elevation of dam impoundment was below 630 m, the influence on the transverse joint aperture was limited, and the compression amount of transverse joint was less than 0.2 mm. On the premise of normal transverse joint aperture, after considering this joint pressing factor, the transverse joint aperture was above 0.5 mm, which will not affect transverse joint grouting.

3) Reasonable control of the water level elevation of water filling in the foundation pit was beneficial to the improvement of the surface stress in the downstream of the dam and the stress in the corridor area. If the water level is too high, it will affect transverse joint grouting, so it should be reasonably controlled according to the actual situation.

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