Journal of Research in Science and Engineering (JRSE)
ISSN: 1656-1996 Volume-6, Issue-11, November 2024
DOI: 10.53469/jrse.2024.06(11).10

# Analysis of Frost Heaving Force in Seasonal Frost Region Tunnels: A Case Study of the Xiangyang Tunnel in China

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**Abstract:** ***Frost damage in seasonally frozen regions is a primary factor affecting tunnel safety, with frost heaving forces being the main external cause. Therefore, analyzing and calculating the distribution and magnitude of frost heaving forces on surrounding rock is essential for addressing frost damage in tunnels. When the frost heaving force exceeds the design strength, it can lead to the cracking of the lining concrete and a reduction in the tunnel's load-bearing capacity and support stability, posing serious safety risks during construction and operation. This paper is based on the Xiangyang Tunnel project and is grounded in elasticity theory for deriving the frost heaving force formula. Utilizing the von Mises criterion, it employs finite element software to perform thermal-structural coupling analysis, which provides insights into the temperature distribution within the tunnel and the stress distribution patterns of both the lining and the surrounding rock under the influence of frost heaving forces. In the shallow-buried section of the Xiangyang Tunnel, the maximum frost heaving force on the lining is concentrated at the junction of the arch and the base slab. In the deeply buried sections, the distribution of the frost heaving force in the lining is relatively uniform. In contrast, the surrounding rock's frost heaving force distribution follows a layered pattern from the inside out. Beyond a burial depth of 7 meters, the lining and surrounding rock frost heaving forces gradually decrease, approaching a constant value.***

**Keywords:** Seasonal Frost Region Tunnel, Temperature Distribution, Frost Heaving Force, Numerical Simulation.

## 1. Introduction

Improving transportation networks requires constructing tunnel projects, as challenges such as mountainous terrain, hills, or unfavorable geological conditions (like landslide areas in canyons). However, globally, permafrost regions account for nearly 50% of the total land area, making it inevitable for many tunnels to be constructed in these frozen ground zones [1]-[2]. Due to significant seasonal temperature variations, many tunnels experience varying degrees of frost heave damage, lining cracking, spalling, and leakage during construction and operation, severely compromising tunnel stability [3]-[5], as illustrated in Figures 1 (a) (b). The frost heaving force, a primary external cause of damage in tunnels in seasonally frozen regions, is a critical issue in underground engineering [6], as illustrated in Figures 1 (c) (d). When pore water in the rock freezes into ice at low temperatures, it expands in volume, generating significant frost heaving forces that can damage the surrounding rock and lining structures. The frost heaving force, a primary external cause of damage in tunnels in seasonally frozen regions, is a critical issue in underground engineering. The frost heaving force, combined with repeated freeze-thaw cycles, exacerbates the deterioration of the surrounding rock, creating conditions that further facilitate the generation and development of frost heaving forces. Therefore, effectively analyzing the frost heaving forces in tunnels is of great significance for engineering construction, as it provides technical support for the structural design and safe construction of tunnels in seasonally frozen regions.

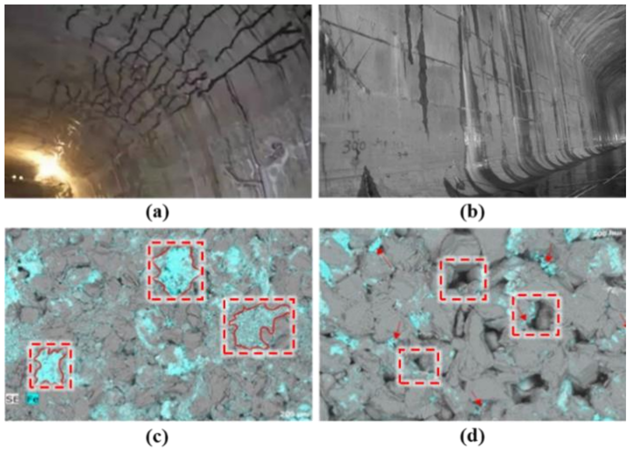

**Figure 1:** Schematic of tunnel damage

The frost heaving mechanism in tunnels in seasonally frozen regions is highly complex. Many researchers have conducted extensive studies on frost heaving forces in tunnels in recent years, yielding numerous valuable findings. In theoretical analysis, Lai developed a three-phase coupling mathematical model and differential equations, which, when applied to practical engineering, demonstrated that frost heaving forces significantly impact tunnel linings and should be considered in engineering design [7]. Lai further derived a viscoelastic analytical solution for frost heaving forces in tunnels. They simplified the surrounding rock's frost heaving force to an isotropic form, reducing computational complexity and providing new insights for frost heaving research [8]. Gao proposed an analytical solution for frost heaving forces that considers freeze-thaw (F-T) damage and the surrounding rock's transversely isotropic characteristics [9]. Feng divided the surrounding rock into four regions and established an elastoplastic computational model for the tunnel surrounding rock in cold regions. This model considers only the frost heaving forces during a single freeze-thaw cycle. However, frost heaving force calculations should consider multiple freeze-thaw cycles and the combined effects of various factors [10]. Liu examined the impact of freeze-thaw cycles on frost heaving forces. Nevertheless, the causes of frost heaving are complex, necessitating consideration of various factors influencing these forces [11]. In terms of numerical simulation, Qi employed numerical methods to analyze the influence of tunnel burial depth on the freeze-thaw extent. They concluded that the elastic modulus of the lining significantly affects the frost heaving forces [12].

This study establishes an analytical solution for frost heaving forces under various temperature fields, based on an elastoplastic computational model and a steady-state heat transfer model. A computational model was established based on existing engineering projects. Using ANSYS, a thermo-structural coupling analysis was conducted to determine the distribution of tunnel temperature fields, freezing depth, and characteristics and magnitudes of frost heaving forces under various temperatures and burial depths. A comparison analysis of theoretical results and actual test results was conducted, with differences falling within the acceptable error range. The design model developed in this study can serve as a reference for further research on temperature fields and frost heaving forces in tunnels in seasonally frozen regions, and it offers valuable insights into tunnel anti-frost design.

## 2. Analysis of the Frost Heaving Force Model

### 2.1 Fundamental Assumptions

To conduct an elastic analysis of the tunnel, the following assumptions are made:

(1) The tunnel is subjected to hydrostatic pressure, and its cross-section is simplified to a circular shape.

(2) The lining and surrounding rock are treated as isotropic elastic media, exhibiting continuity and homogeneity.

(3) The analysis is based on a plane strain condition.

(4) Neglecting the self-weight of the lining and the surrounding rock.

(5) The mountain surrounding the tunnel is assumed to extend infinitely in all directions.

### 2.2 Computational Model

Based on the displacement equations of elastic mechanics, a frost heaving force computational model for tunnels is established by utilizing the displacement relationships between the lining and various sections of the surrounding rock. This leads to the derivation of the frost heaving force calculation formula for the Xiangyang Tunnel. The computational model is a three-layer circular ring structure [13], as illustrated in Figure 2. The three regions, I, II, and III, represent the lining, the frozen surrounding rock, and the unfrozen surrounding rock, respectively. These regions are three axisymmetric elastic bodies forming a force system composed of complete contact. Therefore, the tunnel can be viewed as circular within an infinitely large mountain. The parameters a, b and h represent the inner radius of the lining, the inner radius of the frozen surrounding rock, and the thickness of the frozen layer, respectively. The radial stress at the contact point between the lining and the frozen surrounding rock is denoted as $\sigma_f$, which represents the tunnel's frost heaving force. The radial stress at the contact point between the frozen and unfrozen surrounding rock is defined as $\sigma_h$. The parameters $T_1$ and $T_2$ represent the temperature within the tunnel and the temperature of the surrounding rock.

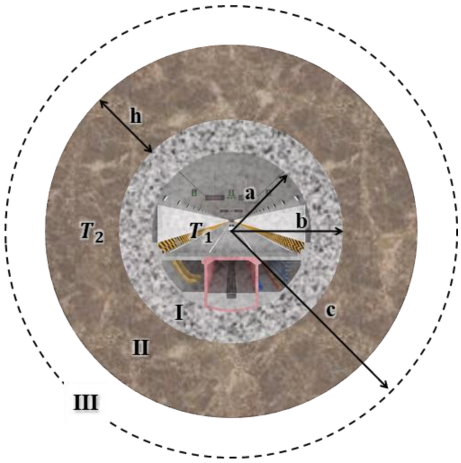


**Figure 2:** Simplified computational model of tunnel structure

### 2.3 Analytical Calculation of Frost Heaving Force

Based on the above fundamental assumptions, after freezing during the winter low temperatures, let the frost heaving rate of the surrounding rock be denoted as $\alpha$. The increase in volume of the frozen surrounding rock (Region II) can be expressed as follows:

$$\Delta V = \alpha\pi[(h+b)^2 - b^2] \quad (1)$$

Therefore, the displacement and expansion of the intersection line between unfrozen surrounding rock and frozen surrounding rock (the intersection line of II and III area) is as follows:

$$\Delta h = -\sqrt{(1+\alpha)(b+h)^2 - ab^2} - (b+h) \quad (2)$$

The computational model is a centrosymmetric system where the tunnel lining (Region I) is subjected only to the frost heaving force $\sigma_f$. Let $E_1$ and $\mu_1$ denote the elastic modulus and Poisson's ratio of the lining, respectively. Based on relevant theories of elastic mechanics, the radial displacement equation at any point within the lining (Region I) can be expressed as follows:

$$u_1(r) = -\frac{b^2\sigma_f}{E_1(b^2-a^2)}\left[(1-\mu_1)r + \frac{(1+\mu_1)a^2}{r}\right] \quad (3)$$

At the outer diameter of the lining, $r=b$, the displacement $\delta_1$ can be solved as follows:

$$\delta_1 = -\frac{b\sigma_f}{E_1}\left(\frac{b^2+a^2}{b^2-a^2} - \mu_1\right) \tag{4}$$

The inner side of the frozen surrounding rock (Region II) is subjected to the frost heaving force $\sigma_f$, while the outer side is constrained by the unfrozen surrounding rock with a pressure $\sigma_h$. Let $E_2$ and $\mu_2$ denote the elastic modulus and Poisson's ratio of the frozen surrounding rock, respectively. According to relevant theories of elastic mechanics, the radial displacement at any point within the frozen surrounding rock (Region II) can be expressed as follows:

$$u_2(r) = \frac{(1+\mu_2)(1-2\mu_2)}{E_2}\frac{[\sigma_f b^2 - \sigma_h (b+h)^2]r}{(b+h)^2-b^2} + \frac{(1+\mu_2)}{E_2}\frac{b^2(b+h)^2(\sigma_f-\sigma_h)}{[(b+h)^2-b^2]r} \tag{5}$$

At the inner diameter of the frozen surrounding rock, $r=b$, the displacement $\delta_{f1}$ can be solved as follows:

$$\delta_{f2} = \frac{(1+\mu_2)(1-2\mu_2)}{E_2}\frac{[\sigma_f b^2 - \sigma_h (b+h)^2](b+h)}{(b+h)^2-b^2} + \frac{(1+\mu_2)}{E_2}\frac{b(b+h)^2(\sigma_f-\sigma_h)}{[(b+h)^2-b^2]} \tag{6}$$

At the outer diameter of the frozen surrounding rock, where $r=b+h$, the displacement at this point is denoted as $\delta_{f2}$. The solution can be expressed as follows:

$$\delta_{f2} = \frac{(1+\mu_2)(1-2\mu_2)}{E_2}\frac{[\sigma_f b^2 - \sigma_h (b+h)^2](b+h)}{(b+h)^2-b^2} + \frac{(1+\mu_2)}{E_2}\frac{b^2(b+h)(\sigma_f-\sigma_h)}{[(b+h)^2-b^2]} \tag{7}$$

According to the principle of relativity of forces in classical mechanics, the inner side of the unfrozen surrounding rock (Region III) is subjected to the frost heaving force $\sigma_h$. In contrast, the outer side can be considered as an infinitely large plane extending in all directions, thus effectively experiencing no external force. Let $E_3$ and $\mu_3$ denote the elastic modulus and Poisson's ratio of the unfrozen surrounding rock, respectively. According to relevant theories of elastic mechanics, at the inner diameter of the unfrozen surrounding rock, where $r=b+h$, the displacement $\delta_2$ can be expressed as follows:

$$\delta_2 = \frac{1+\mu_3}{E_3}(b+h)\sigma_h \tag{8}$$

Based on the continuity condition of displacement and the assumed frost heaving displacement pattern, the geometric relationship of the displacements can be expressed as follows:

$$\begin{cases} \delta_1 - \delta_{f1} = 0 \\ \delta_2 = \delta_{f2} + \Delta h \end{cases} \tag{9}$$

By substituting equations (4), (6), (7), and (8) into equation (9), the frost heaving force $\sigma_f$ can be calculated as follows:

$$\sigma_f = \frac{\Delta h}{\frac{E_2 C}{2A^2}\left[\frac{D}{E_1} + \frac{1}{E_2}\left(\frac{B}{C}+\mu_2\right)\right]\left[\frac{(b+h)(1+\mu_3)}{E_3} + \frac{A}{E_2}\left(\frac{B}{C}-\mu_2\right)\right] - \frac{2Ab^2}{E_2 C}} \tag{10}$$

In the equation:

$$\begin{cases} A = b + h + \Delta h \\ B = A^2 + b^2 = (b+h+\Delta h)^2 + b^2 \\ C = A^2 - b^2 = (b+h+\Delta h)^2 - b^2 \\ D = \frac{b^2+a^2}{b^2-a^2} - \mu_1 \end{cases} \tag{11}$$

According to equation (10), the frost heaving force of the surrounding rock, derived from the plane strain equation, is influenced by four main categories of factors: the physical and mechanical properties of the frozen and unfrozen surrounding rock (elastic modulus and Poisson's ratio), the tunnel cross-sectional dimensions (tunnel inner diameter and lining thickness), the freezing conditions of the surrounding rock (freezing depth and frost heaving rate), and the physical and mechanical properties of the lining (elastic modulus and Poisson's ratio). Since this calculation is based on the actual engineering of the Xiangyang Tunnel, the freezing conditions are related to winter temperatures and the duration of low temperatures. During winter (November, December, January), temperatures decrease and cannot be considered constant. The values of other parameters can be determined based on preliminary geological surveys and the tunnel design drawings.

## 3. Overview of the Project and Calculation Analysis

### 3.1 Project Overview

The Xiangyang Tunnel is located at the border between Baishan and Tonghua, cities in Jilin Province. The tunnel consists of two separate sections: the left section is 1,245 meters long (from stake number XY210+625 to XY211+870), and the right section is 1,335 meters long (from stake number XY210+645 to XY211+980). There is a clear distance of approximately 34 meters between the two sections, classifying it as a separated long tunnel. The tunnel's cross-sectional clearance radius is approximately 5.5 meters, its structural width limit is 10 meters, and its height is 5 meters.

The tunnel is in a continental monsoon climate zone, characterized by cold, dry winters and hot, humid summers. The average annual temperature is approximately 5°C, with the average temperature in the coldest month around -16°C, and the lowest temperature in the year can reach -40°C. In the area where the Xiangyang Tunnel is located, the groundwater primarily consists of quaternary pore water and bedrock fissure water, which is mainly replenished by precipitation during the rainy season. The groundwater types are relatively simple. After excavation, the surface of the surrounding rock was moist, with dripping water in certain sections. The tunnel entrance is shallowly buried and water-rich, with significant temperature variations, making it prone to frost heaving damage.

### 3.2 Analysis of Frost Heaving Force Calculation

This study focuses on the magnitude of the frost heaving force in the tunnel entrance section, where the surrounding rock is relatively fractured. Field investigations classified the surrounding rock as Grade V, with the physical and mechanical parameters of the frozen and unfrozen surrounding rock obtained through on-site tests. The design institute's drawings show that the lining thickness in the tunnel entrance section is 0.6 meters. The thickness of the frozen zone was measured in November, December, and January, yielding values of 1.6 meters, 1.9 meters, and 2.3 meters, respectively. Based on the volume change of water upon freezing, the frost heaving rate is 1.09%. The elastic modulus of the lining is based on the value determined from on-site engineering tests, with its magnitude adjusted to observe the variations in frost heaving force under different elastic moduli. The values of the calculation parameters are presented in Table 1. Figure 2 illustrates the variations in frost heaving force $\sigma_f$(MPa) under different elastic moduli at three frozen depths.

**Table 1:** Calculation parameters

| Material | Parameter | Symbol | Values |
|---|---|---|---|
| Lining | Elastic modulus (Mpa) | $E_1$ | 2.50e2~2.50e7 |
| | Poisson's ratio | $\mu_1$ | 0.20 |
| | Inner diameter (m) | a | 5.50 |
| | Outer diameter (m) | b | 6.10 |
| | Thickness (m) | b − a | 0.60 |
| Frozen surrounding rock | Elastic modulus (Mpa) | $E_2$ | 2900 |
| | Poisson's ratio | $\mu_2$ | 0.35 |
| | Thickness (m) | h | 1.6 1.9 2.3 |
| Unfrozen surrounding rock | Elastic modulus (Mpa) | $E_3$ | 1500 |
| | Poisson's ratio | $\mu_3$ | 0.40 |
| Water | Frost heaving rate | α | 1.09% |

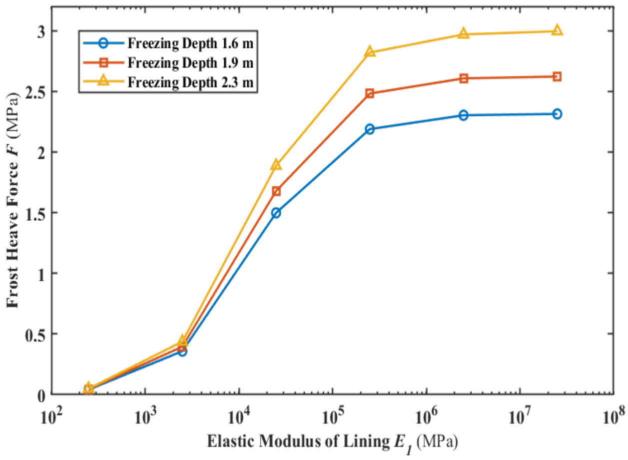


**Figure 3:** Variation curve of frost heaving force $\sigma_f$(MPa)

As illustrated in Figure 3, at a constant elastic modulus, the frost heaving force increases with greater freezing depth; however, the change trend remains consistent across different depths. Taking a frozen depth of 1.6 meters as an example, the initial frost heaving force is 0.042 MPa. Under constant conditions for other factors, the magnitude of the frost heaving force generally increases positively with the elastic modulus of the lining, showing a growth trend that is "slow—steep—slow". When the elastic modulus of the lining ranges from 0.25 GPa to 2.5 GPa, the increase in frost heaving force is relatively slow, with only a 0.3 MPa rise. Between 2.5 GPa and 250 GPa, the frost heaving force rises significantly from 0.359 MPa to 2.188 MPa. After the elastic modulus of the lining reaches 250 GPa, the increase in frost heaving force slows down with further increases in modulus, stabilizing around 2.3 MPa, and the curve tends to level off. Adjusting the insulation layer to reduce freezing depth can effectively lower the frost heaving force in the prevention and control of frost damage. It is also essential to prevent damage to the elastic modulus of the lining, as such damage increases the deformation of the lining under frost heaving force. This reduction in constraint on the surrounding rock makes the tunnel structure more vulnerable to failure.

## 4. Numerical Simulation

### 4.1 Finite Element Model

This study focuses on the left line section of the Xiangyang Tunnel, utilizing ANSYS software for numerical simulation analysis of frost heaving forces in the tunnel. Based on the design drawings of the Xiangyang Tunnel, a circular tunnel profile with a radius of 5.5 m was created. The temperature influence range on the surrounding rock was set to six times the tunnel radius, and the calculation model extended 35 m from the center of the tunnel to the left and right boundaries, as well as the lower boundary. Utilizing an equivalent height for loads and considering geological conditions, construction methods, and other factors, the boundary depth between shallow and deep sections of the Xiangyang Tunnel was determined to be 22 m. Models were established at distances of 5 m, 7 m, 9 m, and 35 m from the crown (including shallow and deep sections). As shown in Figure 4, the finite element model was established using discretization using a mesh size of 1 m.

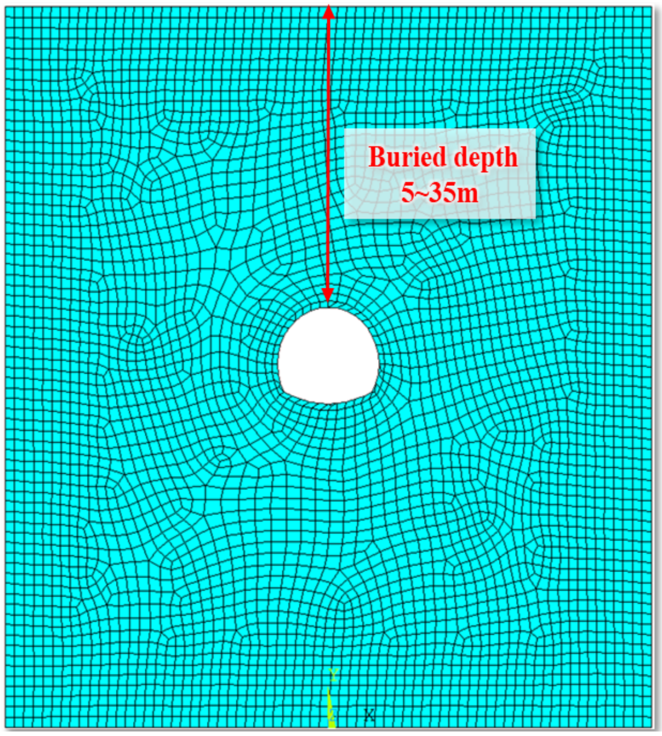


**Figure 4:** Mesh partition diagram

The calculation employs a thermal stress simulation, considering the thermal expansion of typical materials and the frost heaving of frozen surrounding rock. An expansion coefficient is assigned to the frozen layer, with the volume expansion coefficient due to freezing treated as a negative thermal expansion coefficient, valued at 0.0008. The thermodynamic parameters of the surrounding rock and the lining are presented in Table 2. The frozen and unfrozen surrounding rock is treated as the same material; however, the property changes resulting from different freezing states occur abruptly at the freezing point of 0°C.

This study examines the magnitude of frost heaving forces in the tunnel entrance section, where the shallow-buried surrounding rock is relatively fractured. Field investigations estimate the classification of the surrounding rock, which has been assigned a Grade V level. The thickness of the frozen zone, as reported in field measurements, was 0.9 m in November, 1.1 m in December, and 1.3 m in January.

**Table 2:** Margin specifications

| Parameter | Lining | Frozen surrounding rock | Unfrozen surrounding rock |
|---|---|---|---|
| Thermal conductivity (W/(m·°C) | 1.25 | 1.96 | 1.96 |
| Specific heat capacity(J/(Kg·°C) | 920 | 1050 | 1210 |
| Coefficient of thermal expansion (K-1) | $8e^{-6}$ | $6.3e^{-6}$ | $-8e^{-4}$ |
| Elastic modulus (GPa) | 28.6 | 1.6 | 2.2 |
| Density ($Kgm^{-3}$) | 2500 | 2800 | 2800 |

### 4.2 Distribution of Tunnel Temperature Field

The shallow-buried section is located close to the tunnel entrance, which directly influences the surrounding rock's state by air temperature. Consequently, the temperature variations inside the tunnel closely resemble atmospheric temperature changes, following an approximate triangular function [14]. In constructing the finite element model, the surface and the tunnel inner wall temperatures are set at -25°C to simulate the effects of thermal loading. In the deep-buried section of the tunnel, the rock mass's insulating effect reduces disturbances from surface low temperatures. Additionally, being further from the tunnel entrance diminishes the exchange of cold air and the effects of vehicle airflow. As a result, the average temperature in the deep-buried section increases, and the temperature amplitude decreases correspondingly, with an internal tunnel temperature set at -15°C to reflect this characteristic. The model's bottom boundary is set to a ground temperature of 5°C, and for areas outside the influence of low temperatures, an initial reference temperature of 5°C is established. The left and right boundaries do not impose temperature loads, defaulting to insulating boundaries. The temperature distribution is illustrated in Figure 5.

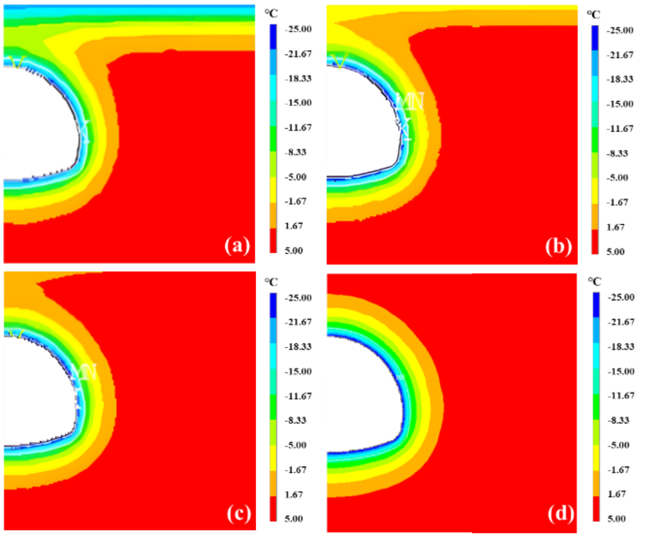


**Figure 5:** Distribution of temperature fields in the Tunnel; (a) Burial depth of 5m, (b) Burial depth of 7m, (c) Burial depth of 9m and (d) Burial depth of 35m

The thickness of the frozen layer (temperature below 0°C) in the temperature distribution chart represents the freezing depth at the tunnel entrance in cold regions where no thermal insulation layer has been installed. Two vertical key points are taken at the upper and lower boundaries of the frozen layer: at shallow depths of 5m, 7m, and 9m, their relative distances are recorded as 2.813m, 2.795m, and 2.507m, respectively, while in the deep-buried section, the relative distance is 2.036m. After three months of sustained low temperatures during winter, the freezing depth of the surrounding rock at the tunnel entrance without a thermal insulation layer is measured at 2.8m, while the freezing depth in the deep-buried section is recorded at 2m.

The analysis results indicate that as the tunnel depth increases, the freezing depth of the surrounding rock gradually decreases. When the simulation results are compared with the actual freezing depth of 2.3m at the shallow entrance, the simulated values are slightly higher. This discrepancy is primarily due to the exclusion of thermal insulation and waterproof layers in the simulation process, leading to a certain degree of error between the simulated and actual conditions. However, this error remains within a reasonable range and only significantly affects the overall understanding of the variations in tunnel freezing depth.

### 4.3 Distribution of Frost Heaving Force

After simulating the temperature field, the stress field was indirectly coupled with the temperature field. Horizontal and vertical displacement constraints were applied to the tunnel's inner walls, while horizontal displacement constraints were enforced on the model's left and right boundaries. Vertical displacement constraints were established at the lower boundary for the shallowly buried section, with the upper boundary remaining free. In contrast, the deeply buried section's upper and lower boundaries were constrained vertically. Following a thermal-structural coupling analysis, an equivalent stress distribution map of the lining was generated based on the Von Mises criterion, which serves as the frost heaving force distribution map for the tunnel, as illustrated in Figure 6.

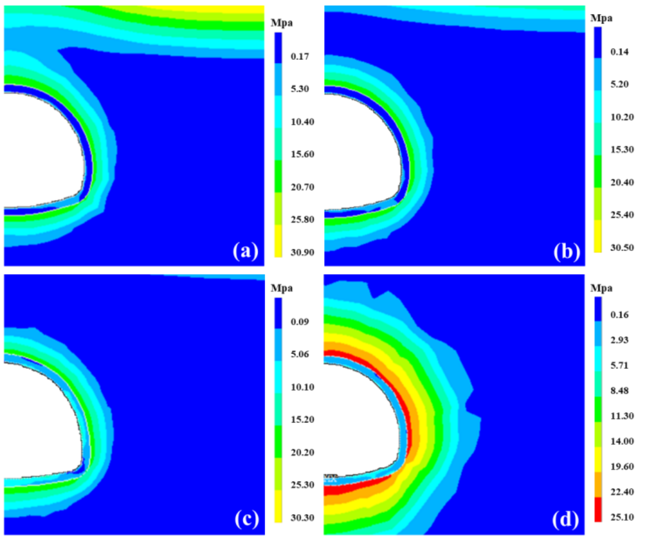


**Figure 6:** Distribution of frost heaving force in the tunnel (a) Burial depth of 5m, (b) Burial depth of 7m, (c) Burial depth of 9m and (d) Burial depth of 35m

At the shallowly buried section, the frost heaving force experienced by the lining reaches its peak at the interface between the arch and the base slab. The maximum frost heaving force in the shallowly buried section is relatively consistent, with a peak value of 6 MPa. In contrast, the frost heaving forces at the crown, arch shoulder, and base slab are notably smaller, remaining below 3 MPa. Notably, the frost heaving force in the surrounding rock outside the arch lining is significantly pronounced, approximately 22 MPa, due to the combined effects of low surface temperatures and the low temperatures of the tunnel's inner walls. Furthermore, the frost heaving force in the surrounding rock outside the lining exhibits a layered distribution, gradually decreasing from the inner to the outer layers. In the deep-buried section of the tunnel, the distribution of frost heaving forces in the lining structure is relatively uniform. However, a significant concentration of frost heaving force is observed at the junction of the base slab and arch, reaching a maximum of 5.7 MPa. The frost heaving force exhibits a layered distribution for the rock mass outside the lining, increasing from the inside out. In proximity to the lining, the frost heaving force at the junction of the arch and base slab is notably higher than in other areas, with a maximum of 25 MPa. As the distance from the lining increases, the distribution of frost heaving forces forms concentric rings of equal thickness that gradually decrease.

The force generated by volumetric expansion significantly impacts the surrounding rock, resulting in much higher frost heaving forces on the rock than the lining. When the burial depth exceeds 7 meters, the rock and soil insulating properties diminish the influence of surface temperatures on the tunnel and its surrounding rock. Consequently, the frost heaving force on the lining and surrounding rock tend to stabilize at a fixed value. A comparison of the numerical simulation results for frost heaving forces with those obtained from the elastic mechanics calculations in Section Three reveals that the numerical ranges are consistent.

## 5. Conclusion

This study, based on the Xiangyang Tunnel project, establishes relevant mechanical and thermal parameters. It skillfully integrates analytical methods with finite element modeling to conduct a comprehensive and in-depth investigation of temperature distribution and frost heaving forces in the tunnel.

The analysis of frost heaving forces in the Xiangyang Tunnel reveals a positive correlation with the elastic modulus when other variables are held constant. This relationship exhibits a non-linear growth pattern characterized by a "slow—steep—slow" trend. Additionally, as the freezing depth increases, the frost heaving force rises, although the values remain relatively low, ranging from 0.5 to 3 MPa.

Through numerical simulation analysis of the Xiangyang Tunnel using a finite element model, it was observed that as the burial depth increases, the temperature within the tunnel gradually rises, leading to a corresponding reduction in the extent of freezing. Once the burial depth exceeds 7 meters, the temperature distribution of the surrounding rock stabilizes and shows little further change.

In the shallow section at the tunnel entrance, the maximum frost heaving force in the lining is primarily concentrated at the junction of the crown and the invert, while the frost heaving force in the surrounding rock decreases in a layered manner from the inside out. In the deep-buried section of the tunnel, the distribution of frost heaving forces in the lining is relatively uniform, with a notable concentration of forces only at the junction of the invert and the crown. The surrounding rock also exhibits a layered decrease in frost, heaving forces from the interior outward. Additionally, it is essential to note that the frost heaving forces experienced by the surrounding rock are significantly greater than those on the lining. After the burial depth exceeds 7 meters, the maximum frost heaving forces for the lining and the surrounding rock stabilize.

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## Author Profile

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