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# Freezing Damage to Tunnels in Cold Regions and Weights of Influencing Factors

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**Abstract:** Concrete materials are widely used in tunnel engineering. In China, the cold regions have gradually become the main area for highway and railway construction. Affected by high altitude, low temperature, turbulent wind, and other conditions, freezing damage, such as tunnel icing, occurs in concrete materials, which seriously affects the quality and operational safety of tunnels in cold regions. Therefore, it is necessary to carry out a quantitative analysis of various factors affecting freezing damage to protect concrete materials in tunnels. This paper summarizes various freezing damage phenomena in tunnels in cold regions and divides them into three types: water seepage and hanging ice type freezing damage, lining interface type freezing damage, and tunnel foundation ice accumulation type freezing damage. Based on the qualitative evaluation of each factor, the affiliation of each factor was divided. Then, the influence weight of each factor on freezing damage was obtained through the analytic hierarchy process, and then each factor was ranked. This study is helpful to the selection of anti-freezing measures for tunnels in cold regions.

**Keywords:** tunnels in cold regions; freezing damage; analytic hierarchy process; quantitative evaluation; weight analysis

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## 1. Introduction

At present, concrete materials are widely used in construction and engineering industries, such as residential, bridge, and tunnel engineering. At present, more and more highways and railways are being built in cold regions of China [1], such as the Sichuan-Tibet Railway and the Sichuan-Tibet Expressway. Constrained by the mountain topography and other conditions in cold regions, tunnels have become the primary choice for efficient construction of railways and highways. However, affected by low temperatures, the structure of the concrete material in the tunnel changes, which is also called freezing damage. Freezing damage not only reduces the quality of the project, but also threatens human safety. Therefore, freezing damage in cold regions has inevitably become an urgent problem to be solved in engineering construction. Judging from the tunnels built in cold regions, the phenomenon of tunnel freezing damage is very universal, and some freezing damage even seriously affects the normal use and safe operation of tunnels. For example, 41.8% of tunnels built in cold regions such as Northeast China, Inner Mongolia, Gansu, and Hebei suffered from freezing damage. Among the 34 tunnels built in Sichuan, Qinghai, Tibet, and Xinjiang, which are located in high-altitude cold regions, 15 tunnels have suffered freezing damage, accounting for 44.1% [2].

Existing research focuses on emphasizing the role of construction technology in tunnel freeze protection. For example, a tunnel in the north, Guanjiao Tunnel, tunnels in the northeast and north China, and a large number of engineering cases have been used to study and analyze the causes of tunnel frost damage. On this basis, researchers have proposed different optimization schemes and comparisons of tunnel frost protection measures [3–8].

The detection technology and reinforcement treatment methods of tunnel frost damage have also attracted the full attention of researchers [9,10] In addition, some researchers believe that the environmental characteristics, engineering design, and frost heaving force of tunnels are also important influencing factors of frost damage. For example, Wan et al. [2] reviewed the environmental characteristics, frost damage phenomena, and prevention technologies of tunnels in cold regions in China in different periods, sorted out the influencing factors of tunnel frost damage, and looked forward to future research and construction control of tunnel frost damage in cold regions in China. Li et al. [5] believed that local climate and engineering design are important factors affecting tunnel frost damage and proposed corresponding measures to prevent tunnel frost damage. Cui et al. [8] believed that climate characteristics and frost heaving force were important factors affecting frost damage in seasonal frozen soil areas and put forward the frost damage mechanism.

These studies are used to guide antifreeze measures for tunnels, but there are still problems including: (1) Most of the previous research took a specific project in the cold regions as the research object and put forward targeted antifreeze measures. This method has obvious limitations due to the influence of different geological conditions on different tunnel projects [8,11–18]. (2) When analyzing the causes of freezing damage, these studies were mainly based on the existing engineering experience and lacked quantitative evaluation of the impact of various factors on the extent of freezing damage, which resulted in a significant limitation when they were used to guide the construction of other engineering projects [19–24]. Therefore, in tunnels in cold regions, the quantitative analysis of the factors and importance of inducing freezing damage should be paid attention to. For the quantitative analysis of engineering-related problems, Zhang et al. put forward a very effective method. They proposed an extended evaluation system of ground collapse risk along the tunnel based on FAHP and correlation analysis [25] and used the fuzzy transformation principle and the maximum membership principle to determine the underground karst state level [26]. In this paper, the characteristics of freezing damage are analyzed, and the disaster-causing factors in cold regions are summarized. Then, the weights are quantified and the core factors that induce freezing damage are determined based on the AHP. Finally, the main and secondary influencing factors of tunnel freezing damage are extracted. The above research can provide theoretical support for the protection and repair of concrete materials in tunnels in cold regions.

## 2. Characteristics and Influencing Factors of Freezing Damage

### *2.1. Characteristics*

Due to environmental constraints and influences, compared with ordinary tunnels, lining icing and tunnel base icing are the unique freezing damage phenomena of tunnels in cold regions [8]. As shown in Figure 1, the common freezing damage phenomena, environmental types, and occurrence locations of tunnels in cold regions are shown in Table 1. The types and characteristics of freezing damage are summarized based on typical cold area engineering cases: (1) The freezing damage is divided into three categories in cold regions, specifically, the freezing damage of seepage and hanging ice, the freezing damage to the lining interface, and the freezing damage to the tunnel foundation [11]. (2) Locality. Freezing damage is affected by the cavity between the surrounding rock and the surrounding rock support. (3) Segmentation. Freezing damage mainly occurs at the tunnel entrance. (4) The source of tunnel freezing damage is mostly the rock-concrete interface, which is the transition section for temperature and groundwater between the surrounding rock and the surrounding rock support.

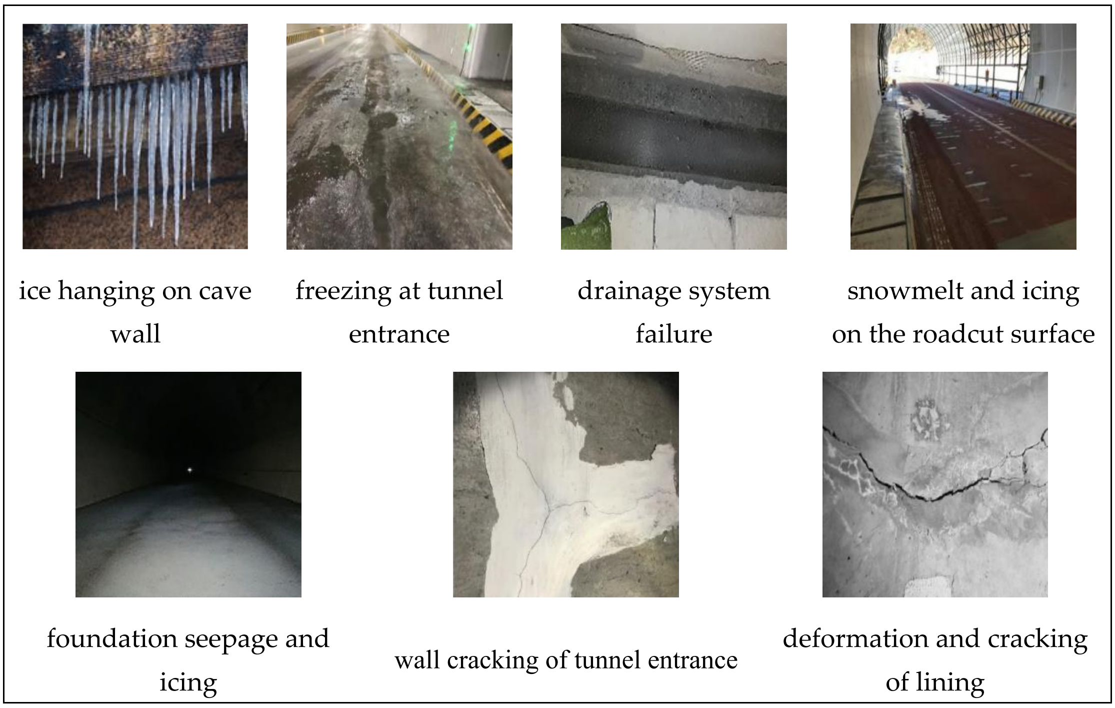


**Figure 1.** Freezing damage to tunnels in cold regions [12–14].

**Table 1.** Freezing damage cases of tunnels in cold regions.

| **Type** | **Name** | **Environment** | | **Location** | **Engineering Case** |
|---|---|---|---|---|---|
| | | **Seasonal Frozen Region** | **Permafrozen Region** | | |
| the freezing damage of seepage and hanging ice | ice hanging on cave wall | √ | √ | middle section of tunnel | Yalin Railway Ridge Tunnel |
| the freezing damage to the tunnel foundation | freezing at tunnel entrance | √ | √ | entrance of tunnel | Balang Mountain tunnel |
| | drainage system failure | √ | √ | the whole tunnel | Cuiling Tunnel |
| | snowmelt and icing on the roadcut surface | | √ | entrance of tunnel | Shendan Tunnel |
| | foundation seepage and icing | √ | √ | middle section of tunnel | Yuxi Moregai Tunnel |
| the freezing damage to the lining interface | wall cracking of tunnel entrance | √ | √ | entrance of tunnel | Nenlin Railway Tunnel<br>Yalin Railway Tunnel |
| | deformation and cracking of lining | √ | √ | entrance of tunnel | Zhegu Mountain tunnel |
| | freeze–thaw deterioration of lining | √ | √ | entrance of tunnel | Yuxi Moregai Tunnel |

### 2.2. Influencing Factors

Studies have shown that the entrance section temperature is most obviously affected by the low temperature of the air inside and outside the tunnel in the cold season, so it is the main distribution area of freezing damage [8,17], which also shows that low temperature is an important factor for the occurrence of freezing damage. Of course, in tunnels, the occurrence of freezing damage not only depends on temperature conditions, but also on groundwater, surrounding rock properties, and many other factors [18–20].

#### 2.2.1. The Freezing Damage of Seepage and Hanging Ice

The groundwater seeping from the support pores freezes on the support surface at low temperatures; sometimes it even falls on the road [10].

#### 2.2.2. The Freezing Damage to the Tunnel Foundation

The freezing damage to the tunnel foundation includes freezing at the tunnel entrance, drainage system failure, snowmelt and icing on the roadcut surface, foundation seepage, and icing. Freezing at the tunnel entrance occurs when the snow, brought into the tunnel by vehicles passing through the tunnel and sucked in when the tunnel is ventilated, freezes when the temperature decreases in the tunnel entrance section [8]. Snowmelt and icing on the roadcut surface occur when soil particles and rock chips repeatedly shrink–expand and displace under freeze–thaw cycles, forming slumps eventually [8]. Drainage system failure occurs when, affected by unreasonable design and construction processes, the tunnel drainage system (such as blind ditches, drainage ditches, and scuppers) freezes and blocks, and groundwater overflows.

#### 2.2.3. The Freezing Damage to the Lining Interface

The freezing damage to the lining interface includes wall cracking of the tunnel entrance, deformation and cracking of the lining, and freeze–thaw deterioration of the lining. It is caused by the frost heave inside and outside the lining [21]. Frost heave outside the lining means that the volume of the residual water between the lining and the surrounding rock increases when it freezes at low temperatures, which exerts a force on the lining structure. It is also affected by the frost heave sensitivity of the surrounding rock. Frost heave inside the lining means that water in the cracks and pores of the lining concrete in the process of freezing exerts a force on the surrounding concrete.

Based on the above discussion, no matter what form of freezing damage, groundwater and temperature are necessary conditions, and part of the freezing damage is also affected by the sensitivity of surrounding rocks to frost heave. Therefore, the main influencing factors of tunnel freezing damage are summarized: groundwater, temperature, and surrounding rock properties. Moreover, the disaster factors of freezing damage are quantitatively evaluated by the analytic hierarchy process (AHP) [22,23].

## 3. Quantitative Evaluation of Disaster-Causing Factors Based on AHP

### *3.1. Calculation Method*

#### 3.1.1. Construct Judgement Matrix

Based on the influence of each index on tunnel freezing damage which has been mentioned and expert evaluation, the importance evaluation value ($a_{ij}$) of each indicator in each factor layer to the target layer is given in Table 2 to form the judgment matrix $A$:

$$A = \begin{Bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{Bmatrix} \tag{1}$$

**Table 2.** Scale method for judging matrix element $a_{ij}$.

| The Importance of Indicator A Relative to Indicator B | Extremely Important | Very Important | Important | Slightly Important | Equally Important | Slightly Unimportant | Unimportant | Very Unimportant | Extremely Unimportant |
|---|---|---|---|---|---|---|---|---|---|
| evaluation value of indicator A | 9 | 7 | 5 | 3 | 1 | 1/3 | 1/5 | 1/7 | 1/9 |
| remarks | 8, 6, 4, 2, 1/2, 1/4, 1/8 is the middle value of the evaluation value | | | | | | | | |

The element $a_{ij}$ (evaluation value) of the judgment matrix was given by the 1–9 scale method proposed by Santy, and the scale method is shown in Table 2. The value of $a_{ij}$ represents the importance of the $i$-th row index compared to the $j$-th column index.

3.1.2. Weight Calculation

The vectors of each row of the judgment matrix A were geometrically averaged and normalized to obtain the characteristic vector $w$ of the matrix and the weight $w_\mathrm{i}$ of each index. The calculation method is as follows [24]:

(1) The product of elements per line of matrix A was calculated by Equation (2):

$$M_i = \prod_{j=1}^{n} b_{ij},\ I = 1, 2, \ldots, \tag{2}$$

(2) Taking the $n$-th root of $M_i$ (Equation (3)), which makes up the vector $W$ (Equation (4)).

$$\overline{W}_i = \sqrt[n]{M_i} \tag{3}$$

$$W = \left[\overline{W_1}, \overline{W_2}, \ldots, \overline{W_n}\right]^T \tag{4}$$

(3) The feature vector $w$ and the weight $w_i$ of each index were obtained by normalizing the vector $W$ (Equation (5)).

$$w_i = \overline{W_i} / \sum_{i=1}^{n} \overline{W_i}, w = [w_1, w_2, \ldots, w_n]^T \tag{5}$$

3.1.3. Consistency Test

The consistency index $CI$ was obtained by Equation (6).

$$CI = \frac{(\lambda_{\max} - m)}{(m-1)} \tag{6}$$

where $n$ is the matrix order, $CI$ is the consistency index, $\lambda_{\max}$ is the maximum eigenvalue.

The average random consistency index $RI$ is introduced to judge whether the judgment matrix of each order satisfies the consistency.

The consistency ratio of the matrix was calculated by Equation (7). A value of $CR$ less than 1 indicates that the calculation result is credible.

$$CR = \frac{CI}{RI} \tag{7}$$

where $CR$ is the consistency ratio of the matrix, $CI$ is the consistency index, $RI$ is the average random consistency index.

*3.2. Index System and Analysis of Freezing Damage in Cold Region Tunnels*

A large number of cases and studies on freezing damage to tunnels in cold regions were referred to, to satisfy the scientific and systematic evaluation of the selected indicators. Finally, the "influencing factor system of freezing damage of tunnels in cold regions" was established [25], including two primary indexes (external environmental conditions and the nature of the tunnel surrounding rock), eight secondary indexes (external temperature, surrounding rock temperature, groundwater abundance, groundwater corrosivity, fracture development features, elastic modulus, tensile strength, and hardness), and two tertiary indexes (tunnel length and wind speed) [26,27]. It is shown in Table 3.

**Table 3.** Hierarchical analysis model of tunnel freezing damage in cold regions [V].

| |
|---|
| **Primary Index:** External Environmental Conditions [$U_1$] |
| **secondary index**: surrounding rock temperature [$U_{11}$] |
| tertiary index: tunnel length [$U_{111}$] |
| wind speed [$U_{112}$] |
| external temperature [$U_{12}$] |
| groundwater abundance [$U_{13}$] |
| groundwater corrosivity [$U_{14}$] |
| **primary index**: the surrounding rock properties (frost resistance) [$U_2$] |
| **secondary index:** fracture development characteristic [$U_{21}$] |
| elastic modulus [$U_{22}$] |
| tensile strength [$U_{23}$] |
| tensile strength [$U_{23}$] |
| hardness [$U_{24}$] |

### 3.2.1. The Primary Index

Based on the statistics and analysis of tunnel freezing damage, the factors affecting freezing damage were divided into two categories in this paper: external environmental conditions and the surrounding rock properties. They are used as the primary index of the analytic hierarchy process system.

### 3.2.2. Secondary Index

There are eight secondary indexes determined in this paper, of which four indexes belong to the external environmental conditions, and the other four indexes belong to the nature of the tunnel surrounding rock.

External environmental conditions include temperature and groundwater [28]. The decrease in temperature in the tunnel causes the freezing of water, and the volume expansion damages the tunnel structure further, driving other forms of freezing damage [29]. Regarding the abundance of groundwater, on the one hand, when groundwater flows into the tunnel, it leads to water leakage and freezes on the lining and road. On the other hand, when groundwater gathers in the cracks of the surrounding rock, the low-temperature period of the tunnel is prolonged due to the subsequent temperature changes in the external environment [30], such as the lowest temperature of groundwater occurring in March and April. At the same time, the flow of groundwater is accompanied by the migration of corrosive substances, leading to crystalline corrosion and decomposition corrosion, which cause damage to the lining structure, resulting in cracks and tunnel leakage [31,32].

The influence of the surrounding rock properties on the freezing damage is mainly reflected in the frost heaving of rock masses [31,33], which is also mentioned in the previous statistical data. However, the degree of performance is different in different tunnels, and it is even very inconspicuous in individual tunnels. The frost heave force that appears in the rock mass has the following characteristics: ① The frost heave force expands to the part with smaller restraint. ② There is an uneven distribution of frost heave force [34]. Based on the above characteristics, combined with the experimental analysis of rock frost heaving by other studies [26,27,35–37], the secondary indicators affecting the frost resistance of rock masses are determined, including fracture development features, elastic modulus, tensile strength, and hardness.

### 3.2.3. Tertiary Index

After a tunnel is constructed, the original temperature equilibrium is broken. The temperature balance is reached by the heat exchange between the surrounding rock, the external environment, and the air [28,38]. The location of tunnel freezing damage is related to the length of the tunnel, but it is mainly distributed at the entrance, which is mainly due to the uneven temperature distribution in the tunnel [39,40]. Therefore, the tunnel length and wind speed are regarded as the third-level indexes affecting the surrounding rock temperature in the tunnel.

### *3.3. Weight Calculation*

#### 3.3.1. Influence Weight of Primary Index on Decision Objectives

Existing research has shown among the various indexes affecting tunnel freezing damage, the external environmental conditions [$U_1$] and the surrounding rock properties (frost resistance) [$U_2$] are equally important to tunnel freezing damage [V] in cold regions. Therefore, the evaluation value of the importance of the primary index to the decision-making objectives can be obtained, and the importance is shown in Table 4.

**Table 4.** Importance of primary index to decision objective.

| V | $U_1$ | $U_2$ |
|---|---|---|
| $U_1$ | 1 | 4 |
| $U_2$ | 1/4 | 1 |

According to the above matrix, $\lambda_{max}$, *CI*, and *CR* are calculated to be 2, and 0, respectively. Additionally, *CR* is less than 0, which indicates that the results are credible. After the feature vector is normalized, the weight of each factor layer index is obtained.

Finally, the weight of the influencing factors of tunnel freezing damage is shown in Table 5. Based on the relationship between the weight values, the influence degree of various factors on tunnel freezing damage in cold regions can be obtained: external temperature (0.385) > groundwater abundance (0.201) > wind speed (0.155) > fracture development characteristics (0.122) > elastic modulus (0.042) > groundwater corrosivity (0.035) > tunnel length (0.031) > tensile strength (0.018) = hardness (0.018). However, some of the tertiary indexes have an indirect impact on the highest level (tunnel freezing damage in cold regions), so they are reordered based on the secondary index. The influence degree of various factors on tunnel freezing damage in cold regions is obtained: external temperature (0.385) > surrounding rock temperature (0.233) > groundwater abundance (0.201) > fracture development characteristics (0.122) > elastic modulus (0.042) > groundwater corrosivity (0.035) > tensile strength (0.018) = hardness (0.018). Obviously, the main influencing factors of tunnel freezing damage in cold regions are external temperature, surrounding rock temperature, groundwater abundance, and fracture development characteristics.

**Table 5.** Index weight relationship of each layer.

| | Primary Index | Weight | Secondary Index | Weight | Tertiary Index | Weight | Weight of Decision Objectives |
|---|---|---|---|---|---|---|---|
| freezing damage to tunnels in cold regions [V] | external environmental conditions [$U_1$] | 0.800 | surrounding rock temperature [$U_{11}$] | 0.233 | tunnel length [$U_{111}$] | 0.167 | 0.031 |
| | | | | | wind speed [$U_{112}$] | 0.833 | 0.155 |
| | | | outside temperature [$U_{12}$] | 0.481 | | | 0.385 |
| | | | groundwater abundance [$U_{13}$] | 0.251 | | | 0.201 |
| | | | groundwater corrosivity [$U_{14}$] | 0.035 | | | 0.028 |
| | characteristics of tunnel surrounding rock [$U_2$] | 0.200 | fracture development characteristics [$U_{21}$] | 0.606 | | | 0.122 |
| | | | modulus of elasticity [$U_{22}$] | 0.209 | | | 0.042 |
| | | | tensile strength [$U_{23}$] | 0.092 | | | 0.018 |
| | | | hardness [$U_{24}$] | 0.092 | | | 0.018 |

#### 3.3.2. The Influence Weight of the Secondary on the Primary Index

Firstly, we determined the influence weight of the surrounding rock temperature [$U_{11}$], external temperature [$U_{12}$], groundwater abundance [$U_{13}$], and groundwater corrosivity [$U_{14}$] on the primary index external environmental conditions [$U_1$] through existing research. Wei et al. [31,41], based on the ANSYS model, not only gave the importance order of surrounding rock temperature [$U_{11}$] and external temperature [$U_{12}$]: external temperature [$U_{12}$] > surrounding rock temperature [$U_{11}$] and not only made the order of importance: external temperature [$U_{12}$] > surrounding rock temperature [$U_{11}$], but also gave the evaluation value of the importance of groundwater abundance [$U_{13}$] and groundwater corrosivity [$U_{14}$] to the target layer. Luo et al. [30] divided the tunnel frost protection level by the weighted average method for the above two factors. Based on the division rules, the influence degree of temperature and groundwater on tunnel freezing damage was summarized and reflected in the judgment matrix. Based on the above research, the evaluation values of the importance of the four factor indicators to the target layer were given, and the importance is shown in Table 6.

**Table 6.** Importance of secondary index to primary index (external environmental conditions).

| $U_1$ | $U_{11}$ | $U_{12}$ | $U_{13}$ | $U_{14}$ |
|---|---|---|---|---|
| $U_{11}$ | 1 | 1/3 | 1 | 9 |
| $U_{12}$ | 3 | 1 | 3 | 9 |
| $U_{13}$ | 1 | 1/3 | 1 | 8 |
| $U_{14}$ | 1/9 | 1/9 | 1/8 | 1 |

According to the above matrix, $\lambda_{max} = 4$, $CI = 0.036$, $CR = 0.041 < 0.1$, which indicates that the results are credible. After the feature vector is normalized, the weight of each index was obtained, which is $w_{U_1} = (w_{U_{11}}, w_{U_{12}}, w_{U_{13}}, w_{U_{14}}) = (0.233, 0.481, 0.251, 0.035)$.

Then, we determined the influence weight of fracture development features [$U_{21}$], elastic modulus [$U_{22}$], tensile strength [$U_{23}$], and hardness [$U_{24}$] on the properties (frost resistance) [$U_2$] of the surrounding rock of the primary index. Wei et al. [31] believed that the hardness of rock can best reflect its frost resistance. Demonstration and research have confirmed that the frost resistance of a rock mass was affected by the fracture development features, elastic modulus, and tensile strength [26,35,42–44]. Based on this, the evaluation value of each index on the importance of tunnel freezing damage is shown in Table 7.

**Table 7.** Importance of the primary index (nature of tunnel surrounding rock) by the secondary index.

| $U_2$ | $U_{22}$ | $U_{22}$ | $U_{23}$ | $U_{24}$ |
|---|---|---|---|---|
| $U_{22}$ | 1 | 5 | 5 | 5 |
| $U_{22}$ | 1/5 | 1 | 3 | 3 |
| $U_{23}$ | 1/5 | 1/3 | 1 | 1 |
| $U_{24}$ | 1/5 | 1/3 | 1 | 1 |

According to the above matrix, $\lambda_{max} = 4$, $CI = 0.084$, $CR = 0.094 < 0.1$; the results passed the consistency test. After the feature vector is normalized, the weight of each factor layer index is obtained, which is: $w_{U_2} = (w_{U_{21}}, w_{U_{22}}, w_{U_{23}}, w_{U_{24}}) = (0.606, 0.210, 0.092, 0.092)$.

### 3.3.3. Weight of the Tertiary Index

In this system, there is only one group of tertiary indexes: tunnel length [$U_{111}$] and wind speed [$U_{112}$] affecting surrounding rock temperature [$U_{11}$]. Li et al. [45–50] analyzed the influence of wind speed and tunnel length on the temperature field in tunnels in cold regions based on experimental research and numerical simulation, which is "wind speed > tunnel length", so the importance evaluation value of the tertiary index was determined. The importance is shown in Table 8.

**Table 8.** Importance of the tertiary index on the secondary index.

| $U_{11}$ | $U_{111}$ | $U_{112}$ |
|---|---|---|
| $U_{111}$ | 1 | 1/5 |
| $U_{112}$ | 5 | 1 |

According to the above matrix, $\lambda_{\max}$, *CI*, and *CR* are calculated to be 2, and 0, respectively. Additionally, *CR* is less than 0, which indicates that the results are credible. After the feature vector is normalized, the weight of each index is obtained, which is: $w_{U_{11}} = (w_{U_{111}}, w_{U_{112}}) = (0.167, 0.833)$.

## 4. Case Verification

Five tunnels in the cold region were selected to verify the weights of the factors affecting the freezing damages obtained by the AHP, which are the Shuangfeng Tunnel, the Partridge Mountain Tunnel, the Xueshanliang Tunnel, the Queer Mountain Tunnel, and the Xianfeng Tunnel. The four indexes of fracture development characteristics, groundwater abundance, groundwater corrosivity, and hardness focus on language description; therefore, specific scores were given by referring to the BQ surrounding rock classification method (BQ) and the international surrounding rock grading method (RMR).

Fracture development characteristics: This index refers to the score for joint state in the RMR, which is shown in Table 9.

**Table 9.** Scores for fracture development characteristics.

| Fracture Development Characteristics | Scores |
|---|---|
| very rough surfaces with limited size | 0 |
| slightly rough surface with less than 1 mm opening | 6 |
| the opening degree is 1–5 mm, and the joints extend over several meters | 12 |
| the opening is greater than 5 mm, and the joints extend over several meters | 25 |

Groundwater abundance: This index refers to the score for groundwater status in the RMR, which is shown in Table 10.

**Table 10.** Scores for groundwater abundance.

| Groundwater Abundance | Scores |
|---|---|
| dry | 0 |
| moist | 4 |
| damp | 7 |
| seepage/drip | 10 |
| gushing water | 15 |

Groundwater corrosivity: This index refers to the score for corrosion evaluation of groundwater on concrete in the BQ surrounding rock classification method (BQ), which is shown in Table 11.

**Table 11.** Scores for groundwater corrosivity.

| Groundwater Corrosivity | Scores |
|---|---|
| weak | 3 |
| middle | 6 |
| powerful | 10 |

Hardness: In the BQ surrounding rock classification method (BQ), there is a corresponding relationship between the degree of hardness and the saturated uniaxial compressive strength of rock. Referring to the scoring method of rock compressive strength in the RMR, the compressive strength of the surrounding rock is used instead of its hardness.

In summary, the indexes for the five tunnels are shown in Table 12.

**Table 12.** Tunnel indexes information.

| Tunnel | | | Partridge Mountain Tunnel | Queer Mountain Tunnel | Xueshanliang Tunnel | Shuangfeng Tunnel | Xianfeng Tunnel |
|---|---|---|---|---|---|---|---|
| external environmental conditions | surrounding rock temperature | tunnel length/m | 4424 | 7079 | 7966 | 7237 | 4345 |
| | | wind speed/m·s | 2 | 1.4 | 22 | 2.5 | 2.3 |
| | outside temperature/°C | | −8 | −16 | −9.5 | −18.4 | −18.1 |
| | groundwater abundance | | 7 | 5 | 10 | 15 | 7 |
| | groundwater corrosivity | | 3 | 3 | 3 | 3 | 6 |
| characteristics of tunnel surrounding rock | fracture development characteristics | | 6 | 4 | 12 | 12 | 8 |
| | modulus of elasticity/Gpa | | 11.82 | 41.4 | 64 | 9.8 | 35.9 |
| | tensile strength/MPa | | 2.10 | 10.6 | 5.2 | 4.38 | 8.90 |
| | hardness/MPa | | 36.57 | 112.49 | 108.75 | 46 | 119.78 |
| Length of freezing damages/m | | | 600 | 850 | 720 | 1900 | 1235 |

After the normality test of the eight indexes of the five tunnels, it was found that all indexes significantly obeyed the normal distribution at the level of 0.01. Therefore, the Pearson correlation coefficient was selected for correlation analysis. The value of the Pearson correlation ($\rho_{X,Y}$) coefficient is between −1 and 1. When the coefficient is 0, there is no linear relationship. The closer the absolute value of $\rho_{X,Y}$ is to 1, the more the correlation can be said to be very obvious. If the coefficient is greater than zero, it indicates a positive correlation; otherwise, it is a negative correlation. The specific correlation coefficient measurement is shown in Table 13.

**Table 13.** Pearson Correlation Coefficient Measurement Table.

| Correlation Coefficient | $\rho_{X,Y} < 0.3$ | $0.3 < \rho_{X,Y} < 0.5$ | $0.5 < \rho_{X,Y} < 0.8$ | $\rho_{X,Y} > 0.8$ |
|---|---|---|---|---|
| degree of association | weak correlation | slight correlation | significant correlation | high correlation |

The influence direction of each index on the tunnel is ignored to reflect the relationship between the correlation coefficient and the weight value. The absolute value of each calculated correlation coefficient is taken, which is shown in Figure 2.

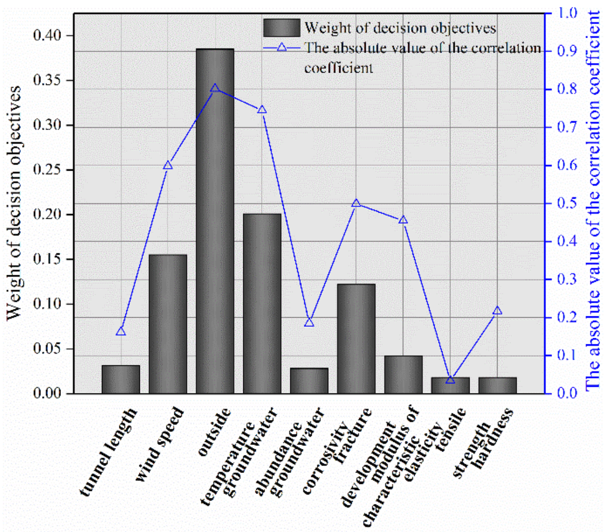


**Figure 2.** Correlation coefficient and weight value comparison.

Obviously, the weight values of the influencing factors of tunnel freezing damage obtained by AHP and the correlation coefficient of each factor on the negative temperature section have a highly overlapping trend, which indicates that the degree of influence of each index on tunnel freezing damage through AHP analysis is credible and could be used to provide a theoretical reference for protecting and repairing concrete materials in tunnels in cold regions from freezing damage. Through case verification, it has been found that the weight value obtained by the analytic hierarchy process is reliable, and the practical significance of the weight value is shown in the degree of influence of each influencing factor on tunnel frost damage (proportional to the weight value).

Therefore, in the process of tunnel frost damage prevention, the frost damage factor with high weight value should be considered first, and the characteristics of this factor in the local climate environment and engineering conditions should be explored, and then reasonable and effective engineering measures should be taken to avoid the occurrence of freezing damage.

## 5. Conclusions

This paper summarizes the phenomenon of freezing damage, analyzes the occurrence characteristics of each phenomenon, qualitatively obtains the influencing factors of freezing damage, then quantitatively evaluates the influence degree of various factors on tunnel freezing damage through AHP, and finally obtains the core factors of tunnel freezing damage.

(1) The freezing damage to tunnels in cold regions has the following characteristics: a. The frost damage to tunnels in cold regions can be divided into the following three categories: water seepage and ice hanging type, lining interface type, and tunnel foundation icing type. b. The frost damage to tunnels in cold regions has obvious characteristics of segmentation, and each frost damage phenomenon occurs in the portal section. c. The tunnel frost damage has certain local characteristics, and its occurrence is affected by the cavity between the lining support and the surrounding rock. d. The source of tunnel frost damage is mostly the rock concrete interface, which is the transition interface between the lining and surrounding rock temperature and groundwater.

(2) Considering the principle of comprehensiveness and importance, this paper considers that tunnel freezing damage is affected by the following factors: external temperature, surrounding rock temperature, groundwater abundance, groundwater corrosivity, fracture development features, elastic modulus, tensile strength, hardness, tunnel length, and wind speed.

(3) Through the analytic hierarchy process, this paper quantitatively evaluates the main controlling factors of tunnel freezing damage: external temperature, surrounding rock temperature, groundwater abundance, and fracture development characteristics. The same level weights of the above factors are: 0.385, 0.233, 0.201, and 0.122. The surrounding rock temperature is influenced by tunnel length and wind speed, and the influence weights of these tertiary indexes on surrounding rock temperature are 0.167 and 0.833, respectively. The weight of other factors on tunnel freezing damage is low, which is respectively: elastic modulus (0.042), groundwater corrosion (0.028), tensile strength (0.018), and hardness (0.018). This result is reliable for tunnel projects in cold regions in the north and west of China.

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