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Detection Methods and Safety Evaluation of Large Aqueduct in Irrigation Districts

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Abstract

Based on the guidelines for safety evaluation of aqueducts and evaluation of hydraulic structures, and taking an aqueduct project in a certain irrigation district in southern China as an example, this study comprehensively analyzed the safety of the aqueduct project by using on-site detection and safety review calculations, considering the characteristics of the aqueduct structure. Additionally, repair and reinforcement suggestions were proposed, which could provide reference and guidance for similar projects.

Keywords

Aqueducts; Quality Detection; Evaluation.

1. Engineering Overview and Inspection Situation

1.1 Project Introduction

The aqueduct is located in Anhui Province, China, with a catchment area above the aqueduct of 206km2. It is designed to withstand a 50-year flood with a peak flow of 1000m3/s. The aqueduct has a hyperbolic arch structure, with 15 openings. The span of the northernmost and southernmost openings is 48.75 m, while the remaining openings have a span of 50 m. The length of the aqueduct body is 785 m, including the inlet and outlet sections, with a total length of 834.20 m. The net width of the aqueduct bottom is 6 m, and the height of the aqueduct walls is 2.75 m. The designed water depth of the aqueduct is 2.2 m, which can be increased to 2.4 m to accommodate a flow of 15m3/s. The channel and aqueduct body at the inlet are connected by arc-shaped wing walls with a radius of 7.2 m. The elevation of the upstream channel bottom is 49.90 m, while the elevation of the aqueduct bottom is 50.50 m, and the elevation of the embankment top is 54.40 m. The outlet and channel are connected by an eight-shaped structure. The elevation of the downstream channel bottom is 49.56 m, while the elevation of the aqueduct bottom is 50.50 m, and the elevation of the embankment top is 54.06m. The aqueduct project started construction in April 1971 and was completed in June 1973. After several years of operation, various degrees of defects have appeared in multiple locations of the aqueduct.

1.2 Detection Contents and Methods

Based on the results of the current investigation and analysis, and combined with the operational status of the project and influencing factors [1], the on-site quality inspection projects are mainly determined as follows:

(1) Inspection of appearance defects. Professional engineering inspection technicians with rich experience inspect the appearance defects of the concrete in the Dashan Channel through close-range visual inspection and the use of drones.

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(2) Concrete strength testing. Concrete strength is an important parameter for measuring concrete quality. Testing the strength of concrete can provide reliable basis for the correct evaluation of the safety and stability of concrete structures. Concrete strength testing can be divided into non-destructive and destructive testing. Non-destructive testing refers to the use of instruments and equipment to judge the strength of concrete without destroying the original concrete structure. The commonly used non-destructive testing methods for concrete strength include rebound method, ultrasonic method, ultrasonic rebound composite method, surface wave method, and pull-out method, etc.

(3) Detection of concrete carbonization depth. The method for measuring the carbonization depth of concrete according to the "Test Code for Hydraulic Concrete" (SL 352-2006) is to drill a hole with a diameter of 20mm and a depth of 70mm at the tested location using an electric impact drill. Blow off the dust and debris inside the hole, drop 1% phenolphthalein ethanol solution on the edge of the hole wall, and then use a caliper to measure the vertical distance from the junction between carbonized and uncarbonized to the surface of the concrete. Measure three times and take the average. The distance is the value of carbonization depth of the concrete, and each reading is accurate to 0.5mm.

(4) Detection of thickness of steel reinforcement protection layer. The thickness of the steel reinforcement protection layer in the concrete has a great influence on the bearing capacity of the concrete structure. In this inspection, the PROMETER 5 type steel reinforcement locator imported from Switzerland is used, which is an instrument that uses an induced electromagnetic field to measure the position of the steel reinforcement and the thickness of the protection layer. The function of "positioning the steel reinforcement" and "measuring the thickness of the protection layer" of the instrument can conveniently measure the thickness of the steel reinforcement protection layer.

(5) Detection of steel reinforcement corrosion condition. The corrosion of steel reinforcement in concrete structures is actually the result of electrochemical reaction of steel reinforcement. Steel reinforcement corrosion will reduce the grip force of concrete and the effective cross-sectional area of steel reinforcement, and may cause the collapse of the concrete protection layer due to the expansion caused by corrosion, affecting the overall structural stability. There are two reasons for steel reinforcement corrosion: one is that the carbonization depth of concrete exceeds the thickness of the concrete protection layer, and the other is the erosion of acidic ions such as Cl^-.

(6) Detection of typical crack depth. Generally, ultrasonic or surface wave methods are used to detect the depth of cracks.

(7) Testing of the strength of plastering mortar. The compression strength of masonry mortar is tested using the penetration method.

(8) Internal quality testing of concrete will be carried out using the Impulse Elastic Wave method. Impulse elastic wave refers to the elastic wave that is generated by the instantaneous excitation of the impact hammer or other strong impact source in the elastic medium and propagates in it. When the point source of vibration is excited on the surface of an ideal semi-infinite elastic body, the distribution ratio of each component of the elastic wave is approximately 7% for P waves (longitudinal waves), 26% for S waves (transverse or shear waves), and 67% for R waves (Rayleigh waves).

1.3 Conclusion of Quality Testing on Aqueduct Concrete

(1) Concrete strength The concrete strength was tested using rebound method, ultrasonic rebound combined method, and drilling core method. The three methods mutually confirmed and complemented each other. The test results showed that the quality of the concrete in the aqueduct was good and exceeded the original design strength.

(2) Reinforcement protection layer thickness The results of the reinforcement protection layer thickness test showed that the average thickness of the aqueduct shell and arch beam protection layer met the original design requirements. Due to the enlarged treatment of the arch foot of the arch beam, the protection layer thickness of the arch foot of the arch beam was far greater than the design value.

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(3) Concrete crack width and depth 32 samples were tested by ultrasonic method, with crack widths ranging from 0.14 to 2.26mm and crack depths ranging from 25.5mm to 356mm. Most of the crack depths were greater than the protection layer thickness. The existence of cracks could easily cause carbonization and steel corrosion, which would have a negative impact on the durability and structure of concrete. The statistical results showed that 34% of the cracks were through cracks.

(4) Concrete carbonation depth the carbonation depth test showed that the internal concrete carbonation depth of the aqueduct shell exceeded the design protection layer thickness, and the risk of steel corrosion existed when the carbonation depth exceeded the protection layer thickness. The concrete carbonation depth of the arch beam was shallow and did not exceed the reinforcement protection layer thickness.

(5) Reinforcement corrosion status Some aqueduct shells have undergone reinforcement corrosion, but the reinforcement of the aqueduct support arch beam is in good condition without corrosion.

(6) The strength of the mortar in each masonry of the aqueduct meets the original design strength requirements.

(7) Impact elastic wave method to detect the internal quality of concrete Under the condition of excluding the influence of cracks, the concrete quality of the five aqueduct shells selected for this test can be evaluated as good, but the distribution of concrete quality is uneven, indicating that there may be local durability deterioration problems in the aqueduct shell. The overall quality of the concrete in the arch beam of the aqueduct is slightly lower than that in its shell, but the distribution of the concrete quality in the arch beam is relatively uniform. According to the elastic wave test results and combined with on-site observation, it can be judged that most of the arch beam structures have good overall integrity, and the concrete has not shown serious durability deterioration. However, the right #5 arch beam of the ninth span is significantly different from other arch beams. From the appearance, this arch beam has a local concrete protection layer collapse phenomenon that other arch beams do not have [2]. This may be due to the significantly lower VP3 of the arch beam. The arch inspection points are shown in Figure 1.

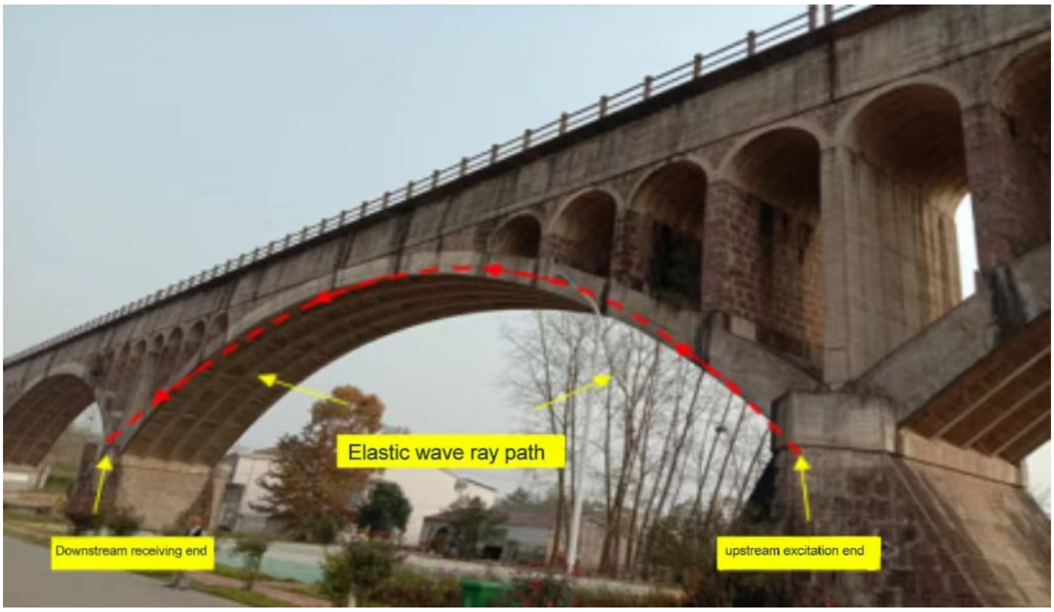

Figure 1. Overall Concrete Quality of the Arch Ring Beams Detected by Impact Elastic Wave Testing

2. Engineering Safety Review and Assessment

2.1 Safety Review Standards

According to the "Classification of Water Conservancy and Hydropower Engineering Grades and Flood Standards" (SL252-2017), the level of permanent hydraulic structures in irrigation projects such as channels and canal systems should be determined based on the irrigation flow rate. According to the design data, the designed flow rate of the aqueduct is $13m^3/s$ and the check flow rate is $15m^3/s$. However, considering the importance of the aqueduct for the water transmission safety of the entire irrigation area, and that it is a large-span aqueduct, the building level of the aqueduct is raised by one level in this safety evaluation, that is, it is classified as a level 3 hydraulic structure.

2.2 Safety Review Results

(1) Under the standard load combination of normal serviceability limit state (structural self-weight + designed water depth of 2.2m), the maximum vertical displacement of the arch beam at the top of the main arch ring of the aqueduct is 10.6 mm. Compared with the arch structure with a span of about 52.5m, $\Delta/L \approx 2.02\times10^{-4}$, which is much smaller than the deflection limit value of L/600 specified in the "Design Code for Hydraulic Concrete Structures" (SL191-2008) for the deflection of the aqueduct body, indicating that the vertical stiffness of the main arch ring structure of the aqueduct is large and can effectively resist the deformation caused by the self-weight of the structure and the water weight in the aqueduct during operation.

(2) Under the action of the basic load combination and considering the safety factor of bearing capacity K=1.20, the main control section of the arch beam of the culvert is in compressive stress, with a maximum stress of 9.58 MPa, which is not exceeding the designed axial compressive strength of C25 concrete, f_c=11.9 MPa.

(3) The inclined sections of the arch rib beams of the culvert satisfy the shear bearing capacity under the basic load combination and considering the bearing safety factor of K=1.20, and the safety margin is very large.

(4) Under the basic load combination and considering the safety factor of K=1.20, the maximum compressive stress on the entire cross-section of the arch beam of the culvert is 10.29 MPa, which is lower than the designed axial compressive strength of C25 concrete of 11.9 MPa. However, under the load combination with a temperature rise of 15°C and considering the same safety factor, the arch foot of the culvert's last (4th) short rib at the lower edge of the support wall experiences a tensile stress of 1.48 MPa, which is higher than the designed tensile strength of C25 concrete of 1.27 MPa and may cause cracking of the concrete.

(5) Under the basic load combination + 15°C temperature drop and considering the safety factor of bearing capacity K=1.20, the compressive bearing capacity of the positive section of the control section of the above-mentioned arch beam that exceeds the limit of tensile stress reaches 175.9% of the design value of axial compressive stress Nd, so the compressive bearing capacity of the positive section of the control section meets the requirements and has a certain safety margin.

(6) Under the basic load combination and considering the safety factor of bearing capacity K=1.20, the upper edge of the control section of the aqueduct arch is subjected to tensile stress of 0.05 MPa and the lower edge is subjected to compressive

(7) stress aqueduct factor of bearing capacity K=1.20, the transverse groove (vertical) section of the aqueduct shell side wall meets the requirements of the single width bending carrying capacity, but the safety margin is not high.

(8) In conclusion, the main structure of the aqueduct should be safe and stable under the condition of 2.2m designed water depth. Considering the different safety factors of bearing capacity K in the basic load combination (K=1.20) and accidental load combination (K=1.0), the main structure of the aqueduct can also be safely and stably operated under the design water depth of 2.4m.

3. Repair and Reinforcement Suggestions

Due to the current situation of aging and damage in the aqueduct, repairs are necessary to improve the safety condition of the structure and delay its aging process. Based on the results of on-site inspections and re-evaluation calculations, the following suggestions are proposed for the repair and reinforcement of the aqueduct [3~7]:

(1) The concrete erosion on the bottom plate of the aqueduct body is severe and covers a large area. Therefore, it is recommended to use polymer cement mortar or polymer small stone concrete for restoration, in order to restore the aqueduct's design cross-sectional shape and smoothness.

(2) There are multiple vertical cracks on the aqueduct body, and some of them are through cracks. It is necessary to classify the cracks according to their widths and treat them accordingly. Cracks with widths less than 0.2mm can be directly polished and sealed with polyurea. Cracks with widths greater than 0.2mm need to be grouted and then sealed with polyurea.

(3) At the concrete peeling locations on the aqueduct wall, polymer cement mortar should be used for repair, and anti-carbonation and wear-resistant coatings should be applied to delay the development of concrete carbonation and prevent further rusting of the steel bars.

(4) The water-stop belts on the expansion joints of the aqueduct bed and some parts of the aqueduct walls have ruptured and leaked. It is recommended to use a U-shaped groove on the expansion joints, and fill it with flexible water-stop materials. The surface should be sealed with hand-spread polyurea.

(5) The localized steel bar corrosion inside the aqueduct is severe (with an area loss rate greater than 10%). It needs to be rust-removed, painted with rust inhibitors, and restored to the thickness of the protective layer using polymer mortar.

4. Conclusion

This study took an aqueduct project in a southern region of China as an example. Based on the guidelines for aqueduct safety evaluation and the evaluation of hydraulic structures, and considering the characteristics of the aqueduct structure, a comprehensive analysis of the safety of the aqueduct project was conducted using on-site inspections and safety review calculations. Suggestions for repairing and reinforcing the aqueduct were also proposed. This study can provide a reference for similar projects.

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