Influencing factors of lining crack width in hydraulic tunnels under high internal water pressure

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Abstract. The crack width of reinforced concrete lining under complex working conditions is a key factor affecting the safety of high-pressure hydraulic tunnels. This research investigates the lining of a pumped storage power station under high internal water pressure of 8.0 MPa. Considering the constraint of reinforcement and the combined bearing of rock mass and lining, the effect of circumferential reinforcement ratio, reinforcement location, tunnel radius, and surrounding rock on crack width is analyzed. On this basis, the relationship between the random distribution of lining parameters and crack width is obtained by numerical calculation. The results show the importance of adjusting the reinforcement spacing and reinforcement ratio to achieve the optimal constraint on the lining crack width. When the parameters are randomly distributed, the cracks appear locally mutated, but still form a strip distribution, with no obvious change in the average crack width.

1. Introduction

With the continuous advancement of infrastructure construction, the pace of development of large-scale underground structures is increasing, especially in high-pressure hydraulic tunnels [1-2]. When conditions satisfy minimum principal stress [3] and hydraulic fracturing [4] criteria, reinforced concrete lining is usually used in hydraulic tunnels. However, the lining of hydraulic tunnels will crack under high internal water pressure [5]. Therefore, it is crucial to study the lining crack width for safety design and operation of hydraulic tunnels.

To date, many achievements have been made regarding the calculation of reinforced concrete cracks. Based on the influence coefficient method and mathematical statistics, the maximum crack width of flexural members under short-term load has been studied [6]. However, when the thickness of the protective layer is large, the error of this method is significant. Therefore, Soltani et al. [7] proposed the estimation formula of maximum crack width for reinforced concrete tension members according to cracking characteristics and experiments of reinforced concrete. Based on the fracture mechanism from large amounts of test data, an approximate empirical formula for crack width was derived [8]; however, the formula is only applicable to specific projects.

The cracking mechanism of lining under high internal water pressure is not completely consistent with that of conventional concrete components. Defects appear when applying formulae based on the cracking mechanism from conventional concrete components to the calculation of lining crack width for hydraulic tunnels [9,10]. In recent years, numerical simulation methods have been used to calculate the crack width in hydraulic pressure tunnels. Huang et al. [11] used the extended finite element method to study the distribution rule, expansion process, and occurrence mechanism of lining cracks.
Zhang et al. [12] simulated the cracking process of lining cracks based on the frequency-domain electromagnetic method. Bian and Xiao [13] applied the finite element iteration method to study the damage evolution and crack propagation process of lining concrete. However, most of the studies have calculated using equivalent or solid models, with few research results reflecting the restraint effect of reinforcement on cracks, or the combined bearing effect of surrounding rock and lining.

2. Engineering situation and models

In view of the above, this study simulates the interaction between concrete and reinforcement in processes of lining cracking using cable structural elements. This research focuses on the restraint effect of reinforcement on lining cracks and optimization design suggestions for high-pressure hydraulic tunnels. The variation of crack width under different reinforcement ratio, reinforcement position, lining thickness, surrounding rock type, tunnel radius, and concrete strength is discussed.

2.1. Engineering situation

The maximum static and dynamic water pressure of the high pressure tunnel at the Yangjiang Hydropower Station are 8.0 and 11.08 MPa, respectively. The maximum internal diameter of the main tunnel is 7.5 m, and the PD value is 8310 t/m. The bedrock is Yanshanian Granite with good rock integrity. Because of the complexity of this high-pressure structure, the traditional formula and the equivalent numerical method cannot reflect the lining crack width and hence cannot evaluate the stability of the lining under the action of high external water load.

2.2. Numerical model

The FLAC³D program and hexahedral grid solid elements are used to simulate surrounding rock and lining. To improve accuracy and control convergence time, the grid-mapping method is mainly used for mesh generation. Considering the reduction of rock resistance and water infiltration along the cracks, soft cushion is set between the surrounding rock and the lining. Cable structure elements are used to simulate the circumferential reinforcement, and the combined bearing effect is calculated from the relative sliding of the reinforcement and concrete at cracks. The end of the bolt is inserted into the lining to effectively control the pressure stress acting on the outer boundary of the structure, so that the lining will not be damaged under external water pressure. To simulate the actual conditions of opening and closing of lining cracks, the interface is designed in the main tunnel at side wall, vault, and invert positions. The three-dimensional (3D) numerical model of the high pressure tunnel is shown in Figure 1.

![Figure 1. 3D model of high-pressure tunnel.](image-url)
2.3. Calculation parameters
The high pressure tunnel is located in slightly weathered granite at ideal engineering geological conditions, so the M-C criterion is applied in the 3D model. The lining is made of C30 concrete with a thickness of 800–2250 mm and a Q235 threaded steel bar with a diameter of 25 mm. The physical and mechanical parameters of materials are shown in Table 1.

Table 1. Physical and mechanical parameters of materials.

| Material     | Modulus of elasticity/GPa | Poisson's ratio | Compressive strength/MPa | Tensile strength/MPa | Cohesion /MPa | Friction angle/° |
|--------------|---------------------------|-----------------|--------------------------|----------------------|---------------|-----------------|
| Rock         | 20                        | 0.18            | -                        | 1.0                  | 5             | 1.0             |
| Concrete     | 30                        | 0.20            | 17.5                     | 1.75                 | 0.5           | 1.75            |
| Steel bar    | 200                       | 0.30            | 325.0                    | 325.0                | -             | 325.0           |
| Anchor bolt  | 200                       | 0.35            | 300.0                    | 300.0                | -             | 300.0           |

3. Process of lining cracking
To study the internal water pressure level of lining cracking in the first filling process of a typical cross-section, pressure of 0–8.0 MPa is applied accordingly. Normal slip in the interface can be taken as the criterion of lining concrete cracking. Figure 2 indicates that during the first filling of a typical section, when the internal water pressure increases to 2.8 MPa, the lining cracks initially form, and when the pressure continues to increase to 4.0 MPa, lining structure cracks propagate throughout.

![Figure 2. Process of lining cracking.](image)

Based on the numerical results of the first filling, the hydrodynamic pressure load (11 MPa) on the inner boundary of the high pressure tunnel is relieved. By gradually reducing the internal water pressure to 8, 4, 2, and 0 MPa, the first filling and drainage comparative analysis of typical sections is shown in Figure 3. During the venting period, with the decrease in the internal water pressure level, the lining cracks gradually closes. The crack width and reinforcement stress, however, are higher than that during the water filling period under the same internal water pressure level. This is mainly because the lining is separated from the surrounding rock during the venting period, and the pressure difference between the inside and outside of the lining increases after the dynamic water load is applied, which limits the crack closure speed to a certain extent.

![Figure 3. Comparative analysis of typical sections.](image)
4. Variation characteristics of lining crack width
The effect of reinforcement ratio, reinforcement location, tunnel radius, and surrounding rock on the crack width of lining is studied by numerical simulation. The distance between the circumferential reinforcement and lining edge is 10 cm, lining thickness is 80 cm, and tunnel radius is 3.75 m. The internal water pressure applied during the operation of the hydraulic tunnel is 8 MPa. The control variable method is applied to analyze the design parameters.

4.1. Reinforcement ratio and crack width
According to the actual hydraulic tunnel engineering situation, the reinforcement ratio of lining is generally 1%–2%. Therefore, φ 22, φ 25, φ 28, φ 30, and φ 32 reinforcements are selected to study the crack development under different reinforcement ratios. The distribution curve of crack width along the horizontal direction is shown in Figure 4. The maximum width of the crack appears on the lining surface, and the crack width along the horizontal direction exhibits larger values in the middle and small values at both ends. The effect of internal and external reinforcement on the crack can be clearly observed. Under 8 MPa internal water pressure, the steel bar is at full tension, and the stress of the steel bar at the crack position is maximum. The maximum crack width decreases from 0.35 to 0.25 mm with the increase in the reinforcement ratio.

4.2. Reinforcement position and crack width
The distance between the internal and external circumferential reinforcement and the lining edge are set as 10, 12, 14, 16, and 18 cm in the numerical models, respectively. The simulation results are shown in Figure 5. With the decrease in the distance between the internal and external circumferential reinforcement, the crack width in the lining decreases from 0.31 to 0.28 mm. By contrast, the crack width on the edge of lining gradually increases from 0.22 to 0.32 mm. The spacing of reinforcement has a strong effect on the width of internal cracks. Thus, the optimum constraint for the whole lining can be found according to the reinforcement position.

4.3. Tunnel radius and crack width
To meet the needs of hydraulic design, the radius of high pressure tunnels varies greatly from 1.5 to 3.75 m. Therefore, tunnel radius is selected as a design parameter to study its effect on lining cracking, and the calculation results are shown in Figure 6. Although the tunnel radius varies, the thickness of lining, reinforcement ratio, thickness of protective layer, and spacing of reinforcement are almost unchanged. Hence, its effect on crack width is small.

4.4. Surrounding rock and crack width
The crack width for different types of surrounding rock is studied, and the distribution curve of crack width along the horizontal direction is shown in Figure 7. With the decrease in the deformation modulus of surrounding rock from 28 to 4 GPa, the maximum crack width of lining increases greatly, and the tensile stress of the internal and external reinforcement of lining also increases. This shows that the surrounding rock has an obvious restraining effect on the lining cracks.

![Figure 6. Relationship between tunnel radius and crack width.](image)

![Figure 7. Relationship between surrounding rock and crack width.](image)

5. Effect of parameter randomness on crack width

A large number of engineering practice studies have shown that it is difficult to maintain ideal state during actual tunnel construction; therefore, the lining parameters are often random. In the process of tunnel lining construction, many uncertain factors, such as the physical properties of structural materials, geometric parameters, and variability of load, exist and are usually treated as variables.

To deal with randomness in lining parameters, the random numbers of uniform distribution from 0 to 1 are adopted as shown in Figure 8. The elastic moduli of elements with a random number less than 0.3 are assigned as 1000, 500, 100, 50, and 10 MPa, respectively. Elements with a random number greater than 0.3 and less than 0.7 are assigned to 15 GPa, and those with a random number greater than 0.7 are assigned to 30 GPa.

The distribution of crack width under different lining parameters is shown in Figure 9. The distribution for lining with random parameters differs slightly from that for the ordinary lining. The crack width of ordinary lining has a strip distribution, while the random parameter distribution shows irregular weakness. The random distribution of the elastic modulus affects the distribution law of the crack width locally but has no obvious effect on the overall crack width of the lining.

![Figure 8. Parameter randomness of lining. (Unit: Pa)](image)

![Figure 9. Crack width at different lining parameters. (Unit: Pa)](image)

6. Conclusions
Based on the case study, the influencing factors of lining crack width for hydraulic tunnels under high internal water pressure were analyzed. The results indicate that the ratio of circumferential reinforcement and the surrounding rock deformation modulus are clearly inversely related to the crack width, whereas the tunnel radius has little effect on it. To achieve the optimum constraint on the entire lining, it is necessary to select the appropriate reinforcement location. When the parameters are randomly distributed, the lining cracks appear locally mutated, but still form a strip distribution, with no obvious effect on the average crack width.

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References
[1] Bian K, Xiao M, Chen J. Study on coupled seepage and stress fields in the concrete lining of the underground pipe with high water pressure. Tunnelling & Underground Space Technology, 2009, 24(3):287-295
[2] Pachoud A J, Schleiss A J. Stresses and Displacements in Steel-Lined Pressure Tunnels and Shafts in Anisotropic Rock Under Quasi-Static Internal Water Pressure. Rock Mechanics and Rock Engineering, 2016, 49(4):1263-1287
[3] Fahimifar A, Soroush H. A theoretical approach for analysis of the interaction between grouted rockbolts and rock masses. Tunnelling & Underground Space Technology, 2005, 20: 333-343
[4] Simanjuntak T D Y F, Marence M, Mynett A E, et al. Pressure tunnels in non-uniform in situ stress conditions. Tunnelling & Underground Space Technology, 2014, 42(5):227-236
[5] Hou J, Hu M Y. Discussion on some problems in design of high-pressure tunnel for hydro projects. Journal of Hydraulic Engineering Shuili Xuebao, 2001, 7:36-40
[6] ACI Committee Institute. Building code requirements for structural concrete and commentary: ACI 318-11. Michigan: The American Concrete Institute, 2011
[7] Soltani A, Harries K A, Shahrooz B M. Crack Opening Behaviour of Concrete Reinforced with High Strength Reinforcing Steel. International Journal of Concrete Structures & Materials, 2013, 7(4):253-264
[8] Yang L, Hou J G. Simple analysis of design method of flexural crack control in American design standard of concrete structures ACI 318. Engineering Journal of Wuhan University, 2008, 7(41):61-64
[9] Barris C, Torres L, Vilanova I, et al. Experimental study on crack width and crack spacing for Glass-FRP reinforced concrete beams. Engineering Structures, 2017, 131:231-242
[10] Simanjuntak T D Y F, Marence M, Mynett A E, et al. Mechanical-hydraulic interaction in the lining cracking process of pressure tunnels. International Journal on Hydropower & Dams, 2013, 20(3):48-54
[11] Huang H W, Liu D J, Xue Y D, et al. Numerical analysis of cracking of tunnel linings based on extended finite element. Chinese Journal of Geotechnical Engineering, 2013, 35(2):266-275
[12] Zhang F, Wang S P, Zhang G F, Hu S K, Feng J L. Numerical modelling of cracking of tunnel lining by combined finite-discrete element method. Chinese Journal of Geotechnical Engineering, 2016, 38(1):83-90
[13] Bian K, Xiao M. Seepage-damage-stress coupling analysis of hydraulic tunnel lining in hydraulic fracturing process. Chinese Journal of Geotechnical Engineering, 2010, 29(S2):3769-3776