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Research Article

Structural Safety Assessment of Existing Multiarch Tunnel: A Case Study

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Structural health assessment is one of the key activities in maintaining the performance of a tunnel during its service life. Due to the development of modern detection technology, comprehensive structural health assessment system is being established for operating tunnels. To evaluate the actual operational state of Shitigou tunnel, overall detection of the liner crack, tunnel seepage, and liner void was conducted by employing the modern detection technology, such as crack width monitoring technology, concrete strength monitoring technology, and electromagnetic wave nondestructive monitoring technology. Through the statistical analysis of the detection results, the distribution characteristic, development law, and damage grade of structural defects were obtained. Tunnel liner cracks are mainly located on the middle wall; serious water leakage is encountered on the side wall, middle wall, and vault; the strength of foundation and liner structure of left tunnel does not meet the design requirement; the liner voids are mostly located at the tunnel entrance section, especially, on the tunnel vault; and the proportion of influence factors of structural defects should be considered. The research results presented for this study can serve as references for effective design and health assessment of existing multiarch tunnel projects.

1. Introduction

An increasing number of tunnels are constructed in disadvantageous environments such as unfavorable geological structures, environments with high in situ stress, and shallow overburden areas [1–3]. Given the circumstances the structure of a tunnel usually suffers attacks from mechanical, physical, and even chemical actions [4]. The highly static indeterminate characteristics of a liner structure cause tunnels to change, frequently resulting in anomalies, such as liner crack, liner void, liner deterioration, and water leakage, with wide-ranging configurations in liner structures [5, 6]. Investigation on some tunnel defects shows that 70% of tunnels have liner damage defects, accounting for about 40% of all tunnel defects. Liner concrete spalling can induce different damage to the entire tunnel structure and lower its reliability. Notably, water leakage will cause liner cracking and accelerate the preexisting crack extension, which damages the liner structure further [7]. Once a tunnel is opened, routine health inspections are necessary to ensure tunnel serviceability and user safety. Consequently, knowing when and where structural anomalies develop is important for tunnel health inspections, especially for diagnosis of tunnel serviceability and necessity of subsequent detailed inspections and monitoring, as shown in Figure 1. More specifically, the real-time data of service states can be collected by employing modern detection technology, which may be of help in understanding structure operational performance, and timely taking effective restoration measures [8–11].

Since the 1980s, with the wide application of probability theory and mathematical statistics in structural engineering, the structural failure probability was proposed to define

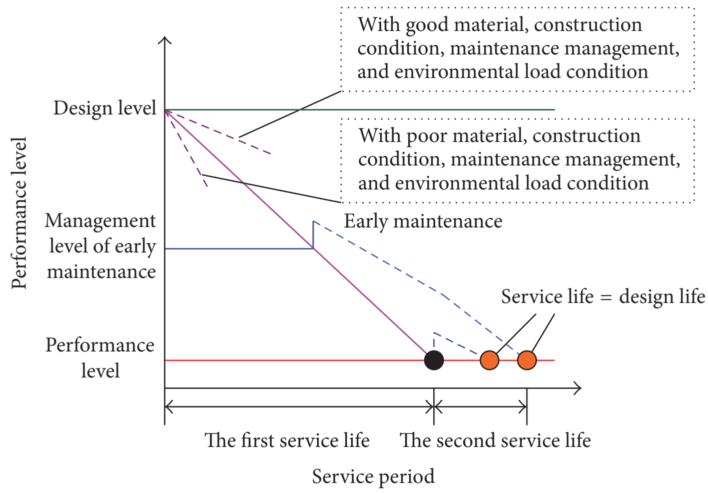

Figure 1: Structure deterioration characteristic.

the structural reliability [12, 13]. For the structural health assessment of operating tunnels, to find out its exact service condition and to check the deviation from its design assumptions are two important aspects. Li et al. [14] performed the stability assessment of a loss tunnel through the established displacement prediction system. To scientifically evaluate the tunnel diseases, such as liner crack, water leakage, liner spalling, liner deterioration, liner deformation, and frost damage, the comprehensive analyses on the inspection results were conducted by Luo and Xia [15]. Zhou et al. [16] proposed a structural health assessment method to determine the tunnel structure's global stiffness based on torsional wave speed, which evaluated the tunnel's structural service states further. Based on simulated structural vibration data, Feng et al. [17] applied cross correlation analysis to perform structural damage detection and localization. Additionally, nondestructive testing approaches, including ground penetrating radar (GPR), ultrasonic wave, electromagnetic radiation, and acoustic emission, are usually employed to detect the location and potential harm of hidden defects, such as void, delaminating behind coating, thickness of concrete cover, or corrosive reinforcing bars [18–21]. In this sense, a number of new research projects have been funded to improve the damage detection methods including the use of innovative signal processing, new sensors, and control theory [22]. Based on the ISTIMES project funded by the European Commission, Proto et al. [23] presented the preliminary results arising from the GPR and infrared thermographic measurements conducted on the Musmeci Bridge in Potenza, located in a highly seismic area of the Apennine chain (Southern Italy). Through ultrasonic and boring core sampling, Nie and Lai [24, 25] investigated the crack and water leakage of a tunnel and detected the strength and thickness of liner structure as well as the backfill tightness of tunnel vault. To obtain the operating state of a tunnel in the cold plateau region, Kang and Yan [26, 27] used the GPR to detect the tunnel disease and assessed the integral safety of liner structure. In situ investigation of the liner cracks was conducted by Ye et al. [28] to obtain the statistics, which includes the number, length, inclination, width, and depth of typical cracks. At present, according to the adaptive neurofuzzy inference system (ANFIS) and neural network, based on the index of tunnel defects, the health assessment management system of tunnel structure is gradually established [29, 30]. Due to the development of modern monitoring technology, comprehensive structural health assessment is being established for the operating tunnels.

China is now enjoying a boom in tunnel traffic construction; evidently, the detection and health assessment of highway tunnel become more and more important [31, 32], especially the health assessment of multiarch tunnels. To investigate the liner cracks, tunnel seepage, and liner voids developed around an existing multiarch tunnel, the health assessment was performed by employing the in situ detection technology. Meanwhile, the change of operating condition as well as the technical state evaluation for the tunnel structure could be obtained.

2. Project Overview

As a multiarch tunnel, Shitigou tunnel, with a total length of $2 \times 320 = 640$ m, was opened in 2002. The mileage of tunnel is K239 + 895–K240 + 215, and the distance between the two tunnels is 10.75 m. The rock mass grade of Shitigou tunnel is IV and many ponds which are higher than the design elevation of pavement locate near the tunnel axis. The groundwater is mainly of bedrock fissure water, which is hosted in silty mudstone and shaly sand. The source for water supply mainly consists of meteoric water and surface water. After several years of operation, through preliminary examination, many defects especially liner void, liner crack, and water leakage have been found in the Shitigou tunnel, where the soil stability is poor and the geological condition is complex. Accordingly, the systematic structural health assessment for the tunnel should be performed, and corresponding treatment measures need to be taken.

Generally, as the core content of the tunnel structure health inspection, data collecting is an important part of

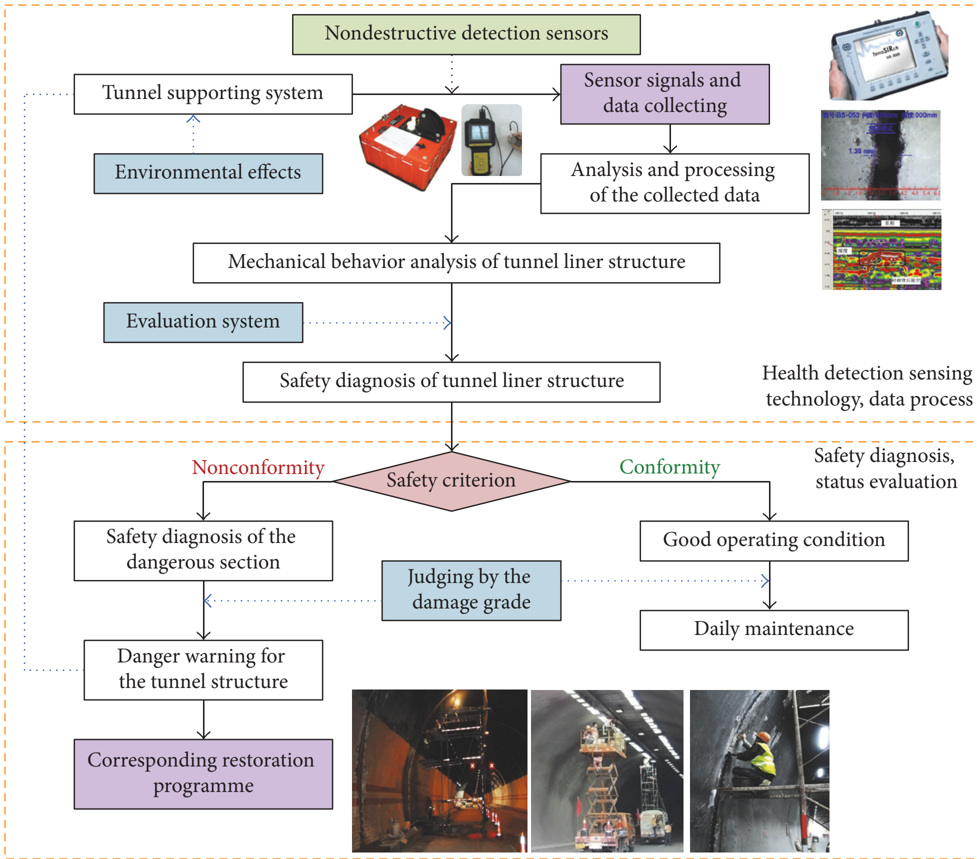

Figure 2: Safety assessment system of the tunnel structure.

the detection system. Through the combined application of the modern detection technology in the operating multiarch tunnel, as shown in Figure 2, several problems could be solved: (1) confirming the actual performance of the multiarch tunnel; (2) mastering the safety degree of the tunnel structure; (3) providing the essential service for the comprehensive management system of the tunnel maintenance; (4) considering the influence factors of structural defects, proposing corresponding restoration programme.

3. Structural Safety Assessment of Shitigou Tunnel

3.1. Liner Crack Condition Assessment. The liner crack not only does harm to the stability and durability of tunnel structure but also directly influences the safety of vehicles and pedestrians in the tunnel [33–35]. Measuring tape and crack width measuring instrument were adopted to detect the length and width of liner cracks, as shown in Figure 3. DJCK-2 intelligent crack width measuring instrument was adopted, and the widest part of the liner crack was chosen as the measuring position. During monitoring, cracks were scanned through the microprobe, and then the liner width was obtained from the instrument screen with the precision of 0.01 mm [36].

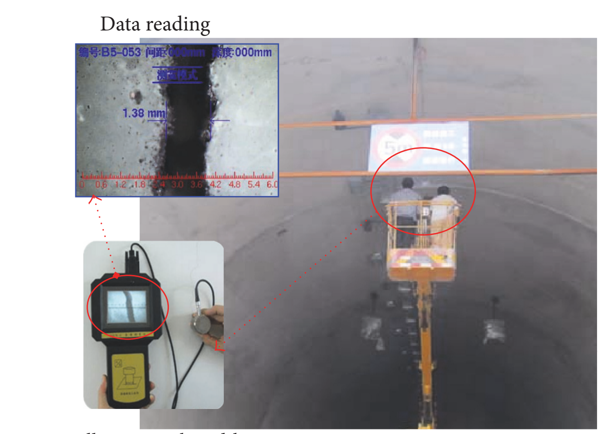

Figure 3: Liner crack width detection for Shitigou tunnel.

(1) Assessment Criteria (Technical Specifications of Maintenance for Highway Tunnel JTG H12-2015). Generally, considering the development of cracks and its influence on the liner structure, four assessment grades (B, 1A, 2A, and 3A) and assessment criteria for structural damage have been judged

Table 1: Assessment criteria for liner crack.

Structure	Crack width b (mm)		Crack length l (m)		Grade
	$b > 3$	$b \leq 3$	$l > 5$	$l \leq 5$	
Liner	√		√		2A/3A
	√			√	A/2A
		√	√		1A
		√		√	1A

based on the crack size [37]. And the assessment criteria for liner cracks are presented in Table 1.

(2) Assessment Results Analysis. There were 56 cracks in total on the right tunnel, which were, respectively, located in left liner, right liner, and tunnel arch. The crack width is mainly $1\,\text{mm} < b \leq 2\,\text{mm}$, accounting for 62 percent of the total cracks (Figure 4). Meanwhile, there were 51 cracks in total on the left tunnel, which were, respectively, distributed in left liner, right liner, and tunnel arch. 21 cracks with the width of $0\,\text{mm} < b \leq 1\,\text{mm}$ accounted for 41 percent of the total cracks. 22 cracks with the width of $1\,\text{mm} < b \leq 2\,\text{mm}$ accounted for 43 percent of the total cracks. Table 2 illustrates the spatial distribution of cracks with different extension directions.

The distribution of cracks was scattered on the side wall of right tunnel, and most cracks were less than 1 mm, without development trend. The distribution of cracks on the middle wall was relatively dense, and many cracks were developing gradually; in particular, the cracks located on the liner surface 170 m away from the tunnel entrance had reached 3 mm. The cracks on tunnel vault were developing along the direction of construction joints. Accordingly, from the inspection data, the criteria grade of structural damage for the right tunnel is 1A; that is, the structural damage may endanger the safety of pedestrians and vehicles, for which the corresponding measures shall be taken. The distribution of cracks was sporadic on the side wall of right tunnel, and the distribution of cracks on the middle wall was relatively dense; in particular, the cracks located on the liner surface 8 m away from the tunnel entrance had reached 3.2 mm. Also, the cracks on tunnel vault were developing along the direction of construction joints. Accordingly, it can be determined that the criteria grade of structural damage for the left tunnel is 1A.

3.2. Tunnel Seepage Condition Assessment. Generally, the groundwater around the tunnel will flow inside the tunnel in a concentrated manner. In case of the poor drainage measures or the damaged waterproof layers, the water leakage damage would be caused, inducing liner peeling-off and the tunnel durability [38]. Furthermore, with a great threat to traffic safety, the leakage-induced road waterlogging will reduce the adhesive force between vehicle and pavement in tunnels [39].

(1) Assessment Criteria (Technical Specifications of Maintenance for Highway Tunnel JTG H12-2015). Usually, the tunnel seepage occurs simultaneously with the liner cracks. Therefore, the water leakage, the development of cracks near the

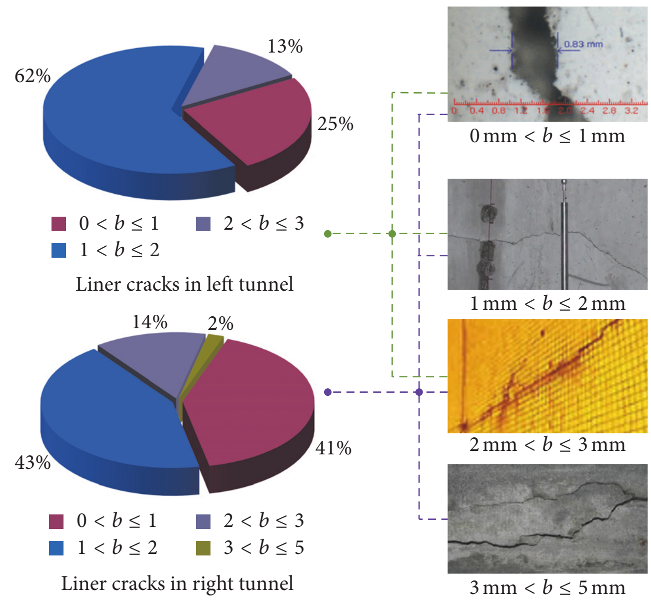

Figure 4: Statistics of liner cracks in Shitigou tunnel.

seepage position, and the sandy soil carried by water leakage should be thoroughly taken into account for the qualitative assessment criteria. And then the tunnel seepage condition is determined into five grades (S, B, 1A, 2A, and 3A) according to the severity of the damage and the assessment criteria for seepage. Specifically, the severity of tunnel seepage can be determined according to the investigation form (Table 3).

(2) Assessment Results Analysis. According to the inspection results, it could be seen that serious water leakage was encountered on the side wall, middle wall, and vault of the right tunnel, especially on site 42 m away from the tunnel entrance. Accordingly, it can be determined that the criteria grade of tunnel seepage for the right tunnel is 1A; that is, the large water seepage that appeared near liner cracks may affect the traffic safety in the near future, for which the corresponding measures shall be taken. Meanwhile, for the left tunnel, the serious water leakage was also encountered on the side wall, middle wall, and vault. Specifically, the drip and leakage with large area were found on the middle wall 55 m–59 m away from the tunnel entrance, as well as on the middle wall 40 m away from the tunnel entrance, as shown in Figure 5. Also, the vault 28 m away from the tunnel entrance had a water dripping area (Figure 6). Accordingly, the criteria grade of tunnel seepage for the left tunnel is 1A.

3.3. Structural Strength and Thickness Assessment

(1) Detection Point Arrangement. To accurately ascertain the construction quality of tunnel supporting structure, the sampling assessment was conducted for tunnel liner, pavement, and foundation employing the boring core sampling method [40]. Figure 7 shows the detection point layout of the boring core sample. The boring core sampling on pavement and liner are, respectively, shown in Figure 8.

Table 2: Spatial distribution statistics of cracks with different extension directions.

Type of crack	Proportion of total cracks (%)	Crack location	Proportion of cracks (%)
Annular crack	55.3	Vault	21.8
		Hance	37.6
		Side wall	40.6
Longitudinal crack	35.9	Vault	69.4
		Hance	19.8
		Side wall	10.8
Inclined crack	8.8		

Table 3: Investigation on the tunnel seepage.

Structure	Main abnormal phenomena	Degree of leakage				Affecting traffic safety		Grade
		I	II	III	IV	Y	N	
Arch	Leakage	√				√		3A
			√			√		2A
				√		√		1A
					√		√	B
Side wall	Leakage	√				√		3A
			√			√		2A
				√		√		1A
					√		√	B
Pavement	Sandy soil outflow					√		2A/3A
							√	B
	Waterlogging					√		2A/3A
							√	B

Figure 5: Leakage on middle wall of left tunnel.

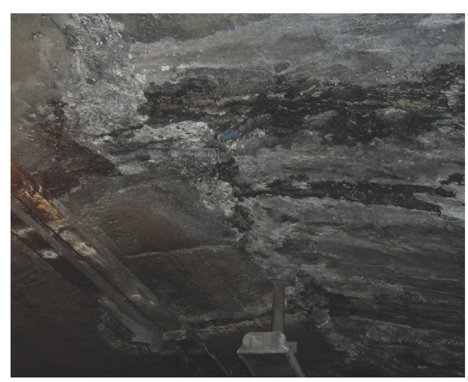

Figure 6: Leakage on vault of left tunnel.

Table 4: Concrete strength grade.

Type	C15	C20	C25	C30	C35
Axial compressive strength f_{cd}	7.5	10	12.5	15	16.1
Flexural compressive strength f_{cmd}	8.5	11	13.5	16.5	17.7
Axial tensile strength f_{ctd}	0.93	1.13	1.33	1.47	1.52

(2) Assessment Criteria (Technical Specifications of Maintenance for Highway Tunnel JTG H12-2015). The assessment criteria for concrete strength are shown in Table 4.

(3) Assessment Results Analysis. The detection results of structural strength and thickness are shown in Figures 9 and 10, respectively. The concrete with intensive grade of C25 was used for tunnel foundation and liner; meanwhile, the C10 concrete was used for tunnel pavement base, and the C35 concrete was used for tunnel pavement surface. Figure 9 shows that the strength of pavement and liner structure of right tunnel meets the design requirement. The minimum axial compressive strength of sampling points on the left tunnel foundation and liner structure, however, is 10.3 MPa, which does not meet the design requirement. The tunnel pavement has the design thickness of 45 cm, and the total

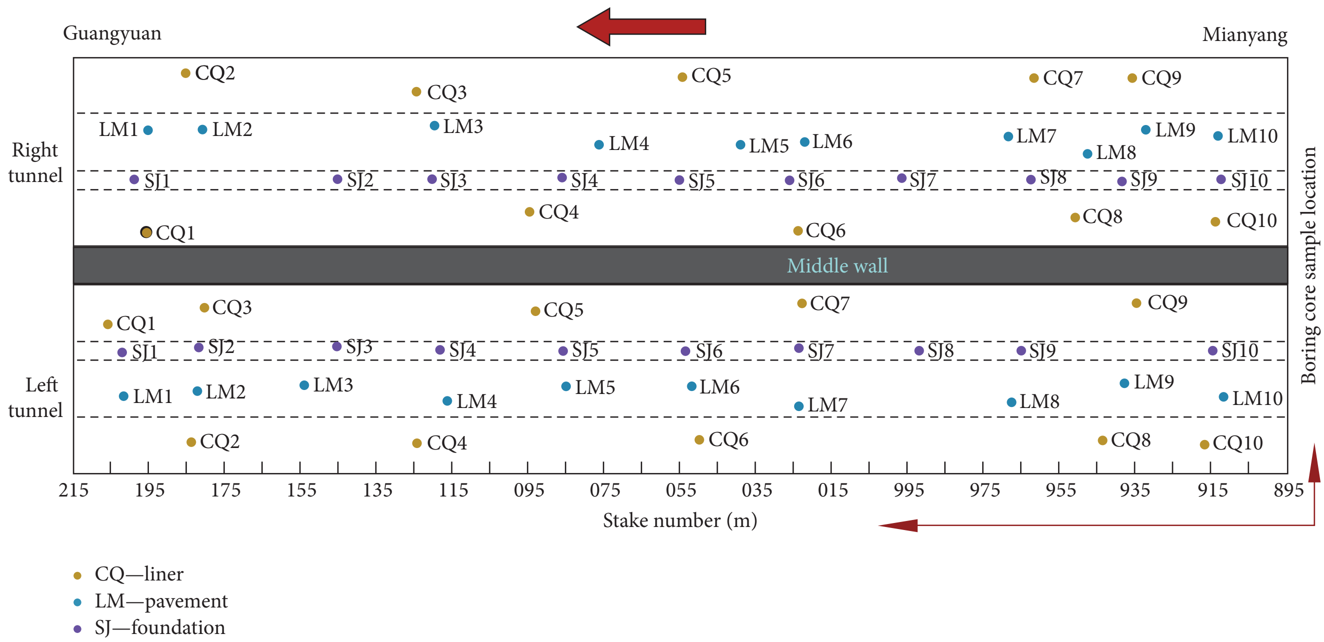

FIGURE 7: Detection point layout of the boring core sample.

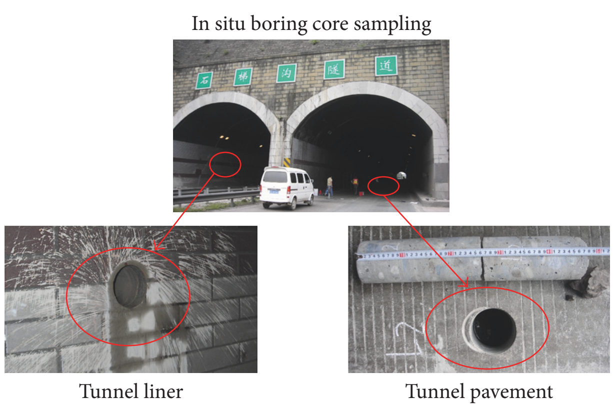

FIGURE 8: Boring core sampling on the tunnel structure.

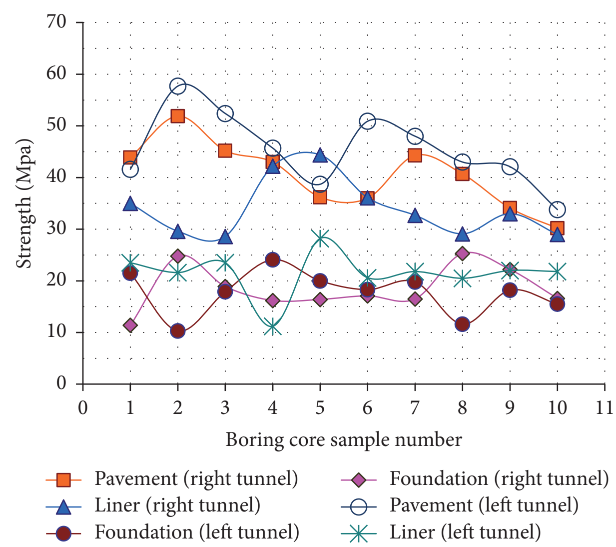

FIGURE 9: Structural strength detection results.

design thickness of primary support and secondary liner is 80 cm. From Figure 10, the thicknesses of tunnel foundation, liner, and pavement of the sampling points all satisfy the design requirements. Based on the observation of boring core samples on the side wall, middle wall, and pavement base, the base backfill was relatively compacted, and the softening phenomena appeared at the entrance and exit section of Shitigou tunnel due to long-term influence of groundwater.

3.4. Liner Void Condition Assessment

(1) Detecting Instrument and Arrangement. Ground penetrating radar (SIR-3000) with antenna frequency of 400 MHz produced by Geophysical Survey Systems, Inc., was used for liner void detection in Shitigou tunnel. The radar consists of host, antenna, corresponding software, and so forth [41]. According to the propagation characteristics of the electromagnetic wave in lossy media, GPR launches high-frequency impulse electromagnetic waves to the measured media by transmitting antenna and then receives the backward electromagnetic waves by the receiving antenna, which can detect and recognize the liner voids with the high accuracy [42]. The reflection coefficient mainly depends on the dielectric constant of the measured media [43–46]. Considering the site condition in Shitigou tunnel, eight detection lines were laid on the tunnel hance (about 6 m away from the pavement), side wall (about 1.36 m away from the pavement), and vault, of which the detection lines of LZ-1, LZ-2, LZ-3, and LZ-4 were laid in left tunnel and the detection lines of LY-1, LY-2, LY-3, and LY-4 were laid in right tunnel. The detection line layout is shown in Figure 11.

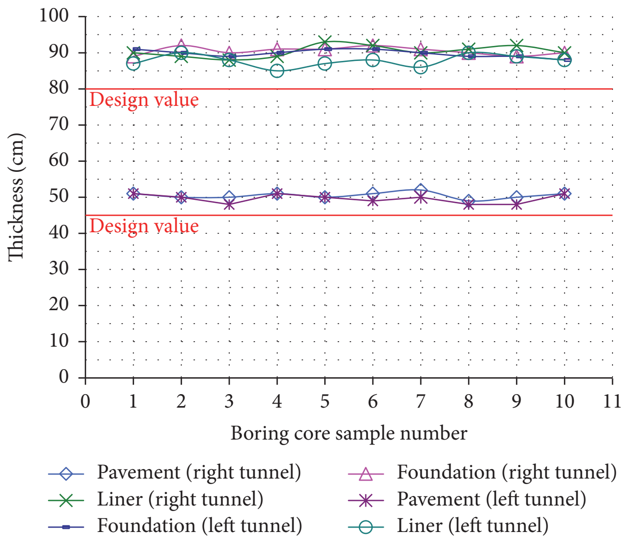

Figure 10: Thickness detection results.

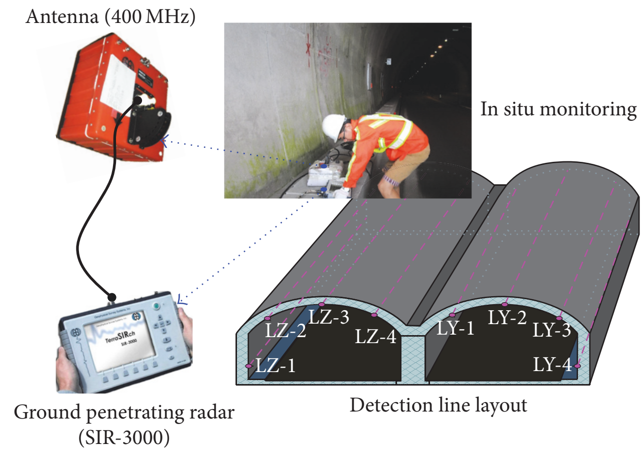

Figure 11: Detection line layout for voids behind the tunnel liner.

Table 5: Grade determination of void behind the liner.

Void location	Void area size (m)			
	<0.5	0.5–1.0	1.0–2.0	>2.0
Vault	A	2A	3A	3A
Hance	A	2A	3A	3A
Side wall	A	2A	2A	3A

(2) Assessment Criteria (Technical Specifications of Maintenance for Highway Tunnel JTG H12-2015). The influence of voids with different sizes in different locations on the tunnel stability is shown in Table 5.

(3) Assessment Results Analysis. Detection data were processed by corresponding data processing software, mainly including amplitude recovery, filtering, F-K filtering, and deconvolution processing. And the time profile with high signal-to-noise ratio (SNR) was obtained, which could improve the identification of useful signals. The time profile of radar can reflect the change of underground media veritably and comprehensively, ensuring the quality of detection data. Based on the detecting results, the liner voids with different sizes were determined in the eight detection lines and the typical oscillogram for liner voids is shown in Figure 12.

The detection range of the vault in right tunnel was YK240+116–YK240+119 (Figure 12). Discontinuous seismic event appeared in this section, and reflected waves with high-energy were formed owing to the large difference of dielectric properties between air and soil, which could accordingly determine the location and size of liner voids. The void area is about 3 m wide and 8 cm thick. Through the statistical analysis of void area in different detection lines, the void area layout can be identified in Figure 13.

The distributions of liner voids with different locations and different lengths are shown in Figures 14 and 15, respectively. From the aforementioned, the liner voids were mostly located at the tunnel entrance section, while relatively few voids were located at the middle section and exit section of the tunnel. Specifically, the voids were mainly located on the tunnel vault, and the void lengths on the vaults of left and right tunnels were 110.6 m and 91.2 m, respectively, accounting for 34.6% and 28.5% of the tunnel length. Meanwhile, the void lengths on the side walls of left and right tunnels were 73 m and 41.3 m, respectively, accounting for 22.8% and 12.9% of the tunnel length. Through contrastive analysis, the occurrence probability of void on the vault was the highest, while the occurrence probability of void on the hance was the lowest. With the increase of void length, the void frequency increased linearly when the void length was less than 5 m. However, the void frequency decreased exponentially when the void length was more than 5 m. The distribution law was similar to the Poisson distribution, which could provide references for the determination of the grouting holes and grouting amount. As a whole, the liner void damage is quite serious in Shitigou tunnel; therefore, the grouting reinforcement should be performed to the void sections.

4. Preliminary Restoration Programme

Based on the structural safety assessment results of Shitigou tunnel, the major restoration programme was proposed, as detailed in Table 6.

Additionally, the inducements for tunnel structural defects are the important basis for proposing the effective restoration programme. According to the statistics of detection data of tunnel structural defects in recent years, as well as the distribution characteristics of structural defects induced by different factors, the proportion of influence factors of structural defects is obtained, which plays a role in guiding the restoration design for later structural health assessment. Specifically, the unsymmetrical pressure and void behind liner and loosening load are the main influence factors for structural defects, which accounts for 15.1%, 12.3%, and 10.9% of the influence factors, respectively (Figure 16).

5. Concluding Remarks

Through the combined application of the modern detection sensors in the operating multiarch tunnel, the structural

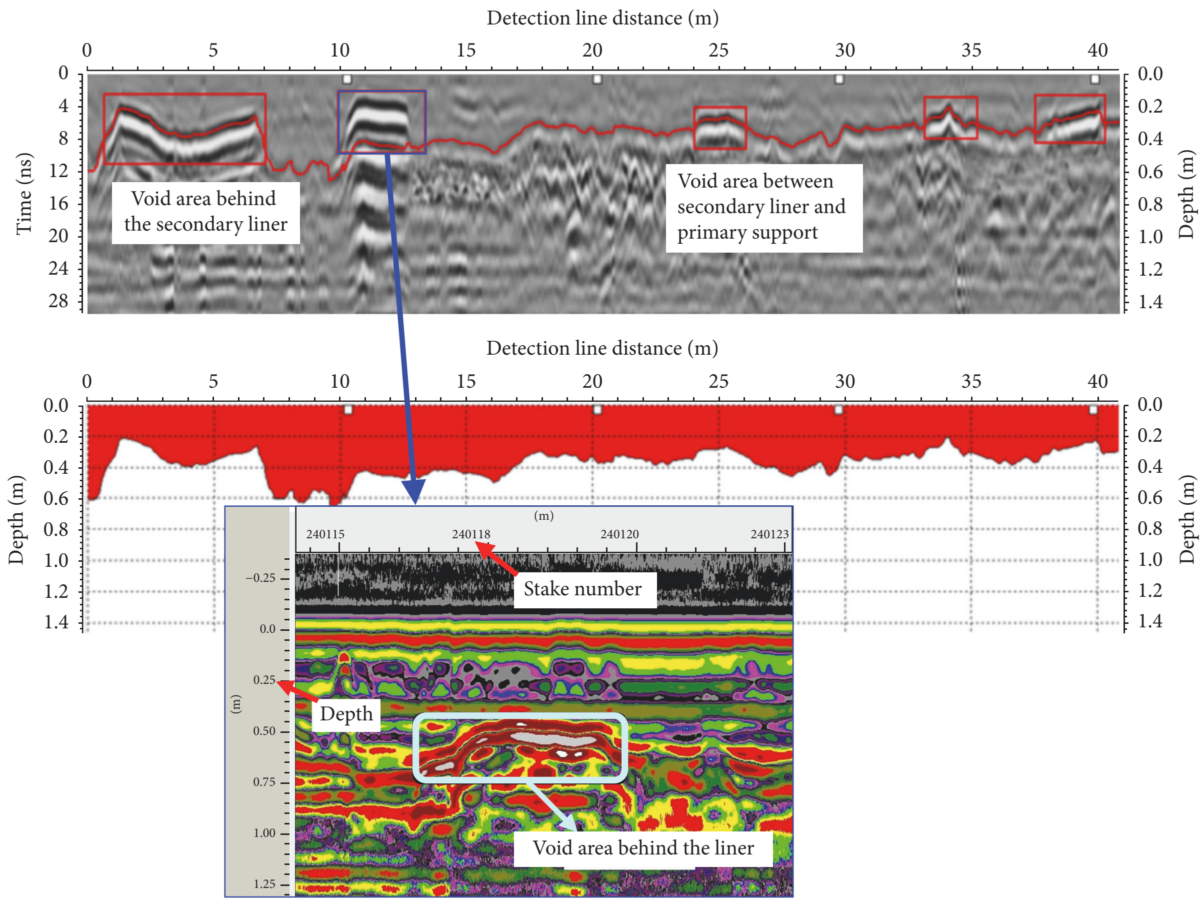

FIGURE 12: Typical oscillogram for liner voids (vault).

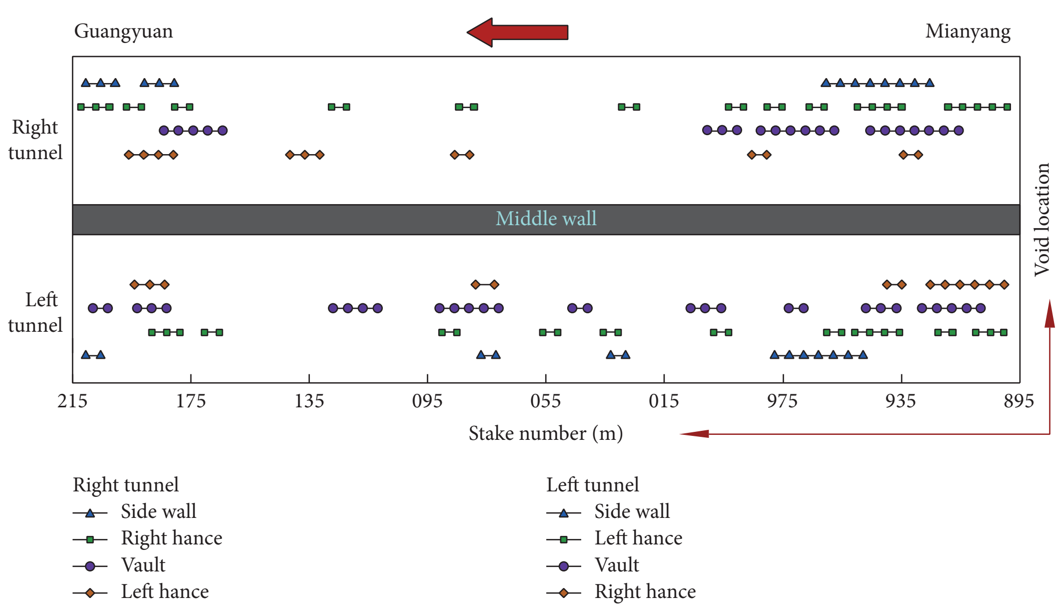

FIGURE 13: Void area layout.

Table 6: Major restoration programme for structural defects of Shitigou tunnel.

Type of defects		Restoration programme
Liner crack		A V-shaped groove 5 cm wide and 3 cm deep was made following the direction of crack, a hole every 0.5 m at the junction of the groove edges was bored, and cement-water glass grout or epoxy resin grout was infused at pressure of 0.15–0.2 MPa.
Tunnel seepage	Side wall	A small groove along the watered points was made and led to the permanent drainage system. The size of the small groove section was 5 × 5 cm. The surroundings of the small groove were smooth, half PVC of 50 mm was reversed into the small groove, and plugging agent or epoxy resin mortar was used to fill in the small groove.
	Arch	Grouting holes with spacing of 1-2 m and diameter of 42 mm were made, and then the grouting pipe was laid. For the little water leakage, plugging agent or epoxy resin mortar could be infused using a small grouter with the grouting pressure of 0.2–0.4 MPa. For the great water leakage, chemical grouting shall be employed.
Liner void		The cement paste mixed liquor was used in grouting, consisting of 80% cement, 20% grade-II coal ash, and aluminum powder expansive agent mixed with 1/10000 cement. The grouting pressure shall be controlled within 0.3–0.5 MPa.

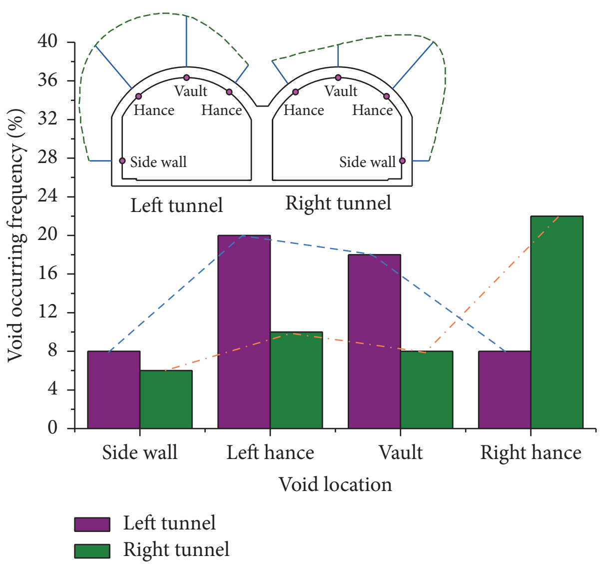

Figure 14: Distribution of liner voids with different locations.

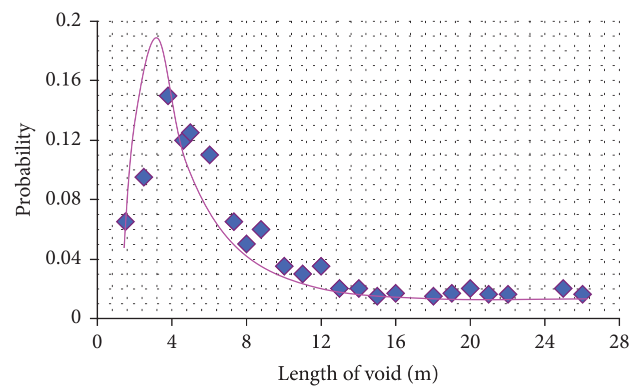

Figure 15: Length distribution of liner voids.

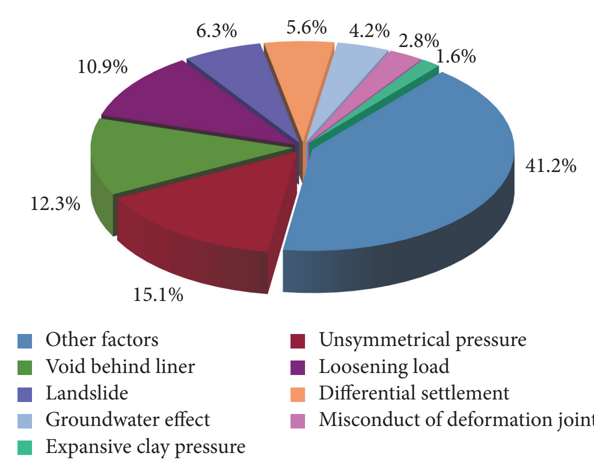

Figure 16: Proportion statistic of influence factors for structural defects.

safety assessment was performed accordingly, and the following conclusions are obtained:

(1) For the right tunnel, the crack width is mainly $1\,\text{mm} < b \leq 2\,\text{mm}$, accounting for 62 percent of the total cracks. Meanwhile, for the left tunnel, 21 cracks with the width of $0\,\text{mm} < b \leq 1\,\text{mm}$ accounted for 41 percent of the total cracks. 22 cracks with the width of $1\,\text{mm} < b \leq 2\,\text{mm}$ accounted for 43 percent of the total cracks. Accordingly, from the inspection data, it can be determined that the criteria grade of liner crack damage is 1A, for which the corresponding grouting should be performed.

(2) Serious water leakage is encountered on the side wall, middle wall, and vault. There is a large seepage area on the wall, and the criteria grade of tunnel seepage is determined to be 1A. It is suggested that the area with serious seepage should be sealed by grouting, and measures of interception and drainage prevention for surface water should be taken.

(3) The strength of pavement and liner structure of right tunnel meets the design requirement. The axial compressive strength of sampling points on foundation

and liner structure of left tunnel does not meet the design requirement. Because of the long-term influence of groundwater, the softening phenomena appear at the entrance and exit section of the tunnel, for which the corresponding measures should be taken.

(4) The liner voids are mostly located at the tunnel entrance section, while relatively few voids are located at the middle section and exit section of the tunnel. Specifically, the voids are mainly located on the tunnel vault, and the void lengths on the vaults of left and right tunnels are 110.6 m and 91.2 m, respectively, accounting for 34.6% and 28.5% of the tunnel length. The liner void damage is quite serious; therefore, it is suggested that the grouting reinforcement should be performed to the void sections.

(5) To propose the effective restoration programme for tunnel structural defects, scientific statistic analysis should be conducted to the detection and assessment results of the defects, such as the liner crack, tunnel seepage, and liner void. Additionally, the distribution characteristics of structural defects induced by different factors and the structural damage grade as well as the different inducements should also be considered.

Conflicts of Interest

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

Acknowledgments

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