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Research Article

Study on the Intelligent Evaluation System of Tunnel Frost Damage in Cold Regions Based on the Fuzzy Comprehensive Evaluation Model

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At present, the tunnel design specifications in China do not provide a clear and systematic intelligent evaluation system of tunnel frost damage in cold regions. Based on the research results of 122 seasonal frozen soil tunnels in high-latitude areas of China, four key influencing factors of geohydrology, temperature, surrounding rock, and engineering measures were determined, the intelligent fuzzy comprehensive evaluation model was established, the weights of all factors were considered, and the intelligent evaluation technology system of tunnel frost damage in cold areas had been put forward. Meanwhile, the rationality of the intelligent model was verified by a specific engineering case. The research suggests that the intelligent evaluation model of tunnel frost damage proposed in this paper can accurately describe the relationship of influencing factors of tunnel frost damage in cold areas, the weight of each influencing factor is calculated by using analytic hierarchy process, and the main risk sources of tunnel frost damage in cold areas are found out. The intelligent evaluation model is an efficient and practical method for Intelligent prediction of frost damage. By using the subordinate function method, the improvement from qualitative analysis to quantitative index calculation is realized. The blindness of engineering analogy construction is avoided, and the scientificity and accuracy of renovation measures for frost damage have been improved. At the same time, the research results provide a theoretical basis for the improvement of the intelligent evaluation system of tunnel frost damage in cold regions.

1. Introduction

With the implementation of the Belt and Road Initiative and the promotion of basic construction of the Beijing Winter Olympic Games, more and more tunnels are built in cold regions of seasonal frozen soil. The problems of frost damage of tunnels have been gradually highlighted, such as leakage of lining, ice hanging, water pouring from tunnel bottom, frost heaving of icing, cracking, crumbling and peeling of lining, freezing of the drainage system, thermal melting, and sliding of the tunnel portal.

In view of the problems of tunnel frost damage in cold areas, the tunnellers have carried out the research work on the temporal and spatial variation law of temperature field [1–9], thermal insulation, and prevention measures of frost damage [10–16]. However, the research on the intelligent evaluation system of tunnel frost damage in cold regions is rarely reported, mainly including as follows: according to the average temperature and freezing depth of the coldest month, the Qinghai-Tibet Plateau, Inner Mongolia, and Northeast China are divided into three cold regions, and the characteristics of frost damage are analyzed according to different cold regions

[17]. The causes of tunnel frost damage in cold areas can be divided into three categories: external force, material cracking, and other reasons. The characteristics of tunnel frost damage in the cold area are qualitatively explained [18]. The frost damage of tunnels in cold areas is considered to be caused by vertical load, plastic load, and creep of the inclined slope, and corresponding preventive measures are put forward according to different classifications [19]. Based on the event tree theory, the frost damage level of tunnels in the cold region has been established, and the scientific and effective measures to control frost damage of tunnels in the cold region have been improved [20]. According to the fatigue strength of concrete frost damage, the durability of the concrete structure under freeze-thaw environment, and the action level of lining frost heaving force, the frost damage level of the tunnel in cold areas is divided, and corresponding preventive measures are put forward according to different classifications [21].

Based on the investigation results of 122 tunnels in high-latitude areas of China, four key influencing factors (geological hydrology, temperature, surrounding rock, and engineering measures) are determined, an intelligent fuzzy comprehensive evaluation model is established, and an intelligent evaluation system of tunnel frost damage in cold areas is proposed considering the weight relationship of key factors.

2. Investigation of Tunnel Frost Damage in Cold Areas

The data of 122 tunnels in cold regions in Northeast China and Inner Mongolia were collected. The frost damage of 12 tunnels is caused by unreasonable design, which accounts for 23% of the total number of tunnels. The frost damage of 27 tunnels is caused by the wrong construction method, which accounts for 53% of the total number of tunnels. The frost damage of 9 tunnels is due to improper operation and maintenance, which accounts for 18% of the total number of tunnels. The frost damage of 3 tunnels is caused by unreasonable remedial measures, which accounts for 6% of the total number of tunnels. The percentage of each influencing factor of tunnel frost damage is shown in Figure 1.

3. Establishment of the Intelligent Evaluation System of Tunnel Frost Damage in Cold Regions

3.1. Establishment of the Intelligent Evaluation Model. Considering the four basic influencing factors of temperature condition, hydrological condition, surrounding rock condition, and engineering measures, an intelligent evaluation model is established by the fuzzy comprehensive evaluation method, and the intelligent evaluation model of tunnel frost damage in cold regions is shown in Figure 2.

3.2. Establishment of Comment Collection. According to the degree of frost damage, the comments on the intelligent evaluation system of tunnel frost damage in cold areas are as follows:

$$V = \{V_1, V_2, V_3, V_4\} = \{\mathrm{I}, \mathrm{II}, \mathrm{III}, \mathrm{IV}\}. \tag{1}$$

In this formula, class I is no frost damage or slight frost damage, class II is moderate frost damage, class III is relatively serious frost damage, and class IV is serious frost damage.

The classification of tunnel frost damage in cold regions is shown in Table 1.

3.3. Determination of the Membership Function. The intelligent evaluation system of tunnel frost damage in cold areas includes 10 quantitative indexes (air temperature outside the tunnel, ground temperature of the surrounding rock, driving density, wind speed inside the tunnel, void area length between surrounding rock and lining, annual precipitation, blockage rate of the drainage pipe, buried depth of the tunnel, fracture rate of the surrounding rock, and lining strength) and 6 qualitative indexes (waterproof design of three joints, solubility of the surrounding rock, design problems, construction problems, operation and maintenance problems, and remedial measures). Among them, the quantitative indexes can be divided into 7 positive quantitative indexes (air temperature outside the tunnel, traffic density, wind speed inside the tunnel, void area length between surrounding rock and lining, annual precipitation, blockage rate of the drainage pipe, and fracture rate of the surrounding rock) and 3 negative quantitative indexes (ground temperature of the surrounding rock, buried depth of the tunnel and lining strength).

3.3.1. Determine the Membership Function of the Quantitative Index. The reduced half trapezoid distribution function is selected as the membership function of the positive-type quantitative index. The membership function is shown in formulae (2) ~ (5). The parameters of the membership function of the positive-type quantitative index are shown in Table 2.

$$\mu_1 = \begin{cases} 1, & x < S_1, \\ \dfrac{S_2 - x}{S_2 - S_1} & S_1 \le x \le S_2, \\ 0, & x > S_2, \end{cases} \tag{2}$$

$$\mu_2 = \begin{cases} 0, & x \le S_1, x > S_3, \\ \dfrac{x - S_1}{S_2 - S_1}, & S_1 < x \le S_2, \\ \dfrac{S_3 - x}{S_3 - S_2}, & S_2 < x \le S_3, \end{cases} \tag{3}$$

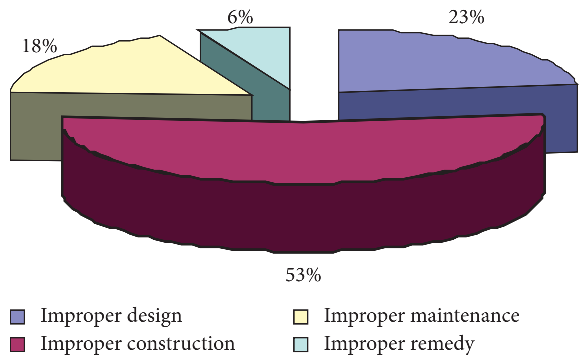

FIGURE 1: Proportion of influencing factors of tunnel frost damage.

$$\mu_3 = \begin{cases} 0, & x \le S_2, x > S_4, \\ \dfrac{x - S_2}{S_3 - S_2}, & S_2 < x \le S_3, \\ \dfrac{S_4 - x}{S_4 - S_3}, & S_3 < x \le S_4, \end{cases} \tag{4}$$

$$\mu_4 = \begin{cases} 0, & x \le S_3, \\ \dfrac{x - S_3}{S_4 - S_3}, & S_3 < x \le S_4, \\ 1, & x > S_4, \end{cases} \tag{5}$$

where S_1, S_2, S_3, and S_4 are determined by each critical state index in the evaluation benchmark.

The reduced half trapezoid distribution function is also selected as the membership function of the negative-type quantitative index. The membership function is shown in formulae (6) ~ (9). The parameters of the membership function of the negative quantitative index are shown in Table 3.

$$\mu_1 = \begin{cases} 1, & x > S_1, \\ \dfrac{S_2 - x}{S_2 - S_1}, & S_1 \ge x \ge S_2, \\ 0, & x < S_2, \end{cases} \tag{6}$$

$$\mu_2 = \begin{cases} 0, & x \ge S_1, x < S_3, \\ \dfrac{x - S_1}{S_2 - S_1}, & S_1 > x \ge S_2, \\ \dfrac{S_3 - x}{S_3 - S_2}, & S_2 > x \ge S_3, \end{cases} \tag{7}$$

$$\mu_3 = \mu_2 = \begin{cases} 0, & x \ge S_2, x < S_4, \\ \dfrac{x - S_2}{S_3 - S_2}, & S_2 > x \ge S_3, \\ \dfrac{S_4 - x}{S_4 - S_3}, & S_3 > x \ge S_4, \end{cases} \tag{8}$$

$$\mu_4 = \begin{cases} 0, & x \ge S_3, \\ \dfrac{x - S_3}{S_4 - S_3}, & S_3 > x \ge S_4, \\ 1, & x < S_4. \end{cases} \tag{9}$$

3.3.2. Determine the Membership Function of the Qualitative Index. Trapezoidal distribution function is selected as the membership function of the qualitative index, and its membership function is shown in formulae (10) ~ (13):

$$\mu_1 = \begin{cases} 0, & x < 0.75, \\ 10x - 7.5 & 0.75 \le x < 0.85, \\ 1, & x \ge 0.85, \end{cases} \tag{10}$$

$$\mu_2 = \begin{cases} 0, & x < 0.55, \\ 10x - 05.5 & 0.55 \le x < 0.65, \\ 1, & 0.65 \le x < 0.75, \\ 8.5 - 10x & 0.75 \le x < 0.85, \\ 0, & x \ge 0.85, \end{cases} \tag{11}$$

$$\mu_3 = \begin{cases} 0, & x < 0.35, \\ 10x - 3.5 & 0.35 \le x < 0.65, \\ 1, & 0.45 \le x < 0.55, \\ 6.5 - 10x & 0.55 \le x < 0.65, \\ 0, & x \ge 0.65, \end{cases} \tag{12}$$

$$\mu_4 = \begin{cases} 1, & x < 0.35, \\ 4.5 - 10x & 0.35 \le x < 0.45, \\ 0, & x \ge 0.45. \end{cases} \tag{13}$$

3.4. Determination of the Weighted Set. Analytic hierarchy process is used to determine the weighted set of the intelligent evaluation system of tunnel frost damage in cold regions. The steps are as follows: establish the evaluation model (Figure 2), build two judgment matrices, and calculate the relative weight of each index and consistency test.

The sensitivity of each index of temperature conditions is ground temperature of the surrounding rock, driving density, wind speed inside the tunnel, and air temperature outside the tunnel. The judgment matrix of temperature conditions is shown in Table 4.

The calculation results of the relative weight of four indexes under temperature conditions are as follows: $W_{U_1} = (W_{U_{11}}, W_{U_{12}}, W_{U_{13}}, W_{U_{14}}) = (0.10, 0.40, 0.30, 0.20)$, $\lambda_{\max} = 4, CI = 0, CR = 0 < 0.1$, and the conformance test meets the requirements.

The sensitivity of each index of the hydrological condition is void area length of the surrounding rock between lining, blockage rate of the drainage pipe,

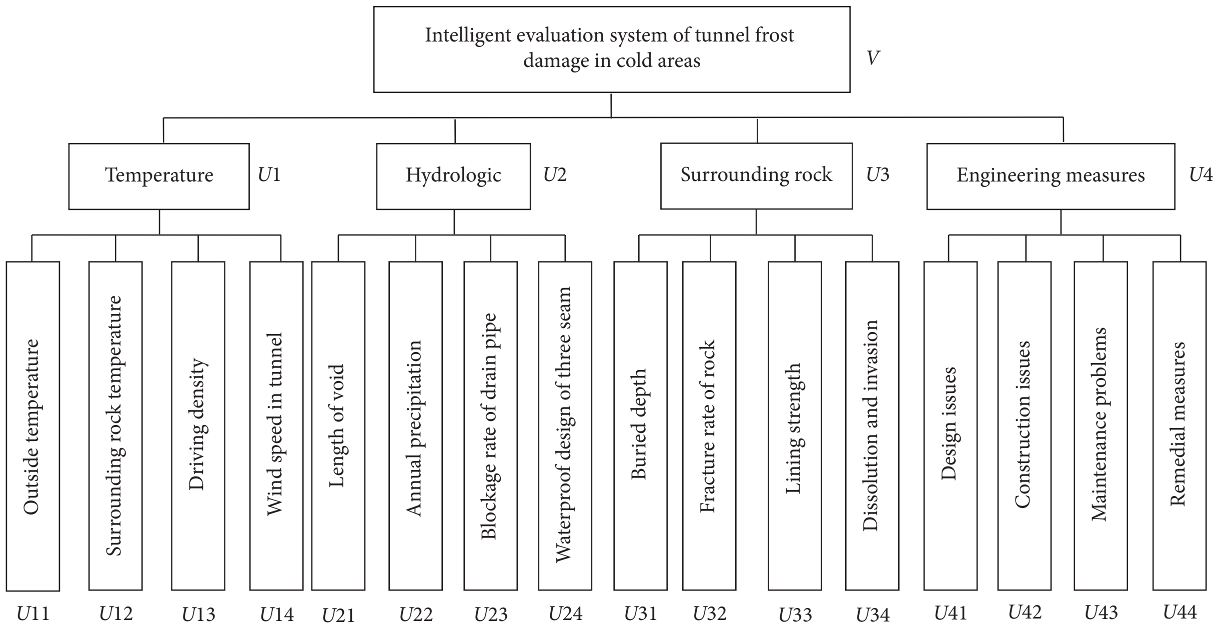

Figure 2: Frost damage intelligent evaluation model of the tunnel in cold areas.

Table 1: Classification of tunnel frost damage in cold regions.

Frost damage classification	Judgment basis	Average temperature in the coldest month/°C
I	Icing at the portal section, leakage and icing of the partial lining surface, slight frost damage, no impact on traffic	−5∼−10
II	Moderate serious icing at the portal section, moderate severe leakage and freezing damage of the lining surface, affecting traffic	−10∼−15
III	Relatively serious icing at the portal section, relatively severe leakage and freezing damage of the lining surface, serious impact on traffic	−15∼−25
IV	Serious crack of the lining surface, serious ice hanging in the tunnel, ice plug of the drain system, traffic disruption	<−25

Table 2: Membership function parameters of the positive quantitative index.

Positive quantitative index	I	II	III	IV
Air temperature outside the tunnel/°C	−5	−10	−15	−25
Driving density/(对/h)	2	4	6	8
Wind speed inside the tunnel/(m/s)	1	2	3	5
Void area length between surrounding rock and lining/m	3	5	10	20
Annual precipitation/mm	200	600	1600	2500
Blockage rate of the drainage pipe	0.2	0.5	0.8	0.9
Fracture rate of the surrounding rock	0.001	0.5	10	15

waterproof design of three joints, and annual precipitation. The judgment matrix of hydrological conditions is shown in Table 5.

The calculation results of the relative weight of four indexes under hydrological conditions are as follows: $W_{U_2} = (W_{U_{21}}, W_{U_{22}}, W_{U_{23}}, W_{U_{24}}) = (0.49, 0.10, 0.25, 0.16)$, $\lambda_{\max} = 4, CI = 0, CR = 0 < 0.1,$ and the conformance test meets the requirements.

The sensitivity of each index of the surrounding rock condition is fracture rate of the surrounding rock, dissolution and invasion of the surrounding rock, lining strength, and tunnel buried depth. The judgment matrix of surrounding rock conditions is shown in Table 6.

The calculation results of the relative weight of the four indexes under surrounding rock conditions are as follows: $W_{U_3} = (W_{U_{31}}, W_{U_{32}}, W_{U_{33}}, W_{U_{34}}) = (0.08, 0.38, 0.23, 0.31)$, $\lambda_{\max} = 4, CI = 0, CR = 0 < 0.1,$ and the conformance test meets the requirements.

According to the investigation on frost damage of 122 tunnels in seasonally cold regions in China (Figure 1), the sensitivity of each index of engineering measures is the design problem, the construction problem, the operation

Table 3: Membership function parameters of the negative quantitative index.

Negative quantitative index	I	II	III	IV
Ground temperature of the surrounding rock/°C	25	15	10	5
Buried depth of the tunnel/m	600	500	300	100
Lining strength	0.66	0.5	0.33	0

Table 4: Judgment matrix of temperature conditions.

U_1	U_{11}	U_{12}	U_{13}	U_{14}
U_{11}	1.000	0.250	0.333	0.500
U_{12}	4.000	1.000	1.333	2.000
U_{13}	3.000	0.750	1.000	1.500
U_{14}	2.000	0.500	0.667	1.000

Table 5: Judgment matrix of hydrological conditions.

U_2	U_{21}	U_{22}	U_{23}	U_{24}
U_{21}	1.000	5.000	2.000	3.000
U_{22}	0.200	1.000	0.400	0.600
U_{23}	0.500	2.500	1.000	1.500
U_{24}	0.333	1.667	0.667	1.000

Table 6: Judgment matrix of surrounding rock conditions.

U_3	U_{31}	U_{32}	U_{33}	U_{34}
U_{31}	1.000	0.200	0.333	0.25
U_{32}	5.000	1.000	1.667	1.250
U_{33}	3.000	0.600	1.000	0.750
U_{34}	4.000	0.800	1.333	1.000

and maintenance problem, and the unreasonable remedial measures. Among the four factors, temperature and hydrological conditions are the most important followed by engineering measures and surrounding rock conditions. The calculation results of the relative weight of four indexes under engineering measure conditions are as follows: $W_{U_4} = (W_{U_{41}}, W_{U_{42}}, W_{U_{43}}, W_{U_{44}}) = (0.23, 0.53, 0.18, 0.06)$. The judgment matrix of engineering measures is shown in Table 7.

The calculation results of the relative weights of four basic influencing factors in the criteria layer are as follows: $W_{U_V} = (W_{U_1}, W_{U_2}, W_{U_3}, W_{U_4}) = (0.29, 0.29, 0.13, 0.29)$, $\lambda_{\max} = 4, CI = 0, CR = 0 < 0.1$, and the conformance test meets the requirements. The weight relationship between criterion level and index level is shown in Table 8.

3.5. Calculation Method of the Intelligent Fuzzy Comprehensive Evaluation Model. The weighted average evaluation model is used in the first-level and the second-level intelligent fuzzy comprehensive evaluation model, namely, model of $M(\circ, \oplus)$.

Table 7: Judgment matrix of engineering measure conditions.

U_4	U_{41}	U_{42}	U_{43}	U_{44}
U_{41}	1.000	1.000	2.000	1.000
U_{42}	1.000	1.000	2.000	1.000
U_{43}	0.500	0.500	1.000	0.500
U_{44}	1.000	1.000	2.000	1.000

The calculation method of the first-level fuzzy comprehensive evaluation result is shown in the following formula:

$$B_k = A_k \circ R_k = (Bk_1, Bk_2, Bk_3, Bk_4), \quad k = (1, 2, 3, 4), \tag{14}$$

where A_k is the weight of the index layer and R_k is the first-level fuzzy relation matrix.

The calculation method of the second-level fuzzy comprehensive evaluation result is shown in the following formula:

$$B = A \circ B_k = (b_1, b_2, b_3, b_4) \quad (k = 1, 2, 3, 4), \tag{15}$$

where A is the weight of the criterion layer and B_k is the first-level comprehensive evaluation result.

4. Rationality Verification of the Intelligent Model

4.1. Example Overview. The total length of the tunnel in cold regions is 2 950 m, the annual average precipitation in the tunnel site is 392.8 mm, the annual average temperature is 6.2°C, the extreme maximum temperature is 37.9°C, the extreme minimum temperature is −27.9°C, the maximum freezing depth of soil is 192 cm, the annual average wind speed is 1.8 m/s, and the maximum snow thickness is 18 cm. Underground water is relatively rich, mainly bedrock fissure water.

4.2. Matrix of Fuzzy Relation. According to the geological data and monitoring data on-site, the value of influencing factors of frost damage in the tunnel portal section is shown in Table 9.

4.3. Operation of the First-Level Intelligent Fuzzy Comprehensive Evaluation Model. Firstly, the influencing factors of frost damage in the tunnel portal are substituted into the membership function, and the fuzzy relation matrix R is obtained. Then, the first-level fuzzy comprehensive evaluation result is obtained by using the weighted average evaluation model:

Table 8: Weight relationship between criterion level and index level.

Criteria layer	Weight	Index layer	Weight	Target weight
U_1 (temperature condition)	0.29	Temperature outside the tunnel	0.1	0.029
		Ground temperature of the surrounding rock	0.4	0.116
		Driving density	0.3	0.087
		Wind speed in the tunnel	0.2	0.058
U_2 (hydrological condition)	0.29	Void area length of the surrounding rock between lining	0.49	0.1421
		Annual precipitation	0.10	0.029
		Blockage rate of the drain pipe	0.25	0.0725
		Waterproof design of three seams	0.16	0.0464
U_3 (surrounding rock condition)	0.13	Buried depth	0.08	0.0104
		Fracture rate of the surrounding rock	0.38	0.0494
		Lining strength	0.23	0.0299
		Dissolution and invasion of the surrounding rock	0.31	0.0403
U_4 (engineering measure condition)	0.29	Design issues	0.23	0.0667
		Construction issues	0.53	0.1537
		Operation and maintenance problems	0.18	0.0522
		Remedial measures	0.06	0.0174

Table 9: Value of influencing factors of frost damage in the portal section.

Influencing factors of frost damage	Measured value
Temperature outside the tunnel/°C	−12.8
Ground temperature of the surrounding rock/°C	7.0
Driving density/(pairs/h)	3.0
Wind speed in the tunnel/(m/s)	1.8
Void area length of the surrounding rock between lining/m	4.2
Annual precipitation/mm	392.8
Blockage rate of the drain pipe	0.1
Waterproof design of three seams	0.85
Buried depth/m	50
Fracture rate of the surrounding rock	1.5
Lining strength	0.8
Dissolution and invasion of the surrounding rock	0.3
Design issues	0.8
Construction issues	0.8
Operation and maintenance problems	0.9
Remedial measures	0.9

$$U_1 = W_{U1} \circ R_1 = \begin{pmatrix} 0.1 & 0.4 & 0.3 & 0.2 \end{pmatrix} \circ \begin{bmatrix} 0.22 & 0.78 & 0 & 0 \\ 0 & 0 & 0.4 & 0.6 \\ 0.5 & 0.5 & 0 & 0 \\ 0.2 & 0.8 & 0 & 0 \end{bmatrix} = \begin{pmatrix} 0.212 & 0.388 & 0.16 & 0.24 \end{pmatrix}, \tag{16}$$

$$U_2 = W_{U2} \circ R_2 = \begin{pmatrix} 0.49 & 0.1 & 0.25 & 0.16 \end{pmatrix} \circ \begin{bmatrix} 0.4 & 0.6 & 0 & 0 \\ 0.518 & 0.482 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix} = \begin{pmatrix} 0.6578 & 0.3422 & 0 & 0 \end{pmatrix}, \tag{17}$$

$$U_3 = W_{U3} \circ R_3 = \begin{pmatrix} 0.08 & 0.38 & 0.23 & 0.31 \end{pmatrix} \circ \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0.9 & 0.1 & 0 \\ 0.5 & 0.5 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{pmatrix} 0.115 & 0.457 & 0.038 & 0.39 \end{pmatrix}, \tag{18}$$

$$U_4 = W_{U4} \circ R_4 = \begin{pmatrix} 0.23 & 0.53 & 0.18 & 0.06 \end{pmatrix} \circ \begin{bmatrix} 0.5 & 0.5 & 0 & 0 \\ 0.5 & 0.5 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} 0.5 & 0.5 & 0 & 0 \\ 0.5 & 0.5 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix} = \begin{pmatrix} 0.62 & 0.38 & 0 & 0 \end{pmatrix}. \quad (19)$$

4.4. Operation of the Second-Level Intelligent Fuzzy Comprehensive Evaluation Model. The second level of fuzzy synthesis is as follows:

$$V = W_U \circ R = \begin{pmatrix} 0.29 & 0.29 & 0.13 & 0.29 \end{pmatrix} \circ \begin{bmatrix} 0.212 & 0.388 & 0.16 & 0.24 \\ 0.6578 & 0.3422 & 0 & 0 \\ 0.115 & 0.457 & 0.038 & 0.39 \\ 0.62 & 0.38 & 0 & 0 \end{bmatrix} = \begin{pmatrix} 0.446992 & 0.381368 & 0.05134 & 0.1203 \end{pmatrix}. \quad (20)$$

The maximum membership principle is used to evaluate the calculation results, that is, which value of V is the largest and the frost damage of the tunnel is in which level. It can be seen that the frost damage degree of the tunnel portal section is class I (no frost damage or slight frost damage). It is recommended to set the thermal insulation layer and adopt general ditch in the portal section. The thermal insulation ditch is set up within 500 m of the tunnel portal. Since 2014, only slight freezing phenomenon has been seen at the tunnel portal section, and no obvious frost damage has occurred. The tunnel is in good operation condition, which is consistent with the results of analysis of the intelligent evaluation model proposed in this paper.

5. Conclusion

(1) Based on the investigation results of 122 seasonal frozen soil tunnels in high-latitude areas of China, four key influencing factors are determined, and an intelligent evaluation system of tunnel frost damage in cold areas is proposed. Taking a tunnel in cold regions as an application example, the scientificity and rationality of the intelligent evaluation system are proved.

(2) The intelligent fuzzy comprehensive evaluation method can be used to describe the relationship among influencing factors of tunnel frost damage in cold regions, the weight of influencing factors is calculated by analytic hierarchy process, and the main risk sources of tunnel frost damage are found out, which is an efficient and practical method for pre-evaluation.

(3) By using the subordinate function method, the improvement from qualitative analysis to quantitative index calculation is realized. The blindness of engineering analogy construction is avoided, and the scientificity and accuracy of renovation measures for frost damage have been improved. At the same time, the research results provide a theoretical basis for the improvement of the intelligent evaluation system of tunnel frost damage in cold regions.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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