Performance Analysis and Related Data Utilization of Rapid Crack Inspection Technology for Railway Tunnel Lining Surface

Qiankuan Feng[1], Yan Huang[2], Guohua Song[1], Zhaoning Wang[1], Yan Gao[1]*, Shilei Wang[1]

[1]Infrastructure Inspection Research Institute, China Academy of Railway Sciences Corporation Limited, NO. 2 Daliushu Road, Haidian District, Beijing, China 100081

[2]Track Maintenance Department, China Railway Nanning Bureau Group Corporation Limited, NO. 21 Foziling Road, Qingxiu District, Nanning City, Guangxi China, 530022

e-mail: fqk@rails.cn, jcsqsb@rails.cn, songguohua@rails.cn, wangzhning@rails.cn, gaoyan@rails.cn, wangshilei@rails.cn）

Abstract: As an important means, the vehicle-mounted imaging technology is usually used to acquire the status data of cracks on lining surfaces of large-scale railway tunnels in operation. Taking a 4 km railway tunnel as a test sample, this paper firstly verified the performance of a vehicle-mounted lining crack inspection system, and analyzed the key performance parameters such as crack inspection rate, length recognition accuracy, mileage positioning error, etc. After its effectiveness was verified, the inspection system was used to inspect the lining cracks of operation railway tunnels with total length of 55 km. The test results show that 60% of cracks with the width of less than 0.3 mm could be inspected, while the figure for the cracks with the width of more than 0.3 mm was 93%. At the confidence level of 90%, the errors in crack mileage and longitudinal crack length are ±0.8 m and ±0.7 m respectively. There exists splicing redundancy between circumferential cracks, and the error is proportional to the number of channels spanned by the cracks. The statistics of lining cracks of operation railway tunnels with total length of 55 km show that circumferential cracks, longitudinal cracks, oblique cracks and water seepage cracks accounted for 55%, 23.1%, 16.9%, and 1.5% of the total, respectively. According to the lining crack state assessment criteria, single-inspected cracks are classified as those that need "focus" and "attention" respectively. In consideration of the impact of crack shapes on the lining structure safety, data utilization strategies for different types of cracks are proposed in this paper.

Keywords: operation railway tunnel; lining; surface crack; rapid inspection; inspection data utilization

1 Introduction

As in 2021, the operating mileage of railway tunnels in China had totaled up to 19,000 km. The tunnels put into operation in the past 10 years and 20 years accounted for 64% and 81% of the total tunnels, respectively [1].

Due to differences in construction periods, uncertainties in construction quality, and complexity in geological and hydrological conditions, the tunnels in operation have various types of defects and diseases. After a long-term evolution, most of tunnel linings are subject to damages mainly including cracking, water seepage, deformation, etc. Shear cracks are the main diseases that affect the overall performance of lining. Concrete shear failure is a premature, brittle failure that leads to the progressive collapse of the entire structure. In most cases, severe cracking emerges, and propagation takes place immediately [2]. Therefore, tunnel lining conditions are related to diseases' development rate and impact, and need to be observed for a long-term [3].

At present, the diseases of tunnel lining are mainly inspected manually. However, the inspection accuracy is limited due to the restriction in skylight time, lighting condition, inspection distance, etc., thereby resulting in the increasingly prominent contradiction between the inspection technology and the scale of operating tunnels [4]. Digital Image Correlation Method (DICM) is a new technique that can be used to detect the pattern of cracks in concrete [5] [6]. Károlyfi et al. [7] [8] studied the correspondences between formwork geometry and concrete composition in the case of fair-faced concrete elements, and proposed an evaluation method for discoloration of the fair-faced concrete surfaces using digital image processing techniques. Now the apparent imaging inspection system based on the mobile platform can be used to obtain the data on the distribution of apparent lining diseases such as cracking and water seepage [9] [10]. The development of machine learning technology has made it possible to conduct the large-scale periodic inspection of tunnels via the apparent imaging technology. In this regard, a lot of studies and practices have been carried out at home and abroad [11] [12]. The inspection speed of the equipment used in these studies is mostly 5~10 km/h, and relatively few fast detection equipment with detection speed above 20 km/h. In 2013, the Spanish company Euroconsult developed a rail-road tunnel inspection vehicle with an inspection speed of up to 30 km/h [13]; In 2020, JR East launched the fourth-generation tunnel lining inspection system (TuLIS) equipped with 12 sensors (lasers + cameras). With a inspection speed of 20 km/h, it is mainly used to inspect lining surface conditions and 3D shapes of tunnel section [14]. In 2018, China Academy of Railway Sciences developed an inspection vehicle for high-speed railway tunnels [15] to inspect the defects behind the lining, and surface diseases. This inspection vehicle features a geological radar inspection speed of 3 km/h, an imaging inspection speed of 50 km/h, and a crack recognition accuracy of 0.5 mm.

Digital tunnel inspection has received extensive attention because it is conducive to more efficient, objective and scientific analysis and management of tunnel conditions. In 2016, VRVIS Research Center and Vienna University of Technology in Austria jointly developed an integrated geometric view-based system for visual analysis of tunnel lining damage data on the basis of using the visual analysis tool Visplore and the 3D real-time rendering engine Ardvark [16]. The digital management software developed by German company SPACETEC for the purpose of tunnel inspection is mainly composed of Tunnel-Info, Tu-View, Tunnel-Inspector, Tu-Drive and other modules [17].

2 Lining Surface Inspection System (LSI system)

This paper introduces a system for rapid inspection of cracks on the railway tunnel lining surface. This system is used to quickly capture high-definition images of lining surface and automatically identify lining surface defects.

2.1 Integrated System Hardware

The LSI system mounted on the wheel-track tunnel inspection vehicle comprises a high-definition acquisition module, a mileage positioning module, and a data processing module (Figure 1). Among them, the high-definition acquisition module consists of 8 CCD line-scan cameras, lighting units, and synchronization control units. The 8 cameras with a laser-assisted illumination instrument are controlled by the synchronization unit, which can ensure the data collected via each channel are related to the same lining section. The mileage positioning module is used to obtain the pulse count of the encoder mounted on the axle, calculate the real-time mileage and speed, and realize the longitudinal mileage positioning of images. This system supports a maximum inspection speed of 80 km/h.

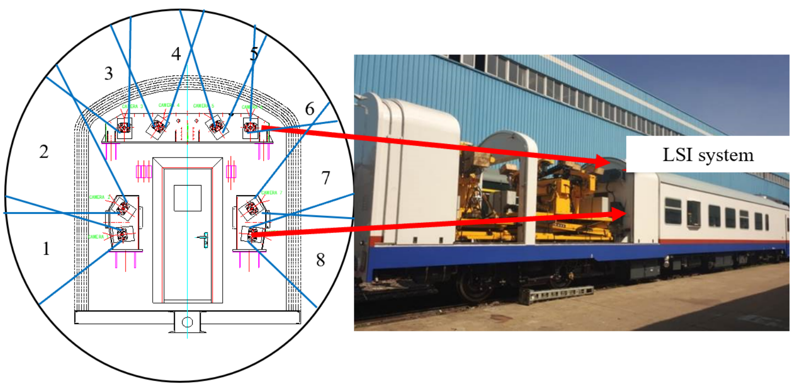


Figure 1
Lining surface inspection system

2.2 Data Processing and Crack Recognition

Lining surface cracks are identified mainly through automatic recognition and manual verification. Automatic recognition is based on the optimized Simple Linear Iterative Clustering (SLIC) algorithm as a gradient-based super-pixel segmentation algorithm, and the lining crack dataset CLS-CRACK is constructed. In addition, the ResNet18 network architecture and Caffe deep learning framework are used for crack recognition, and the DeepLabv3 framework is used to extract crack data through the segmentation network. Through automatic recognition, the images indicating the existence of cracks will be preliminarily screened out, and abnormal areas of the image with suspected cracks will be marked. After the mistakes of automatic recognition are corrected through manual verification, it is possible to confirm the cracks and calculate their lengths, widths, areas and other characteristics parameters.

3 Performance Analysis of Lining Surface Inspection System

In order to verify the performance of the LSI system, the data on actual distribution of lining cracks of a 4 km railway tunnel in operation were obtained via site survey and Amberg imaging equipment. Then, those data were compared with the results of LSI system under the condition of 50 km/h, to assess key performance parameters such as crack inspection rate, length measurement error, mileage positioning error, etc.

3.1 Site Survey

The 4 km site survey area of railway operation tunnel was tested (2 km inward from the large and small mileage entrance of tunnel), covering the plain concrete section and reinforced concrete section (Figure 2). The scope of site survey covers the left and right side walls of lining, namely an area 3 m upward the sidewalk slab.

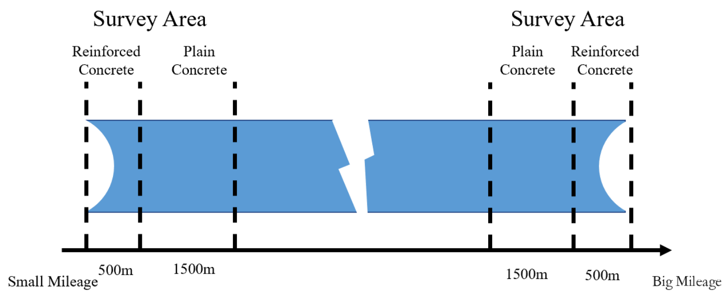
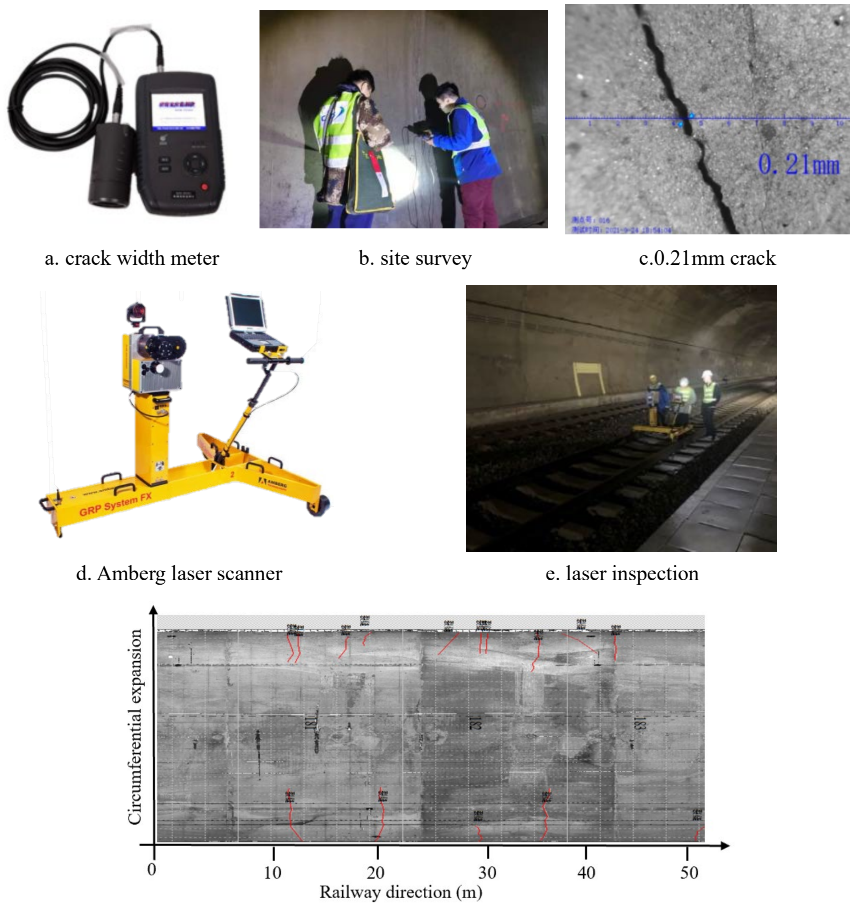


Figure 2
Schematic diagram of the distribution of site survey sections

Site survey of the tunnel includes the measurement of crack number, mileage, width and length. Specifically, the width was measured using a crack width meter (Figure 3a), and the measurement accuracy was 0.01 mm, with details shown in Figure 3c. In addition, the crack length was measured based on the expanded view of the lining section (Figure 3f) obtained by an Amberg laser scanner (Figure 3d, Figure 3e).



a. crack width meter b. site survey c.0.21mm crack

d. Amberg laser scanner e. laser inspection

f. expanded view of the lining section

Figure 3

Inspection devices for site survey, and effects of field application

Table 1

Statistics of cracks with different states

Statistics	Circumferential cracks	Longitudinal cracks	Total
Repaired cracks	251	6	257
Unrepaired cracks	216	0	216
Total	467	6	473

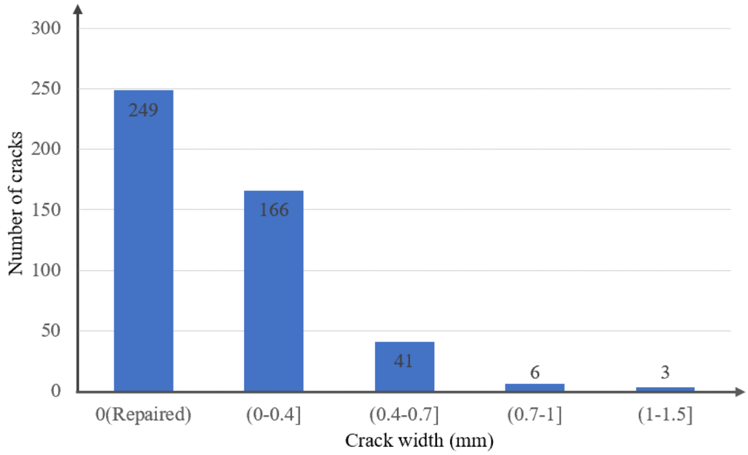
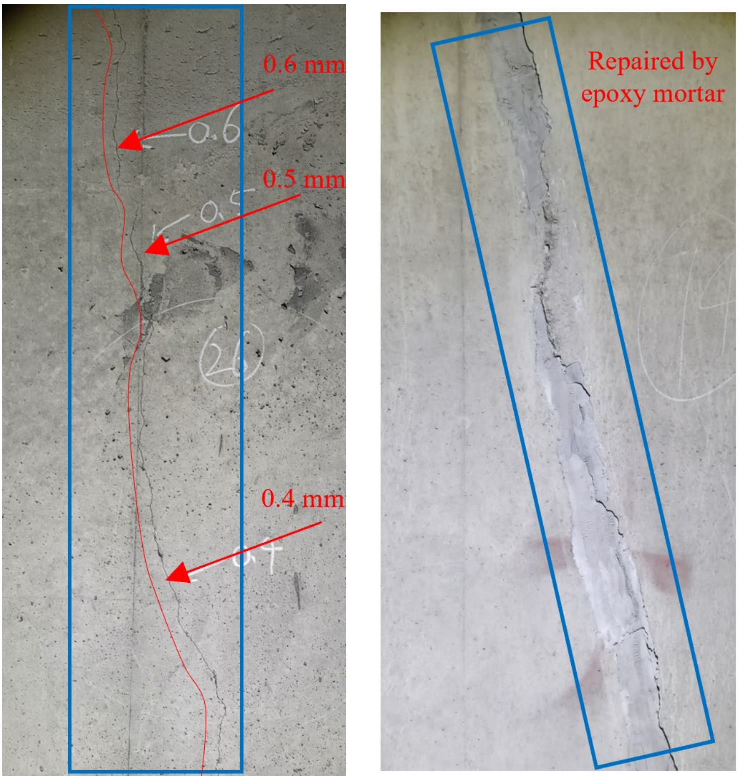


Figure 4
Distribution of cracks by width

Through the site survey, a total of 465 cracks on the left and right lining walls of the 4 km survey area were found and recorded, including 459 circumferential cracks and 6 longitudinal cracks (Table 1). So far, 249 of 465 cracks have been repaired by epoxy mortar (Figure 5b), indicating the remaining 216 ones need to be repaired (Figure 5a). The widths of measurement positions of the 216 ones range from 0.1 mm to 1.5 mm. The distribution of cracks by width is shown in Figure 4.



a. unrepaired cracks b. repaired cracks

Figure 5
Comparison of cracks with different states

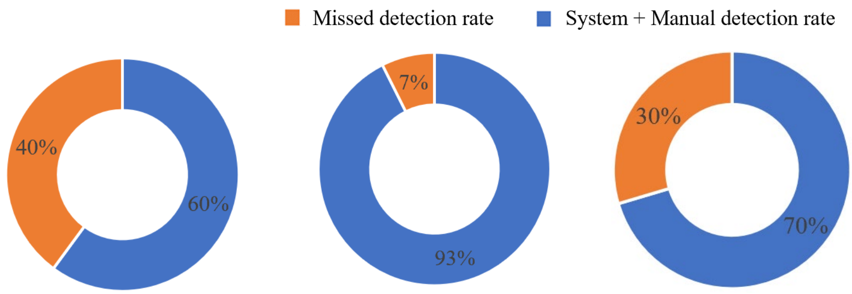
3.2 Crack Inspection Rate Analysis

As shown in Figure 5, the cracks' characteristics are significantly different before and after repair. Therefore, the repaired cracks were not selected to analyze the inspection rate. As the samples, 216 unrepaired cracks mentioned above were used for inspection rate analysis. Analysis results shown in Figure 6 and Table 2. Crack inspection through the LSI system is based on the neural network and manual intervention.

After training, the caffe-based neural network algorithm can be used to effectively identify the abnormal area of an image, but is unable to directly screen out the cracks. In other words, manual intervention is required to ultimately identify the cracks. However, manual intervention was affected by subjective factors such as personal experience and operational standardization, thereby making the final crack inspection rate be lower than the system prompt rate. Such a decreasing trend became increasingly apparent with a decrease in crack width. For example, the crack inspection rate was 92.6% when the width was greater than 0.3 mm, but reduced to 60% when the width was less than 0.3 mm (Figure 6).

Table 2
Analysis of crack inspection rates through the LSI system

Crack width	Site survey	System prompt rate	System + manual inspection rate
(0, 0.3] mm	148	81.8%	60.1%
Above 0.3 mm	68	98.5%	92.6%
Total	216	87.0%	70.4%



(a) Width (0, 0.3] mm (b) Width (0.3,+∞] mm (c) Overall

Figure 6
Analysis of crack inspection rates through the LSI system

3.3 Error Analysis

3.3.1 Mileage Error Analysis

In order to ensure the consistency of analysis samples, 251 circumferential repaired cracks with obvious characteristics were selected for mileage error analysis. According to the crack morphology and location, the LSI system inspected cracks correspond to the site survey results one by one, and then the mileage difference of the starting point of the lowest circumferential crack is calculated.

Results show that mileage errors of the LSI system are normally distributed, with an error mean of 0.2 m, a standard deviation of 0.42, and a mileage deviation between –0.8 m and 0.9 m when the confidence level is 90% (Figure 7).

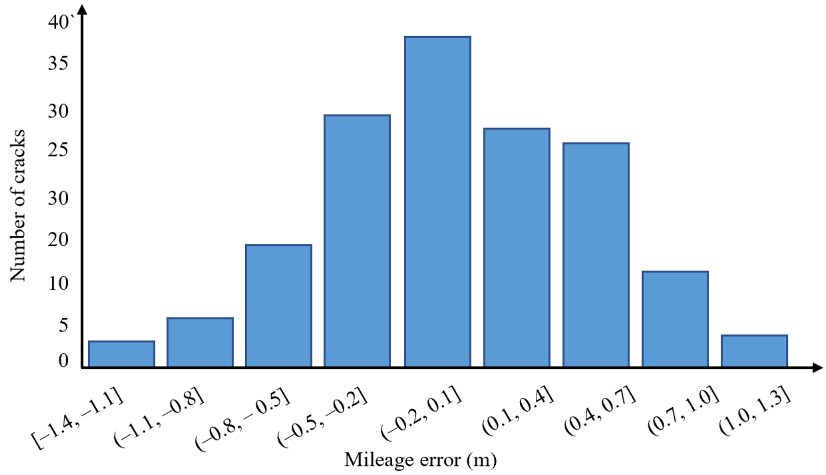


Figure 7
Statistical analysis of mileage errors in repaired cracks

3.3.2 Length Error Analysis

Laser scanning makes it possible to accurately obtain the geometrical shape of a lining section. In addition, image distortion can be avoided by projecting pixel points along the lining section, so as to ensure the measurement accuracy. As the samples, 115 repaired circumferential cracks whose starting points could be clearly identified through laser imaging were analyzed, to extract the data of crack length. The regression analysis of crack lengths determined through laser imaging and LSI system is itemized in Figure 8. As shown in the graph, the crack length identified by the LSI system is systematically enlarged by about 27% than the actual crack length determined through site survey. In addition, the upper and lower bounds of the 90% confidence interval are also indicated. It can be seen that on the basis of systematic amplification, the crack length identified by the LSI system has a dispersion of –0.4~1 m.

The crack lengths identified through the LSI system were further analyzed for staged fitting. Figure 9 shows that the system had an error of 5%, and measurement results changed by step significantly with an increase in crack length. When the crack length covered one channel, two channels and three channels, the measurement errors were about 0.5 m, 1.2 m, and 1.8 m, respectively. Analysis results show that the LSI system is based on the data acquired through multiple cameras, thus resulting in a strong correlation between the measurement error and crack length.

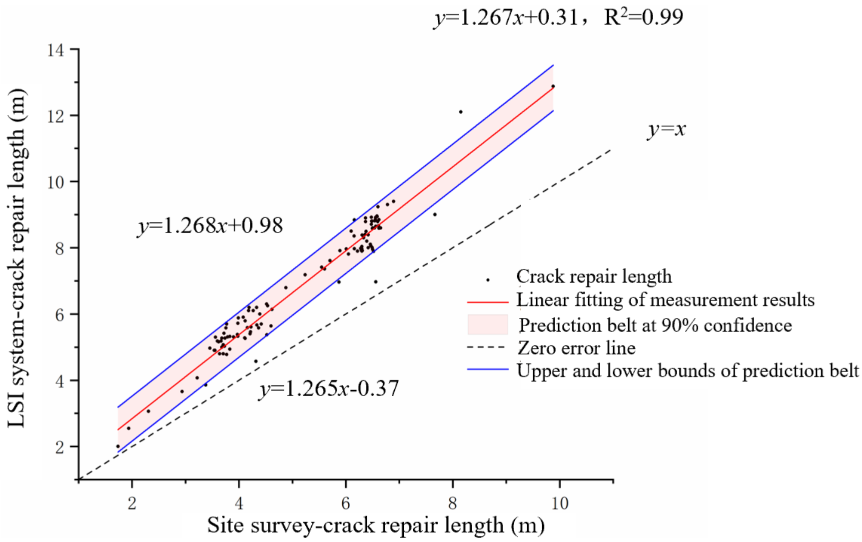


Figure 8
Regression analysis of circumferential crack length

Moreover, 5 repaired longitudinal cracks whose starting points could be clearly identified through laser imaging were analyzed. The regression analysis of crack lengths determined through laser imaging and LSI system was made (Figure 10). The longitudinal crack length obtained by lining scan imaging is highly correlated to that identified through the LSI system. The upper and lower bounds of the 90% confidence interval are indicated and the crack length identified through the LSI system had a dispersion of ±0.7 m. Longitudinal cracks are distributed along the line direction, and generally located in single channels of the LSI system. The results of comparing the lengths errors of circumferential cracks and longitudinal cracks further show that the length error of circumferential cracks is caused by the redundancy of image stitching.

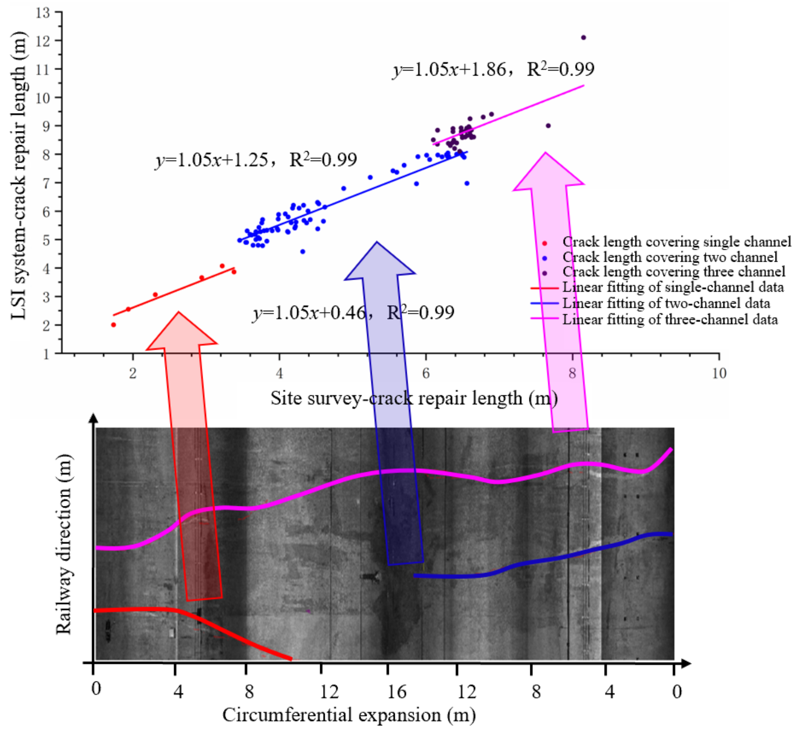


Figure 9

Staged fitting results of circumferential crack length

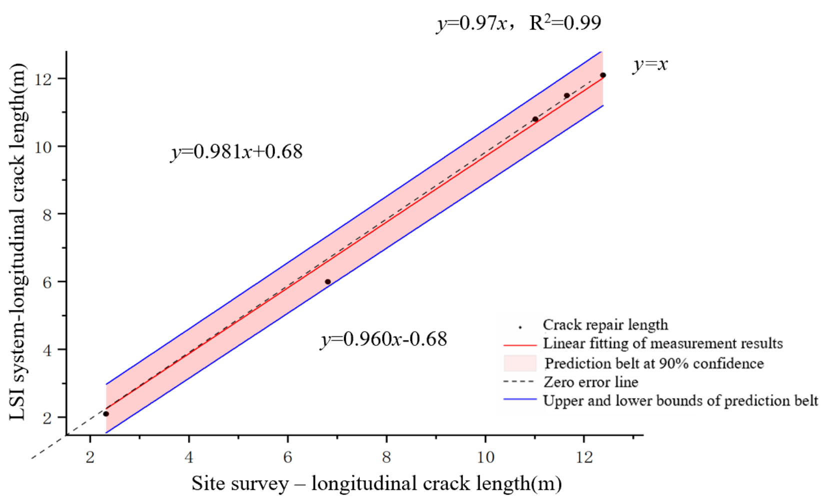


Figure 10

Regression analysis of longitudinal crack length

3.4 Summary

According to the application results of LSI system in 4 km test tunnel, key performance parameters such as crack inspection rate, mileage, length, and measurement error were studied in this section. The results show:

(1) 60% of cracks with a width of less than 0.3 mm could be inspected through the LSI system, while the figure for the cracks with a width of more than 0.3 mm was 93%.

(2) The mileage deviation ranged from –0.8 m to 0.9 m.

(3) The systematic length error of circumferential cracks caused by the redundancy of image stitching was 27%. The circumferential crack length had a dispersion of –0.4~1 m within the 90% confidence interval.

(4) Also, the longitudinal crack length had a dispersion of ±0.7 m within the 90% confidence interval.

After automatic recognition and manual verification of the lining surface images collected at an inspection speed of 50 km/h, it was found that the inspection system could meet the requirements for fast railway tunnel lining crack inspection. In view of a large error in circumferential crack length recognition, a priority will be given to the research on the technology of multi-channel image stitching with little redundancy, to improve the accuracy of circumferential crack length recognition.

4 Tunnel Lining Apparent Inspection Data Utilization Strategy

4.1 Characteristics of Apparent Cracks in Operating Tunnel Lining

Through the LSI system, a total of 6,629 lining cracks were inspected along the 55 km railway tunnel. Specifically, circumferential cracks, longitudinal cracks, oblique cracks, massive cracks and water seepage cracks accounted for 55%, 23.1%, 16.9%, 4.9%, and 1.5% of the total, respectively. There were 8.3 cracks per 100 meters on average (Table 3, Figure 11).

Table 3

Lining crack inspection results of the 55 km operation railway tunnel

Crack type		Quantity	Density (Quantity/100 m)	Proportion
Crack	Circumferential crack	3598	6.5	54.3%
	Longitudinal crack	1498	2.7	22.6%
	Oblique crack	1101	2	16.6%

	Massive crack	327	0.6	4.9%
Water seepage crack	Circumferential crack	49	0.1	0.7%
	Longitudinal crack	36	0.1	0.5%
	Oblique crack	20	0	0.3%
Total		6629	8.3	100.0%

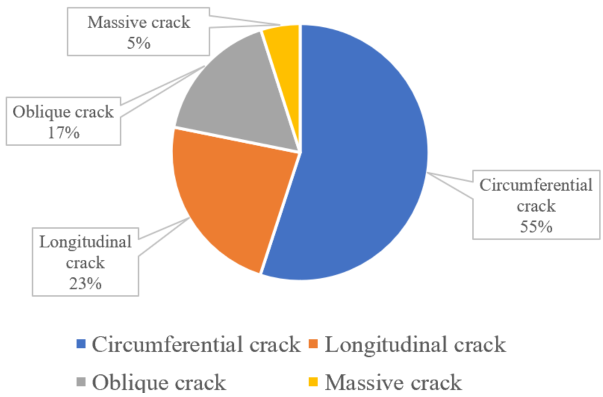


Figure 11

Distribution of apparent lining cracks in operating tunnels

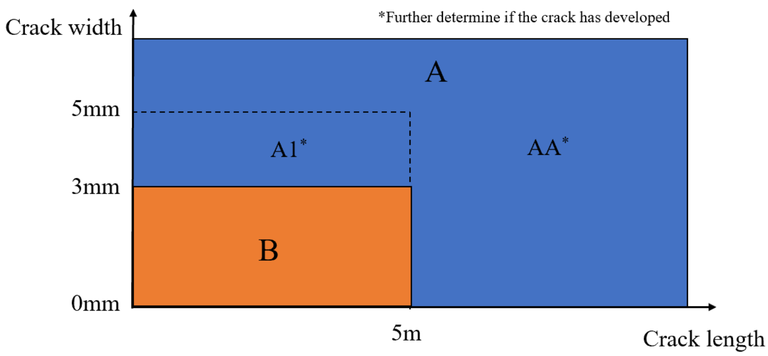


Figure 12

Evaluation standard for crack inspection grade of Railway tunnel in China

Crack ratings AA, A1, and B are specified in Assessment standard for structure deterioration of railway bridge and tunnel Part 2: Tunnel (Q/CR 405.2–2019). The specific rating standards and disposal measures are shown in Figure 12. Only the cracks under development can be rated as A. Single inspection is not enough to ascertain whether the cracks continue to develop. Therefore, the single-inspected cracks are classified as those that need "focus" and "attention" respectively. The state assessment criteria are itemized in Table 4. According to such criteria, the A-grade cracks along the 55 km railway tunnel were further distinguished.

In addition, crack grades and disposal urgency were optimized to a certain extent. After such optimization, there were 1,919 cracks worthy of focus, accounting for 28.9% of the total (Table 5). As a result, it significantly reduced the workload of routine inspection by the maintenance unit.

Table 4

Lining surface crack rating criteria

Crack type	Action proposal
Crack length: L＞12 m	**Focus**, rated as AA if monitoring results show the sign of development
Crack width: δ＞5 mm	**Focus**, rated as AA if monitoring results show the sign of development
Crack length: 5 m≤L＜12 m	**Attention**, rated as AA if monitoring results show the sign of development
Crack length: L＜5 m, and Crack width :5 mm≥δ≥3 mm	**Attention,** rated as A1 if monitoring results show the sign of development

Table 5

"Focus" and "Attention" cracks

Crack type		Focus	Attention	Total	Proportion of focus
Crack	Circumferential crack	930	2668	3598	25.8%
	Longitudinal crack	397	1101	1498	26.5%
	Oblique crack	218	883	1101	19.8%
	Massive crack	327	0	327	100.0%
Water seepage crack	Circumferential crack	20	29	49	40.8%
	Longitudinal crack	16	20	36	44.4%
	Oblique crack	11	9	20	55.0%
Total		1919	4710	6629	28.9%

4.2 Data Utilization Strategy

Inspection results show that there might be thousands of cracks in a single tunnel due to the environmental effects, construction defects and external forces, thus posing some challenges to the analysis and management of lining conditions. Moreover, the development of cracks is neither continuous, nor certain. Cracks will not continue to develop unless they are affected by external forces or in case of significant changes in environmental conditions. Therefore, it is suggested to inspect the tunnel lining conditions through the LSI system once every six months, so as to understand the service status of lining in a timely manner.

In consideration of LSI system performance verification results, and the impact of crack shapes on the lining structure safety, data utilization strategies for different types of cracks are proposed based on the mechanism for periodic inspection of lining surface conditions (Table 6).

(1) The cracks with a width of less than 0.3 mm are fine cracks having little impact on lining safety. Thus, it is suggested that only the cracks with a width of 0.3 mm and above are worthy of attention in the disease recognition process.

(2) In consideration of systematic errors, the longitudinal cracks with a length increment of no more than 0.7 m, and the circumferential cracks with a length increment of no more than 1.2 m shall be deemed as normal cracks in case of periodic inspection.

(3) Circumferential cracks occupy a large proportion but have a low impact on structural safety, it is suggested to conduct the comparative analysis once every two years, to effectively reduce the workload of the maintenance unit.

(4) Longitudinal cracks and oblique cracks are mostly stress cracks. Particularly when longitudinal cracks penetrate through the lining surface, the overall performance of lining under stress will decline, with a huge local stress. After the inspection each time, it is necessary to focus on analyzing the development trend of such cracks, assess them according to the criteria listed in Table 4, and put forward the disposal measures in a timely manner.

(5) Water seepage indicates that the cracks have been penetrated through by the water source behind the lining. Therefore, it is suggested to strengthen manual inspections before and after rainfall or during the freezing and thawing period, and to place emphasis on the crack development and local deformation of surrounding lining.

(6) Most massive cracks are near construction joints, and are likely to fall off. Thus, it is suggested to take corrective measures in time.

Table 6
Comparative analysis cycles for different types of cracks

Crack type	LSI system survey	Comparative analysis cycle	Check items/Actions
Circumferential crack	Once half a year	Once every two years	Crack length
Longitudinal crack and Oblique crack		Once half a year	Deformation and crack width
Water seepage crack		strengthen manual inspections before and after rainfall or during the freezing and thawing period	Water seepage and local deformation
Massive crack		Take corrective measures in time.	Chisel or anchor reinforcement

Conclusions

(1) After automatic recognition and manual verification of the lining surface images collected at an inspection speed of 50 km/h, it was found that the inspection system

could meet the requirements of the maintenance unit. Results show that the inspection rate of the cracks with a width of more than 0.3 mm, longitudinal crack length error, systematic length error of circumferential cracks, and dispersion are 93%, ±0.7 m, 27% and –0.4~1 m, respectively. The analysis of crack length errors will facilitate the subsequent identification of crack development conditions.

(2) The statistics about the 55 km railway tunnel show that there were 8 cracks per 100 meters on average. In addition, circumferential cracks accounted for 55% of the total, while oblique and longitudinal cracks took up only 40%. Based on the existing criteria, new criteria of crack classification for aperiodic inspection were proposed. According to the new criteria, the cracks are classified as those that need "focus" and "attention" respectively. After such optimization, there were 1,919 cracks worthy of focus, accounting for 28.9% of the total. As a result, it significantly reduced the workload of routine inspection by the maintenance unit.

(3) Based on the periodic inspection mechanism, this paper proposes corresponding analysis cycles for different types of cracks, to ensure the timely analysis of the cracks affecting the lining structure safety, and to reduce the workload of the maintenance unit busy dealing with excessive circumferential cracks.

(4) Tunnel lining defects are characterized by a complexity in types, a large number, and a large difference in the impact on lining safety. In the process of risk investigation, cancellation confirmation, and follow-up observation, it is necessary to develop a system for digital management of inspection results, and build a closed-loop digital management model integrating inspection data display, integrated analysis, disease database construction, site review, and track monitoring.

Acknowledgement

This research was funded by Science and Technology Research and Development Program of China State Railway Group Co., Ltd. [J2023G013]: Research on comprehensive lining evaluation technology of high-speed railway tunnel in operation, and Research and Development project of China Academy of Railway Science Co., Ltd. [2022YJ180]: Study on lining image-form symbiosis technology of high-speed railway tunnel in operation.

References

[1] S. Wang, Y. Gao, F. Qi, Z. Ke, H. Li, Y. Lei, Z. Peng: Review on Inspection Technology of Railway Operation Tunnels. Journal of Traffic and Transportation Engineering, Vol. 20, 2020, No.5, pp. 41–57

[2] Al-Rousan R. Z., Alnemrawi B. R. Prediction of Interface Shear Strength of Heat Damaged Shear-keys using Nonlinear Finite Element Analysis, J. Appl. Comput. Mech., 04(1), 2023, 1-16, https://doi.org/10.22055/jacm.2023.42998.4000

[3] Q. Feng, S. Wang, Y. Gao, G. Song, F. Qi: Comparative Study on Monitoring System and State Assessment of High-Speed Railway Bridge Tunnel Inspection. Railway Engineering, Vol. 61, 2021, No. 1, pp. 140–146

[4] Q. Feng, S. Wang, F. Qi, Y. Gao, G. Song: Research on Framework of the Inspection and Monitoring System about Railway Bridge and Tunnel. Railway Technology Innovation, 2021, No. 6, pp. 44–49

[5] Major, Z., Ibrahim, S.K., Movahedi Rad, M., Németh, A., Harrach, D., Herczeg, G., Szalai, S., Kocsis Szürke, s., Harangozó, D., Sysyn, M., Kurhan, D., Baranyai, G.,Gáspár, L., Fischer, s. Numerical Investigation of Pre-Stressed Reinforced Concrete Railway Sleeper for High-Speed Application. Infrastructures, 2023, 8(3), 41. doi: https://doi. org/10.3390/infrastructures8030041

[6] Szalai, S., Eller, B., Juhász, E., Movahedi, M. R., Németh, A., Harrach, D., Baranyai, G., Fischer, S. Investigation of deformations of ballasted railway track during collapse using the Digital Image Correlation Method (DICM). Reports in Mechanical Engineering, 2022, 3(1), 168–191, doi: https://doi. org/10.31181/rme20016032022s

[7] Károlyfi, K. A., Horváth, A. Papp, F. Digital image processing method for evaluation of discoloration on fair-faced concrete surfaces Építöanyag-Journal of Silicate Based and Composite Materials, Vol. 74, 2022, No. 02, pp. 67–70, https://doi. org/10.14382/epitoanyag-jsbcm.2022.11

[8] Károlyfi, K., Papp, F. The correspondences between formwork geometry and concrete composition in the case of fair-faced concrete elements. Pollack Periodica An International Journal for Engineering and Information Sciences Vol. 13, 2018, No. 02, pp. 43–54. https://doi. org/10.1556/606.2018.13.2.5

[9] W. Qiu, Y. Cheng: High-Resolution DEM Generation of Railway Tunnel Surface Using Terrestrial Laser Scanning Data for Clearance Inspection. Journal of Computing in Civil Engineering, 2017, Vol. 31, No. 1, pp. 4016045

[10] Z. Huang, H. Fu, X. Fan, J. Meng, W. Chen, X. Zheng, F. Wang, J. Zhang: Rapid Surface Damage Detection Equipment for Subway Tunnels Based on Machine Vision System. Journal of Infrastructure Systems, Vol. 27, 2021, No. 1, pp. 04020047

[11] S. Stent, R. Gherardi, B. Stenger, *et al*: Visual Change Inspection on Tunnel Linings. Machine Vision and Applications, Vol. 27, 2016, No. 3, pp. 319–330

[12] R. Montero, G. Victoresj, S. Martinez, *et al*: Past, Present and Future of Robotic Tunnel Inspection. Automation in Construction, Vol. 59, 2015, pp. 99–112

[13] J. Laurent, F. Dominguez: Use of 3D Scanning Technology for Automated Inspection of Tunnels. Proceedings of the World Tunnel Congress, 2014, pp. 1–10

[14] Y. Fujino, D. Siringoringo: Recent Research and Development Programs for Infrastructures Maintenance, Renovation and Management in Japan. Structure and Infrastructure Engineering, Vol. 16, 2020, No. 1, pp. 3–25

[15] X. Chai, X. Zhu, J. LI, *et al*: Tunnel Lining Crack Identification Algorithm Based on Deep Convolutional Neural Network. Railway Engineering, Vol.58, 2018, No.6, pp. 60–65

[16] T. Ortner, J. Sorger, H. Piringer, *et al*: Visual Analytics and Rendering for Tunnel Crack Analysis. Ieee Transactions on Visualization and Computer Graphics, Vol. 32, 2016, pp. 859–869

[17] K. Tabrizi, M. Celaya, B. Miller, *et al*: Damage Assessment of Tunnel Lining by Mobile Laser Scanning: Pittsburgh, Pennsylvania, Implementation Phase of FHWA SHRP 2 R06G Project. Transportation Research Record, Vol. 2642, 2017, No.1, pp. 166–179