Cause and Stability Analysis of Cracks in Concrete Slab of Rockfill Dam under High Temperature Difference Condition

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Abstract. The causes of cracks in concrete slab from the aspects of structural stress and non-structural stress are summarized firstly. And then, based on the relationship between the stress intensity factor and the fracture toughness, a 3D finite element model of a concrete face rockfill dam, with concrete slab under partial cracking, is established to study effects of rockfill body deformation, water level and temperature change on the stress distribution. On the basis, the stability and expansion trend of a typical crack are evaluated by numerical simulation of different sizes in depth, especially the influence of the cold-air outbreak.

1. Introduction

The working conditions of concrete face rockfill dam are complex and there are cracks in most concrete slabs more or less [1-2]. For example, due to the lack of design and construction experience in the Northwest face rockfill dam, and the improper storage time of the reservoir, a large number of cracks appeared on the slab [3]. The leakage of Zhushuqiao rockfill dam was serious and the maximum leakage amount was up to 2500 L/s, the inspection of emptying reservoir showed that the concrete slab peripheral joint and vertical joint were damaged, the concrete slab collapsed seriously, the cracks were dense and the width was larger [4-5]. In Gouhou concrete face gravel dam, the joint of concrete slab and the lower platform of wave-proof wall was damaged, the reservoir water seeped into the dam from the joint, caused the piping damage and formed the initial break and finally broke the dam [6-7]. It can be seen that as the main impervious structure, the concrete slab is key to ensure long term safety operation of rockfill dams. Therefore, it is of great significance to make clear the causes of cracks in the concrete slab and to study the stability of cracks in the concrete face rockfill dam.

2. Causes of cracks in concrete slab

In 2011, the site inspection of Gongboxia concrete face rockfill dam found 135 cracks above water level, including 129 vertical cracks and 6 transverse cracks [8]. The results of crack detection showed that the cracks were up wide and down narrow, whose width was 0.02mm~0.45mm. The length of core sampling was 11~25cm, in which 8 samples were penetrated by cracks and 5 cracks extended below the water level. As shown in figures 1~2, the core sample of the length 22cm was perforated by cracks, and the steel bar near the core sample was corroded. Considering that the thickness of the upper panel was only about 30cm, some cracks might be close to penetrating the slab. Moreover, cracks increased year by year and there were more cracks in winter and less cracks in summer, which was consistent with the general understanding that concrete shrinkage could cause cracking.
There are many factors affecting the formation of cracks in concrete slab, which are summarized as follows.

- **Structural stress**
  The causes of structural stress mainly include slab void and the incongruity deformation between the slab and the cushion. 1) Slab void deformation: under the action of water pressure and dam gravity, because the rockfill body produces uneven settlement or lateral displacement, which can cause the slab to empty when serious, the concrete slab will appear the stress concentration phenomenon. 2) Deformation between the slab and the cushion does not coordinate: the upstream water pressure can pass through the slab to the downstream rockfill body. Under the action of water pressure, if the deformation between the rigid slab and the flexible cushion cannot coordinate, the internal stress of the concrete slab will be reorganized.

- **Non-structural stress**
  Non-structural stress mainly includes the dry shrinkage stress caused by the dry shrinkage of the slab itself and the temperature stress caused by the temperature change. 1) The mechanism of the dry shrinkage is that the slab will change the microstructure of cement minerals during the drying process. At the same time, there is an interaction between the aggregate and the steel bar in the slab, which results in the dry shrinkage stress. 2) The direct influence of temperature stress are temperature difference and constraint conditions. When the external temperature changes, there is an internal and external temperature difference in the slab. Then there is a tendency of deformation, but external and internal constraints will limit the deformation, which results in the thermal stress. Cracks will occur when the stress exceeds the resistance of the concrete slab.

### 3. Evaluation criterion for crack stability of concrete slab

There are three types of crack propagation in concrete [9]. The type I is open type, which is produced by the tension stress, which is perpendicular to the crack propagation direction. The type II is slip type, produced by the shear stress, and the crack direction spreading is parallel to the shear stress. The type III is tear type, whose shear stress is perpendicular to the crack surface. The stress near the crack tip of the three extension types can be expressed as follows.

\[
\sigma_{ij} = \frac{K}{\sqrt{r}} f_i(\theta)
\]

Where \((r, \theta)\) is a polar coordinate with a crack vertex as the origin and a definite function for each crack. \(K\) is the stress intensity factor.

When \((r, \theta)\) is a certain value, it will correspond to a certain position at the crack top. Since \(r\) is far less than the crack length, (1) is only suitable for the region near the crack tip. The crack initiation and propagation occur in the region near the crack tip, so the solution of (1) can satisfy the requirements.
Among the three types of crack propagation, the type I open crack is the most common one. For the type I, the stress field at the front edge of the crack is determined by the stress intensity factor $K$ [10], which is related to the shape and position of the crack, loading conditions and geometric conditions. The stress intensity factor $K$ can be expressed as follows.

$$K = \sigma \sqrt{\pi a}$$  \hspace{1cm} (2)

The research results show that the crack expands when $K$ reaches the critical value $K_c$, called the fracture toughness, depending on the performance of the concrete slab and representing the resistance of the concrete slab to crack propagation [11]. When the structure is complicated, it is difficult to obtain the stress intensity factor $K$ at the crack end by the analytical method. The better method is to use the finite element calculation. After calculating the stress intensity factor $K$, the stability of crack can be judged according to the relationship between $K$ and $K_c$.

$$\begin{align*}
K &< K_c \quad \text{Crack does not expand} \\
K &= K_c \quad \text{Crack is in a critical state} \\
K &> K_c \quad \text{Crack continues to expand}
\end{align*}$$  \hspace{1cm} (3)

According to the reference [11], the fracture toughness $K_c$ can be estimated as follows.

$$K_c = 0.197 + 0.232 \ln C \pm 1.96S$$  \hspace{1cm} (4)

Where $C$ is crack depth (cm), $S$ is the standard deviation and equals to 0.075.

4. Case study

The concrete slab crack distribution of a concrete face rockfill dam presents the following characteristics. The number of crack distribution: near the left, the right bank abutment crack distribution is more, on the contrary it is less. There are more deep cracks on the R15 and R16 of the concrete slab, but less on the L6, L7 and L8. And most cracks near the top is narrower and shorter with filling (elevation more than 740m). The number of cracks below 740m is relatively small, but most of them are longer and wider. The finite element is divided into three kinds of solid elements: eight-node hexahedron, six-node three-prism and tetrahedron. The 3D model is set up as shown in figures 3 ~ 4, where the slab, cushion, transition zone, primary and secondary rockfill zone are divided.

4.1. Numerical simulation analysis on crack causes

The slab stress of rockfill dam during construction is affected by rockfill deformation, hydration heat of cement, temperature, sunshine and construction process [12]. For example, when the slab is casted with jump blocks, the horizontal crack occurs in the slab which is easily caused by the constraint of the first pouring block. The slab stress of rockfill dam during operation is the result of the joint action of water pressure, structural stress caused by rockfill deformation and temperature stress caused by temperature change [13]. When the slab stress exceeds the strength of concrete, the slab cracks. The maximum temperature tension stress occurs during the low temperature season or the cold cold-air
outbreak period, while the high water level period may produce greater tension stress on the slab of the cross-strait area. Because the extreme low temperature in winter is more unfavourable to the distribution of the slab stress, the tension stress is larger than the cold wave transit. Therefore, taking January 14, 2010 as an example, when the maximum temperature tension stress of the slab was generated, the contour of the temperature stress produced by the extreme low temperature of the slab over 725m in winter and the contour of the structural stress produced by the corresponding water level at the corresponding time (729m) are drawn, as shown in figures 4 ~ 5 (Take pull as positive).

The maximum principal tension stress produced by the extreme low temperature in winter is 1.52 MPa, occurred on January 14, 2010, on the surface of the slab near the 729m~730m elevation. At low temperature in winter, the concrete temperature above water surface is lower than that of concrete under water level, while the concrete temperature below water level is higher than that of reservoir water. The slab near the water level is located on the interface between reservoir water and air, where the temperature gradient is large, which makes it easy to produce large temperature tension stress. When the cold wave passes through or under the condition of continuous low temperature, the temperature gradient of the slab will increase significantly and the temperature tension stress will also increase, which may lead to the cracking of the slab.

According to the calculation results, the stress distribution of the slab is in compression in the middle and in tension in the bank abutment slab. The compression stress of the riverbed in the middle of the slab is 1.31 ~ 1.51 MPa, and the slab tension stress of the bank is 0.2 ~ 0.3 MPa. The higher the water level, the more adverse the stress on the slab, the greater the tension stress on the bank, which is consistent with the general law.

In order to comprehensively consider the influence of the non-structural stress (temperature stress) and the structural stress (deformation of the rockfill body), the structural stress of the slab and the temperature stress are superposed, then the large tension stress of the slab will occur in two banks, while the slab section of the riverbed is under pressure or a small-value tension stress state. It is because of the compressive stress caused by the deformation of the rockfill body in the riverbed, which can offset the tension stress caused by the temperature change. This is consistent with the phenomenon that there are more cracks on both sides of the bank and small in the riverbed according to inspection results.

Table 1 shows the results of the superposition of the temperature stress on January 14, 2010 and the structural stress at 729m water level in a typical position. When the principal tension stress is superimposed, the principal tension stress of the riverbed decreases greatly, while the principal tension stress of some slabs on the bank increases and the maximum is 1.94MPa, which appears at the right 0+108m of 732m elevation. Except this position, the maximum principal tension stress of the slab is also less than the average tension strength of 1.83MPa in the test.
Table 1. Principal tension stress in typical position. (Unit: MPa)

| Elevation | 0+042m on the left | 0+108m on the right | 0+006m on the right |
|-----------|--------------------|---------------------|--------------------|
| 747m      | 1.65               | 1.81                | 0.55               |
| 741m      | 1.51               | 1.74                | 0.17               |
| 738m      | 1.57               | 1.73                | 0.03               |
| 735m      | 1.68               | 1.77                | 0.01               |
| 732m      | 1.63               | 1.94                | 0.01               |
| 729m      | 0.97               | 1.57                | 0.00               |

As can be seen in Table 1, at the elevation of 732 m, the tension stress of the concrete slab exceeds the design value of 1.83 MPa, and the principal stress direction at this time is basically perpendicular to the actual crack direction, which is caused by the adverse temperature drop. Therefore, when the reservoir is operating in winter, the water level should be kept above 730 m as much as possible to reduce the adverse effect of the low temperature and prevent the generation of cracks.

In conclusion, the cracks in the slab of the rock fill dam are mainly affected by the action of temperature and water pressure. At the same time, the pouring process of the slab during the construction period has an important effect on the appearance of the initial cracks, too.

4.2. Numerical simulation analysis on crack stability

Because there are many cracks on the slab close to the left and right bank abutments and the cracks on the right are longer and wider, the stability analysis of the R11-7 crack on the right bank is carried out, as shown in Table 2.

Table 2. Typical crack condition.

| Crack number | Elevation | Length | Width | Depth |
|--------------|-----------|--------|-------|-------|
| R11-7        | 725.7m    | 5.62m  | 0.31mm| 237mm |

It can be seen that the main cause of the crack is the joint action of the thermal stress and the structural stress, so double nodes are set up at the corresponding position to simulate the cracks. The calculated water level is 729m with low temperature in winter. The simulated crack R11-7 is a horizontal type I crack, and the stress value at the crack tip obtained from the finite element calculation is substituted into (2) to obtain its stress intensity factor \( K \). Calculated values are shown in Table 3. As can be seen from Table 3, in the two days before and after the cold-air outbreak, the crack R11-7 do not expand due to the high temperature and the compression of the crack end. When entering the low temperature process, \( K \) at the crack tip increases with the decrease of temperature. \( K \) is 0.98 less than the fracture toughness at the low temperature of -3℃, so \( K \) is almost stable along the length direction of the crack R11-7.

Table 3. Stress intensity factor \( K \) at the end of the horizontal crack R11-7. (Unit: MPa·m\(^{1/2}\))

| Temperature/℃ | 8.6 | 8.8 | 7.0 | 6.3 | 5.8 | 6.3 | Crack toughness |
|---------------|-----|-----|-----|-----|-----|-----|----------------|
| R11-7         | press | press | 0.21 | 0.70 | 0.98 | 0.54 | press press | 0.78~1.08 |

For the horizontal crack R11-7, assuming different crack depths with water level 729m, corresponding stress intensity factors are calculated as shown in Table 4. It can be seen that \( K \) at the crack end of R11-7 increases with the decrease of temperature. When the crack depth is 10cm, \( K \) is greater than the fracture toughness under the calculated condition. When the temperature is lower than 7℃, \( K \) is 0.87 between 0.75 and 1.04 with the crack depth 20cm, which indicates that the crack is not completely stable and still likely to continue to develop subjected to the low temperature. When the crack depth is 25cm, \( K \) is less than the fracture toughness of 0.84~1.13, that is to say, the crack will not develop to 25cm and the depth is basically stable between 20~25cm. Because the thickness of the slab is 0.3~0.7m, the crack will not run through the slab. According to the inspection, the depth of the crack is 23.7 cm, which shows that it has stabilized.
| Temperature/℃ | 8.6 | 8.8 | 0.7 | -2.2 | -3 | -0.7 | 5.8 | 6.3 | Crack toughness |
|---------------|-----|-----|-----|------|----|------|-----|-----|-----------------|
| 10cm          | press | press | 0.21 | 0.70 | 0.98 | 0.54 | press | press | 0.58~0.88 |
| 20cm          | press | press | 0.16 | 0.67 | 0.87 | 0.42 | press | press | 0.75~1.04 |
| 25cm          | press | press | 0.07 | 0.57 | 0.73 | 0.33 | press | press | 0.84~1.13 |

5. Conclusions
The cracking of concrete slab is a bottleneck problem restricting the development of concrete face rock fill dam. Only by fully understanding the distribution mechanism of stress and deformation of the concrete slab can reasonable engineering measures be formulated to prevent the slab cracking. In this paper, relying on practical engineering, influence factors and stability of cracks in the concrete slab are evaluated by finite element analysis. However, the deformation of the rockfill body here only takes into account the short term deformation. The effect of long term deformation on the stress-deformation characteristics of concrete slab under the influence of consolidation and cyclic rise and fall of reservoir water level will be further studied in the future.

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References
[1] ICOLD committee on materials for fill dams. (2004) Concrete face rockfill dams for design and construction.
[2] Cao K.M., Wang Y.S., Xu J.J., Liu S.H. (2008) Concrete face rockfill dam. China water conservancy and hydropower publishing press, Beijing.
[3] Luo X.Q., Ge X.R. (2007) Study on stress-strain analysis methods of concrete face rock fill dam. China water conservancy and hydropower publishing press, Beijing.
[4] Gu G.C., Dai Y.Z. (2002) Analysis of the leakage accident happened on Zhushuqiao concrete face rockfill dam (CFRD). Hongshui River, 21(2): 39-43.
[5] Sheng J.B., Xie X.H., Li L. (2003) Serious leakage analysis for Zhushuqiao Dam. Hydro science and engineering, 12, 4: 25-30.
[6] Liu J. (1994) Preliminary analysis of the causes of the dam break of the Gouhou reservoir. Yellow River, 07: 28-32+62.
[7] Cheng Y.C., Qi F.D. (1994) The reasons and lessons of collapse of Gouhou concrete face slab sand-gravel dam. Journal of Nanchang University, 29(04): 13-16.
[8] Gongboxia Hydropower Station. (2011) Report on underwater Inspection of hydraulic structures in Gongboxia Hydropower Station. Xining
[9] Xu S.L. (2011) Concrete fracture mechanics. Science publishing press, Beijing.
[10] Li Q.B., Zhang C.H., Wang G.L. (1993) Static and dynamic damage fracture analysis of mode I crack in concrete. China Civil Engineering Journal, 26(06): 20-27.
[11] Xu S.L. (2010) The standard methods of fracture toughness measurement and fracture test of concrete. Mechanical industry press, Beijing.
[12] Wang R.J., Li Z.H., Wang D.Z., Chen Y.L. (2006) Research on computation model of thermal stresses of interface between slabs and cushion layer. Journal of hydroelectric engineering, 25(3): 58-61+71.
[13] Zhang Z.M., Wang J.H., Jiang D.J., Song Z.T. (2003) Study on cold wave-induced temperature stresses of mass concrete. Journal of Hohai University (Natural Sciences), 31(1): 11-15.