Causes of Crack and Durability Analysis of Corroded Reinforcing Bars in Three-Orientation Pre-stressed Aqueduct with Long-span at Cold Areas

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Abstract: A large aqueduct located in the cold region of north China adopts three-orientation pre-stressed reinforced concrete structure with large span. During the construction period, after the third spring, the quality inspection of the aqueduct wall has a phenomenon of vertical long cracks, white paste, alkali corrosion and water seepage, and there is also an empty drum sound inside the wall. Using theoretical solution and numerical calculation method, the causes of cracks on the surface and the internal hollow of the aqueduct wall are analysed from the aspects of pre-stressed tension, frost heave and ambient temperature. A nonlinear finite element model with fine mesh is established to simulate the initiation of the crack and penetration process through the single hole and multiple holes frost heaving process of the bellows. Finally, the durability and hazard of aqueduct are evaluated by calculating the influence of different seam depths on the pre-stressed steel bars and ordinary steel corrosion, which provides a basis for the later crack repair protection scheme, and also provides reference for the construction and operation management of such aqueducts.

1. Introduction
In the long-distance water division project, such as the South-to-North Water Division Project, the Central of Yunnan Water Diversion Project, the Central of Guizhou Water Division Project, and the Yin’ejiuw Water Transfer Project, the aqueduct of water transfer that spans the canal, the valley, the depression and the road is a widely used type of hydraulic structure \cite{1-4}. Due to the influence of the service environment, design, construction and operation management of the aqueduct, once the aqueduct is destroyed, it will bring serious economic losses and social harm. Therefore, it is essential to carry out research on the load force, durability and failure mode of the aqueduct \cite{5-6}. From the aspect of load, the aqueduct is susceptible to structural damage caused by load factors such as temperature, water, earthquake, wind load, durability (frozen, aging, rust) and overload \cite{7-13}; in terms of materials, the aqueduct is composed of concrete and steel bars, which are damaged by concrete aging, cracks and steel corrosion, fatigue fracture, etc. \cite{14-16}

A large water supply aqueduct in the north china is built in a cold area, with cold and dry winters and hot and rainy summers. The annual average temperature is 12.9°C, the average annual temperature in January is -3.2°C, and the extreme minimum temperature is -19.9°C; an average annual temperature in July is 26.3°C, and the extreme maximum temperature is 42.5°C. The maximum frozen soil depth
reaches 60cm. The aqueduct has a single span of 40m, a designed flow velocity is 230m$^3$/s, and an increased flow velocity is 250m$^3$/s. It is the longest aqueduct of single span in Asia, which is a three-slot joint one rectangular pre-stressed reinforced concrete structure, the typical cross section of the aqueduct structure is shown in Figure 1. The aqueduct adopts three-orientation pre-stressed structure design. The groove wall is a longitudinal and vertical two-way pre-stressed structure, and the bottom plate adopts a lateral pre-stressed structure. The side wall and the middle wall are longitudinally 1860MPa rank 7-$\varnothing^{15.2}$, 9-$\varnothing^{15.2}$ pre-stressed steel strand, vertically grad PSB785MPa pre-stressed steel bar. The top and bottom of the lateral bottom plate are respectively arranged with 4 bundles and 2 bundles of 7-$\varnothing^{15.2}$ pre-stressed steel strands.

After the third year spring of the construction of the project, a large number of vertical long cracks was found on the surface of the trench wall during the quality inspection of the project. The wall has flowed white paste and alkali corrosion from the inside, and the outer surface has obvious hollow sound of knocking wall, see figure 2. The causes of cracks in aqueduct are also different. There are many reasons such as structural design and improper temperature control measures during construction, poor grade of concrete materials, freeze-thaw damage during operation, steel corrosion, uneven foundation settlement, etc., resulting in crack morphology and different distribution. After preliminary analysis, it is believed that there may be two reasons for the hollowing crack of the wall: 1) The occurrence of the hollow drum crack phenomenon is related to the pre-stressed tension of the concrete; 2) It is highly probable that there is residual water in the bellows that causes frost to damage the concrete, forming surface cracks and hollows crack of the aqueduct wall. In addition, experts with on-site inspections also suggested that “the side wall is eccentrically compressed due to the inconsistent tension of the vertical steel bars on both sides, resulting in tensile stress on one edge. After the wall is poured, the outer protective layer of the bellows is easily dehydrated due to improper curing, resulting in low strength of the part, which is easy to crack from the weak part when the concrete shrinks and deforms.

Comprehensive analysis of various aspects, the possible causes of defects are as follows: 1) The quality of the bellows grouting is poor, and the internal water frost heave causes cracks; 2) Pre-stressed over tension and improper tension; 3) Temperature-induced cracks. In this paper, theoretical analysis and FEM are used to study the influence of various factors on the stress of aqueduct wall, analyze the mechanism of crack generation, and evaluate the durability of aqueduct from the perspective of steel corrosion.

Figure1. Cross section layout of aqueduct structure (unit:cm)
2. Effect of tension on crack formation

2.1 Tension overload analysis

Table 1 shows the statistics of vertical rebar tension in a single aqueduct. The tensile extension is 3.4 mm/m. The control force of the longitudinal pre-stressed steel strand is 1.03σ_con, and the control force of the transverse and vertical prestressed tension is 1.05σ_con. σ_con is the tension of control force. It can be seen from Table 1 that the elongation of N1 steel bars is between 28.0 and 31.0 mm, and the deviation from the calculated tensile value is between -0.71% and 9.93%; The elongation of N2 steel bars is between 30.0 and 32.0 mm, and the deviation from the calculated tension value is between 1.35% and 8.11%; The elongation of N3 steel bars is between 31.0 and 34.0 mm, and the deviation from the calculated tension value is between 0.32% and 10.03%. On the whole, the deviation of the measured tensile elongation of some steel bars N1~N3 compared with the calculated value is greater than ±6% of the design requirement, and the individual reaches 10.03%. Therefore, there is a problem of tension overrun in some vertical pre-stressed steel bars on site.

Table 1. Statistical information for vertical steel tension of single-span aqueduct

| Type of bar | Number of steel bundles | Measured tension Value/mm | Calculate tension value/mm | deviation/ % | Number of steel bundles with deviations exceeding ±6% | Proportion of steel bundles with deviations exceeding ±6% |
|-------------|-------------------------|---------------------------|----------------------------|--------------|-----------------------------------------------------|--------------------------------------------------|
| N1          | 128                     | 28.0~31.0                 | 28.2                       | -0.71~9.93  | 68                                                  | 53.13%                                           |
| N2          | 57                      | 30.0~32.0                 | 29.6                       | 1.35~8.11   | 9                                                   | 15.79%                                           |
| N3          | 29                      | 31.0~34.0                 | 30.9                       | 0.32~10.03  | 13                                                  | 44.82%                                           |

2.2 Tension analysis

2.2.1 Pre-stressed overrun tension

(1) Pre-stressed tension by theoretical analysis

When applying vertical pre-stress \( \sigma_y = \frac{P}{A} \) show as figure 3, where P is the tensile force of a single steel bar and A is the cross-sectional area of a single pre-stressed rebar. Since the two sides of the vertical wall are free and there are bellows inside, the vertical tensile stress will be generated in the lateral direction when the vertical pre-stressing tension is applied, but the tensile stress is extremely small. The calculation of the FEM can calculate the level less than 0.1MPa locally. The tensile stress is applied, and the material mechanical method or the structural mechanical method can’t calculate the transverse tensile stress.

After longitudinal pre-stressed tensioning applied, see figure 4, according to the analytical solution of elastic mechanics, it is known that cyclic tensile stress will be generated along the X longitudinal direction around the grouting hole, and the value is \( \sigma_\theta = \frac{\sigma}{2} \left( 1 + \frac{a^2}{r^2} \right) - \frac{\sigma}{2} \left( 1 + 3 \frac{a^2}{r^2} \right) \). The tensile stress \( \sigma_\theta \) is 0 at the position of \( r = \sqrt{3}a \), wherein the radius of the grouting bellows is a=26 mm, and r represents the stress position.
After the longitudinal pre-stressing tension is completed, the longitudinal compressive stress $\sigma_{\text{max}}=4.8\text{MPa}$ will be generated in the cross section of the groove wall.

According to the theoretical formula of elastic mechanics, the area where the $\sigma_0$ exceed concrete tensile strength can be calculated is about 3.2mm. The crack diagram is shown in Fig.5, and the crack will not be penetrate.

![Diagram](image1)

**Figure 3.** Schematic diagram of the force of the aqueduct wall during vertical tension

![Diagram](image2)

**Figure 4.** Schematic diagram of the force of the aqueduct wall during longitudinal tension

![Diagram](image3)

**Figure 5.** Longitudinal pre-stressing may cause circumferential cracks schematic holes

(2) Calculate analysis by FEM

Through the calculation result of FEM, the stress distribution around the hole after vertical and longitudinal pre-stressing tension is shown in Figure 6 and Figure 7. Figure 6 shows that the circumferential stress is not large after vertical pre-stressing tensioning. Figure 7 shows that after the longitudinal pre-stressing tension, the circumferential tensile stress of 1.34-2.65 MPa is generated around the grouting hole. The tensile stress at the bottom of the grouting hole is larger, the upper part is smaller, and the bottom tensile stress is more than 1 MPa. The bottom hole will produce excessive stress (greater than 1.89MPa), the area of excessive stress is about 5mm, which will result in local micro radial cracks, but the crack depth is less than 3mm, no penetrating crack will be formed.
2.2.2 Inconsistent tension order
Considering on-site inspection found that there is a problem that the pre-stress tension in the construction is not tensioned according to the tension order of the design. Theoretical analysis shows that the tension order of the vertical pre-stressing steel bars on both sides of the side wall is inconsistent, resulting in eccentric compression and tensile stress of one edge in the section of the groove wall. However, this tensile stress is a vertical tensile stress but it is not very large, even if the stress is large, the crack is also a horizontal crack. With regard to this, consider the extreme tension of the outer vertical reinforcement and the inner reinforcement without tension, as shown in Figure 8. The calculation results are shown in Figure 9. It can be seen that the induced tensile stress of the inner wall of the groove wall does not exceed 0.7 MPa, which is less than the tensile strength of the concrete, and the concrete of the inner wall doesn’t crack.

3. Simulation analysis of aqueduct crack problem

3.1 Defect detection of aqueduct
The aqueduct wall is tested by the ground penetrating radar of Mala CX12 imaging system to detect the position of the steel bar mesh together with grouting compactness of bellows. In Figure 11(a), the first layer of longitudinal X and vertical Y steel mesh sections of the aqueduct are scanned, and it can be clearly seen that the grid spacing is 15×10 cm²; Fig. 11(b) shows the slice plot of the grouting compactness of bellows. It can be seen that the image at two positions along the Y direction of X=210cm and X=250cm shows two bellows, and the position of the first bellows displays the in-phase axis is continuous and the amplitude does not change abnormally, indicating that the filling is dense. The amplitude response of the second bellows is strong, and the in-phase is interrupted, which can be seen that the bellows is not densely grouted.

The water was discharged from the bottom of the bellows, which shows as Figure 11(a); The bottom area of the broken bellows sees a large amount of white mortar coming out inside, see Figure 11(b);
Through radar detection and perforation inspection, it is verified that the grouting in the bellow of the aqueduct wall is not dense enough and the internal water is stored also, and the volume of the self is expanded during the wintering process. The expansion ratio is about 9%, and a large circumferential tensile stress is generated around the bellows, which is sufficient to frozen rupture the concrete around the bellows [17].

3.2 Crack simulation of aqueduct

3.2.1 FEM model with fine mesh
The calculation model with fine mesh selects a beam along the direction of the water flow and takes the half-groove side wall of the 1/2 bottom plate length range on both sides as the calculation object. The calculation model includes half of top beams, one side walls, half of bottom floor and other structures, as well as pre-stressed anchor cables and pre-stressed structural members such as steel bars, bellows, anchor heads and grouts.

Simulation model is adopted the solid element and pre-stressed steel element, and applied linear strain to simulate the ice frost heave load, and establishes a nonlinear finite element calculation mode. The calculation program uses the finite element calculation software Saptis [18], which is independently developed by the Chinese Institute of Water Resources and Hydropower Research. To simulate frost heaving of single grouting holes and the multi-grouting holes, the surface crack and the internal hollow crack initiates and expands process, the calculation model is shown in Figure12.
3.2.2 Analysis of crack simulation result

The single-hole bellow simulates frost heaving process, stress $\sigma_1$ of groove wall concrete distribution cloud map as shown in Figure 13. When the three-way pre-stressing of the bellows has been stretched with not frosted, a small range and tensile stress exceeding 1 MPa will appear around the vertical grouting hole, which is mainly caused by the application of longitudinal and lateral pre-stressing, see Figure13 (a); When the frost heave of the bellows reaches 0.1% ($1000\mu\varepsilon$), the area of the longitudinal direction of the groove is obviously over-stressed, and the longitudinal crack appears inside the bellows. As the frost heave amount of the bellows increases, the over-standard stress gradually increases along the longitudinal and circumferential directions. When the frost heaving amount reaches 1% ($10000\mu\varepsilon$), a large area of over standard stress zone appears around the hole, and the depth is about 4cm and the width is about 5cm, see Figure 13(b). When the frost heaving amount reaches 2% ($20000\mu\varepsilon$), a large area of over standard stress zone appears in the vertical direction of the groove wall, and a significant vertical long crack has been formed, as shown in Figure 13(c). When the frost heaving reaches 3% ($30000\mu\varepsilon$), the over-standard stress zone of the groove wall has penetrated the vertical surface groove wall.

(a) Pre-stressed tension without frozen  (b) frozen 1.0%$\mu\varepsilon$  (c) frozen 2.0%$\mu\varepsilon$

Figure13. Stress $\sigma_1$ distribution and surface vertical crack propagation process of single-hole frost heave simulation of groove wall

The simulation of the frost heaving failure process of the multi-hole grouting shows that when the frost heave of bellows reaches 0.10% ($1000\mu\varepsilon$), the yielding zone appears around the grouting hole, and the depth is about 6mm, as shown in Figure14(a). As the frost heaving increases, the yielding zone expands in the longitudinal direction. When the frost heaving reaches 0.24% ($2400\mu\varepsilon$), the yielding areas of the inner side of groove wall pass through each other, and the outer yields of groove wall without penetrating, as shown in Figure14(b).

As the frost heave increases, the yield expands along the longitudinal direction of the groove. When the frost heave reaches 1% ($10000\mu\varepsilon$), the yielding areas of the inner and outer groove wall have expanded to form a hollow crack, as shown in Figure14(c). Based on the above analysis, it is known that the incomplete grouting and the winter frost heaving of the residual water of the bellows over winter
are the origin causes of concrete damage.

![Figure 14](image)

Figure 14. Crack initiation, expansion and penetration process of multi-hole frost heaving simulation

4. Durability analysis of aqueduct reinforcement

4.1 Influence Analysis of Surface Cracks and the Internal Spitted Cracks of the Groove Wall on the Corrosion of Pre-stressed Steel

The aqueduct wall has a large number of vertical cracks on the surface, and hollow cracks are formed inside wall, which provides a way for the water, CO2, O2 and other substances in the environment to penetrate into the concrete. Due to the damage of some of the bellows, these substances can penetrate directly into the surface of the  $\Phi^{32}$ reinforced steel bar along the cracks and defects. Therefore, even if the grouting opening is blocked, there is still the possibility of further corrosion of the pre-stressed steel bar.

Assuming that the grouting opening is blocked, external substances can no longer penetrate the pre-stressed steel bar through the opening. At this time, water, CO2, O2 and other substances in the environment can only penetrate into the concrete interior along the cracks and defects of the groove wall, as shown in fig.15. In the grouting hole, the cement slurry does not exist according to the most unfavorable situation.

The rust rate of pre-stressed steel bars is affected by two factors: humidity and oxygen concentration in the grouting hole. Because the aqueduct is subjected to the penetration of pressurized water flow under operating conditions, when the inner wall is not treated with anti-seepage treatment, the water seepage in the hole makes the humidity condition easy to be satisfied. Therefore, the oxygen concentration is the key factor that restricts the development of rust pre-stressed steel.

Oxygen starts from the surface of the aqueduct and penetrates into the concrete along the crack. According to the most unfavorable working conditions, assuming that oxygen can reach the crack tip directly, the distribution of oxygen concentration along the infiltration path is shown in Fig. 16.

According to Fick’s first law, there are:

$$N_{O2} = -D_{O2} \frac{dC_{O2}}{dx} = -D_{O2} \frac{C_0}{L_2} \quad (1)$$

In formula (1), $N_{O2}$ represents the oxygen diffusion mass transfer flux, and the negative sign indicates that the diffusion direction is opposite to the concentration growth direction. $C_0$ represents the concentration of oxygen on the inner wall surface of the aqueduct, generally taken as $8.93 \times 10^{-6}$ mol/cm³; $L_1$ represents the crack depth, and $L_2$ represents the residual protective layer thickness; $D_{O2}$ represents the effective diffusion coefficient (cm²/s) of oxygen in concrete and can generally be calculated according to the following formula:

$$D_{O2} = \left( \frac{32.15}{f_{cuk}} - 0.44 \right) \times 10^{-4} \quad \text{cm}^2/\text{s} \quad (2)$$

In formula (2), $f_{cuk}$ indicates concrete strength, for the aqueduct is C50 concrete, $f_{cuk} = 50$ MPa.

Therefore, when the oxygen supply is insufficient, the average corrosion current density of the cathode is:

$$i_{corr} \leq i_{lim} \quad (3)$$
\[ i_{\text{lim}} = i_c = \alpha z_{O_2} F N_{O_2} \]  \hspace{1cm} (4)

In the formula (4), \( \alpha = 0.0298 \) represents the solubility of oxygen in the water film; \( z_{O_2} \) represents the number of electrons obtained by a single oxygen molecule, \( z_{O_2} = 2 \); \( F \) is a Faraday constant, \( F = 96485 \text{ C/mol} \).

Then the rust depth \( dh \) of the steel bar in the time \( d\tau \) can be obtained:

\[ dh = \frac{dW}{\rho \pi DL} = \frac{M_{Fe}-i_{\text{corr}}}{z_{Fe} F \rho} d\tau \]  \hspace{1cm} (5)

Then the corrosion rate of the steel bar can be obtained. In the above formula, \( M_{Fe} \) represents the molar mass of Fe element \( M_{Fe}=55.8 \text{g/mol} \), \( z_{Fe} \) represents the number of electrons lost by iron atoms in the electrochemical reaction, \( z_{Fe}=2 \), and \( \rho \) is the concrete resistivity. Field investigations show that most of the hollow crack depth \( L_1=5\sim10\text{cm} \). Therefore, according, sensitivity analysis is performed here for each case of \( L_1=5\text{cm},6\text{cm},7\text{cm},8\text{cm} \) and \( 8.5\text{cm} \). The calculation results of rust are shown in Table 2. It can be seen from the table that when the hollow crack depth is less than 8.5cm, since the groove wall concrete adopts C50W8F200, the material itself has good frost resistance and impermeability, and the strength is higher and the compactness is higher. It is difficult to diffuse oxygen into it, so the rate of corrosion of pre-stressed steel bars is low, and the corrosion depth of steel bars in the first year is less than 0.025 mm. When the depth of the hollow crack is equal to 8.5cm, the rust depth is more than 0.1 mm, and the rust rate is increased by 4 times. At this time, the grouting holes are directly connected to the atmosphere, so that the pre-stressed steel bars are liable to rust corrosion.

It is assumed that the pre-stressed steel bars are uniformly rusted and the cross section is uniformly reduced. The sensitivity calculation result of cumulative weight loss rate of the steel bars under different crack depth is given by Fig. 17. When the hollow crack depth of the groove wall reaches 8 cm, the corrosion of the pre-stressed steel bar develops rapidly, and the weight loss rate can reach 6% or more after 15 years, which is shown in Fig. 17. According to the durability standard [20], the aqueduct structure is prone to decrease carrying capacity and degradation stiffness problem. It is necessary to implement hollow crack with a repair depth of 8 cm or more as early as possible. In particular, the hollow crack of the groove wall with a depth of more than 8 cm must be repaired early.

| Hollow Crack depth L1(cm) | Residual protective layer thickness L2(cm) | Corrosion current density \( i_{\text{corr}} \)(mA/m²) | Average rust depth in the first year (mm/a) |
|---------------------------|------------------------------------------|--------------------------------|---------------------------------|
| 5                         | 3.5                                      | 2.98                           | 0.003                           |
| 6                         | 2.5                                      | 4.17                           | 0.005                           |
| 7                         | 1.5                                      | 6.95                           | 0.008                           |
4.2 Influence Analysis of Surface Cracks and the Internal Spitted Cracks of the Groove Wall on the Corrosion of Ordinary Steel

As shown in Figure 18, due to the existence of vertical cracks and inner hollow crack, the thickness of the protective layer of longitudinal steel bars and vertical ordinary steel bars in the groove wall is reduced, which is easily eroded by moisture, CO2, O2 and other substances in the environment, resulting in rust\textsuperscript{[19,20]}.

For the outdoor environment, when the concrete protective layer is not damaged, the annual average corrosion rate of the internal reinforcement is $\lambda_0$ (unit: mm/a), which can be calculated according to the following formula\textsuperscript{[20]}:

$$\lambda_0 = 7.53K \cdot m \cdot (0.75 + 0.0125T) \left( RH - 0.45 \right)^{2/3} \cdot C^{2/3} \cdot f_{cuk}^{-1.8}$$  \hspace{1cm} (6)

Where $K$ is the coefficient of influence of the position of the steel bar, 1.6 is taken when the bar is at the corner, and 1.0 is taken for other cases. $m$ indicates the environmental impact coefficient, and for outdoor rainy environments in dry areas, $m$ take 3.5–4.0; $T$ represents the annual average temperature of the environment, which is taken as $T=14^\circ\text{C}$; $RH$ represents the annual average humidity of the environment, here taken as $RH=60\%$; $C$ indicates the thickness of the protective layer of the steel bar; $f_{cuk}$ indicates the compressive strength of reinforced concrete.

When the concrete protective layer is cracked, the annual average corrosion rate $\lambda_1$ of the internal steel bars can be calculated according to the following formula:
In the above formula, when \( \lambda_1 < 1.8\lambda_0 \), take \( \lambda_1 = 1.8\lambda_0 \).

For the aqueduct groove wall, when the concrete protective layer is damaged, the critical rust depth \( \delta_{cr} \) is calculated according to the following formula:

\[
\delta_{cr} = 0.015 \left( \frac{C}{d} \right)^{0.15} + 0.0014 f_{cak} + 0.016
\]  

(8)

According to the difference of \( L_x \), the development rate of corrosion under the environmental material erosion of vertical ordinary steel bars is calculated. The calculation results are shown in Table 3.

It can be seen that with the decrease of \( L_x \), the corrosion rate of vertical ordinary steel bars increases remarkably, the corrosion velocity is faster, and the critical rust depth is small. Therefore, when the rust products are expanded, the protective layer will be generated new crack.

The calculation shows that when the distance from the hollow crack to the outer surface of the groove wall is 7–8cm, the rust expansion of the vertical ordinary steel bar within 10 years will cause new cracks.

Since the aqueduct is a wall structure, the reinforcement mesh is generally dense and the spacing is small, so the rust expansion crack usually appears as a continuous expansion along the axis of the plurality of vertical steel bars, as shown in Figure 19. Therefore, when the vertical reinforcement produces rust expansion cracks, it will cause new cracks in the groove wall structure, further weakening the integrity and bearing capacity of the cavity wall.

| Hollow cracks to structural surface distance \( L_x \)(cm) | Actual protective layer thickness of vertical ordinary bar \( C \)(cm) | Corrosion rate of concrete protective layer before crack \( \lambda_0 \)(mm/a) | Corrosion rate of concrete protective layer after cracking \( \lambda_1 \)(mm/a) | Cracking critical rust depth of concrete protective layer \( \delta_0 \)(mm/a) |
|---|---|---|---|---|
| 7.7 | 0.5 | 0.016 | 0.030 | 0.088 |
| 8.2 | 1.0 | 0.010 | 0.019 | 0.093 |
| 9.2 | 2.0 | 0.004 | 0.015 | 0.107 |
| 10.2 | 3.0 | 0.004 | 0.014 | 0.126 |

Figure 19. Schematic diagram of rusty expansion cracks of vertical ordinary steel bars

5. Conclusions

Based on theoretical analysis and finite element calculation, causes of cracks on the surface and the internal hollow of concrete wall are explained. A nonlinear finite element model was established to simulate cracking process of the single hole &multi-hole frost heave of the grouting bellows. As well as
calculating and analysing the influence of steel corrosion on the durability of the aqueduct, the following conclusions can be drawn:

(1) Field investigation, theoretical analysis and numerical simulation results show that the frost heaving damage of the water in the bellows is the main cause of the formation of hollow cracks and vertical surface cracks on the groove wall. During the construction period, there are pre-stressed overrun tension problems and inconsistent tension sequences, which will not cause cracks and internal cracks in the groove wall. On-site inspection and perforation exploration, combined with the results of single hole and multi-hole frost heaving simulation analysis, the poor quality of bellow grouting and frost heave of water in the bellow over the winter are the main causes of the damage.

(2) The simulation results show that when the frost heave of the grouting bellows reaches 0.4%, longitudinal cracks appear around the grouting hole. When the amount of frost heave reaches 1%, vertical cracks begin to appear on the surface of the grouting hole, and some hollow crack formation. When the frost heave reaches 3%, the vertical crack on the surface has formed a long crack, and the inside of the groove wall expands a large hollow cracks and forms a through cracks.

(3) Considering that the grouting bellow has atmospheric connection and long-term water accumulation under severe conditions, the pre-stressed steel bar is rusted, and its rust depth reaches 0.102mm/a. When the depth of the hollow crack is 8cm to reach the bellows and the internal rupture enters the water, the corrosion of the pre-stressed steel bars develops rapidly, and the rust rate is 0.024mm/a. After 15 years, the weight loss rate can reach 6%, which may trigger some risk of service aqueduct, such as steel corrosion, fatigue fracture, and aqueduct structure to accelerate the risk of failure.

(4) The surface cracks and the internal hollow cracks of the groove wall cause corrosion of ordinary steel bars in the groove wall. The calculation shows that the vertical steel bar has a faster corrosion rate. When the distance from the hollow crack to the outer wall surface is less than 8cm, after 10 years, corrosion expansion of the vertical steel will cause new cracks in the groove wall.

(5) It is recommended to carry out secondary grouting on the aqueduct and control the quality of grouting. It is not suitable for bellows grouting construction in cold regions in winter. During the operation period, the surface of the aqueduct should be well insulated and waterproofed to prevent cracks in the aqueduct. For the cracks that have been generated should be treated in time to prevent the damage caused by the pre-stress loss of steel bars and the corrosion of steel bars, and ensure the structural safety of the service aqueduct.

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