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Research Article

Study on Disease Mechanism and Theoretical Quantification Method of Tunnel Structure

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Most tunnel structures tend to have different degrees of structural damage such as leakage, concrete cracking, lining salinization, and falling blocks after the operation for a period. Compared with the diversity of tunnel disease detection methods, there are few studies on the methods of quantifying and evaluating the main structural diseases of the lining. Based on the regular inspection data of expressway tunnels in Liaoning Province, this paper summarizes the distribution characteristics and laws of existing structural defects of tunnel lining. In addition, based on the in-depth study of the main structural diseases of the tunnel, the extenics theory is used to extract, quantify and classify several indicators that can accurately reflect the health status of the structure, and then establish the corresponding matter-element model to determine the weight of each indicator and the tunnel structure. The comprehensive correlation degree of disease grades is combined with the qualitative evaluation and quantitative research of lining structure diseases to construct a health evaluation system for tunnel lining structures, which is convenient for managers to make reasonable decisions. At the same time, combined with the actual test data of tunnel engineering, the calculation and analysis of the extension model are carried out to verify the engineering applicability of the model.

1. Introduction

The structural defects of tunnel engineering may occur at any stage in the whole life cycle. The common lining structure diseases in the industry mainly include leakage water, concrete deterioration, lining corrosion peeling, and back voids [1, 2]. In the same tunnel engineering main body, various structural diseases often do not exist alone. They affect each other, and the occurrence of one disease will aggravate the development of other diseases, thereby reducing the bearing capacity and structural durability of the tunnel structure, threatening driving safety and comfort [3–5]. Nanakorn and Horii [6] studied on the defects of tunnel structure based on the fracture mechanics design method. Singh et al. [7] proposed the method of surrounding pressure assessment based on the pressure assessment in the Himalayan tunnel. Richards [8] made a systematic review of tunnel monitoring and repair, including international practice and lessons. Meguid and Dang [3] evaluated the effect of corrosion defects on tunnel structure. The analysis showed that corrosion can significantly affect the surrounding stress of the tunnel structure. In situ monitoring is one of the key activities in tunnel construction. Lai et al. [9] used a fiber Bragg grating (FBG) sensing technology to monitor the loess tunnel structure and conducted the structural safety assessment based on the monitoring results. FBG is suitable for remote real-time monitoring, which has many advantages including high accuracy, multiplexing, electromagnetic interference resistance, and good repeatability. It provided a new method for in situ monitoring and safety assessment of tunnels under complex geological conditions. Asakura and Kojima [10] classified the structural safety grade into four grades: 3A, 2A, A, and B. And they more clearly and carefully classified the types of tunnel diseases and the discrimination criteria. Inokuma and Inano [11] qualitatively judged the soundness of the tunnel, but did not quantitatively evaluate the safety state of the tunnel. Friebel and Krieger [12] indicated how to measure, describe, and evaluate the results, but only the method of evaluating the test results was presented and the method of quantitatively evaluating the tunnel safety was not given.

In Chinese disease evaluation standard [13], the subitem of disease evaluation included the pavement, overhaul road, suspender and buried parts, and traffic signs. Therefore, it can evaluate the overall condition of the tunnel, including auxiliary facilities and structures, but it cannot evaluate the lining structure of the tunnel alone. Lai et al. [14] have carried out the in situ monitoring of the defects such as the liner crack, tunnel seepage, and liner void of the multiarch tunnel, analyzing the distribution characteristics and development law of the defects. Based on the test results, the safety assessment of each defect was carried out according to the Assessment Criteria [13], but the overall evaluation conclusion of the tunnel structure defects was not given.

In tunnel engineering, most problems can be studied and analyzed quantitatively with a lot of scientific research. Due to the influence of multiple factors, the qualitative evaluation of the tunnel structure often has randomness, ambiguity, and variability, and it is difficult to ensure the health of the tunnel structure. The above literature mainly classified diseases according to the severity of possible hazards caused by diseases. The standard and number of classifications of this classification method are qualitative and lack detailed quantitative analysis and research of diseases, so it is difficult to directly apply to structural safety calculation. Therefore, it is necessary to study the classification, quantification, and classification methods of tunnel diseases thoroughly in combination with the needs of tunnel health diagnosis methods and calculation models, sequentially put forward perfect classification, quantification, and classification methods, and lay a foundation for the safety research and health diagnosis of tunnel diseases.

This paper will combine the periodic inspection data of highway tunnel engineering in Liaoning Province, China, to summarize the common types of tunnel diseases, analyze the impact of tunnel construction defects and structural deterioration on structural durability, and explore the regular characteristics and development mechanism of durability diseases. At the same time, considering the disease site detection data of typical interval tunnels in the province, this study not only qualitatively put forward the evaluation index of tunnel diseases, but also established the health evaluation model of tunnel lining structure by quantitative method, which realized the quantitative treatment of main structural diseases of tunnels and then took the quantitative index of diseases as the basis for subsequent evaluation of lining health status. The mechanical characteristics of disease structure are theoretically supported and have important engineering value.

2. Types of Tunnel Structure Diseases and Analysis of Tunnel Lining Deterioration Diseases and Causes

The cracking of the lining structure is one of the most common diseases in tunnel engineering. The lining disease statistics of more than 5,000 road tunnels in China have found that about one-third of the tunnel lining structures have different forms of cracking and dislocation; most cracks that appear in the tunnel were put into operation early, even in the tunnel lining construction process [15, 16]. The diseases can be classified into different types which are shown in Table 1, which focuses on the lining deterioration disease including types and main causes.

2.1. Tunnel Lining Cracking Disease and Its Cause Analysis. The cracking of the lining structure can be divided into circumferential crack, longitudinal crack, and oblique crack according to the positional relationship between the crack direction and the longitudinal axis of the tunnel [17, 18], and according to the crack space staggered way, it can be divided into one-way displacement and two-way displacement. As to a three-way shift, it is generally considered that the circumferential crack is a crack caused by the tunnel structure adapting to the temperature shrinkage and the deformation of the construction pouring concrete, which has little effect on the overall bearing capacity of the lining structure. The longitudinal cracks and oblique cracks at the top of the tunnel arch or the position of the sidewall are mostly stress cracks, and the overall bearing capacity of the lining structure is greatly weakened. The longitudinal crack is parallel to the tunnel axis, which has the greatest impact on the bearing capacity of the tunnel structure. In severe cases, it may even cause tunnel collapse [8, 19–21].

2.1.1. Cause Analysis. According to the crack statistics and inspection report of the tunnel lining, the cause of the lining cracking can be classified as the internal cause of the structure and the external cause of the environment. From the internal point of view, the concrete lining must have fine pores and structural defects during the pouring process. These tiny defects are the source of structural cracks. The environmental external factors mainly include uneven confining pressure, frost heave, and steel rusting. Under the combined action of internal and external factors, the internal forces of the lining structure will gradually increase, and the partial lining stress imbalance will be intensified. According to the strength theory, the strength of the material with open cracks is controlled by the concentrated stress near the crack tip [22–24]. When the stress near the crack tip exceeds its tensile strength, the crack propagation will occur.

2.2. Tunnel Lining Corrosion, Steel Rust Rise, and Cause Analysis. Most of the tunnel lining is made of concrete. After the operation of the tunnel for a period, the surface corrosion of the concrete and the rust of the steel will inevitably occur. This is caused by many factors such as

Table 1: The types of tunnel diseases.

Tunnel diseases	Manifestation	Causes
Leakage water	Seepage Dripping Gushing	Geological conditions High water pressure Geological exploration inaccurate Construction factor Operation maintenance
Frost damage	Icecovering Freezing Icicle Lining cracks	Temperature Water Surrounding rock Engineering measure
Lining voids	Lining cracks	Over excavation Concrete properties
Lining deterioration	Lining corrosion peeling Lining cracks Lining corrosion Steel rust rise	Leakage water Frost damage Salt injury Surrounding rock pressure

construction quality, operating environment, and materials themselves (Figure 1).

Concrete materials will have carbonization, salt rot, and slag removal as the operating time increases. The carbonization phenomenon will reduce the compactness of the concrete structure to a certain extent, thereby reducing the strength and durability of the lining and accelerating the corrosion rate of the material.

Freezing and thawing cycles are often accompanied by delamination and leakage of the lining. The temperature of highway tunnels in Liaoning Province is lower than −5°C. The occurrence of freeze-thaw cycles tends to aggravate the deterioration of concrete, resulting in an increase of internal cracks in concrete structures. The cracks gradually expand or even penetrate, resulting in a decline in the bearing capacity of the lining structure, and the safety of vehicle traffic will be impacted [25, 26].

The root cause of concrete salt damage is that the salt in the pore water of the surrounding rock under the lining is too high. When the waterproof layer behind the lining is damaged, the high-salt pore water will diffuse along the water seepage channel and penetrate into the concrete. Due to the decrease of water content, it gradually precipitated to form crystals. The formation of crystals often leads to the expansion of the volume of the salt, and the surface of the concrete is highly susceptible to corrosion and spalling, which weakens the stiffness of the section of the lining.

Figure 1: Corrosion of tunnel lining and corrosion of steel bar.

2.3. Tunnel Lining Spalling, Falling-Off Block, and Cause Analysis. Generally speaking, the lining of the tunnel lining is often a direct manifestation of the structural deterioration to a certain extent (Figure 2). The reason is that the internal factors such as material cracking, corrosion, and strength reduction are formed together with external factors such as structural bias and frost heave. For example, the lining of the lining during construction is uneven. When the structure is subjected to a bias load, the cracking load of the concrete is reduced, and the concrete in the bending zone is easily crushed. In addition, because the construction quality is difficult to control during the concrete pouring process, the load void area is easy to appear behind the cavity, which is not conducive to the formation of the tunnel lining annular force system.

Figure 2: Tunnel lining exfoliation in the operation stage.

3. Statistical Analysis of Road Tunnel Diseases

3.1. Overview of Road Tunnels. There are more than 30 ordinary highway tunnels in Liaoning Province, with a total length of 22102 m. They are distributed in 8 prefecture-level cities. There are 6 long tunnels with a total length of 9353 m, accounting for 42.3%; 12 tunnels with a total length 8862 m, accounting for 40%; and 12 short tunnels with a total length of 3887.9 m. A total of 12 tunnels were tested in this study, with a total length of 11576 m. There are 5 long tunnels with a total length of 7358 m, 4 medium tunnels with a total length of 3,080 m, and 3 short tunnels with a total length of 1138 m.

3.2. Structural Elements

3.2.1. Sanjialing Tunnel. There are 139 cracks in the tunnel with a total length of 1169.7 m. Among them, there are 93 tunnel lining cracks, accounting for 66.9% of the total, and 46 noncircular cracks, accounting for 33.1% of the total; there are 27 longitudinal cracks in the crack, accounting for 58.7% of the total number of noncircumferential cracks, and other cracks account for 41.3% of the total number of noncircumferential cracks. As shown in Figure 3, the concrete lining of the tunnel lining is exposed and rusted; the joints of the construction joints, the sidewalls, and the arched joints are severely infiltrated; and the sidewalls and arches are seriously eroded by water.

3.2.2. Bapanling Tunnel. There are 211 cracks in the tunnel, with a total length of 2009 m: 142 were circumferential cracks and the cumulative length is 1702 m, accounting for 67.3% of the total, and 69 were noncircular cracks and the cumulative length is 306 m, accounting for 32.7% of the total; there are 45 longitudinal cracks in the noncircumferential crack, and the cumulative length is 267 m, accounting for 65.2% of the total number of noncircumferential cracks, and the oblique cracks account for 34.8% of the total number of noncircumferential cracks. The circumferential crack is 0.5~5 mm wide, the noncircular crack is 0.3~2 mm wide, and the individual cracks seep water. The circumferential crack length distribution ranges from 1 to 5 m, and the longitudinal crack distribution length is 0.8~20 m (Figure 4).

3.2.3. Tiebeishan Tunnel. There are 5 seepage phenomena in the lining. 2 locations are on the left side of the arch, and 3 places are on the right side of the arch, accumulating 6.4 m^2; the tunnel has 11 circumferential cracks, the length range is 1 m~20 m. The maximum crack width is 0.75 mm; there are 30 longitudinal cracks, the maximum crack width is 2 mm, and the length range is 5 m~15 m; there are 2 oblique cracks, the maximum crack width is 1 mm, and the length is 10 m. There are 5 peelings at the construction joint, with a total area of 0.22 m^2. The thickness inspection of the lining is shown in Figure 5. Only limited typical radar images of structural defects are taken.

3.2.4. Dakongling Tunnel. There are 39 cracks in the tunnel with a total length of 1065.5 m: one is tunnel lining ring crack, accounting for 2.6% of the total, and 38 are noncircular cracks, accounting for 97.4% of the total, and the crack width is 0.25~2 mm. The noncircular direction is mainly dominated by longitudinal cracks at the sidewalls and the arch waist, as shown in Figure 6. Most of the cracks in the arch have water seepage marks, mostly whitening. During the test, it was found that the lining surface was mostly wet and there was water on both sides of the road.

3.3. Statistical Analysis of Structural Diseases. Due to space limitations, only the typical tunnels and related diseases are listed in this test. Through the statistical analysis of the main forms and locations of various diseases in the tunnel, the following can be obtained:

(1) The proportion of cracks in the tunnel lining is usually between 60% and 70%, and it occurs mostly in the separation zone of the lining, indicating that the cracks are mostly structural cracks.
(2) The longitudinal cracks mostly exist in the tunnel arch waist position, the maximum length of the continuous length is less than 15 m, and the crack width is between 0.1 mm and 1.5 mm.
(3) The leakage problem of the lining is not prominent. The maximum leakage of a single tunnel is 5, and the cumulative maximum area is 17.15 m^2.
(4) Through the geological radar, the lining thickness and the back cavity are detected. The lining thickness compliance rate is above 70%, and the individual tunnels are not densely connected.
(5) The maximum delamination of the single tunnel lining is 5, and the location is at the arched construction joint. The total area of the flaking is 0.22 m^2.

4. Construction of Disease Evaluation Model for Tunnel Lining Structure

The combination of extension theory and analytic hierarchy process is used to construct the evaluation model of tunnel structure disease. By constructing the evaluation model to explain the law of the problem, the incompatibility problem can be compatibilized and the quantitative analysis of the analysis results can be realized. Therefore, the results are more reasonable and clear.

4.1. Model Building Steps. The specific steps are as follows: determination of the classical domain, the local domain, and the object to be evaluated of the tunnel structure disease. When the object to be evaluated is determined, the evaluation index of the tunnel disease evaluation model is compared by the analytic hierarchy process and the relative importance judgment criterion to form a judgment matrix, and then the mean or the square root of each row of judgment indicators is calculated. After the numerical value, the corresponding values of each index are normalized, and the corresponding weights of each index in the target problem are obtained. The open-square values corresponding to each index are normalized, the weight vector of each index in the target model is

(a) (b)

Figure 3: Typical disease map of Sanjialing tunnel.

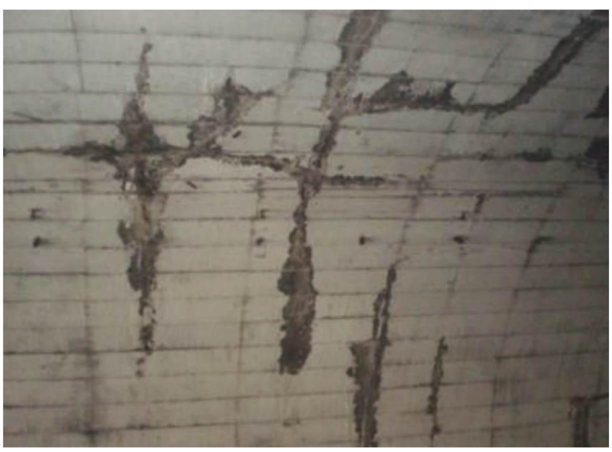

Figure 4: Typical disease map of Bapanling tunnel.

Figure 5: Typical disease map of Tiebeishan tunnel.

obtained, the maximum eigenvalue calculation of the judgment matrix is performed, and finally, the consistency test is performed [27]. When all the above parameters are determined, the target tunnel structure disease level can be determined.

4.2. Selection of Evaluation Indicators and Status Values. In the process of evaluating the disease level of the tunnel structure, the disease level and evaluation index are very important. The determination of these control items often requires experts or referring to industry norms. However, for the classification of tunnel engineering structural disease grades, the only specifications that can be referred to are the "Technical Specifications for Highway Tunnel Maintenance." As shown in Table 2, the diseases in the scoring weight table include roads, maintenance roads, and traffic signs. Therefore, it is not appropriate to apply this specification to determine the disease level of the tunnel structure.

In view of the above situation, referring to the technical assessment standard of civil engineering structure in the Technical Specifications for Highway Tunnel Maintenance and the common diseases occurring in the actual tunnel, the tunnel structural disease evaluation index is defined as lining cracking, water leakage, and insufficient lining thickness. There are five items in the back hole, lining delamination, and concrete material strength deterioration. The value of the status value corresponding to each evaluation index is 0–4, as shown in Tables 3–8. The evaluation indicators were scored according to the test results and the technical status evaluation criteria, and then the tunnel structure evaluation level was determined by the extension theory. The technical status of the tunnel structure is divided into four levels: intact state, slight damage, medium damage, and severe damage.

5. Application of Evaluation Model in Tunnel Engineering

5.1. Project Overview. The Tiebeishan tunnel was built in 2006 with a total length of 178 m and a tunnel section with a net width of 7 m. Each side has a 1.0 m maintenance road with a vertical height of 5 m and a longitudinal slope of 2.5%. The lining is made of reinforced concrete and the design standard is the secondary road standard. Maintenance records over the years are as follows: in 2008, the drainage facilities of the tunnel were repaired, and drainage pipes were added; the concrete was paved for maintenance. In

Figure 6: Typical disease map of Dawaling tunnel.

Table 2: Weight table of various subitems of civil construction.

Suboption		Item weight w_i	Suboption	Item weight w_i
Hole		15	Overhaul	2
Hole gate		5	Drainage facility	6
Lining	Structural damage Leaking water	40	Suspended ceiling and embedded parts Interior decoration	10 2
Pavement		15	Traffic signs, markings	5

Table 3: Evaluation criteria for the development of cracks.

Crack width b (mm)		Crack length l (m)		Rating status
$b > 3$	$b \leq 3$	$l > 5$	$l \leq 5$	
✓		✓		3/4
✓			✓	2/3
	✓	✓		2
	✓		✓	2

2014, the tunnel was bonded with steel and carbon fiber cloth. The scene of the tunnel structure damage is shown in Figure 7.

5.2. Summary of Tunnel Test Results. Leakage water disease and lining surface detachment: there are 5 water seepage diseases in the lining. 2 locations are on the left side of the arch, and 3 positions are on the right side of the arch, accumulating 6.4 m^2. There are 5 delaminations, and the locations are all in the sidewall construction joints, with a total area of 0.22 m^2 (Figure 8).

Cracking disease of lining: there are 11 circumferential cracks. The maximum crack width is 0.75 mm, and the length range is 1 m–20 m. There are 30 longitudinal cracks. The maximum crack width is 2 mm, and the length range is 5 m–15 m. There are 2 oblique cracks. The width is 1 mm, and the length is 10 m (Figure 9).

The insufficient thickness of lining and disease in the back cavity were measured by ground-penetrating radar equipment, where the abscissa of the radar image represents the longitudinal direction of the tunnel, and the unit is m; the ordinate represents the depth along the radial direction of the tunnel, and the unit is m. The detection results show that the effective thickness of the two linings is 10% smaller than the minimum design thickness, and the tunnel has a large range of initial lining and two linings combined not dense. Due to space limitations, only typical structural defect radar images are captured.

The change of the strength of the concrete material: in the strength test of the concrete, the strength of the tunnel lining concrete was found to be 21.1 MPa, and the design strength of the concrete was 18 MPa, so the requirements were met.

5.3. Determination of Classic Domains and Sections in the Evaluation Model. According to the matter-element theory, the classical domain of matter elements in the disease evaluation system is shown in the following equation:

$$
\begin{aligned}
R_{ab} = (N_i, C, \mu) &= \begin{bmatrix} N_i & C_{i1} & \mu_{i1} \\ & C_{i2} & \mu_{i2} \\ & \vdots & \vdots \\ & C_{im} & \mu_{im} \end{bmatrix} \\
&= \begin{bmatrix} N_i & C_{i1} & [\mu_{i1\,\min}, \mu_{i1\,\max,}] \\ & C_{i2} & [\mu_{i2\,\min}, \mu_{i2\,\max,}] \\ & \vdots & \vdots \\ & C_{im} & [\mu_{im\,\min}, \mu_{im\,\max,}] \end{bmatrix},
\end{aligned}
\tag{1}
$$

Table 4: Evaluation criteria for failure to determine whether cracks develop.

Crack width b (mm)			Crack length l (m)			Rating status
$b > 5$	$5 \geq b > 3$	$3 \geq b$	$l > 10$	$10 \geq l > 5$	$5 \geq l$	
✓			✓			3/4
✓				✓		2/3
✓					✓	2/3
	✓		✓			3
	✓			✓		2/3
	✓				✓	2
		✓	✓	✓	✓	1/2

Table 5: Standard for evaluation of lining section deterioration and peeling.

Structure	Main reason	Peeling possibility		Degree of deterioration			Status value
		Have	No	<1/2	1/2–2/3	>2/3	
Arch	Deterioration, freezing damage, improper design, construction, etc.	✓					4
			✓				1
				✓			3
					✓		2
						✓	1
Sidewall		✓					3
			✓				1
				✓			3
					✓		2
						✓	1

Table 6: Evaluation criteria for corrosion of steel bars.

Structure	Main reason	Degree of corrosion	Rating status
Lining	Salt damage, water leakage, acid (alkali), etc.	Surface or small area corrosion	1
		Shallow hole corrosion or rebar rusted all around	2
		Steel section reduction is obvious, and steel structure engineering is damaged	3

Table 7: Evaluation criteria for leakage of tunnel lining.

Structure	Main situation	Degree of water leakage				Whether it affects driving		Status value
		Injection	Inrush	Hourglass	Impregnation	Yes	No	
Arch	Leaking water	✓				✓		4
			✓			✓		3
				✓		✓		2
					✓		✓	1
	Hanging ice					✓		3
							✓	1
Sidewall	Leaking water	✓				✓		3
			✓			✓		2
				✓		✓		2
					✓		✓	1
	Icicle					✓		3
							✓	1
Pavement	Sand outflow					✓		3/4
							✓	1
	Sediment					✓		3/4
							✓	1
	Freeze					✓		3/4
							✓	1

Table 8: Standard for condition evaluation of lining thickness and cavity.

Status value	Technical status description
0	The thickness of the lining meets the design requirements, and there is no void behind it
1	There is a gap behind the sidewall or vault, but there is no possibility of expansion
2	There is a gap behind the sidewall lining, which may expand
3	The concrete may fall, there is a large hollow on the back of the arch, and the upper tribal stone can fall to the arch back; the lining structure invades the inner contour boundary
4	There is a large cavity on the back of the lining arch, and the effective thickness of the lining is very thin. The upper part of the cavity may fall to the arch back; the lining structure invades the building boundary

(a)

(b)

Figure 7: Pictures of structure condition of the Tiebeishan tunnel.

where R_{ab} is the classical domain matter element representing the tunnel disease evaluation system, N_i represents the evaluation level of the i-th system, C_{im} represents the i-th evaluation indicator in the i-th evaluation level, and $\mu_{im\,\min}$ and $\mu_{im\,\max}$ represent the i-th evaluation level regarding evaluation indicators C_m, the range of the classical domain of the value, where the value range of i corresponds to the value of the system evaluation level.

Figure 8: Water damage and surface exfoliation of Tiebeishan tunnel structure.

Figure 9: Picture of Tiebeishan tunnel structure lining cracking disease.

The structural disease grades are divided into 4 categories: N_1 indicates good condition, N_2 indicates slight damage, N_3 indicates moderate damage, and N_4 indicates severe damage. According to the above-established evaluation indicators and quantitative classification of the standard, the classic domain corresponding to each level of the tunnel lining is expressed as follows:

$$R_1=\begin{bmatrix} N_1 & c_1 & (0,1] \\ & c_2 & (0,1] \\ & c_3 & (0,1] \\ & c_4 & (0,1] \\ & c_5 & (0,1] \end{bmatrix},\quad R_2=\begin{bmatrix} N_2 & c_1 & (1,2] \\ & c_2 & (1,2] \\ & c_3 & (1,2] \\ & c_4 & (1,2] \\ & c_5 & (1,2] \end{bmatrix},\quad R_3=\begin{bmatrix} N_3 & c_1 & (2,3] \\ & c_2 & (2,3] \\ & c_3 & (2,3] \\ & c_4 & (2,3] \\ & c_5 & (2,3] \end{bmatrix},\quad R_4=\begin{bmatrix} N_4 & c_1 & (3,4] \\ & c_2 & (3,4] \\ & c_3 & (3,4] \\ & c_4 & (3,4] \\ & c_5 & (3,4] \end{bmatrix}. \tag{2}$$

The section of the matter-element model mentioned above is determined by the maximum and minimum values of the classical domain corresponding to the evaluation grade and index. Therefore, the domain matter of the tunnel disease evaluation grade model is as shown in the following equation:

$$R_{\mathrm{p}}=\left(P,C,\mu_{\mathrm{p}}\right)=\begin{bmatrix} P & C_1 & \mu_1 \\ & C_2 & \mu_2 \\ & \vdots & \vdots \\ & C_m & \mu_m \end{bmatrix}=\begin{bmatrix} P & C_1 & [\mu_{1\min},\mu_{1\max}] \\ & C_2 & [\mu_{2\min},\mu_{2\max}] \\ & \vdots & \vdots \\ & C_m & [\mu_{m\min},\mu_{m\max}] \end{bmatrix}, \tag{3}$$

where R_{p} represents the domain matter elements of the tunnel disease evaluation system, P represents the range of values of various evaluation indicators corresponding to all evaluation levels, and $\mu_{im\min}$ and $\mu_{im\max}$ represent the range of values of the classical domain in all evaluation levels, that is, the matter-element domain corresponding to the indicator m.

Determine the section of the matter element as follows:

$$R_{\mathrm{p}}=\begin{bmatrix} P & c_1 & (0,4] \\ & c_2 & (0,4] \\ & c_3 & (0,4] \\ & c_4 & (0,4] \\ & c_5 & (0,4] \end{bmatrix}. \tag{4}$$

5.4. Determination of the Object to Be Evaluated in the Disease Evaluation Model. According to the detected disease classification and related data information, the model of the object to be evaluated can be obtained by the above-mentioned construction method of the domain and the classical domain:

$$R=\begin{bmatrix} P & C_1 & \mu_1 \\ & C_2 & \mu_2 \\ & \vdots & \vdots \\ & C_m & \mu_m \end{bmatrix}. \tag{5}$$

In the middle, μ_m is the evaluation of the tunnel and C_m is the amount of the value which usually needs to be obtained according to the relevant specifications or the assessment of professional technicians.

There are cracks in the tunnel joints. There are 11 circumferential cracks in the tunnel lining. The maximum crack width is 0.75 mm and the length range is 1 m–20 m. There are 30 longitudinal cracks, the maximum crack width is 2 mm, and the length range is 5 m–15 m. There are 2 oblique cracks, the maximum crack width is 1 mm, and the length is 10 m, so the lining cracking index is 4.

According to the periodic test results of the tunnel and combined with various evaluation indicators for scoring. There are 5 water leakage diseases in the left and right arches of the lining, and the vehicle traffic has a certain degree of influence, so the lining leakage index is taken as 2.

The test results show that the measured strength of the tunnel lining concrete is 21.1 MPa, and the concrete design strength is 18 MPa. The concrete strength meets the design requirements, so the material strength degradation evaluation value is set to 1. Considering that the tunnel has a large range of initial lining and the second lining is not densely integrated, the lining effective thickness index is taken as 3. There are 5 delaminations in the lining, the location is at the sidewall construction joint, the area is 0.22 m^2, so the lining detachment evaluation value is taken as 3.

Based on the above analysis, the material elements to be evaluated are initially obtained:

$$R=\begin{bmatrix} P & c_1 & 4 \\ & c_2 & 2 \\ & c_3 & 1 \\ & c_4 & 3 \\ & c_5 & 3 \end{bmatrix}. \tag{6}$$

5.5. Determination of the Weight of Evaluation Indicators and Consistency Test. After the matter to be evaluated is determined, the analytic hierarchy process is combined with the relative importance judgment criterion (Table 9) to compare the evaluation indicators of the tunnel disease evaluation model to form a judgment matrix (Table 10).

According to the above theory, the five evaluation indicators in the tunnel evaluation model of this paper form the judgment matrix as shown in Table 11.

After obtaining the above-mentioned judgment square matrix, the mean value or square root value of each row judgment index is calculated, and then the corresponding values of each index are normalized, and the corresponding weights of each index in the target problem are initially obtained. The row vector corresponding to each evaluation index is multiplied and squared, as shown in Equation (7):

$$A_i = \sqrt[n]{\prod_{j=1}^{n} a_{ij}}, \tag{7}$$

where A_i is the value obtained by multiplying the square root value corresponding to the i-th evaluation index in the matrix by the square root; a_{ij} is used to determine the i-th row and j-th column elements in the matrix.

Then, the normalization value corresponding to each index is normalized, and the specific gravity vector of each index in the target model can be obtained:

$$\alpha_i = \frac{A_i}{\sum_{j=1}^{n} A_j}. \tag{8}$$

Then, the maximum eigenvalue calculation of the judgment matrix is performed:

$$\lambda = \sum_{i=1}^{n} \frac{(\mathrm{RA})_i}{nA_i}, \tag{9}$$

where R is the judgment matrix, A is A_i, the vector obtained after normalization, and n is the number of evaluation indicators, which is the judgment matrix order.

After obtaining the maximum eigenvalue, the consistency check of the construction matrix is needed. This is because the judgment matrix is derived from the relative importance of the two factors. However, due to the complexity of the objective world and the diversity of people's perceptions of specific issues, there is no fixed reference standard when comparing multiple elements in the matter-element model, which may result in the violation of people's cognition in the importance comparison stage. When this judgment against common sense occurs, the judgment matrix is not completely consistent. In theory, the judgment matrix is not completely consistent, but it is required to have general consistency, so the consistency check is required.

The consistency index in the inspection process is CI, and the random consistency index is RI. The value is determined by the order of the matter-element judgment matrix. The RI of 6 orders or less are shown in Table 12:

$$\mathrm{CI} = \frac{\lambda - n}{n-1}. \tag{10}$$

The consistency ratio is expressed as

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}}. \tag{11}$$

Theoretically, it is considered that the value of CR is less than 0.1, and it can be determined that the matter-element judgment matrix satisfies the consistency requirement, and the determined weight meets the requirement.

After the judgment matrix is obtained, the calculation of the weight value of the evaluation index is first performed, and the process is as follows:

$$\begin{aligned}
A_1 &= \sqrt[5]{\prod_{j=1}^{5} a_{1j}} = (1 \times 2 \times 3 \times 3 \times 3)^{1/5} = 1.944,\\
A_2 &= \sqrt[5]{\prod_{j=1}^{5} a_{2j}} = (1/2 \times 1 \times 2 \times 3 \times 3)^{1/5} = 1.442,\\
A_3 &= \sqrt[5]{\prod_{j=1}^{5} a_{3j}} = (1/3 \times 1/2 \times 1 \times 2 \times 2)^{1/5} = 0.935,\\
A_4 &= \sqrt[5]{\prod_{j=1}^{5} a_{4j}} = (1/3 \times 1/3 \times 1/2 \times 1 \times 2)^{1/5} = 0.693,\\
A_5 &= \sqrt[5]{\prod_{j=1}^{5} a_{5j}} = (1/3 \times 1/3 \times 1/2 \times 1/2 \times 1)^{1/5} = 0.550.
\end{aligned} \tag{12}$$

Normalize the results obtained above to obtain

$$\begin{aligned}
\alpha_i &= \frac{A_i}{\sum_{j=1}^{n} A_j},\\
A &= \left(\, 0.3490.259 \;\; 0.168 \;\; 0.125 \;\; 0.099 \,\right)^T.
\end{aligned} \tag{13}$$

The proportion of each evaluation index in the tunnel disease evaluation model is obtained, and the maximum eigenvalue λ of the judgment matrix is calculated. The calculation process is as follows:

$$\mathrm{RA} = \begin{bmatrix} 1 & 2 & 3 & 3 & 3 \\ \frac{1}{2} & 1 & 2 & 3 & 3 \\ \frac{1}{3} & \frac{1}{2} & 2 & 3 & 3 \\ \frac{1}{3} & \frac{1}{3} & \frac{1}{2} & 1 & 2 \\ \frac{1}{3} & \frac{1}{3} & \frac{1}{2} & \frac{1}{2} & 2 \end{bmatrix} \begin{bmatrix} 0.349 \\ 0.259 \\ 0.168 \\ 0.125 \\ 0.099 \end{bmatrix} = \begin{bmatrix} 2.042 \\ 1.440 \\ 0.861 \\ 0.609 \\ 0.448 \end{bmatrix}, \tag{14}$$

$$\lambda = \sum_{i=1}^{5} \frac{(\mathrm{RA})_i}{nA_i} = \frac{2.042}{5 \times 0.349} + \frac{1.440}{5 \times 0.259} + \frac{0.861}{5 \times 0.168} + \frac{0.609}{5 \times 0.125} + \frac{0.448}{5 \times 0.099} = 5.190.$$

Table 9: Criterion of relative importance judgment.

Scaling	Comparison of importance
1	Compared with the same importance
3	One factor is slightly more important than the other
5	One factor is significantly more important than the other
7	One factor is more important than the other
9	One factor is more important than the other
2, 4, 6, 8	Adjacent judgment intermediate value
$1/a_{ij}$	Compared with the two factors, if the former has the above value for the latter, the latter takes the reciprocal

Table 10: General form of judgment matrix.

R	C_1	C_2	….	C_n
C_1	**1**	a_{12}	….	a_{1n}
C_2	$1/a_{12}$	**1**	….	a_{2n}
….	….	….	….	….
C_n	$1/a_{1n}$	$1/a_{2n}$	….	**1**

Table 11: Evaluation model of tunnel structure disease evaluation model.

R	C_1	C_2	C_3	C_4	C_5
C_1	1	2	3	3	3
C_2	1/2	1	2	3	3
C_3	1/3	1/2	1	2	2
C_4	1/3	1/3	1/2	1	2
C_5	1/3	1/3	1/2	1/2	1

Table 12: Random consistency index value.

Order	1	2	3	4	5	6
RI	0	0	0.58	0.90	1.12	1.24

The maximum eigenvalue is 5.190, and then, the consistency check is performed:

$$\begin{aligned} \mathrm{CI} &= \frac{\lambda - n}{n-1} = \frac{5.190-5}{5-1} = 0.048, \\ \mathrm{CR} &= \frac{\mathrm{CI}}{\mathrm{RI}} = \frac{0.048}{1.12} = 0.043 < 0.1. \end{aligned} \tag{15}$$

The results show that the judgment matrix meets the consistency requirement, and the calculation weight set of each matter element can be determined as the proportion of each evaluation index.

5.6. Calculation of the Correlation Degree of the Object to Be Evaluated and the Determination of the Disease Level. The relevance degree of the evaluation index i to the tunnel disease level j is shown in the following equations:

$$k_{ji} = \begin{cases} \dfrac{\rho(\mu_i, \mu_{ji})}{\rho(\mu_i, \mu_{pi}) - \rho(\mu_i, \mu_{ji})} (\mu_i \in \mu_{ji}), \\ \dfrac{\rho(\mu_i, \mu_{ji})}{|\mu_{ji}|} (\mu_i \in \mu_{ji}), \end{cases} \tag{16}$$

$$\rho(\mu_i, \mu_{ji}) = \left|\mu_i - \frac{1}{2}(\mu_{ji\,\min} + \mu_{ji\,\max})\right| - \frac{1}{2}(\mu_{ji\,\max} + \mu_{ji\,\min}), \tag{17}$$

$$\rho(\mu_i, \mu_{pi}) = \left|\mu_i - \frac{1}{2}(\mu_{pi\,\min} + \mu_{pi\,\max})\right| - \frac{1}{2}(\mu_{pi\,\max} + \mu_{pi\,\min}), \tag{18}$$

where k_{ji} is the degree of association of the index i with respect to the evaluation level j for the matter-element model, μ_{ji} is the range of values of the classical domain matter elements, μ_{pi} is the range of values of the domain matter elements, $\rho(\mu_{i,} \mu_{ji})$ is the point, μ_i *is* the interval, $\mu_{ji\,\min}$ and $\mu_{ji\,\max}$ is the distance, and $\rho(\mu_{i,}\ \mu_{pi})$ is the point.

The calculation of the correlation degree of the matter element to be evaluated in the tunnel structure disease evaluation model is carried out, and then, the comprehensive correlation degree of the evaluation index is calculated. The specific process is as follows:

$$
\begin{aligned}
k_{11} &= \frac{\rho(\mu_1,\mu_{11})}{\rho(\mu_1,\mu_{p1}) - \rho(\mu_1,\mu_{11})} = \frac{|4-(1/2(0+1))| - (1/2(1-0))}{|4-(1/2(0+4))| - (1/2(4-0)) - \rho(\mu_1,\mu_{11})} = -1,\\
k_{21} &= \frac{\rho(\mu_1,\mu_{21})}{\rho(\mu_1,\mu_{p1}) - \rho(\mu_1,\mu_{21})} = \frac{|4-(1/2(1+2))| - (1/2(2-1))}{|4-(1/2(0+4))| - (1/2(4-0)) - \rho(\mu_1,\mu_{21})} = -1,\\
k_{12} &= \frac{\rho(\mu_2,\mu_{12})}{\rho(\mu_1,\mu_{p2}) - \rho(\mu_2,\mu_{12})} = \frac{|2-(1/2(0+1))| - (1/2(1-0))}{|2-(1/2(0+4))| - (1/2(4-0)) - \rho(\mu_2,\mu_{12})} = -\frac{1}{3},\\
k_{22} &= \frac{\rho(\mu_2,\mu_{22})}{|\mu_{22}|} = -\frac{|2-(1/2(1+2))| - (1/2(2-1))}{|2-1|} = 0.
\end{aligned}
\tag{19}
$$

The above is the correlation degree between the first and second evaluation indicators and the evaluation levels 1 and 2, and the calculation process of other relevance degrees limited by the space is omitted. The calculation principle is the same as above, and the calculation results of the correlation degree matrix are summarized in Table 13.

5.7. Determination of Comprehensive Relevance. After obtaining the weighted proportion vector of each evaluation index of the matter-element model by the analytic hierarchy process, considering the correlation degree of the evaluation index on the disease level, the comprehensive relevance degree of each evaluation index with respect to the evaluation grade of the evaluated tunnel can be calculated:

$$k_j = \sum_{i=1}^{n} \alpha_i k_{ji}, \tag{20}$$

where a_i is the proportion of each evaluation index in the matter-element model and k_{ji} is the evaluated degree of association of indicator i with respect to tunnel disease level j. Finally, the comprehensive correlation degree of the evaluation model disease level is calculated:

$$
\begin{aligned}
k_1 &= 0.349\times(-1) + 0.259\times\left(-\frac{1}{3}\right) + 0.168\times 0 + 0.125\times\left(-\frac{2}{3}\right) + 0.099\times\left(-\frac{2}{3}\right) = -0.585,\\
k_2 &= 0.349\times(-1) + 0.259\times 0 + 0.168\times 0 + 0.125\times\left(-\frac{1}{2}\right) + 0.099\times\left(-\frac{1}{2}\right) = -0.461,\\
k_3 &= 0.349\times(-1) + 0.259\times 0 + 0.168\times\left(-\frac{1}{2}\right) + 0.125\times 0 + 0.099\times 0 = -0.433,\\
k_4 &= 0.349\times 0 + 0.259\times\left(-\frac{1}{3}\right) + 0.168\times\left(-\frac{2}{3}\right) + 0.125\times 0 + 0.099\times 0 = -0.198.
\end{aligned}
\tag{21}
$$

The calculation yields k_1, k_2, k_3, and k_4 values of −0.585, −0.461, −0.433, and −0.198, respectively.

5.8. Determination of the Disease Level of the Tunnel Structure. After all the above parameters are determined, the target tunnel structure disease level can be determined: according to the rating rules specified above, the tunnel disease rating is determined as follows:

$$k = \max\{k_j \mid j = 1,2\ldots n\} = -0.198\,(j=4). \tag{22}$$

The tunnel structure disease evaluation rating is 4, indicating that the tunnel is severely damaged.

5.9. Analysis of Evaluation Results. Combining the analytic hierarchy process with the extension theory, the main structural disease characteristics in the tunnel are determined according to the importance degree, and the main

Table 13: The correlation degree of evaluation index on evaluation grade.

Evaluation index	K_1 (level 1)	K_2 (level 2)	K_3 (level 3)	K_4 (level 4)
$C1$	−1	−1	−1	0
$C2$	−1/3	0	0	−1/3
$C3$	0	0	−1/2	−2/3
$C4$	−2/3	−1/2	0	0
$C5$	−2/3	−1/2	0	0

diseases of the structure are quantified. After calculation, it is found that the structural evaluation grade of the Tiebeishan tunnel has reached the level 4, it means the structure is seriously damaged, and it is in line with the actual situation of the tunnel site, which indicates that the constructed tunnel structure disease evaluation model conforms to the actual situation of the project and has certain engineering practical value.

6. Conclusions and Recommendations

(1) Based on the regular inspection data of expressway tunnels in Liaoning Province, China, a brief overview of common tunnel structure types, manifestations, and mechanisms is presented.

(2) Combining the on-site inspection data of typical tunnels in Liaoning Province, the characteristics of the main structural diseases of the tunnel are clarified, and the disease law of the tunnel structure is summarized. Most of the tunnels lining cracks occur in the separation zone of the lining and pouring, which indicates that the cracks are mostly structural cracks. The longitudinal cracks of the lining mostly occur in the tunnel arch waist position, and the crack width is generally smaller than the circumferential crack width. Comprehensively, the tunnel second lining thickness compliance rate is 70%–80%, and the individual tunnels are not densely covered by the lining, and there are cavities behind the lining.

(3) Based on the qualitative description of the tunnel lining disease, by using the analytic hierarchy process and the extenics theory, the type and value criteria of the tunnel disease evaluation index are defined, and the tunnel structure disease grade evaluation model is constructed.

(4) Applying the evaluation model to the assessment of the structural damage level of the Tiebeishan tunnel, determining the main evaluation indicators in the disease level evaluation model, and giving the classical domains and the local regions of each index, the structural safety assessment of the Tiebeishan tunnel was quantified, and the judgment matrix of the object to be evaluated was correlated with the disease level. Finally, the structure damage degree of the Tiebeishan tunnel was grade 4, and the structure was seriously damaged, which was consistent with the actual situation.

Data Availability

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

Conflicts of Interest

The authors declare no conflicts of interest.

Authors' Contributions

The concepts and designs were provided by Yu Liu, Chun-an Tang, and Shu-hong Wang, in situ data were obtained by Peng-yu Wang, and data were analyzed by Yu Liu and Yong-ping Guan.

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References

[1] M. Fujii, Y. J. Jiang, and Y. Tanabashi, "Database development for road tunnel maintenance and management by using geographical information system," in *Proceedings of the 1st Joint Seminar between Tongji University and Nagasaki University*, pp. 104–108, Tongji University, Shanghai, China, 2004.

[2] E. B. Lars, A. Anders, and H. Jonas, "Investigation of restrained shrinkage cracking in partially fixed shotcretelinings," *Tunnelling and Underground Space Technology*, vol. 42, no. 5, pp. 136–143, 2014.

[3] M. A. Meguid and H. K. Dang, "The effect of erosion voids on existing tunnel linings," *Tunnelling and Underground Space Technology*, vol. 24, no. 3, pp. 278–286, 2009.

[4] J. S. Lee, I.-Y. Choi, H.-U. Lee, and H.-H. Lee, "Damage identification of a tunnel liner based on deformation data," *Tunnelling and Underground Space Technology*, vol. 20, no. 1, pp. 73–80, 2005.

[5] S. Seki, S. Kaise, Y. Morisaki et al., "Model experiments for examining heaving phenomenonin tunnels," *Tunnelling and Underground Space Technology*, vol. 23, no. 2, pp. 128–138, 2008.

[6] P. Nanakorn and H. Horii, "A fracture-mechanics-based design method for SFRC tunnel linings," *Tunnelling and Underground Space Technology*, vol. 11, no. 1, pp. 39–43, 1996.

[7] B. Singh, R. K. Goel, J. L. Jethwa, and A. K. Dube, "Support pressure assessment in arched underground openings through poor rock masses," *Engineering Geology*, vol. 48, no. 1-2, pp. 59–81, 1997.

[8] J. A. Richards, "Inspection, maintenance and repair of tunnels: international lessons and practice," *Tunnelling and Underground Space Technology*, vol. 13, no. 4, pp. 369–375, 1998.

[9] J. Lai, J. Qiu, H. Fan et al., "Fiber bragg grating sensors-based in-situ monitoring and safety assessment of loess tunnel,"

Journal of Sensors, vol. 2016, Article ID 8658290, 10 pages, 2016.

[10] T. Asakura and Y. Kojima, "Tunnel maintenance in Japan," *Tunnelling and Underground Space Technology*, vol. 18, no. 2-3, pp. 161–169, 2003.

[11] A. Inokuma and S. Inano, "Road tunnels in Japan: deterioration and counter measures," *Tunnelling and Underground Space Technology*, vol. 11, no. 3, pp. 305–309, 1996.

[12] W. D. Friebel and J. Krieger, "Quality assurance and assessing the state of road tunnels using non-destructive test methods," *Tunnel*, vol. 8, no. 10, pp. 3–34, 2002.

[13] Ministry of Transport of the People's Republic of China, *Technical Specification for Maintenance of Highway Tunnels JTG H12-2015*, Ministry of Transport of the People's Republic of China, Beijing, China, 2015.

[14] J. Lai, J. Qiu, H. Fan et al., "Structural safety assessment of existing multiarch tunnel: a case study," *Advances in Materials Science and Engineering*, vol. 2017, Article ID 1697041, 11 pages, 2017.

[15] T.-T. Wang, "Characterizing crack patterns on tunnel linings associated with shear deformation induced by instability of neighboring slopes," *Engineering Geology*, vol. 115, no. 1-2, pp. 80–95, 2010.

[16] D.-H. Lee, H.-K. Lee, and Y.-G. Kim, "A study on mechanical behavior and cracking characteristics of tunnel lining by model experiment," *Geosystem Engineering*, vol. 5, no. 4, pp. 104–112, 2002.

[17] M. Usman and R. Galler, "Long-term deterioration of lining in tunnels," *International Journal of Rock Mechanics and Mining Sciences*, vol. 64, pp. 84–89, 2013.

[18] H. Ishioka, "Security management for underground space," *Tunneling and Underground Space Technology*, vol. 7, no. 4, pp. 335–338, 2000.

[19] H. Mashimo, "State of the road tunnel safety technology in Japan," *Tunnelling and Underground Space Technology*, vol. 17, no. 2, pp. 145–152, 2002.

[20] H. Mashimo, N. Isago, T. Kitani, and T. Endou, "Effect of fiber reinforced concrete on shrinkage crack of tunnel lining," *Tunnelling and Underground Space Technology*, vol. 21, no. 3-4, pp. 382-383, 2006.

[21] C. Tang, J. Wang, and J. Zhang, "Preliminary engineering application of microseismic monitoring technique to rockburst prediction in tunneling of Jinping II project," *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 2, no. 3, pp. 193–208, 2010.

[22] J. S. Chen and H. H. Mo, "Numerical study on crack problems in segments of shield tunnel using finite element method," *Tunnelling and Underground Space Technology*, vol. 24, no. 1, pp. 91–102, 2009.

[23] W. C. Zhu and C. A. Tang, "Numerical simulation of Brazilian disk rock failure under static and dynamic loading," *International Journal of Rock Mechanics and Mining Sciences*, vol. 42, no. 2, pp. 236–252, 2006.

[24] S. W. Park, Y. S. Shin, Y. S. Oh, and S. R. Ahn, "A guideline on condition assessment of existing old railway tunnels," *Tunnelling and Underground Space Technology*, vol. 21, no. 3-4, pp. 329-330, 2006.

[25] E. Cardarelli, C. Marrone, and L. Orlando, "Evaluation of tunnel stability using integrated geophysical methods," *Journal of Applied Geophysics*, vol. 52, no. 2-3, pp. 93–102, 2003.

[26] A. F. Siggins and R. J. A. Whitely, "Laboratory simulation of high frequency GPR responses of damaged tunnel liners," *Proceedings of SPIE-The International Society for Optical Engineering*, vol. 40, no. 11, pp. 805–811, 2000.

[27] B. Chiaia, A. P. Fantilli, and P. Vallini, "Evaluation of crack width in FRC structures and application to tunnel linings," *Materials and Strctures*, vol. 42, no. 3, pp. 339–351, 2009.