Hindawi
Advances in Civil Engineering
Volume 2019, Article ID 8267406, 10 pages
https://doi.org/10.1155/2019/8267406

Research Article

Reliability Evaluation of Water-Rich Loess Tunnel with Lining Crack Based on Extension Theory

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Received 22 November 2018; Revised 14 February 2019; Accepted 6 March 2019; Published 7 April 2019

Academic Editor: Amir Si Larbi

Crack is the most prevalent disease of water-rich loess tunnels, which impacts the tunnel safety and reliability. The study aimed to investigate the multi-index of tunnel lining crack based on extension theory and reliability evaluation. A new evaluation model was built, and the matter-element concept was used to describe the reliability of a water-rich loess tunnel with lining crack. Crack width, crack depth, crack length, crack geometry, and water seepage of the Qiaoyuan tunnel were measured by intelligent crack measuring instrument, 10 m tape, laser scanner, and dosing cup. According to the analytic hierarchy process (AHP), the judgment matrix could be used to describe the relative importance of each index. Combining the maximum eigenvalue with checking consistency, the weight coefficients of 5 factors were calculated. A probabilistic statistic method and comparison of specification are performed to confirm the validity of extension theory in reliability evaluation. The results showed that the extension theory provided a reliability evaluation method of a water-rich loess tunnel with lining crack.

1. Introduction

Loess is widely distributed in the central and western China. In recent years, with the rapid development of traffic foundation construction, a large number of highway tunnels had been constructed in the loess region. Owing to the effect of rainfall and other seasonal and transient infiltration, there are many local water-rich loess layers in the loess region. The special engineering properties of loess, such as significant structural characteristic and intense water sensitivity [1, 2], make its physical and mechanical indexes to decline sharply in the water-rich environment, which will cause the lining cracks, leakage, and other problems during construction and operation [3–5]. The lining crack is the most general disease of a water-rich loess tunnel, and it impacts the tunnel safety and reliability [6–8]. Therefore, it is important for the water-rich loess tunnel with lining crack to study the reliability evaluation. Many traditional methods had been used to evaluate the reliability of tunnel lining, including field monitoring [9–11], physical model experiment [12], numerical simulation [13], probability analysis [14], and engineering analogy method. However, these methods did not take the comprehensive influencing factors of tunnel lining into consideration, and they also did not solve the incompatibility problem during the difference factors.

Extension theory has been widely used in the field of engineering technology after 1983 [15], which can solve the contradiction problem of evaluation indexes very well. But, the application of reliability evaluation method of tunnel engineering is relatively hysteretic. Kong et al. [16] established the health diagnosing method for a shield tunnel based on extension theory, and this method was applied to the Shanghai Yangze River Tunnel. Yong et al. [17] presented the comprehensive assessment of tunnel collapse risk based on integration of statistical analysis and extension theory. Hare [18] founded the model of evaluating the tunnel construction environment using the two methods (game theory and extension theory incorporating). Analytic hierarchy process (AHP)—extension synthesis method—was proposed [19], and it was known as an effective tool to evaluate the safety level of an operating tunnel.

In this study, the aim is to investigate the reliability evaluation of water-rich loess tunnel with lining crack based on extension theory. Crack width, crack depth, crack length, crack geometry, and water seepage of the Qiaoyuan tunnel were measured. The reliability evaluation model of a water-rich loess tunnel with lining crack was built, and the matter-element concept had been put forward.

2. Experiments and Methods

2.1. Extension Theory Method. The extension theory is an effective model to solve the contradictory problem of quantitative evaluation indexes. It imports the correlation function in the quantitative calculation process based on the matter-element theory, extension mathematics, and AHP. Therefore, it can transfer each evaluation index into a compatible issue and make the evaluation results and the actual situation consistent.

In the matter-element concept, the symbol of matter is defined as N, the character C, and the character value V. Therefore, the ordered triple $R = (N, C, V)$ denotes the elementary unit to describe the characteristics of things. If the matter N has n characters, we can express this matter using the following matrix:

$$R = \left(N_i, C_i, V_{ij}\right) = \begin{bmatrix} N_i, C_1, V_{i1} \\ C_2, V_{i2} \\ \vdots \\ C_n, V_{im} \end{bmatrix}. \quad (1)$$

For a transition from qualitative description to quantitative analysis, the "distance" parameter was imported in the correlation function. Then, the value of the correlation function can denote different grades of samples with characteristics C_i. Let x_0 be one point on the real axis, and let $X_0 = (a, b)$ be a given interval, the extension distance of point x_0, and interval X_0 is written as follows:

$$\rho\left(x_0, X_0\right) = \left|x_0 - \frac{a+b}{2}\right| - \frac{1}{2}(b-a). \quad (2)$$

According to the extension theory, the elementary correlation function is established to calculate the rank of things with characteristics C_i, whose formulas are shown as follows:

$$k_{c_i}\left(x_{ij}\right) = \frac{\rho\left(x_{ij}, X_0\right)}{\rho\left(x_{ij}, X\right) - \rho\left(x_{ij}, X_0\right)}, \quad (3)$$

where $\rho(x_{ij}, X_0)$ and $\rho(x_{ij}, X)$ are the extension distances between point x_{ij} and intervals X_0 and X, respectively.

As mentioned above, the correlation parameter of each index x_{ij} of evaluation matter N_i about each rank t is shown as follows:

$$k_{it}\left(x_{ij}\right) = \begin{cases} \dfrac{-\rho\left(x_{ij}, V_{ij}\right)}{\left|V_{ij}\right|}, & x_{ij} \in V_{ij}, \\[2ex] \dfrac{\rho\left(x_{ij}, V_{ij}\right)}{\rho\left(x_{ij}, V_{pi}\right) - \rho\left(x_{ij}, V_{ij}\right)}, & x_{ij} \notin V_{ij}, \end{cases}$$

$$\begin{cases} \rho\left(x_{ij}, v_{ij}\right) = \left|x_{ij} - \dfrac{a_{0ij} + b_{0ij}}{2}\right| - \dfrac{b_{0ij} - a_{0ij}}{2}, \\[2ex] \rho\left(x_{ij}, v_{pi}\right) = \left|x_{ij} - \dfrac{a_{pi} + b_{pi}}{2}\right| - \dfrac{b_{pi} - a_{pi}}{2}. \end{cases} \quad (4)$$

The correlation of each evaluation matter N_i about each rank t is defined as follows:

$$k_{it}\left(N_i\right) = \sum W_{ij} k_{it}\left(x_{ij}\right), \quad (5)$$

where W_{ij} is the weight coefficient of each evaluation character C_i, whose specific calculating method will be elaborated in the follow-on work.

After calculating the correlation value of each evaluation matter N_i about each rank t, $k_i'(N_i)$ is set to be the max $k_{it}(N_i)$, that is,

$$k_i'\left(N_i\right) = \max\left\{k_{it}\left(N_i\right), t = 1, 2, \ldots, s\right\}. \quad (6)$$

So, the value of $k_i'(N_i)$ can reflect the evaluation grade of matter N_i.

2.2. Standardization of Evaluation Parameter. The dimensions of each in situ monitoring data are not consistent, so it is necessary to weaken the dimensional effect of each index. The threshold is the most common method of standardization [20].

If the evaluation parameter is close to the minimum value, the index will be favorable, and the basic formula is shown as follows:

$$x_{ij}' = \frac{x_{ij} - x_j^{\min}}{x_j^{\max} - x_j^{\min}}. \quad (7)$$

If the evaluation parameter is close to the maximum value, the basic formula is shown as follows:

$$x_{ij}' = \frac{x_j^{\max} - x_{ij}}{x_j^{\max} - x_j^{\min}}, \quad (8)$$

where x_{ij}' is the dimensionless value, x_{ij} is the sample value, $x_j^{\max}$ is the maximum of the jth type sample value, and $x_j^{\min}$ is the minimum of jth type sample value.

2.3. Extension Theory Evaluation Procedure. Based on the extension theory, the evaluation procedure of the water-rich loess tunnel with lining crack is as follows:

First, identify the reliability evaluation indexes and influencing factors of the water-rich loess tunnel with lining cracks based on the comparability principal, integrity principal, and simplified principal. Then, determine the evaluation indexes values and grades by field monitoring, engineering analogy, and literature investigation. Next, calculate the correlation degree of each evaluation matter about each rank. Finally, specify the evaluation rank and provide technology support for the disease treatment of water-rich loess tunnel.

The concrete flowchart of the evaluation procedure is shown in Figure 1.

2.4. Project Overview. As shown in Figure 2, the Qiaoyuan tunnel is located in Qiaoyuan Village, Xiangning County, Shanxi Province, China, which passes through Lvliang Mountains, with the maximum buried depth of 114.9 m. It is a separated tunnel with uplink and downlink, and the uplink and downlink of the Qiaoyuan tunnel are 1572 m and 1626 m, respectively. The tunnel width is 10.25 m, and the height is 5 m. This tunnel is located at a loess tableland district. The tableland surface is relatively flat with a developed gully. According to the geological survey report, the stratum structure is simple with an aeolian sediment layer of Quaternary Upper Pleistocene (Q_3^{eol}) and a drifted deposit layer of Quaternary Middle Pleistocene (Q_2^{al+pl}) in top-down process. The drifted deposit layer is the most dominant surrounding rock of the tunnel, which is a self-weight collapse loess (III grade) with loose structure and developed vertical joints.

In the section ZK9 + 725~ZK9 + 845, there is a "V"-shaped gully on the surface of the mountain. The tendency of "V"-shaped gully is perpendicular to the tunnel axis. Moreover, the valley bottom appears in the section ZK9 + 785. Furthermore, the hillslope angle of valley is 25°~30°. During the construction of the tunnel, there is a bleeding phenomenon on the tunnel working face, and the concrete structure of primary support is becoming wet gradually with continuous dropping water and white crystals in regional. After one year, there are many cracks on the tunnel lining, whose width are 0.2~3.0 mm, with water seepage disease in regional. Thus, the crack is the most dominant influencing factor of safety and reliability of tunnel lining in the operation stage (Figure 2).

2.5. Monitoring of Evaluation Factors. According to the field investigation, formation and evolution mechanism of lining cracks are selected to be evaluated by five factors: crack width, crack depth, crack length, crack geometry, and water seepage. In order to guarantee the objectivity and accuracy of evaluation factors, the advanced methods are used to monitor the evaluation data in field.

2.5.1. Crack Width. GTJ-FKY intelligent crack width measuring instrument is adopted to monitor the width of lining crack. Firstly, in the process of on-site monitoring, aiming the microcamera at the crack on the surface of the lining structure and clicking the "scan" button in the touch screen to issue the command, the crack will be automatically scanned by the camera. Secondly, crack images are clearly displayed on the main screen based on the principle of electronic imaging, and the automatic acquisition and digital display of crack width are realized by using red laser scale and blue crack mark. Finally, the crack image and width data are stored automatically by the data storage in the host computer. The on-site monitoring is shown in Figure 3.

2.5.2. Crack Depth. A GTJ-FSY crack sounder can accurately monitor the crack depth of tunnel lining based on the principle of acoustic diffraction. The ultrasonic waves, which were adopted by GTJ-FSY, were used to measure the cracks. The transmitting and receiving transducers are firstly placed on the same side of the crack during the field monitoring process. When the inner edge spacing l_i of the two transducers is different (50 mm, 100 mm, and 150 mm), the sound time value t_i is read. Then T and R transducers are placed on both sides of the symmetry line with the crack as the center line. The central line of the two transducers is perpendicular to the crack strike. When l_i is different, the sound time value t_i' is read, and the crack depth is defined by the following equation:

$$d_i = \frac{l_i}{2}\sqrt{\left(\frac{t_i'}{t_i}\right)^2 - 1}. \quad (9)$$

As shown in Figure 4, to improve the accuracy of crack depth monitoring, the core-drilling method was used to verify the results as the assistant measure. Firstly, the tunnel with a lining crack was drilled by rig, and it appeared at the center position. Secondly, obtaining the concrete core and measuring the crack depth by the tape, the values could be used to verify the aforementioned results objectively.

2.5.3. Crack Length. The "marking and periodic measure" method was used to monitor the crack length, which could reflect the development trend in its right perspective. Mark both ends of cracks by the red spraying paint, and then measure the crack length by a tape. After a regular interval, the aforementioned method is adopted again so that the final steady-state value of lining crack is obtained, as shown in Figure 5.

2.5.4. Crack Geometry. As shown in Figure 6, the crack geometry can be classified to meshy crack, inclined crack, longitudinal crack, and circumferential crack through the laser scanning and artificial judgment, which can be represented by dimensionless numbers (G_i = 1, 2, 3, 4) in line with the reliability influence degree of crack geometry. Then, according to the quantity of all types of lining cracks, the weight coefficient (W_i) of cracks are determined, and the final measurements of crack geometry are calculated by the formula $G_i' = G_i \cdot W_{is}$ (Figure 6).

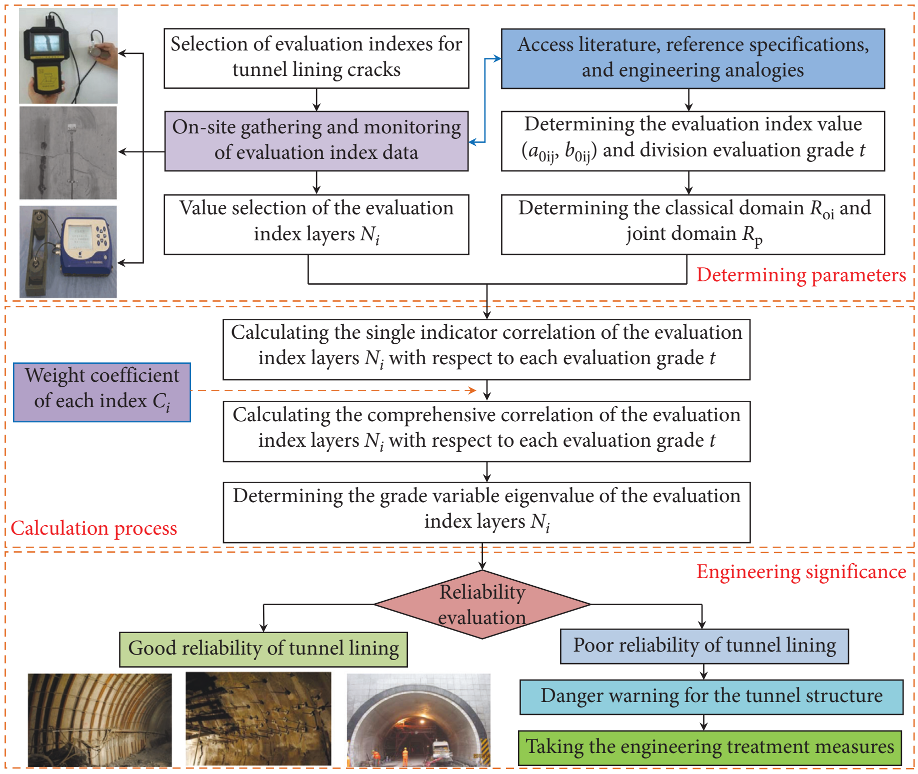

Figure 1: Reliability evaluation flowchart of a tunnel with lining crack.

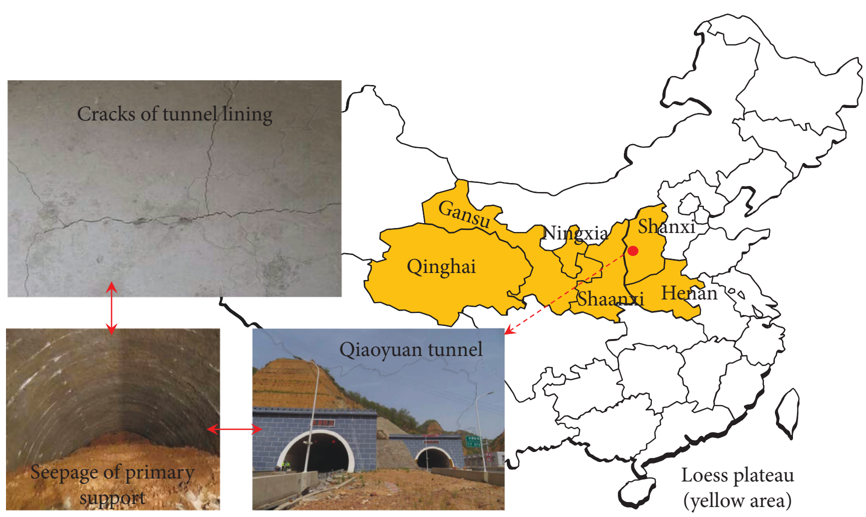

Figure 2: The study of tunnel lining with crack during operation stage.

2.5.5. Water Seepage. According to the amount of water leakage, there are four categories: wet stain, seepage, dripping, and gushing. In the field, it can be classified by using the dosing cup to collect the water and calculate the amount of water seepage in unit of time, such as ml/min and L/h, as shown in Figure 7.

3. Results and Discussion

3.1. Field Monitoring. As for the Qiaoyuan tunnel, there are farmland irrigation and heavy rainfall on ground surface, which cause the dynamic increase of the water content of surrounding rock and the rapid development of lining cracks in the section ZK9 + 725~ZK9 + 845. According to the engineering practice, 6 typical sections of tunnel lining (K_1~K_6) are monitored by the aforementioned methods. Each section length is 10 m, and the start-end period of field monitoring are 2016.6~2017.4. The detailed monitoring results are shown in Table 1.

As shown in Table 1, the values are very complex and disorderly. Taking tunnel segment K_1 as an example, the

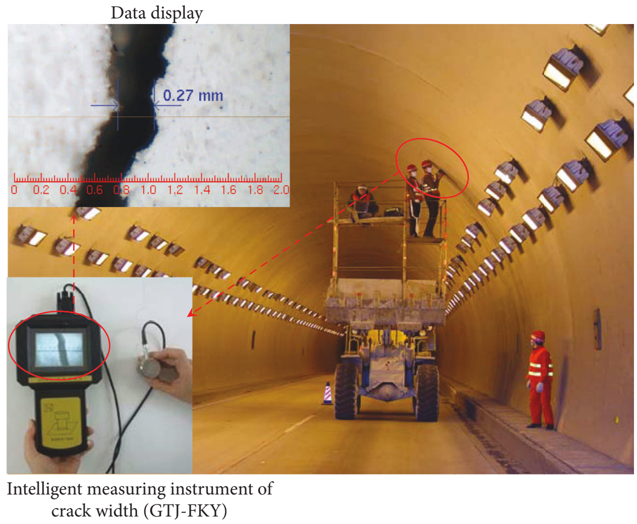

Figure 3: Crack width monitoring.

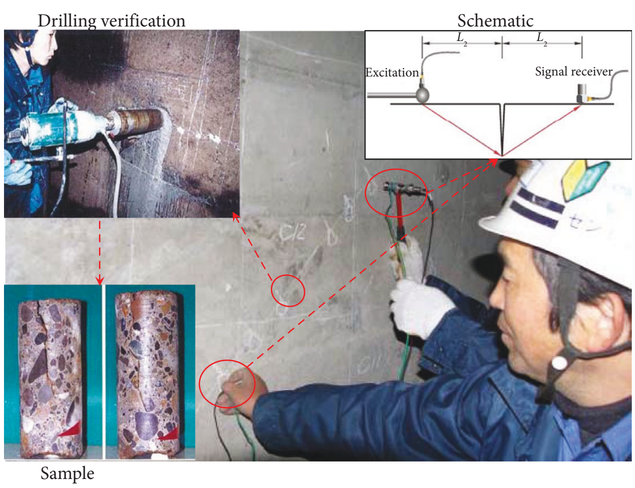

Figure 4: Crack depth detection.

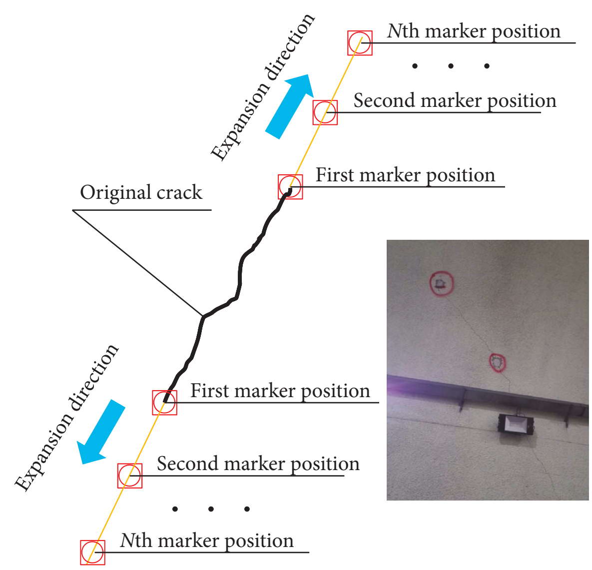

Figure 5: Crack length monitoring.

crack width is 0.38 mm, and the crack length is 4.60 m. If the traditional evaluation system with a single index of crack width or crack length is used, the evaluation grades are II and I, respectively, and the evaluation results are self-contradictory. So it is necessary to study the new method of reliability evaluation to avoid contradictory.

3.2. Reliability Grade Evaluation. At present, there are different standards in dealing the reliability classification of tunnel lining. The evaluation grade is classified into such four categories (very good, good, fair, and poor) based on the current codes. Previous researches and literature reviews used the symbols I, II, III, and IV to represent the grades of reliability [16, 19]. The reliability grades are shown in Table 2.

3.3. Standardization Value. As shown in Tables 1 and 2, the smaller the value is, the more favorable the index is. So equation (7) could be used to calculate for standardization. The results are shown in Table 3.

As shown in Table 3, after the standardization treatment, the values of field monitoring and evaluation grade are represented by the numerical ranges of 0~1, which eliminate the negative effects of the dimension and magnitude entirely. Moreover, it would improve the accuracy and objectivity of the evaluation results.

3.4. Grade Evaluation of Judgment Matrix. According to the above description, 5 main factors and 4 evaluation grades are calculated. The matter-element matrix and classical-domain matrix are established, based on the standardization values:

Figure 6: Crack geometry monitoring.

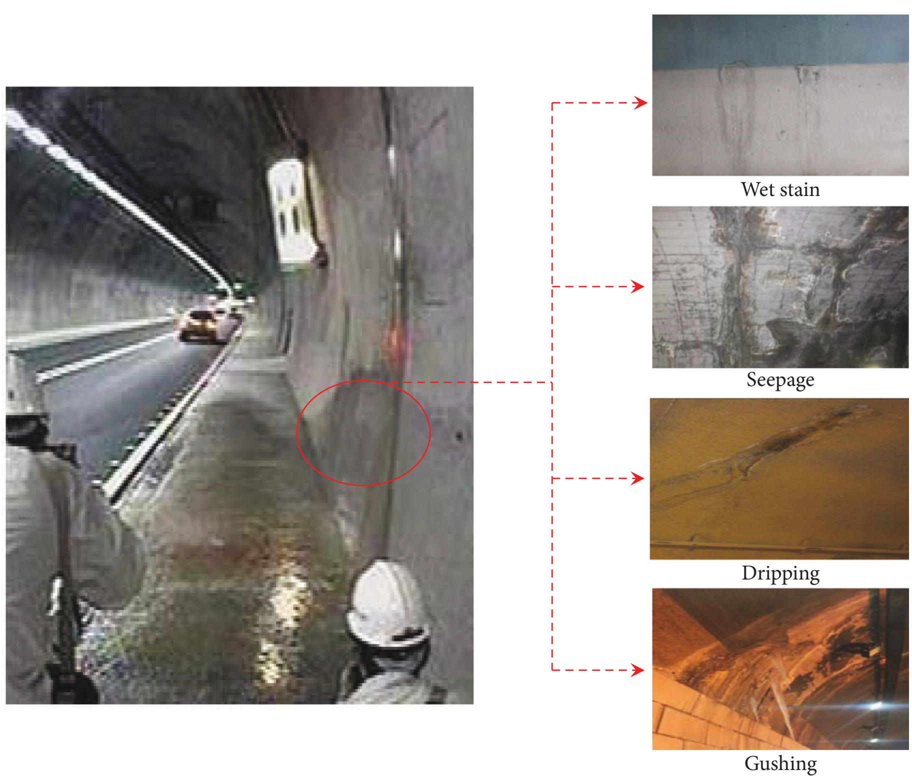

Figure 7: Water seepage monitoring.

$$R_{\mathrm{P}} = \begin{bmatrix} K & K_1 & K_2 & K_3 & K_4 & K_5 & K_6 \\ c_1 & 0.07 & 0.53 & 0.23 & 0.18 & 0.31 & 0.80 \\ c_2 & 0.36 & 0.14 & 0.11 & 0.21 & 0.71 & 0.92 \\ c_3 & 0.09 & 0.13 & 0.01 & 0.40 & 0.04 & 0.76 \\ c_4 & 0.76 & 0.68 & 0.28 & 0.32 & 0.64 & 0.88 \\ c_5 & 0.29 & 0.16 & 0.11 & 0.23 & 0.07 & 0.86 \end{bmatrix},$$
$$R_{\mathrm{K}} = \begin{bmatrix} N & N_1 & N_2 & N_3 & N_4 \\ C_1 & <0, 0.04> & <0.04, 0.20> & <0.20, 0.60> & <0.60, 1.00> \\ C_2 & <0, 0.20> & <0.20, 0.40> & <0.40, 0.60> & <0.60, 1.00> \\ C_3 & <0, 0.10> & <0.10, 0.23> & <0.23, 0.49> & <0.49, 1.00> \\ C_4 & <0, 0.40> & <0.40, 0.60> & <0.60, 0.80> & <0.80, 1.00> \\ C_5 & <0, 0.09> & <0.09, 0.19> & <0.19, 0.49> & <0.49, 1.00> \end{bmatrix}, \qquad (10)$$

where R_{p} is the matter-element matrix after standardized treatment, which lists five evaluation indexes $C_1 \sim C_5$ of $K_1 \sim K_6$ in the tunnel section to be evaluated and the corresponding values of each index. R_{k} is the classical-domain matrix after standardized treatment, corresponding to each evaluation index. This matrix gives the prespecified evaluation criteria and lists the range of classical-domain values.

3.5. Weight Coefficient. The weight coefficient is one of the important parameters in the evaluation system, which has a great effect on the veracity of reliability evaluation. At present, the AHP (analytic hierarchy process) is the optimal method to determine the weight coefficient with logicality, practicality and systemicity. The procedure of determining weight coefficient is shown in the following sections.

3.5.1. Building the Judgment Matrix. As shown in Table 4, according to the multiple comparison calibration and the judgment principle, the compare standards of parameters are established by the fuzzy mathematics theory.

According to the compare standard, combining with the field situation of the Qiaoyuan tunnel, the importance standard value among the 5 main parameters are established, and the judgment matrix S is shown as follows:

$$S = \begin{bmatrix} 1 & 2 & 5 & 7 & 4 \\ \frac{1}{2} & 1 & 3 & 5 & 4 \\ \frac{1}{5} & \frac{1}{3} & 1 & 3 & 5 \\ \frac{1}{7} & \frac{1}{5} & \frac{1}{3} & 1 & \frac{1}{3} \\ \frac{1}{4} & \frac{1}{4} & \frac{1}{5} & 3 & 1 \end{bmatrix}. \qquad (11)$$

3.5.2. Calculating Weight Set. The characteristic vector of the judgment matrix is determined by calculating the maximum feature root based on the linear algebra method. Then, correspondingly, we can get the weight set of evaluation indexes through the normalization processing of the characteristic vector by the following formulas:

$$W = \left\{ \frac{w_1}{\sum_{i=1}^{n} w_i}, \frac{w_2}{\sum_{i=1}^{n} w_i}, \dots, \frac{w_n}{\sum_{i=1}^{n} w_i} \right\}. \qquad (12)$$

According to the judgment matrix of this engineering example and the abovementioned formulas, the weight set is $W = \{0.448, 0.286, 0.145, 0.046, 0.075\}$.

3.5.3. Checking Consistency. Whether the weight coefficient is reasonable or not, it is necessary to carry out the checking consistency. The consistency index C_{I} and random consistency ratio C_{R} are solved by the formulas:

$$C_{\mathrm{I}} = \frac{\lambda_{\max} - n}{n - 1}, \qquad (13)$$

$$C_{\mathrm{R}} = \frac{C_{\mathrm{I}}}{R_{\mathrm{I}}}. \qquad (14)$$

In formula (13), $\lambda_{\max}$ is the maximum eigenvalue of the judgment matrix, which is solved by the square root method, and the formula is

$$\lambda_{\max} = \sum_{i=1}^{n} \frac{(AW)_i}{n\omega_i}. \qquad (15)$$

As shown in Table 5, according to the order of 5, the value of random consistency index R_{I} is taken as 1.12.

After a series of calculation, the $\lambda_{\max}$ value is 5.352, the C_{I} value is 0.88, and the C_{R} value is 0.079. Owing to $C_{\mathrm{R}} < 0.1$, the consistency of weight coefficient is satisfied.

3.6. Correlation Degree. As shown in Table 6, the specific classification criteria showed that probability statistics method mainly used probability statistics knowledge to

Table 1: Monitoring results of crack disease.

Tunnel section	Width (mm)	Depth (cm)	Length (m)	Geometry	Water seepage ($L/m^2 \cdot d^{-1}$)
K_1	0.38	18.21	4.60	2.90	0.30
K_2	2.68	6.82	6.10	2.70	0.17
K_3	1.18	5.64	1.20	1.70	0.12
K_4	0.92	10.42	16.70	1.80	0.24
K_5	1.56	35.47	2.60	2.60	0.08
K_6	4.02	46.17	30.80	3.20	0.86

Table 2: Reliability evaluation grade of tunnel lining with crack.

Reliability grade	Width (mm)	Depth (cm)	Length (m)	Geometry	Water seepage ($L/m^2 \cdot d^{-1}$)
I	0.02~0.2	0~10	1.0~5.0	1.0~2.0	0.01~0.10
II	0.2~1.0	10~20	5.0~10.0	2.0~2.5	0.10~0.20
III	1.0~3.0	20~30	10.0~20.0	2.5~3.0	0.20~0.50
IV	3.0~5.0	30~50	20.0~40.0	3.0~3.5	0.50~1.00

Table 3: Standardization values of the evaluation parameter.

Category	Item	Width	Depth	Length	Geometry	Water seepage
Tunnel section	K_1	0.07	0.36	0.09	0.76	0.29
	K_2	0.53	0.14	0.13	0.68	0.16
	K_3	0.23	0.11	0.01	0.28	0.11
	K_4	0.18	0.21	0.40	0.32	0.23
	K_5	0.31	0.71	0.04	0.64	0.07
	K_6	0.80	0.92	0.76	0.88	0.86
Reliability grade	I	0~0. 04	0~0.20	0~0.10	0~0.40	0~0.09
	II	0.04~0.20	0.20~0.40	0.10~0.23	0.40~0.60	0.09~0.19
	III	0.20~0.60	0.40~0.60	0.23~0.49	0.60~0.80	0.19~0.49
	IV	0.60~1.00	0.60~1.00	0.49~1.00	0.80~1.00	0.49~1.00

Table 4: Meaning of the compare standard.

Importance standard value	Meaning
1	The parameters X_i and X_j are equally important
3	The parameter X_i is slightly more important than X_j
5	The parameter X_i is more important than X_j
7	The parameter X_i is very important than X_j
9	The parameter X_i is absolutely important than X_j

The standard values 2, 4, 6, and 8 denote the median value of 1–3, 3–5, 5–7, and 7–9, respectively.

Table 5: The value of the random consistency index R_I under different order n.

n	3	4	5	6	7	8	9	10	11
R_I	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51

Table 6: Probability statistics method for evaluation grading.

Reliability probability	$P_s \geq 95\%$	$85\% \leq P_s < 95\%$	$75\% \leq P_s < 85\%$	$65\% \leq P_s < 75\%$
Grade	I	II	III	IV

determine the reliability probability of the tunnel lining structure so as to determine the reliability level according to the reliability probability [21].

Table 7: Comparing specification method for evaluation grading.

Grade	Crack state
I	General cracking, no development trend
II	l (length) < 5 m, b (width) < 3 mm
III	l (length) < 5 m, 3 mm ≤ b (width) < 5 mm, rapid development
IV	l (length) ≥ 5 m, b (width) ≥ 5 mm, rapid development, arch cracking was massive, may drop, and peeling

As shown in Table 7, the results evaluated from the referencing code method are taken to confirm the accuracy and objectivity of the extension theory method. The comparing specification method mainly refers to the qualitative judgment standards for lining cracks given by "Technical Specifications of Maintenance for Highway Tunnel" (JTG H12-2015) and "Assessment Standard of the Bridge and Tunnel Structural Degradation for Railway Tunnel" (TB/T 2820.2-1997).

As shown in Table 8, the correlation between each tunnel segment (K_1–K_6) and each evaluation grade (I–IV) is accurately calculated. The correlation coefficient is [−0.252, 0.038, −0.253, −0.645], when we take tunnel segment K_1 as an example. Therefore, according to the principle of maximum membership degree, $k_1'(N_1) = \max[-0.252, 0.038, -0.253, -0.645] = 0.038$. So, the reliability grade of the tunnel lining section K_1 is determined as II (good).

Table 8: Correlation degrees of tunnel lining, evaluation grades, and results comparison of the difference methods.

Sections	Correlation degree				Extension theory	Probabilistic statistic	Comparing specification
	I	II	III	IV			
K_1	−0.252	0.038	−0.253	−0.645	II	II	II
K_2	−0.129	−0.257	−0.136	−0.567	I	I	I
K_3	0.009	−0.349	−0.401	−0.653	I	I	I
K_4	−0.129	−0.360	0.015	−0.780	III	III	III
K_5	−0.071	−0.156	0.108	−0.563	III	II	IV
K_6	−0.315	−0.241	−0.376	−0.093	IV	III	IV

Stability of water-rich loess tunnel with lining crack is divided into four classes named very good (I), good (II), fair (III), and poor (IV) by the orders of stability from the highest to the lowest.

As shown in Table 8, it is found that the evaluation results of extension theory are in good agreement with the other two methods; besides, there is only a little of difference. It deduced that the extension theory presented the validity in tunnel lining reliability evaluation, integrated indexes of crack, and avoided the evaluation bias.

4. Conclusions

The field monitoring and theoretical analysis were used in the water-rich loess tunnel, and the reliability evaluation of tunnel lining was performed. The following conclusions are obtained:

(1) The extension theory provides a good method for reliability evaluation. It overcomes the drawback of conventional methods with fixed factors.

(2) The determination of weight coefficient is the most important step in the entire process of reliability evaluation, which influences the accuracy of the evaluation results significantly. The AHP and weight coefficients are determined, which overcomes the subjectivity of expert assessment.

(3) Judgment matrix can provide the reliability grades of the water-rich loess tunnel with lining cracks. Moreover, the values of correlation degrees achieve a quantitative description of the reliability grades, which can provide the "distance" from the actual situation to the each evaluation grades.

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The authors thank the workers, foremen, and safety coordinators of the main contractors for their participation. The authors also wish to thank the engineers Chuanchuan Zhang and Tongsheng Yu for assistance in gathering field data. This work was financially supported by the Science and Technology Demonstration Project of Transport Ministry in China (grant no. 2016009), the Science and Technology Project of Transportation Department in Shanxi Province (grant nos. 2013-1-3 and 2015-1-18), and Shanxi Provincial Key Research and Development Program (grant no. 201703D111027).

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