Numerical Modeling Method and Experimental Verification of Prestressed Lining with Unbonded Annular Anchors

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Abstract. Prestressed lining with unbonded annular anchors is a new type of lining used in hydraulic pressure tunnels. First, the key points of numerical modeling are analyzed based on the stress characteristics of the lining. Thus, the corresponding modeling methods are proposed: the contact relationship is set to simulate the different constraint effects of surrounding rock on the lining, the equivalent load and solid model are superposed to simulate the changing prestress state of anchors, and the nonlinear distribution of prestress loss is simulated by applying the gradient load in sections. Finally, based on the finite-difference software FLAC3D, the modeling analysis of Xiaolangdi pressure silt-releasing tunnel in an engineering case is conducted to verify the correctness of the modeling method presented in this study. The research shows that the new modeling method has a clear principle, fast modeling, and reliable results, which is of guiding significance to structure design.

1. Introduction

It is difficult to design the prestressed lining-engineering structure due to the complexity of the structure, the unclear mechanical mechanism of interaction between the surrounding rock, the lining, and the pressurized water, as well as lack of practical design specification since it is a new type of hydraulic structure. The asymmetric distribution of structural-mechanics model due to friction loss in the prestressed system makes it difficult to analyze stress and strain using an analytical method, especially the constraints of surrounding rock on the lining, the mechanical properties of unbonded annular-anchor change, including the difficulty in analyzing the prestress loss nonlinear distribution; therefore, we need numerical simulations to understand the mechanical characteristics of prestressed lining with unbonded annular anchors.

Constraint on lining by surrounding rock is variable, and the contact relationship between the surrounding rock and lining, in pressure tunnels, appears a recurrent alternation of fitting and connections during the construction, operation and maintenance period. The unbonded post-tensioned prestressed-steel strand is embedded in the smooth grease-coated PE pipe, and the unbonded annular anchor is not integrated with concrete casting. Therefore, the steel strand and surrounding concrete cannot meet the conditions of coordinated deformation. The structural elements (e.g., Link and Beam elements in ANSYS, Beam elements in ABAQUS, Beam or Pile elements in FLAC3D, etc.) built-in existing numerical software to simulate the mechanical properties of bonded annular anchors do not apply to unbonded annular anchors. The prestress loss of annular anchor is an important factor that affects the overall prestress effect of lining concrete and also relates to the value of prestressing at the tensioning end.
This study focuses on the structural–mechanical properties and the corresponding numerical modeling mechanism of lining, as well as the numerical modeling and calculation method. Based on the finite-difference software, FLaC3D, and using the prestressed annular-anchor linings of the Xiaolangdi Project as engineering cases, the mechanical characteristics of prestressed lining with unbonded annular anchors are analyzed, and the results of the calculations are compared with the monitoring data to verify the correctness of the numerical modeling method.

2. Numerical simulation method for prestressed annular-anchor lining

2.1. Constraint on lining by surrounding rock

Various states of constraint on lining by a surrounding rock can be simulated by establishing reasonable contact relationships, and the contact-surface properties can be established using the Coulomb shear strength criterion. Fig. 1 is the schematic of the elementary principle of the constitutive model of the contact surface. The contact surfaces have properties, such as sticking close to each other, sliding toward each other, and disconnecting from each other; the contact force is transmitted through nodes.

The state of the contact surface is determined according to the strength criterion. The tangential force $\tau_{\text{max}}$ required for the contact surface to slide is

$$\tau_{\text{max}} = c_y A \tan \phi_y \left( \sigma_n - PA \right)$$

(1)

Where $c_y$ is the cohesion of contact surface; $\phi_y$ is the friction angle of contact surface; $A$ is the representative area of contact-surface nodes; $\sigma_n$ is the substantive normal stress on the boundary surface; $P$ is pore water pressure.

The normal shear deformation increases effective normal stress, and the normal force $\sigma_{\text{max}}$ required for the contact surface to disengage is

$$\sigma_{\text{max}} = \sigma_n + \frac{\tau_s - \tau_{\text{max}}}{A k_s} k_s \tan \psi_y$$

(2)

Where $\tau_s$ is the initial shear force value of the boundary surface entity; $k_s$ is normal stiffness; $k_s$ is shear stiffness; $\psi_y$ is the dilatancy angle of the contact surface.

![Components of the bonded interface constitutive model](image1.jpg)

Fig. 1. Components of the bonded interface constitutive model.

2.2. Mechanical properties of unbonded annular anchors

The joint method of equivalent load and solid modeling is used to simulate the force transmission of the unbonded prestressed annular anchor. According to the mechanical characteristics of the unbonded prestressed-anchor cable in the concrete lining, the annular-anchor stress is divided into constant prestressed and variable nonprestressed components.

During numerical modeling, the interface property is established on the interface between the annular anchor and the concrete to simulate the friction and slip relationship between the steel strand and the casing. Then, as shown in Fig. 2, equal normal and tangential loads are used to simulate the unchanged prestress after the annular anchor is fixed, whereas the solid model is used to simulate the changing
nonprestress of the annular anchor. Finally, the stress and strain states of annular anchors in different engineering stages are calculated using the superposition of forces.

![Equivalent load](image1)

**Fig. 2.** Schematic of unbonded annular anchors load in MUAA lining.

### 2.3. Nonlinear distribution of prestress loss

The outer annular of the anchor cable is a closed circle, and the inner annular includes large arcs, small arcs, and straight lines. According to the geometric dimensions in the figure, the friction loss-distribution coefficient is calculated using Equation (3). After the prestress value is reduced by $\sigma_2 - \sigma_1$, the continuous actual prestress and corresponding equivalent load values can be calculated using the friction loss-distribution coefficient. Then, the nonlinear equivalent normal and tangential load are applied to the nodes of the annular-anchor model according to the gradient law using a programming language.

$$
\beta_i = \begin{cases} 
0 & R\theta_i \leq L_f \\
\frac{e^{-(2\theta_i + \mu\theta_i) - 2L_f(\mu + k)(1 - \frac{R\theta_i}{L_f})}}{e^{-(2\theta_i + \mu\theta_i)}} & R\theta_i > L_f
\end{cases}
$$

(3)

Where, $k$ and $\mu$ are the friction and deviation coefficient of the anchor cable, determined by the field friction test, respectively; $\beta_1$ and $\beta_2$ are the distribution coefficient of friction loss of the first and second annular of anchor cable; $\theta_1$ and $\theta_2$ are the angle between the calculated section and tensioning end of the first and second annular of anchor cables; $L_f$ is the influence range of anchorage retraction.

### 3. Numerical calculation scheme and modeling

During the operation period, the maximum inner water head of the prestressed lining tunnel of the mainline is 66 m, and the minimum overburden thickness, above the vault of local tunnel sections, is low. The prestressed lining test section uses C40 concrete, with a 3.45-m inner radius and 0.45-m wall thickness. The elastic modulus of the concrete is set as $E_c = 3.25 \times 10^4$ MPa, Poisson's ratio $\mu = 0.167$, and the design value of axial tensile strength $f_t = 19.5$ MPa; the design value of axial tensile strength $f_i = 1.80$ MPa; concrete deadweight (lining dead weight) is set as 2400 kg/m$^3$, which means that $\gamma_c = 23.52$ kN/m$^3$.

In the numerical calculation, considering the complexity of the model and several elements, if the external water load is applied according to the seepage force, the convergence rate of the model calculation will be reduced; the external water pressure is low (the buried depth is low). Therefore, the external water pressure is loaded using equivalent surface force. The physical and mechanical parameters of the model are calculated based on the results of indoor and field tests.

In numerical modeling, the hexahedral grid solid elements, subject to linear elasticity criterion, are
used for lining; the hexahedral grid solid elements, subject to Mohr–Coulomb elastoplastic criterion, are
used for the surrounding rock; the "solid + equivalent load + contact surface" model is used for
prestressed annular anchor, and the Shell model is used for nonprestressed tendon. The interface
properties, which are subject to Mohr's yield criterion are set between the lining and the surrounding
rock to simulate their state of clinging to each other, sliding toward each other, and disconnecting from
each other. The three-dimensional numerical model of the annular-anchor lining is shown in Fig. 3.

4. Mechanical properties of prestressed annular-anchor lining

4.1. Overall prestressing effect of annular-anchor lining
The minimum and maximum principal stresses of the annular-anchor lining after tensioning are shown
in Fig. 4. The overall prestress effect of the lining is uniform after the annular-anchor lining is tensioned,
except for the anchorage block-out part, and the main annular prestress value is between 3.0 and 4.5
MPa. The prestress values of the surface parts, on the left and right-side walls of the lining, are larger
(between 4.5 and 5.5 MPa).

4.2. Lining prestressing effect of anchorage block-out
The difference in lining stress calculated using the four kinds of numerical software is small. The
maximum value was 20.48 MPa using FLAC3D, the minimum value was 17.23 MPa using ANSYS,
and the difference between them is about 15% (Fig. 5), which indicates that the calculation accuracy
can meet the engineering application requirement.
5. Verification of annular-anchor lining prestressing effect

From the comparison diagram (Fig. 6) of the prestressing values between the monitoring data of the annular-anchor lining and the numerical simulation results, we can see that the numerical calculation results are consistent with the measured data in terms of lining prestress distribution regularity. Toward the lining thickness, the prestress value decreases from both sides to the top and bottom. Except for the stress concentration in the concrete near the anchorage block-out, the overall prestress distribution is uniform.

We use strain gauges to monitor the stress in the concrete around the anchorage block-outs, and the Surfer program to draw the stress contour map. The numerical calculation results are consistent with the rules of the basic response of field monitoring. The anchorage block-out and its surrounding area are weak areas of prestressing effect, and the prestressing values at both ends of the anchorage block-out...
length direction (tensioning and anchoring end) are low. The weak lining areas are distributed near the free face of the circumferential anchorage block-out, and areas with the largest lining pressure are distributed between adjacent anchorage block-outs. The maximum compressive stress value calculated using the numerical method is 7.85 MPa, and the field-monitoring value is 8.21 MPa. The stress-state regularities of the anchorage block-outs are consistent.

6. Conclusions
Based on the finite-difference software FLAC3D, the modeling analysis of Xiaolangdi pressure silt-releasing tunnel, as an engineering case, is conducted to verify the correctness of the modeling method presented in this study. Setting the contact relationship to simulate different constraint functions of surrounding rocks on the lining, using the superposition method of equivalent load and the entity model to simulate the changing prestressed state of the anchor cable, and applying the gradient load in sections to simulate the nonlinear distribution of prestress loss, is clear in calculation principle, fast in modeling, and reliable in results.

7. References
[1] 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
[2] Pi, J., Wang, X. G., Cao, R. L., Zhao, Y. F., Hung, X. Innovative loading system for applying internal pressure to a test model of prestressed concrete lining in pressure tunnels. *Journal of Engineering Research*, 2018, 6(2):24-44
[3] Sadd, M.H. Elasticity, Theory, Applications, and Numeric. Academic Press, Oxford, 2009, pp. 172–174.
[4] Shen, F. S., Liu, X. Long and deep diversion tunnels of 1st stage project in west route of South-North Water Transfer Project. *Chinese Journal of Rock Mechanics and Engineering*, 2003, 22(9): 1527-1532
[5] Showkati, A., Maarefvand, P., Hassani, H. An analytical solution for stresses induced by a post-tensioned anchor in rocks containing two perpendicular joint sets. *Acta Geotechnica*, 2016, 11(2): 415-432
[6] Simanjuntak, T. D. Y. F., Marence, M., Schleiss, A. J., Mynett, A. E. The interplay of in situ stress ratio and transverse isotropy in the rock mass on prestressed concrete-lined pressure tunnels. *Rock Mechanics and Rock Engineering*, 2016, 49(11): 4371-4392
[7] Sulem, J., Panet, M., Guenot, A. An analytical solution for time-dependent displacements in a circular tunnel. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, 1987, 24(3):155-164
[8] Tate, E. L., Farquharson, F. A. K. Simulating reservoir management under the threat of sedimentation: the case of Tarbela dam on the river indus. *Water Resources Management*, 2000,14(3):191-208
[9] Zareifard, M R, Fahimifar, A. A simplified solution for stresses around lined pressure tunnels considering non-radial symmetrical seepage flow. *KSCE Journal of Civil Engineering*, 2016, 20(7): 2240-2654
[10] Zarghamee, M. S., Ojdrovic, R. P., Dana, W. R. Coating delamination by radial tension in prestressed concrete pipe. II: analysis. *Journal of Structural Engineering*, 1993,119 (9):2720-2732

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