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Hazard Analysis of Dam Corridor Cracks Based on Field Detection and Numerical Calculation

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Abstract: The longitudinal cracks distributed along the dam axis in the corridor of a dam may have potential safety hazards. According to the detection results of crack depth and width and the analysis of monitoring data, a three-dimensional finite element model is established for numerical simulation calculation and the influence of cracks on the safety of dam structure is analyzed from different aspects such as deformation, stress value, and distribution range. The calculation results show that the maximum principal tensile stress value and the location of the dam body are basically independent of the change of crack depth (within 1.0 m). Regarding local stress around the corridor, the high upstream water level causes cracks to deepen, resulting in an increase in the maximum tensile stress near the crack tip and an expansion of the tensile stress region.

Keywords: Gallery cracks; Field test; Finite element calculation; Hazard analysis

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1. Introduction

The concrete cracks of the dam affect the appearance, durability and safety performance of the dam structure, especially the unstable cracks, which bury hidden dangers to the stable operation of the dam [1]. It may not only cause economic losses, but also lead to dam accidents and endanger the safety of people's lives and property [2]. Therefore, the study of structural safety of slit dam is one of the important topics of dam construction and operation in various countries [3–11].

In this paper, the longitudinal cracks distributed along the dam axis in a dam corridor are taken as an example. The physical and mechanical parameters of the dam body and foundation materials are inversely calculated using dam monitoring data from the past 10 years. The derived parameters are then incorporated into the finite element analysis. Combined with the field crack survey, the depth and width data of the crack are detected. The dam model containing cracks data is established in finite element analysis and the harmfulness of the current cracks is analyzed. The analysis results indicate that under the influence of a high upstream water

level, an increase in crack depth leads to higher maximum tensile stress near the crack tip and an expansion of the tensile stress region, posing a threat to dam safety. This paper also pre-analyzes the further expansion of cracks to a certain depth, which can provide reference for similar projects.

2. Project profile

A hydropower station project is composed of main dam, auxiliary dam, flood discharge building, dam powerhouse, vent pipe and switch station. The main dam of the river is a concrete open-web gravity dam. The maximum dam height is 95.5 m, and the total length of the dam top is 379.2 m. It is divided into 24 dam sections, of which 10^{th} – 16^{th} dam sections are concrete open-web gravity dam sections. In June 2007, during the daily inspection, it was found that there were longitudinal cracks distributed along the dam axis in the vault of the 7^{th} – 20^{th} dam section of the 85 m elevation corridor, the vault of the 55 m elevation corridor and the arch of the powerhouse.

3. Crack detection and preliminary analysis

In September 2015, 94 and 6 typical detection points were respectively arranged in the dam section with cracks in the 85 m elevation corridor and the 55 m corridor, and the depth and width of cracks were detected by ultrasonic wave. The results show that the maximum crack width of the 55 m elevation corridor is 0.74 mm and the maximum crack depth is 228 mm. The maximum seam width of the corridor at 85 m elevation is 1.00 mm and the maximum seam depth is 344 mm. The surface properties of the cracks are characterized by cracking or subtle regularity. Typical on-site inspection photos are shown in **Figure 1**.



Figure 1. Field detection photos of typical cracks.

From the crack detection results, the crack depth and width of the 55 m elevation corridor are not large, and the cracks in the 85 m elevation corridor are relatively serious. Considering that the 85 m elevation corridor is close to the overflow surface, it may have a relatively large impact on the safety of the dam structure.

4. Hazard analysis of cracks

The 12th dam section of the installation room is selected to establish a three-dimensional model for calculation and analysis. Here, the hazard of cracks is evaluated from two aspects: one is to compare the difference of stress value and distribution around the corridor under the two conditions of with and without cracks; the second is to predict the change of stress value and distribution around the corridor by assuming that the crack further deepens to a certain depth. Based on the results of crack detection, the 12th typical dam section is selected as the research object to analyze the influence of cracks on the safety of dam structure.

4.1. Finite element model

The dam height of the 12th dam section is 90.5 m, and the width of dam bottom is 67.5 m. The range of finite element calculation model is that the dam foundation extends vertically downward more than twice the maximum dam height, and extends horizontally twice the dam height in the upstream and downstream directions. The finite element calculation model is shown in **Figure 2**. The bottom boundary of the foundation part of the model is a fixed constraint, the upstream and downstream sides of the foundation, the left and right sides of the foundation and the dam body are normal constraints, and the rest of the interface is free.

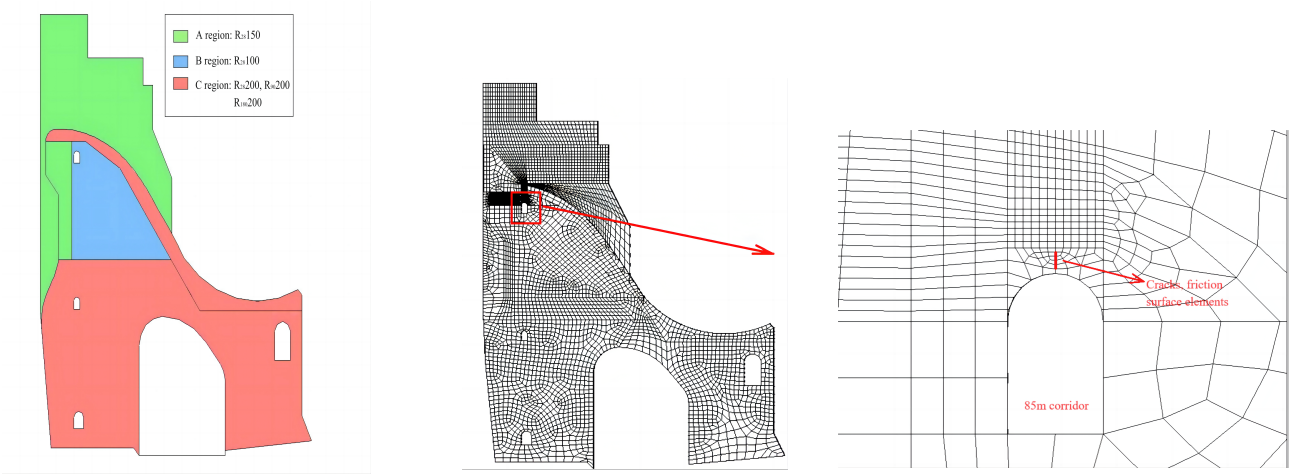


Figure 2. The finite element model and crack grid division of the 12th dam section: (a) Dam material subzone in finite element model; (b) Dam grid division in finite element model; (c) Local amplification in finite element model of 85 m corridor.

4.2. Load and calculation conditions

The calculated load mainly includes hydro-static pressure, dam body weight, dam foundation uplift pressure and silt pressure. The upstream water level is set under four conditions: normal storage level (105 m), design flood level (107.94 m), check flood level (112.04 m), and dead water level (80 m). For each water level condition, three crack scenarios—no crack, crack depth of 0.4 m, and crack depth of 1.0 m—are considered, resulting in a total of 12 calculation conditions.

4.3. The initial value of the material parameter

According to the working conditions and stress characteristics of different parts of the dam, the dam is divided

into three areas as shown in **Figure 2 (a)**. Different materials and material parameters are selected for each area to achieve the purpose of optimizing design, saving materials, reducing costs, and improving engineering safety. Based on the 10 years of serial measured deformation monitoring data, an inversion analysis is made on the physical mechanical parameters of the dam body and foundation and the physical mechanical parameters of the dam body and the bedrock materials are obtained as shown in **Table 1**.

Table 1. Material calculation parameters of dam body, dam foundation and friction surface

Material	A region	B region	C region	Bed rock	Cracks (friction surface)
Volumetric weight γ(kN/m^3)	24	24	24	26.8	/
Elastic modulus E(GPa)	21.96	18.23	26.12	26.0	/
Poisson ratio μ	0.167	0.167	0.167	0.167	0.167
Prism compressive strength fc(MPa)	6.24	3.84	8.64	150	/
Axial tensile strength ft(MPa)	0.79	0.58	1.02	/	/

4.4. Calculation and analysis results of crack hazard

4.4.1. Deformation characters analysis

The calculation results show that in terms of the overall deformation of the dam, the presence or absence of cracks or the increase of crack depth (within 1.0 m of crack depth) does not affect the deformation value and distribution law. Under the action of three typical high water levels, which are normal water level (105.00 m), design flood level (107.94 m), and check flood level (112.04 m) in the upstream the cracks in the vault of the corridor become narrower than the initial crack width (1.0 mm). As the water level rises, the degree of crack closure increases. In the same water level and different crack depth conditions, the closure decreases with the increase of crack depth. The maximum closure of the seam width relative to the initial 1 mm is 0.11 mm. Under the influence of the upstream low water level (dead water level 80 m), the crack is primarily affected by the self-weight of the dam body, causing it to widen beyond the initial crack width. With the increase of crack depth, the opening amount increases, and the maximum opening of the crack width relative to the initial 1 mm is 0.04 mm.

4.4.2. Analysis of stress characteristics

The calculation results show that the maximum principal tensile stress value and the location of the dam body are basically independent of the change of crack depth (within 1.0 m). In terms of local stress around the corridor, under the action of high water level in upstream, the deepening of cracks leads to the increase of the maximum tensile stress near the crack tip and the expansion of the tensile stress area. When the fracture depth is 1.0m and the upstream water level is 105.00 m, 107.94 m, and 112.04 m respectively, the maximum tensile stress near the fracture tip is 0.23 MPa, 0.31 MPa, and 0.36MPa respectively. Under the influence of the upstream low water level (80 m), the maximum tensile stress around the corridor at the same fracture depth is higher than that under high water level conditions and increases as the crack deepens. When the fracture depth reaches 1.0 m, the maximum principal tensile stress reaches 0.37 MPa. The local stress around the corridor under various working conditions is shown in **Table 2** and the stress distribution of the dam under typical working conditions is shown in **Figure 3**.

Table 2. Summary of stress characteristic values under different working conditions

Working condition	Water level	Penetration concept of fracture	Maximum tensile stress (MPa)	Extreme stress position	Distribution characteristics of tensile stress zone
1	105 m (Normal water level)	crack-free	0.03	Upstream side wall	The middle of the upstream side wall extends about 0.5 m upstream. The center of the bottom plate extends downward about 0.2 m.
2		0.4 m seam depth	0.15	Seam tip	The middle of the upstream side wall extends about 0.5 m upstream. The upstream and downstream sides of the fracture extend about 0.4 m, and the extension to the interior does not exceed the depth of the fracture.
3		1.0 m seam depth	0.23	Seam tip	The middle of the upstream side wall extends about 0.5 m upstream. The upstream and downstream sides of the fracture are expanded by about 0.8 m, and the internal extension does not exceed the depth of the fracture.
4	107.94 m (Design flood level)	crack-free	0.04	Upstream side wall	The middle of the upstream side wall extends upstream by about 0.6 m. The center of the bottom plate extends about 0.3 m.
5		0.4 m seam depth	0.20	Seam tip	The middle of the upstream side wall extends upstream by about 0.6 m. The upstream side of the fracture expands by about 0.7 m, and the downstream side expands by about 0.4 m. The extension to the interior does not exceed the depth of the fracture.
6		1.0 m seam depth	0.31	Seam tip	The upstream side wall is connected with the top arch crack and extends upward.
7	112.04 m (Check flood level)	crack-free	0.05	Upstream side wall	In the middle of the upstream side wall, it extends about 0.7 m upstream; the center of the bottom plate extends about 0.3 m.
8		0.4 m seam depth	0.22	Seam tip	In the middle of the upstream side wall, it extends about 0.7 m upstream; the upstream side of the fracture expands by about 0.8 m, and the downstream side expands by about 0.5 m, and the extension to the interior does not exceed the fracture depth.
9		1.0 m seam depth	0.36	Seam tip	The upstream side wall is connected with the top arch crack and extends upward.
10	**80 m (Dead water level)**	crack-free	0.25	Top arch	Area near the top arch and floor.
11		0.4 m seam depth	0.34	Seam tip	Area near the top arch and floor.
12		1.0 m seam depth	0.37	Seam tip	Area near the top arch and floor.

As shown in **Table 2**, the maximum tensile stress increases with the increase of crack depth under four different water levels. Compared with the upstream high water level state (105 m, 107.94 m and 112.04 m), the cracks will produce larger tensile stress.

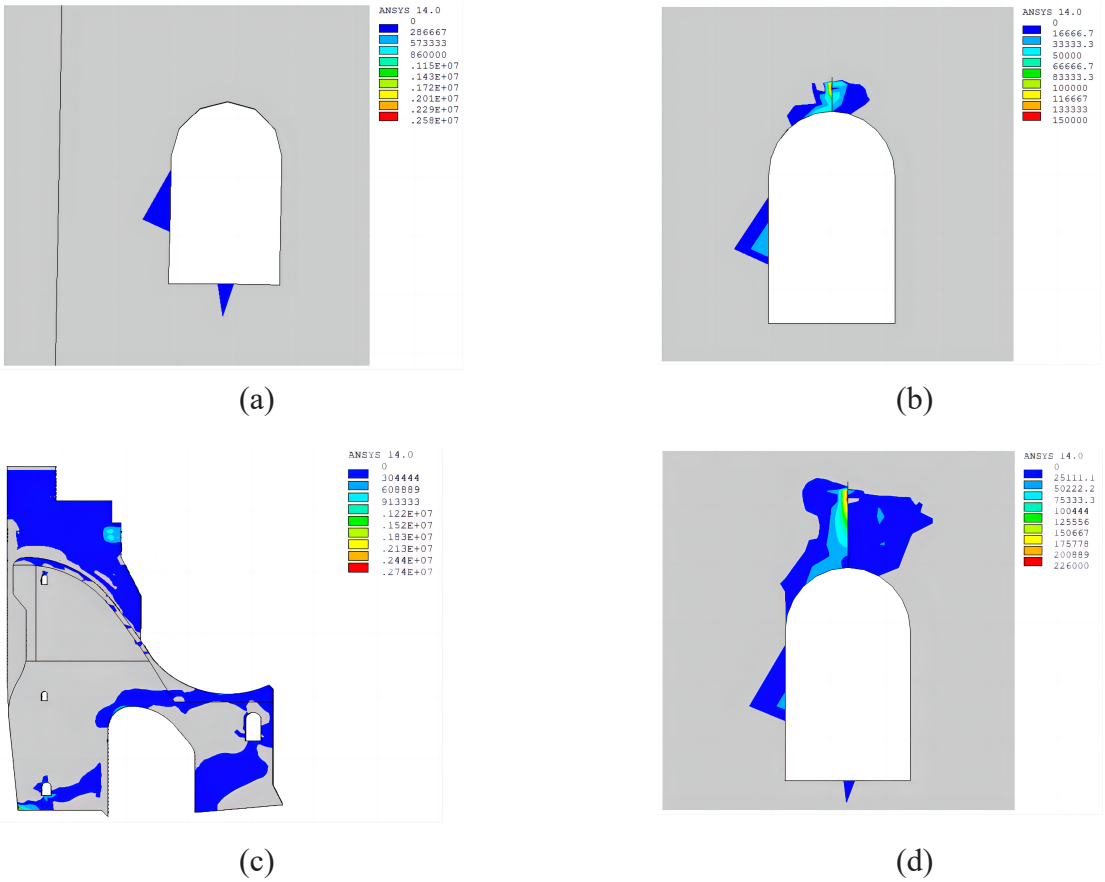


Figure 3. Stress distribution diagram of typical working conditions under normal water level(Unit: Pa): (a) Local stress distribution of corridor in working condition 1; (b) Local stress distribution of corridor in working condition 2; (c) Tensile stress distribution of dam body in working condition 3; (d) Local stress distribution of corridor in working condition 3.

As shown in **Figure 3**, under the normal water level (105 m), the tensile stress distribution around the corridor shows that the tensile stress is mainly distributed in the middle of the wall near the upstream side of the corridor. As the crack depth deepens, the tensile stress of the corridor vault increases, and the maximum tensile stress is generated near the crack tip.

5. Conclusion

The longitudinal cracks along the dam axis in the corridor of this project may pose potential safety hazards. The corridor at the 85 m elevation is near the overflow surface, which could have a significant impact on the structural safety of the dam. Based on the test results of crack depth and width, the 12th typical dam section was selected as the research object, and a three-dimensional finite element model was developed for numerical simulation analysis. The stress value and distribution around the corridor are compared under conditions with and without cracks. Additionally, assuming the crack deepens to a certain extent, the resulting changes in stress value and distribution around the corridor are analyzed.

After calculation and analysis, the maximum principal tensile stress of the dam around the corridor under

12 working conditions is lower than the allowable tensile strength of 100 concrete (0.58MPa). The influence of cracks on the stress around the corridor is still limited under the condition of checking flood level. It can be considered that the cracks in the corridor do not threaten the safety of the dam structure when the water level is high.

During the future operation of the dam, when the reservoir water level is low, the tensile stress on the gallery vault increases due to the influence of the dam's self-weight. Therefore, monitoring the crack opening should be strengthened. When the reservoir water level is high, monitoring the overall displacement of the dam, including the displacement of the dam top and the 85 m elevation corridor, should be strengthened. Additionally, attention should be given to changes in crack opening and closing, and any abnormalities should be promptly analyzed to determine their causes. If necessary, some reasonable measures should be taken such as chemical grouting, surface sealing treatment, and use of seam materials to reinforce the structure of corridor cracks.

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Disclosure statement

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