The Influence of the Variable Thickness of Prestressed Linings with Annular Anchors on its Mechanical Properties

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Abstract: By embedding annular anchors, prestressed linings with annular anchors provide active prestress, which can effectively resist the high internal water pressure in large-diameter hydraulic tunnels. The variable thickness of concrete liners along the circumference can significantly influence the mechanical properties of the lining. On the basis of the prestressed lining of a 6.8-m-diameter pressure tunnel in the Yinsong Diversion Project, we adopted a 3D numerical modeling method to study the influence of the average and local thicknesses of the lining on its mechanical properties. The results show that the prestress of the lining used in resisting the internal water pressure is ultimately derived from tensioning the annular anchors. The average thickness of the lining has little effect on its load-bearing capacity. In elliptical lining, an annulus of a slight tensile stress area appeared on the inner side of the lining, whereas the crown and invert sections will form the weak area because of structural bending moments.

1. Introduction

Recently, with the rapid development of underground engineering worldwide, a large number of large-diameter tunnels with high internal water pressure have emerged in multiple significant water diversion and hydropower projects [1, 2]. Under the action of high internal pressure, conventional reinforced concrete linings tend to easily crack [3]. It is difficult to weld on the outer side of the structure using the steel plate-reinforced concrete lining, often leading to insufficient durability [4]. High-pressure grouting linings require the surrounding rock mass to provide the full reaction force for applying prestress [5], which is rigorous with the strengthen of rock and the thickness of overburden. Therefore, it is a huge challenge to cope with the problem of the lining in large-diameter tunnels experiencing poor rock quality, thin overburden, and high internal pressure.

Hereinafter, reinforced concrete linings prestressed with annular anchors are referred to as annular anchors lining. Annular anchors exert a circumferential tension within the reinforced concrete lining, which is converted into the radially inward prestress of the lining through the “hoop effect,” and it can effectively resist the internal water pressure [6]. Presently, annular anchors linings have been successfully applied in the Crimsel Tailrace surge shaft in Switzerland [7], the Italian Presenzano pressure tunnel [8], the Xiaolangdi desilting pressure tunnel [9], and the Songhua long-distance water diversion tunnel in Jilin province [10].
The prestressed anchors embedded in the lining are encircled by the one-layer and two-hoop ways to reduce the lining thickness [11]. A thinner lining can both decrease the construction cost and increase the cross-sectional area of water conveyance to promote the operational efficiency of a tunnel. Because annular prestressed anchors are tied to the inner side of non-prestressed steel bar, the quality of the cast-in-situ concrete will be affected if the lining thickness is rather reduced [12]. Previously, studies demonstrated that the circumferential compressive stress in the lining will decrease as the lining thickness increases during the tensioning of annual anchors, which indicates that the thinner the lining, the more obvious the prestressing effect [13]. However, with the reduction of lining thickness, the circumferential tensile stress because of the internal water pressure will correspondingly increase. Moreover, the overbreak of tunnel sides generally occurred to meet the traffic demand and the passage of the second-lined steel bar trolley, which will change the lining shape from a circle to an ellipse. To date, the influence of lining shape change on the mechanical properties of annual anchors linings has not been studied.

This study focuses on investigating the stress variation of the lining with an average thickness of 45, 50, 55, and 60 cm during construction and operation period through a 3D numerical modeling method. Furthermore, we discussed the stress spatial distribution characteristics and the weak loading area of the lining with elliptical casting section. Moreover, we studied the influence of lining thickness on its mechanical properties.

2. Practical project and numerical model

2.1. Project background

The Yinsong Diversion Project is a large-scale long-distance water transfer project addressing the urban water supply problem in northeast China. The total length of the water transmission line is 263.45 km. Pressure tunnels are adopted to promote the efficiency of long-distance water delivery. The overburden depth of the tunnel in some sections is quite low, and the minimum of that is only 11.8 m. The surrounding rock mass is heavily weathered tuff of poor quality with grade V. The initial in-situ stress is only ~0.23 MPa, whereas the maximum internal water pressure is 0.60 MPa. Under the action of internal water pressure, the shallowly buried section of 14.678 km cannot meet the minimum principal stress criterion and the minimum overburden criterion. Conventional reinforced concrete linings do not apply to this project because of larger plastic deformation of surrounding rock mass and possible cracking failure of the lining. To resist high internal water pressure, we proposed a new type of prestressed lining with annual anchors. To clarify the mechanical characteristics of the lining under the action of high internal water pressure and ensure the safety of the structure, we performed a study about the influence of cast-in-situ thickness on the mechanical properties of the annual anchors lining.

2.2. Numerical model

Figure 1 shows the numerical model of the prestressed lining with unbonded annular anchors. To simulate the force transmission process of annular anchors, we used the combination method of equivalent load and solid modeling. On the basis of the mechanical properties of annular anchors in the concrete lining, the stress of annular anchors is divided into a constant prestress component and a variable non-prestressed component. The equivalent normal load is used to simulate the constant prestress after the annular anchors are anchored, whereas the solid model is loaded passively to simulate the variable non-prestressed of anchor. The stress and strain of annular anchors in different tensioning stages are calculated using the load superposition principle.

The grade of concrete is C40 of the section of the annular anchors lining. The internal diameter is 6.8 m. The prestressed annular anchors are wrapped by a single-layer double-circle method with a spacing of 0.5 m. The standard value of the tensile strength is 1860 MPa, the friction coefficient of the steel strand is 0.032, and the swing coefficient is 0.0007. The anchorage block-out is set at the 45° left and right lower sides of the lining, and its length, width, and depth are 1.20, 0.20, and 0.20 m, respectively. Because of the complexity of the model and a large number of elements, if the seepage force applies...
the external water load, the model will slowly converge during the numerical calculation process. Therefore, the external water pressure is applied by the equivalent force on the surface.

![Figure 1](image_url)

**Figure 1.** The numerical model of the prestressed lining with annular anchors in pressure tunnel: (a) integral model, (b) lining with annular anchors, (c) circular cross-section, and (d) elliptical cross-section.

2.3. *Calculation parameters*

The major surrounding rock is weathered tuff with grade V. Table 1 lists the physical and mechanical parameters of materials.

| Material       | Modulus of elasticity (GPa) | Poisson’s ratio | Density (kg/m³) | Grade | Cohesion (MPa) | Friction angle (°) |
|----------------|-----------------------------|-----------------|-----------------|-------|----------------|-------------------|
| Tuff           | 0.9                         | 0.18            | 2500            | V     | 0.1            | 10                |
| Concrete       | 40                          | 0.35            | 2650            | C40   | -              | -                 |
3. The influence of the average thickness of lining on its mechanical properties

With a 50-cm thickness, the minimum principal stress and maximum principal stress of the lining after tensioning is shown in Figure 2. In addition to the anchorage block-out, the overall prestressing effect of the lining is uniform. The primary circumferential prestress is between 3.0 and 4.5 MPa. The prestress on the surface of the left and right side walls of the lining is slightly larger between 4.5 and 5.5 MPa.

Figure 2. Stress distribution of the lining with a 50-cm thickness (unit: Pa): (a) minimum principal stress and (b) maximum principal stress.

As shown in Figure 3, the prestress gradually increases as the thickness of the lining decreases. If the thickness decreases by 5 cm, the overall prestress increases by 0.3–0.5 MPa. The prestress distribution pattern remains basically consistent with the change of the lining thickness. Overall prestressed distribution is that the maximum prestress is at the sidewall and that of the vault is slightly lower.

Figure 3. Prestress circumferential distribution of the lining with different thickness after tensioning (unit: MPa): (a) minimum principal stress and (b) maximum principal stress.
Because of the setting of the tension block-out, there is local prestress loss at the 45° left and right lower sides of the lining. Moreover, the load status close to the tension block-out is complicated. The tensile stress area of the lining distributes close to the circumferential free surface of the tension block-out, whereas the maximum compressive stress area distributes at the section between the adjacent tension block-outs. With 50-cm lining thickness, after annular anchors tensioning, the maximum compressive stress near the anchorage block-out is 7.16 MPa and the maximum tensile stress is 1.13 MPa. With 55-cm lining thickness, after annular anchors tensioning, the maximum compressive stress near the anchorage block-out is 6.45 MPa and the maximum tensile stress is 1.08 MPa. As shown in Figure 4, the tensile stress area of the lining is mainly distributed close to the circumferential free surface of the anchorage block-out, and the maximum compressive stress area is distributed at the section between the adjacent anchorage block-outs. The lining thickness has little effect on the stress of the lining concrete close to the anchorage block-out.

![Figure 4. Prestress circumferential distribution of the anchorage block-out with different lining thickness after tensioning (unit: MPa): (a) minimum principal stress and (b) maximum principal stress.](image)

4. The influence of local thickness changes of the lining on its mechanical properties

To meet the traffic demand during the construction and the passage of the second-lined steel bar trolley, we ensured that the over-excavation is larger in the horizontal direction of the hance of local tunnel segments. Steel bars and annular anchors are installed as an ellipse. The thickness of the protective layer of reinforcing steel on the inner side of the lining increases from 5 to 34 cm. It is significant to clarify the influence of such variation on the mechanical properties of the lining.

4.1. Comparison of minimum principle stress of the lining after tensioning

Stress within annular anchors lining will redistribute with the action of tensioning. From the contour of compressive stress in Figures 5 and 6, the compressive stress distribution characteristics of the structure are distinct with the local thickness changing.

As the lining thickens, the overall prestress of the lining reduces. The average prestress are 5.5 and 4.3 MPa for the circular lining and elliptical lining, respectively. The difference between the two values is 1.2 MPa, i.e., ~21.8%. At the largest thickness section of the lining on both sides, the prestress is 5.3 MPa for the circular lining and 3.9 MPa for the elliptical lining. The difference between the two values is ~26.4%.
Figure 5. Minimum principal stress of the lining after tensioning (unit: Pa): (a) circular cross-section and (b) elliptical cross-section.

The prestress at the crown and invert of the circular lining distributes uniformly. Because of the different thickness, the elliptical lining leads to the axial pressure and bending moments on the structure. The stress concentration exists at the crown and invert of the lining. The concrete at the invert of the lining is dense, and the structure is relatively safe. The crown of lining must be dense through the backfill grouting or consolidation grouting; otherwise, the crown section may develop into a potential damage area.

The stress near the anchorage block-out is often uneven. As the lining thickening, the uneven degree of the stress near the anchorage block-out of the elliptical lining decreases. Therefore, changes in the thickness of the lining will not harm the safety of the anchorage block-out and its nearby concrete.
Figure 6. Minimum principal stress of the lining near the anchorage block-out after tensioning (unit: Pa): (a) circular cross-section and (b) elliptical cross-section.

4.2. Comparison of maximum principle stress of the lining after tensioning

After annular anchors being tensioned, the evaluation of lining quality is considerably dependent on its prestressing status. Moreover, tension strength value and distribution characteristics of the concrete of the lining are very important. The tensile stress of the concrete must be less than the allowable value. Figure 7 shows the maximum principle stress distribution. The lining is under compression integrally. In addition to the section of annular anchors, there is rarely a tensile stress zone in the circular lining and elliptical lining. At the larger thickness section of the elliptical lining, there is an annulus (blue in Figure 7b) in the middle, all of which is compression stress. There is no tensile stress area and the structure is safe. However, the crown and invert of the elliptical lining exist slight tensile stress (0–0.4 MPa), which is consistent with the above compressive stress analysis results. This indicates that the crown and invert section are still adverse areas.
Figure 7. Maximum principal stress of the lining after tensioning (unit: Pa): (a) circular cross-section and (b) elliptical cross-section.

4.3. Safety of the lining after applying internal water pressure

After applying internal water pressure, the compressive stress of the lining concrete gradually decreases, whereas the tensile stress correspondingly increases. The stress state of the prestressed lining has significantly changed. The major distinction between the circular lining and elliptical lining is that, under the internal water pressure, the overall prestress margin of the circular lining is 1.30 MPa, which indicates that the circular lining is safe. When the elliptical lining is only 0.35 MPa, it indicates that the elliptical lining is less safe than the circular lining.

After applying internal water pressure, the overall maximum tensile stress is 0.2 MPa for the circular lining and 0.45 MPa for the elliptical one. There is no large tensile stress zone for both of them, and no obvious damage is reported in the elliptical lining. The non-central symmetry of the structure leads to the bending moment in the elliptical lining and a tensile stress of 1.0 MPa on the inner side. Cracks are more prone to occur on the surface of the elliptical lining, which has a potentially adverse effect on the durability of the structure.

5. Conclusions

Along with a practical project, we studied the influence of variable thickness of prestressed annular anchors lining on its mechanical properties. The main conclusions are as follows. (1) Annular anchors linings generate the circumferential tensile stress by the annular anchors pre-buried inside it, which can resist internal water pressure and prevent it from cracking. (2) The prestress of the lining used to resist internal water pressure is ultimately derived from tensioning the annular anchors; the average thickness of the lining has little effect on its load-bearing capacity. (3) In the elliptical lining, an annulus of a slight tensile stress area appeared on the inner side of the lining, and the crown and invert sections will form the weak area because of the structural bending moments.

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