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Numerical modeling of the water pressure influence on the mechanical behaviour of lining

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ABSTRACT: Groundwater exerts a continuous load on tunnel structures and has a critical impact on the mechanical behaviour of the tunnel lining. If not properly managed, this load may result in serious problems such as cracking, excessive deformation, or even collapse of the lining. Based on a review of commonly used methods for calculating water pressure in tunnels, this paper investigates the mechanical response of the tunnel lining under different water pressure scenarios using numerical modeling. The results indicate that water pressure has a significant influence on the mechanical behaviour of the lining.

1 INTRODUCTION

Water-rich zones with complex hydrogeological conditions are frequently encountered in tunneling projects.The water pressure exerted on the tunnel lining is a key factor affecting the tunnel's safety and long-term stability. Uncontrolled groundwater may cause seepage, deformation, or even structural failure of the lining, thereby compromising the tunnel's integrity and operational safety, and posing potential risks to transportation systems [1]. Therefore, effective groundwater control measures are essential throughout the entire tunnel lifecycle—not only to ensure structural safety during both construction and operation, but also to minimize adverse impacts on the surrounding hydrogeological environment [2].

The calculation of water pressure on tunnel linings is closely related to the adopted groundwater control strategy. In China, different sectors apply varying principles for groundwater management. In the highway and railway tunnel sectors [3,4], an integrated approach combining prevention, drainage, interception, and sealing is commonly adopted. This approach is tailored to site-specific geological conditions and considers factors such as the external hydrogeological environment, groundwater richness, and lining stress, aiming to develop a comprehensive waterproofing and drainage scheme. In contrast, metro tunnel projects prioritize a prevention-based groundwater control strategy to minimize impacts on urban hydrogeology [5]. These projects often utilize a combination of rigid and flexible waterproofing materials and adopt a multi-layered waterproofing design for enhanced protection. The overall waterproofing and drainage system of a tunnel typically comprises three key components: the rock mass grouting system, the waterproofing system, and the drainage system. In Europe, drainage design approaches are currently diverse and project-specific. Both drainage-dominated and full or partial waterproofing strategies are employed depending on the project requirements. For example, Germany—where the number of tunnels is relatively limited—often adopts a "fully sealed and non-drainage" design philosophy. In contrast, France generally favors drainage-based solutions [6]. In countries such as Norway, single-shell lining systems are widely used, incorporating drainage-based waterproofing systems and flexible waterproof membranes [7]. A comparative analysis of European practices reveals a general principle for tunnel groundwater control: in the absence of special environmental or structural constraints, tunnels in water-rich mountainous areas are preferably designed with drainage systems to reduce water pressure on the lining. However, in environmentally sensitive zones or where critical infrastructure is located above the tunnel, a fully sealed design capable of withstanding full hydrostatic pressure is adopted.

This paper first reviews commonly used methods for calculating groundwater pressure on tunnel linings and then investigates the mechanical behaviour of the tunnel lining under different water pressure conditions using numerical modeling.

2 WATER PRESSURE CONSIDERATIONS IN TUNNEL LINING DESIGN

In China, a variety of methods are employed to calculate groundwater pressure in tunnel design. However, the selection of a specific method typically depends on the waterproofing and drainage strategy adopted for the project. The three commonly used approaches for water pressure calculation are as follows:

(1) No Water Pressure Considered

For certain shallow-buried mountain tunnels in China, a full-drainage approach is commonly adopted, whereby all infiltrating groundwater is effectively discharged through the drainage system. In such cases, groundwater flows unobstructed, resulting in negligible pressure on the lining. Consequently, this design approach assumes that the water pressure acting on the tunnel lining can be ignored.

(2) Reduction Coefficient Method

In water-rich zones with significant overburden and relatively stable groundwater conditions, a semi-enclosed waterproofing scheme is often adopted. Due to the effect of seepage, the water pressure acting on the lining is lower than the full hydrostatic head. The water pressure reduction coefficient is defined as the ratio of the water pressure head acting on the lining to the vertical height of the groundwater column from the water table to the tunnel crown.

This method has been extensively studied in China, with various empirical and analytical formulas proposed for determining the reduction coefficient. In this study, a method derived from hydraulic tunnel design specifications is adopted. According to these specifications, the external water pressure can be represented by the pressure head below the calculated water level. The pressure head from the calculated water level to the tunnel invert equals the product of the total water column height and the corresponding reduction coefficient. Specifically, Zhang Youtian's correction factor method is employed in this paper. The external water pressure coefficient is determined using the following formula [8]: $\beta = \beta_1 \times \beta_2 \times \beta_3$. β_1 is the correction factor for water pressure in the initial seepage field. β_2 is the correction factor for external water pressure acting on the lining after tunnel completion. β_3 is the correction factor accounting for the influence of waterproofing and drainage measures on the external water pressure of the lining.

(3) Theoretical Analytical Method[9]

For tunnels located in water-rich regions, it is essential to account for the influence of rock mass grouting on water pressure and to evaluate the associated seepage inflow. The theoretical analytical method is typically employed to calculate both the external water pressure acting on the lining and the seepage quantity. This method assumes that the surrounding rock behaves as a homogeneous, isotropic, and continuous medium. Based on Darcy's law of seepage, the method derives the distribution of pore water pressure within the grouted zone and the area adjacent to the tunnel lining. Drawing on research related to water pressure distribution in high-pressure mountain tunnels, and following the theoretical analytical framework, the external water pressure on the lining is calculated using the following formula:

$$P_l = \gamma_w H_l = \frac{\gamma_w H_0 \ln \frac{r_l}{r_1}}{\ln \frac{r_l}{r_1} + \frac{K_l}{K_g} \ln \frac{r_g}{r_l} + \frac{K_l}{K_r} \ln \frac{H_0}{r_g}} \tag{1}$$

Where: P_l—Water pressure behind the lining, γ_w—Unit weight of water, H_l—Water head behind the lining, H_0—Static water head outside the tunnel lining, r_l—External radius of the lining, r_1—Internal radius of the lining, r_g—Radius of the grouting zone, K_l—Permeability coefficient of the lining, K_r —Permeability coefficient of the surrounding rock, K_g —Permeability coefficient of the grouting zone.

3 THE NUMERICAL MODEL

To investigate the influence of water pressure on the mechanical behaviour of tunnel linings, a case study was conducted using numerical modeling based on a single-track tunnel constructed with the New Austrian Tunneling Method (NATM). The tunnel has an overburden depth of approximately 120 meters, and the lining thickness is 0.45 meters. The groundwater table is located 70 meters above the tunnel crown, and the water pressure acting on the lining is calculated using the methodology described below.

The surrounding rock is modeled as an elastoplastic material, while the tunnel lining is represented by elastic beam elements. Geological investigations indicate that the tunnel primarily passes through Class IV surrounding rock. The lining structure is designed in accordance with relevant specifications for deep-buried tunnels in Class IV geological conditions. The reinforcement effect of grouting is simulated by increasing the deformation modulus of the surrounding rock.

The numerical modeling domain extends 40 meters radially in all directions from the tunnel periphery. The finite element model configuration and mesh discretization are shown in Figure 1, while the material properties and mechanical parameters are summarized in Tables 1 and 2.

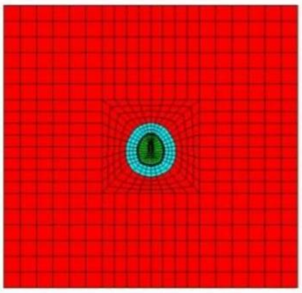


Figure 1. Computational model

Table 1 The calculating parameters of wall rock

Grade IV Rock Mass Parameters					Water Parameters		
Unit Weight (kN/m^3)	Deformation Modulus (GPa)	Poisson's Ratio	Internal Friction Angle (Degree)	Cohesion (MPa)	Unit Weight (Kg/m^3)	Tensile Strength (MPa)	Bulk Modulus (MPa)
20	3	0.3	30	0.4	1000	0	2x10^3

Table 2 The calculating parameters of concrete

Lining Concrete	Deformation Modulus GPa	Ultimate Compressive Strength Ra/MPa	Ultimate Flexural Strength Rw/MPa	Ultimate Tensile Strength R1/MPa	Poisson's Ratio	Unit Weight (kN/m3)
C35	1	26	32.5	2.45	0.2	25

Three water pressure conditions are considered in the numerical modeling: (1) no water pressure, (2) partial water pressure based on a reduction coefficient, and (3) theoretical water pressure derived from analytical methods. Following the numerical simulation, the mechanical response at key locations of the tunnel lining is analyzed. A schematic diagram illustrating these key locations is provided in Figure 2.

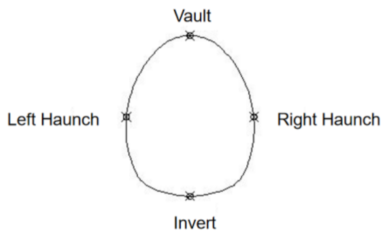


Figure 2. Location of key points on the tunnel lining

4 THE MODELING RESULTS

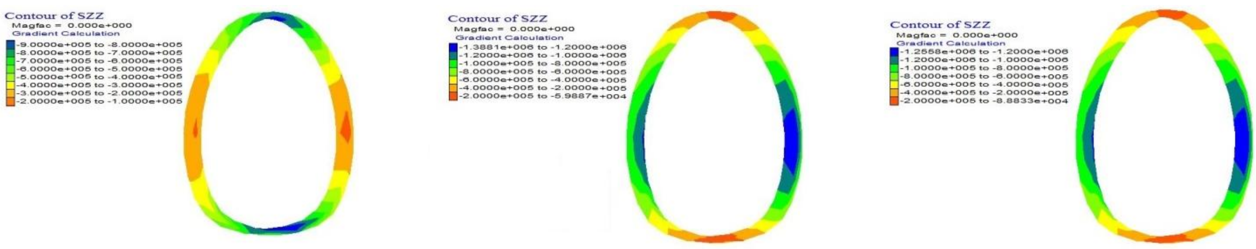
The numerical modeling results are discussed below.

(1) Stress Analysis

Stress contour plots of the tunnel lining under the three different water pressure calculation methods are shown in Figure 3. From the analysis of these plots, the following observations are made: Without considering water pressure, the maximum lining stress occurs at the tunnel crown, with a peak value of 0.9 MPa. Under the reduction coefficient method, the maximum stress shifts to the haunches on both sides of the tunnel, reaching 1.3 MPa. Using the theoretical analytical method, the maximum stress is also located at the haunches, with a value of 1.25 MPa.

Comparing the stress contours across the three scenarios reveals a distinct shift in the location of maximum stress: Without water pressure, the crown bears the maximum stress. When water pressure is considered (either via the reduction coefficient or theoretical analytical methods), stress concentration moves to the haunch regions on both sides.

This change in stress distribution is attributed to the multidirectional influence of groundwater pressure acting after tunnel excavation. Given the tunnel's relatively high flattening ratio (i.e., vertical height greater than horizontal width), the lateral sections of the lining—particularly the haunches—experience increased stress due to the greater horizontal component of the water pressure.



No Water Pressure Reduction Coefficient Theoretical Analytical

Figure 3. Lining stress of different working conditions

(2) Structural Force Analysis

Stress components in all directions were extracted at key locations on the tunnel lining to calculate the bending moments and axial forces at the crown, haunch, and invert. The results are summarized in Tables 3 and 4.

Table 3 The axial force of lining (KN)

	Vault	Left Haunch	Right Haunch	Invert
No Water Pressure	410.34	163.53	163.53	437.79
Theoretical Analytical	460.58	187.95	187.95	511.48
Reduction Coefficient	536.47	235.78	235.78	567.45

Table 4 The moment force of lining (KN·M)

	Vault	Left Haunch	Right Haunch	Invert
No Water Pressure	645.38	327.56	327.56	613.07
Theoretical Analytical	734.09	357.87	357.87	665.26
Reduction Coefficient	815.75	410.58	410.58	748.17

Analysis of Table 3 and Table 4 indicates that axial forces exhibit patterns similar to those of stresses: the No Water Pressure case yields the smallest values, followed by the Theoretical Analytical method, while the Reduction Coefficient method produces the largest axial forces. Compared to the No Water Pressure baseline, the Theoretical Analytical method shows increased axial forces at the corresponding locations: a 12.2% increase at the crown, 16.8% at the invert, and 14.9% at both haunches. Similarly, the Reduction Coefficient method demonstrates axial force increases relative to No Water Pressure of 30.7% at the crown, 29.6% at the invert, with the maximum increase of 44.2% occurring at both haunches.

Regarding bending moments, all three methods show maximum values at the invert. Both the Theoretical Analytical and Reduction Coefficient methods exhibit increased bending moments compared to No Water Pressure. At the crown, the Theoretical Analytical method increases bending moments by 13.75%, while the Reduction Coefficient method shows a 26.39% increase. At the invert, the Theoretical Analytical method shows an 8.5% increase and the Reduction Coefficient method a 22.04% increase.

(3) Displacement Analysis

Displacement data at key points of the tunnel lining were extracted, and the displacement values at each critical location are presented in Table 5 (with vertical displacement at the invert recorded as zero). Using the Reduction Coefficient method as an example, it is observed that the pattern of displacement variation differs from that of stress. The maximum displacement occurs at the crown, with a vertical settlement of 28.7 mm. At the haunches on both sides, the horizontal displacement is relatively small, measuring 13.6 mm. A comparative analysis reveals that at the haunches—where vertical stress is relatively high—the displacement is relatively low, whereas at the crown—where vertical stress is lower—the displacement is relatively higher. This phenomenon is attributed to the redistribution of internal forces caused by lining deformation, which alters the stress and displacement patterns.

The trend in displacement magnitudes across the three water pressure calculation methods aligns with that observed in the internal force analysis: The No Water Pressure case results in the smallest displacements. The Theoretical Analytical method yields moderate displacement values. The Reduction Coefficient method produces the largest displacements, indicating that this method predicts the greatest deformation of the tunnel lining. This further underscores the significant impact of water pressure assumptions on the structural response of tunnel linings.

Table 5 The displacement of lining

	Vertical Settlement at Vault	Horizontal Convergence at Haunches
No Water Pressure	18.2	8.3
Theoretical Analytical	22.1	10.3
Reduction Coefficient	28.7	13.6

Based on the characteristics of the tunnel section, burial depth, and case study calculations in this project, combined with the results from stress, structural force, and displacement analyses, a preliminary evaluation of the three groundwater pressure calculation methods is presented. From an overall perspective, the No Water Pressure method, which neglects the influence of groundwater pressure, results in the smallest stress and displacement values. The Theoretical Analytical and Reduction Coefficient methods yield relatively close results; however, the Reduction Coefficient method tends to produce slightly higher stress and displacement values than the Theoretical Analytical method. While conceptually clear, the Theoretical Analytical method has certain limitations. It relies on Darcy's law, which may not always be applicable, and requires simplification of the tunnel cross-section into an equivalent circular shape, limiting its practical accuracy in complex geometries. On the other hand, the Reduction Coefficient method is more commonly used by design engineers due to its simplicity. However, the reduction coefficient value exhibits significant variability and depends heavily on extensive statistical analysis of engineering cases. Currently, this method remains mostly confined to academic research without widely recognized regulatory guidelines.

5 CONCLUSION

This paper, based on an actual engineering case, analyzes the impact of three groundwater pressure calculation methods on the structural behavior of tunnel linings. In summary, the No Water Pressure method yields the lowest internal forces, while the Theoretical Analytical and Reduction Coefficient methods produce overall similar results. Each method has its own advantages and disadvantages: the Reduction Coefficient method is convenient for calculation but requires large datasets to accurately determine reduction parameters; the Theoretical Analytical method possesses a solid theoretical foundation but necessitates integration of field measurements and refinement of model assumptions to enhance its applicability.

For future groundwater pressure analyses, it is recommended to adopt a comprehensive approach that integrates multiple calculation methods and validates results against actual engineering projects. Such an approach will facilitate the development of water pressure calculation guidelines that balance safety and economy, thereby providing scientific support for tunnel design under complex hydrogeological conditions.

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