Cause Analysis of Cracks in Concrete Panels during Operation Period of Pumped Storage Power Station in the Cold Area and Corresponding Treatment

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Abstract: Cracks tend to appear on the concrete panels of pumped storage power stations during operation with frequent changes in water level in cold regions in winter. The number of cracks increases gradually with time, which adversely affects the seepage resistance and durability of the panels. This paper conducts calculation and analysis of the temperature stress of the concrete panel during winter operation, by taking the Shisanling Pumped Storage Power Station as an example, taking full consideration of the external climatic conditions of the reinforced concrete panel operation and the operating conditions of the power station, thus obtaining the variation law and distribution characteristics of temperature stress of concrete panels. According to the above calculation and the test result of concrete panel cracks, it is considered that the temperature stress during winter operation is the main reason for the generation and development of cracks on the concrete panel. In order to ensure the long-term safe operation of the reinforced concrete panel of the upper reservoir, this paper selects SK cracked polyurea to treat the concrete cracks, which delivers good result and achieves the intended purpose of the crack treatment, thus ensuring its long-term safe operation.

1. Preface
The pumped storage power station is fast in start-up and unloading, and flexible and reliable in operation, thus can be used to improve the operating conditions of thermal and nuclear power units, providing peak-valley adjustment and frequency modulation, phase modulation and emergency backup services for the power grid, and improving the reliability and economic efficiency of power supply. With the continuous improvement of China's economy and society, economic restructuring and the improvement of people's living standards pose higher demands for power usage. The power system requires a larger share of pumped storage power station in the power grid, therefore, China is and will be at the stage of the vigorous development of pumped storage power stations. In such power stations, the concrete panel is the main body to realize anti-seepage of the pumped storage power station basin, so its shall perform well in terms of impermeability, crack resistance and durability. However, cracking of the panel has become a significant weakness. Practice has shown that the concrete panels of several pumped storage power stations that have been built in the northern China are susceptible to cracks in winter due to the cold weather, hydrogeological conditions and frequent change of water level during operation. The crack destroys the integrity of the panel and weakens its anti-seepage performance; the water seepage then leads the steel corrosion, thus
affecting the safe operation of the dam. Therefore, this paper takes the concrete panel of the upper reservoir of Shisanling Pumped Storage Power Station as an example, aiming to find out the causes of cracks and the corresponding measures, which is of guiding significance for the analysis and repair of the concrete cracks of similar engineering panels later on.

2. Project Overview

The Shisanling Pumped Storage Power Station, the first of its kind built in northern China, is located in Changping, Beijing, China. Its upper reservoir uses concrete panel for anti-seepage. The elevation of the top of the pool is 568 m; the circumference 1595 m; the normal high water level 566 m; the working water depth 35 m. The concrete anti-seepage panel of the upper reservoir began at the end of March 1994 using slipform construction, and was completed in early June 1995 (suspended in winter), with the total area of 174,800 m², of which the slope panel is 91,200 m², which is made of 30 cm thick reinforced concrete structure. The standard panel is 16 m wide, with the maximum length of 65.4 m and the reinforcement ratio of 1% (the steel bars are arranged in 1/3 below the panel) and the panel slope of 1:1.5. The design strength of the concrete panel is $R_{28}^2=25$ MPa, with the impermeability rating of S8. Taking into consideration the severe environment and operating conditions of the upper reservoir, the anti-freezing label is designed to be D300.

3. Crack detection of concrete panels

3.1 General inspection of cracks

In order to track the distribution and development of cracks on the concrete panel of the upper reservoir, this paper inspects the cracks of some concrete panels above 556.0 m of the upper reservoir in 2005, 2010, 2012, 2014, and 2016 respectively. In 2005, it was found that the cracks increased compared to 1998 with the total length of 2689 m. The total length of cracks in 2010, 2012, 2014 and 2016 above 556.0 m were 5252.8 m, 6444.4 m, 11292.3 m and 13179.8 m, respectively.

Based on the crack inspections, it is found that the cracks in the concrete panels of the power station during operation have been growing quite rapidly. In 2014, the number of cracks increased significantly compared to previous years. The distribution of cracks above 556.0 m is basically the same with horizontal cracks accounting for about 80% of the total length and some cracks in the direction of the slope. The cracks are mainly distributed in the north, northeast, west and northwest of the upper reservoir (dense in the north and northeast and sparse in the southwest panel) and the main dam has the least cracks. The crack distribution is regular: the rock slope panel has more cracks than the dam slope panel; the curved section panel has more cracks than the straight section panel.

3.2 Depth detection of cracks

In 2005, seven typical new cracks with a width between 0.2 and 0.4 mm were selected in the concrete panel of the upper reservoir. Detection using ultrasonic method shows that the depth of the new crack was between 4.5 cm and 12.4 cm, with an average depth was 7.5 cm. In general, the new cracks are basically on the surface.

In 2010, 18 cracks with a width between 0.2 mm and 0.5 mm were selected. Detection using ultrasonic method shows that the crack depth was between 4.7 cm and 14.0 cm with average crack depth was 8.2 cm. Among them, four cracks were 10 cm to 14 cm deep, reaching the steel layer, while other cracks were less than 10 cm deep. The cracks are basically surface cracks.

In 2012, in order to further understand the depth of cracks, 12 cracks with the width between 0.2 mm and 0.4 mm were selected for non-destructive testing of crack depth using the surface wave method. 6 cracks were drilled and cored for measurement. The result shows that the crack depth measured using non-destructive method was between 8.8 cm and 21.6 cm with an average depth of 13.6 cm; the actual depth of the six cracks measured was 13.8 cm to 24.0 cm, slightly larger than former values.

In 2014, the depth of two seams with a width of 0.2–0.25 mm was tested using ultrasonic method. The result shows that the crack depth was 21.3 cm and 28.1 cm, respectively, indicating that they have
exceeded or even broken through the panel steel mesh.

In 2016, 8 cracks with the width between 0.2 mm and 0.3 mm were selected for crack depth detection using the ultrasonic method. The result shows that the depth was between 11.0 cm and 21.1 cm, exceeding the depth of the panel steel mesh.

From the above results, it can be seen that with the increase of the operating time, the concrete crack appears to get deeper, with some cracks exceeding or even penetrating the panel steel mesh. Cracks may cause corrosion of the steel bars in the panel, thereby make the concrete panels less durable.

4. Analysis of the cause of cracks in concrete panel during operation

4.1 Calculation of temperature stress of concrete panel

This paper calculates the temperature field and temperature stress of the panel using three-dimensional finite element method, with the conditions of external climate and power station operation taken into consideration, by taking a whole panel as the object. When calculating the temperature stress, the creep effect of concrete is not considered. The air temperature is measured in the field, while the water temperature is measured using a 557.0m elevation underwater thermometer.

![Air and water temperature records of the upper reservoir during operation period](image1)

In order to accurately simulate the change of temperature and stress of concrete panel with the change of water level in the upper reservoir, it is necessary to consider the temperature change in the 24 hours of a day, which is simulated by the fitting formula [2]:

\[
T_a = \frac{T_{ah} + T_{al}}{2} + \frac{T_{ah} - T_{al}}{2} \left\{ 0.96 \cos \left[ \frac{\pi}{12} (t - 8) \right] + 0.146 \cos \left[ \frac{\pi}{6} (t - 8) \right] \right\}
\]

Based on the measured temperature of the upper reservoir, the typical working day in winter is selected with \( T_{ah} = 4.0 \) °C and \( T_{al} = -8.0 \) °C.

The water level change is a continuous process during the actual operation of the power station. But, in the numerical calculation, it is simplified into the process line based on the actual change of water level in the upper reservoir, as shown in Figure 2.

![Typical day hydrograph of the upper reservoir in winter](image2)

The calculation results show that: (1) The temperature stress of the rock slope panel is larger than that of the dam slope panel. In the water level changing zone, the maximum tensile stress along the slope
at the surface, 10 cm and 20 cm of the dam slope panel were 1.64 MPa, 1.03 MPa and 0.41 MPa, respectively, while that of rock slope panel were 2.97 MPa, 2.25 MPa and 1.73 MPa, respectively; (2) The maximum vertical slope stress appeared in the top of the panel, and the maximum tensile stress of the surface, 10 cm and 20 cm of the rock slope panel were 1.56 MPa, 1.41 MPa, and 1.37 MPa, respectively, while that of dam slope panel at the above positions were 2.55 MPa, 2.44 MPa, and 2.43 MPa, respectively.

4.2 Cause analysis of cracks in concrete panels
During the normal operation of the power station in winter, the water level of the upper reservoir remains high for a long time and low for a short time, which is beneficial for insulation in winter. However, since the low water level mainly occurs at night when the temperature is low, the panel is hit by the cold air, resulting in large temperature stress on the panel. Based on the structural characteristics of the concrete panel, its length is much larger than its width, resulting in greater temperature stress of the panel along the slope than that of the vertical slope, which should be the main reason causing the horizontal crack of the concrete panel.

The temperature stress of the rock slope panel is greater than that of the main dam slope panel, which is mainly because that the rock mass has greater elastic modulus than the rockfill and constrains the panel more. On-site inspection [3][4][5] found that the cracks on the rock slope panel are much more than that on slope panel of the main dam, which agrees with the calculation results.

4.3 Cause analysis of sharp increase in panel cracks in 2014
From 2010 to 2016, the total length of the panel cracks in the upper reservoir and the length of the panel cracks in different areas increased year by year with the cracks in the concrete panel more rapidly than others. Among them, the two lengths mentioned above increased significantly in 2014, with the total length of panel cracks has increasing by 75.2%. compared to 2012.

Based on the operating characteristics of the pumped storage power station, the factors affecting the temperature stress of the concrete panel of the upper reservoir in the winter operation period mainly include two aspects, namely, external temperature condition and the operation mode of the power station. During power generation in winter, the water level of the upper reservoir drops, and the concrete panel originally submerged under water is hit by the cold air; in this way, the concrete panel generates large temperature stress, resulting in cracks. When the outside temperature is low, or the power station runs for a long time, the water level of the upper reservoir drops and the panel is exposed to cold air for long, resulting in larger temperature stress and more cracks.

The temperature and operational data of the upper reservoir shows that the lowest temperature in winter from 2011 to 2016 was 14 °C in January 2013; the lowest operating water level in the winter from 2011 to 2012 was basically above 550 m. But from December, 2013 to February, 2014, the lowest operating water level of the upper reservoir was 545m~550m, with the lowest water level even close to 540 m. Thus, it can be seen that during the operation of the power station in the winter of 2013~2014, the upper storage panel suffered from larger temperature stress compared with 2011~2012, which may be the reason of the many cracks in the panel concrete.

5. Repair of panel cracks
The results of crack tracking inspection show that the number and depth of cracks in concrete panels continues to increase as time passes. Therefore, it is necessary to repair them in time to prevent it is adverse effect on the seepage resistance and durability of concrete panels, so as to ensure the safe and efficient operation of concrete panels.

5.1 Repair method and materials
According to the development status of cracks in the concrete panel of the upper reservoir of the Shisanling Pumped Storage Power Station, the repairing plan of adhering waterproof materials to the crack surface is adopted. Based on the climate and the operating conditions of the power station, SK
hand scraping polyurea, featuring high elongation, low-temperature flexibility, strong adaptability to crack deformation; anti-seepage and aging resistance; high bonding strength with concrete base; simple and convenient construction, is selected as the bonding material.

5.2 Repair process and technical requirements

The process and requirements for crack treatment are as follows:

1. Grind the concrete crack along the surface (20 cm wide); grind the edge in the range of 15 cm into a triangle shape, with the edge depth of 3mm; then clean it;

2. After drying the crack surface, apply BE14 interface agent (18 cm wide);

3. After the interface agent is dry, apply the SK hand scraping polyurea (15 cm wide) and composite the base fabric with the width of 10 cm. SK hand scraping polyurea requires the working time to be within 2 hours for two or three times of brushing to ensure that its thickness is greater than 3 mm. For the treatment of the edge between the polyurea and the concrete lap, see Figure 3. Coat the edge with polyurea and concrete for a smooth transition.

4. After the polyurea is applied, naturally maintained it for three days, with the temperature higher than 5 °C.

![Figure 3. Schematic diagram of crack treatment of concrete face slab](image)

5.3 Repair effect

Years of operation has not seen any aging cracking or shedding of SK hand scraping polyurea, but good bond with the concrete with the measured bonding strength greater than 2.5 MPa. The overall repair effect is good, reaching the expectation of crack treatment.

6. Conclusion

During the regular inspection of the cracks in the reinforced concrete panel of the upper reservoir of the Shisanling Pumped Storage Power Station, it was found that the cracks are constantly developing. The calculation and analysis of the temperature stress of the concrete panel during operation shows that the temperature stress resulted from the temperature fluctuation caused by the cold air due to lower water level in winter is the main reason for the generation and development of cracks in the upper concrete panel. Based on the development status of the crack and the operating conditions of the power station, this paper adopts SK hand scraping polyurea to bind the concrete crack, which delivers good result, reaching the expectations of crack treatment, thus ensuring the long-term safe operation of the reinforced concrete panel.

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References

[1] Jiang, G., Fu, Z. Concrete face dam project. Wuhan: Hubei science and technology press, 1997.
[2] Jing, T., Yan, Z. (1980). Investigations on Temperature Conditions of Cement Concrete Pavements. Journal of Tongji University, (3), 88-97.
[3] Xia, S. (2005). The Test Report on Concrete Face Slab of the Upper Storage of the Shisanling
Pumped Storage Power Station. Beijing: China Institute of Water Resources and Hydropower Research.

[4] Li, M. (2010). The Test Report on Reinforced Concrete Face Slab of the Upper Storage of the Shisanling Pumped Storage Power Station. Beijing: China Institute of Water Resources and Hydropower Research.

[5] Li, M. (2012). Crack detection and Analysis Report on Concrete Face Slab of the Upper Storage of the Shisanling Pumped Storage Power Station. Beijing: China Institute of Water Resources and Hydropower Research.