Review of Railway Operation Tunnel Inspection System and Condition Assessment Method

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Abstract: Currently, the expanding scale of railway tunnels in operation raises higher requirements for effective management thereof so as to ensure their safe operation. Just in this context, this paper compares and analyzes the tunnel inspection systems, condition assessment methods and technical equipment prevailing in many countries including Japan, European countries, the United States and China. Study results show that in terms of tunnel inspection systems, various countries have set their respective tunnel inspection cycles according to the tunnel integrity, service duration, service status, speed level and other factors. In particular, Japan and Europe have designed the tunnel inspection procedures, putting forward requirements for the professional competence of inspectors. In terms of condition assessment, Japanese standards are more hierarchical and systematic in the integrated application related to lining crack, deformation and defect, but are insufficient in the assessment of serious internal lining defects. In contrast, European standards focus on the impact of diseases on the overall performance of the tunnel structure. In addition, Chinese standards highlight the single-indicator assessment, but ignore the correction of assessment results in case of multiple deterioration types. It’s worth noting that Japan and China have respectively developed their own rail-mounted tunnel inspection devices to replace manual inspection. Based on a comprehensive comparison of tunnel inspection systems and condition assessment methods of different countries, according to the scale, inspection device technical level and service characteristics of China's railway tunnels, this paper proposes a framework of railway tunnel inspection regulation, while optimizing and supplementing the contents and requirements of relevant tunnel inspection regulation.

Keywords: Railway Tunnel; Inspection System; Inspection Device; Condition Assessment Method

Introduction

By the end of 2020, the total mileage of China's railways in operation reached 145,000 km. Over the same period, a total of 16,798 railway tunnels and 3,631 high-speed railway tunnels had been put into operation, with a total length of about 19,630 km and 6,003 km, respectively. All these indicate that China has become the country with the largest scale of railway tunnels in operation in the world [1, 2]. In China with a vast territory, environments along railway lines are complex and changeable in climatic, geological and hydrological conditions. Similarly, tunneling is vulnerable too many complex factors such as corrosion, freeze thawing, etc. Due to differences in construction periods, construction standards, and uncertainties in construction quality, railway tunnels in operation are exposed to various types of defects and diseases [3]. In fact, any minor defect or disease of tunnel lining might affect the safe operation of a railway in operation [4].

The railway infrastructure inspection system is vital for and of great significance to the safe operation of railways in China, as well as scientific and rational guidance in maintenance and repair [5]. After analyzing the service characteristics and maintenance modes of Chinese bridges and tunnels, Lu Chunfang [4] pointed out that preventive maintenance is a trend of maintenance and repair of high-speed railway bridges and tunnels in China. In addition, Chen Qi [6] et al. proposed to optimize the technical rules and procedures of infrastructure maintenance to better achieve the safety management, monitoring and inspection, application of machinery and devices, and production organization, etc. Also, Chen Dongsheng [7] proposed several management modes for high-speed railway maintenance in China according to the foreign experience in this regard. Ma Weibin [8] summarized the existing technologies for railway tunnel inspection, monitoring, assessment and disease treatment in China, and then proposed a technical system for disease treatment of railway tunnels in operation.

Despite the constant progress in tunnel damage identification technology and quality inspection method [9-14], currently tunnel condition data are acquired mainly through manual inspection, and there still exists a certain gap to achieve targeted maintenance and preventive maintenance of railway infrastructure due to the deficiencies in inspection method efficiency, and accuracy. Furthermore, as the railway maintenance management units face increasingly pressures in reducing production costs and improving the efficiency of maintenance and repair, it is found that conventional inspection systems, devices and condition assessment methods are becoming hard to meet the requirements with the scale development of tunnels. In view of this, it is necessary to optimize the inspection systems and improve the condition assessment standards on the basis of comparing and analyzing the railway tunnel inspection situations of different countries. Specifically, it is required to study and establish a scientific and efficient inspection system in line with the scale of railway tunnels, so as to timely identify railway transportation safety risks, objectively understand the law of tunnel structure performance evolution, and provide a reasonable guidance in the targeted maintenance of tunnels.

1 Tunnel Inspection Systems

In order to ensure the safe and efficient operation of railways, many countries including Japan, Europe, the United States and China have established different tunnel infrastructure inspection systems. In particular, along with the development of inspection technologies and devices, they have successively updated their respective professional inspection standards and systems since the beginning of the 21st Century.

1.1 Japanese Tunnel Inspection System

Upon entrustment by the Railway Bureau of the Ministry of Land, Infrastructure, Transport and Tourism of Japan, Railway Technical Research Institute (RTRI) founded the Research Committee on Maintenance Management of Railway Civil Engineering Structures and the Research Committee on Track Maintenance Management in 2000, initiating the research on identifying the inspection cycles and integrity of civil engineering structures and tracks. In January 2007, the said Railway Bureau promulgated the Standards for the Maintenance Management of Railway Structures [15, 16] (hereinafter referred to as the "Standards"). Focusing on the safety, usability and restorability of structures, the Standards clarify the railway structures maintenance management system and procedures, including the basic concepts, inspection methods, integrity assessment criteria, maintenance management measures and records, etc. The required performance, performance item and judgment criterion of the tunnel structure are detailed in Table 1.

Table 1
Required performance, performance item and judgment criterion of the tunnel structure

Required performance	Performance items	Judgment criterion
Safety	Stability of tunnel structure	No risk of tunnel collapse
	Structure boundary	No invasion into the boundary
	Line stability	No uplift, subsidence and movement of railway subgrade that might affect the safe operation of trains
	Spalling stability	No spalling of concrete, maintenance materials and so on that might affect the safe operation of trains
	Safety in case of water	No phenomenon of water seepage or freezing

	seepage and freezing	that might affect the safe operation of trains
Usability	Usability in case of water seepage or freezing	No phenomenon of water seepage or freezing that might affect the functions of devices in the tunnel
	Dirt on the surface	No dirt that would seriously hinder the normal inspection
	Impact on surrounding environment	No impact on surrounding environment
Restorability	Post-disaster recovery	Easiness in post-disaster repair of damaged tunnels

Tunnel inspection falls into several categories, i.e., preliminary inspection, comprehensive inspection, individual inspection and random inspection. Among them, comprehensive inspection can be divided into comprehensive inspection and special comprehensive inspection. Specifically, a preliminary inspection is required before any railway structures newly-built, renovated or expanded is put in to use. The comprehensive inspection is conducted regularly, to identify the integrity of the entire structure, and the necessity of individual inspection, while the special comprehensive inspection aims to improve the accuracy of integrity identification. In contrast, an individual inspection is conducted in the course of any comprehensive inspection or random inspection, and is specific to a railway structure with an integrity rating of A or any other railway structure for which such inspection is deemed necessary. In addition, random inspection aims to find out exceptions arising from the occurrence of a natural disaster. For example, a random inspection is required if concrete spalling might seriously affect the safety of any third party or adjacent engineering might affect the target structure.

The cycles of preliminary inspection and comprehensive inspection are detailed in Figure 1. Specifically, a comprehensive inspection is generally conducted once every two years, and the first special comprehensive inspection is conducted within 10 years after the railway structure is put into operation. If the results of special comprehensive inspection show the target structure has the required performance, the comprehensive inspection cycle may be extended accordingly. The process of tunnel inspection and maintenance is shown in Figure 2.

In accordance with Japanese standards, qualified tunnel inspectors with rich experience accumulated through receiving training over years shall be able to identify tunnel risks comprehensively according to various factors, and particularly have the skills of special comprehensive inspection conducted to extend the comprehensive inspection cycle.

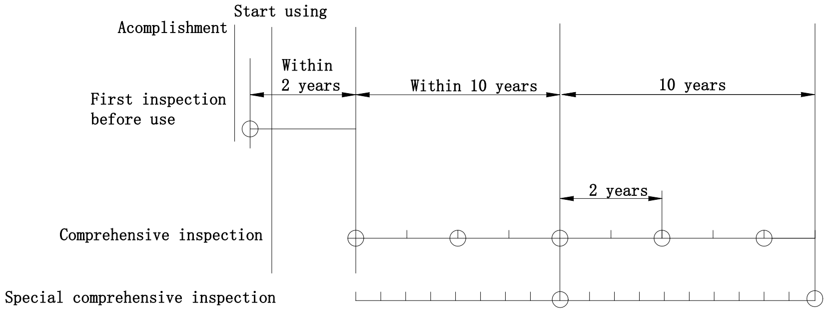


Figure 1
Schematic diagram of preliminary inspection and comprehensive inspection cycles

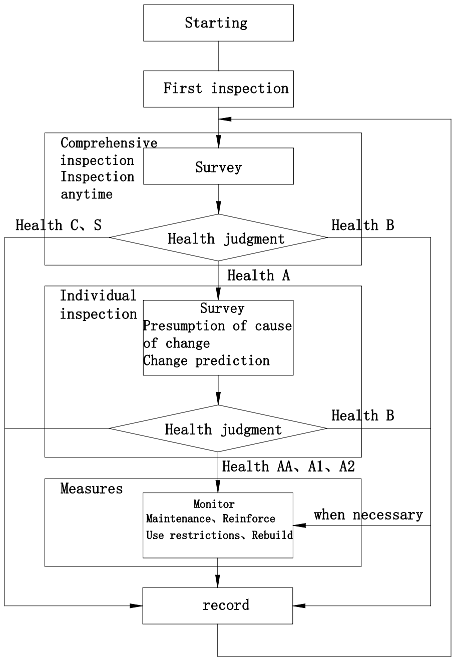


Figure 2
Process of Japanese structure inspection and maintenance

1.2 European Tunnel Inspection System

Although their tunnel maintenance systems vary to a certain extent, European countries generally follow the principle of moderate separation of "management, inspection, and maintenance", and actively promote the business outsourcing [17]. Whereas EU standards and International Union of Railways (UIC) standards are integrated, the tunnel inspection systems of European countries are generally consistent with the tunnel inspection requirements raised by UIC. The Code for Management and Maintenance of Tunnels in Service (“the Code” for short) [18] (UIC Code 779-10) specifies the contents of management, maintenance, performance improvement, and operation of tunnels in operation. Inspection constitutes an important part of tunnel maintenance. According to the Code, the inspection work is composed of planned monitoring and unplanned monitoring. Further, planned monitoring consists of routine monitoring, annual monitoring, detailed inspection, and special monitoring. The content, personnel and period of each inspection are shown in Table 2. If it is hard to identify the tunnel conditions after the conventional condition assessment, some geotechnical and geological professionals and experts shall be organized to conduct the supplementary inspection and theoretical analysis.

Table 2

Types of European tunnel inspection

Inspection type		**Duties**	**Implementer**	**Cycle**
Planned monitoring	Routine monitoring	General inspection of tunnels in combination with line inspection	Lineman	Line inspection
	Annual monitoring	Reviewing various inspection results in the detailed inspection report, and making supplementary explanations	Tunnel inspector	1 year
	Detailed inspection	Issuing a detailed inspection report, updating and distributing the disease records to all the parties of maintenance management, and clarifying the maintenance work recommendations and their urgency in the report	Professional engineers, assisted by experts if necessary	4-6 years
	Special monitoring	Inspecting the sensitive areas (such as the areas featuring the rapid disease development or marked “unstable” in the inspection report) more frequently, taking corresponding safety measures (such as train speed limitation) if necessary, before disposal (generally accompanied by the measurement of geometry such as convergence, crack)	/	/
Unplanned monitoring		Carrying out any special inspection, or any meticulous	External experts or	/

	inspection of structures or parts thereof in unforeseen circumstances (such as occurrence of a natural disaster or sudden appearance of some special problems)	specialized firms, with assistance needed if necessary	

1.3 American Tunnel Inspection System

In 2005, the Federal Highway Administration of the U.S. Department of Transportation and the Federal Transit Administration jointly promulgated the Highway and Rail Transit Tunnel Inspection Manual (“the Manual” for short) [19]. In the Manual, tunnel inspection was expounded from the perspectives of structure, machinery, electrical engineering and others, and the inspectors, responsibilities, devices, preparations, and safety measures were introduced. According to structural requirements, new tunnels shall be inspected once every 5 years, while old tunnels shall be subject to the short-distance inspection once every 2 years. In addition, old tunnels shall be inspected on a daily, weekly and monthly basis.

In 2008, American Railway Engineering and Maintenance-of-Way Association (AREMA) published the Railway Bridge Inspection Manual [20], recommending some methods for the inspection of railway bridges and tunnels (including tunnel structures). The Manual mainly introduces the general concepts of bridge and tunnel inspection, and different types of inspections for specific structures.

Unlike the railways in Japan, Europe, and China, American railways are owned by private companies. Thus, for their own sake, such private companies would minimize the maintenance costs. Specially, annual maintenance costs of bridges and tunnels only account for about 10% of the overall costs. In addition because American railways are privately owned, and the official tunnel structure rating methods issued by the U.S. railway authority involve the potential liability issues, currently there are no uniform rating methods for railway tunnel structures. Thus, various railway companies in the United States usually establish their own procedures for the inspection, maintenance, rating and safety management of tunnel structures in accordance with general guidelines released by the federal government as well as their internal management rules.

1.4 Chinese Tunnel Inspection System

In China, railway bridges and tunnels are maintained and repaired based on the speed grades, namely high-speed and normal speed. In addition, types and frequencies of tunnel inspection are specified. The tunnel inspections for both high-speed trains and normal-speed trains are basically the same, including periodic inspection, temporary inspection, and special inspection. In accordance with the Rules for Maintenance and Repair of Bridges and Tunnels for Normal-speed Railways (TG/GW 103-2018) [21], important tunnel devices shall be inspected once every six months. In addition, each tunnel shall be comprehensively inspected during the comprehensive maintenance period. However, the inspection cycle may be appropriately extended if a line only allows the passing of freight vehicles and the annual transport volume is less than 5 million tons. In accordance with the Rules for Maintenance and Repair of Bridges and Tunnels for High-speed Railways (Trial) (TG/GW 114-2011) [22], important tunnel devices shall be inspected once every quarter, while the inspection frequency for others depends on the structural position. For example, tunnel entrances and exits shall be inspected once every six months, while tunnels and surroundings shall be inspected once a year. In contrast, with normal-speed rail tunnels, high-speed rail tunnels are inspected more frequently, and the inspection cycle for each part of the tunnel structure is clarified. However, the requirements for temporary inspection and special inspection are the same for both normal-speed rail tunnels and high-speed rail tunnels, depending on the environmental conditions and service time thereof.

1.5 Comparison of Different Inspection Systems

In accordance with Japanese tunnel inspection standards, comprehensive inspection cycle shall be 2 years, and a special comprehensive inspection shall be conducted in not less than 10 years. In addition, the comprehensive inspection cycle may be extended if conditions permit after the special comprehensive inspection, and basic qualifications and skills of relevant inspection personnel are specified. Throughout the inspection process, inspection personnel focus on inplying and predicting the causes of changes in tunnel performance.

In accordance with European tunnel inspection standards, mainly the tunnel diseases specified in the detailed inspection report shall be reviewed, and the detailed inspection cycle shall be 4-6 years. The process of condition assessment based on conventional condition assessment, supplementary inspection and theoretical analysis is proposed, and the responsibilities and roles of different positions are specified.

In accordance with American tunnel inspection standards, the short-distance inspection cycle shall be 2-5 years, depending on the service time of tunnels. However, because American railways are privately owned, currently there are no uniform rating methods for railway tunnel structures.

In accordance with Chinese tunnel inspection standards, inspection cycles for high-speed railway tunnels and normal-speed railway tunnels shall vary to some extent. Specifically, the comprehensive inspection cycle of high-speed railway tunnels shall be one year, while the inspection cycles of normal-speed railway tunnels shall depend on the time of comprehensive maintenance.

2 Tunnel Condition Assessment

2.1 Japanese Tunnel Condition Assessment

In Japan, the structure integrity is identified according to the inspection results, change causes and prediction results. The integrity ratings include A, B, C, and S. Among them, A is further divided into AA, A1, and A2. The tunnel integrity identification criteria and corresponding maintenance measures are itemized in Table 3.

In accordance with Japanese standards, mountain tunnels and urban tunnels shall be inspected and assessed separately. The integrity of mountain tunnels is affected by external factors and environmental effects. Specifically, there are 9 types of external actions, mainly including surrounding rock pressure, landslide, water pressure, frost heave and adjacent construction. Also, there are 7 kinds of environmental effects, mainly including concrete carbonization and harmful water erosion. In addition, tunnel conditions can be identified according to the deterioration forms under typical external actions such as rock mass bias, landslide, unbalanced water pressure, and frost heave. Based on the analysis of change causes, the tunnel integrity can be further assessed.

Table 3

Criteria for assessing the tunnel integrity

<table>
<tr><th colspan="2">Integrity</th><th>Tunnel conditions</th><th>Maintenance measures</th></tr>
<tr><td rowspan="3">A</td><td>AA</td><td>Threatening the safety of passengers and masses, affecting the normal operation of trains and having other possible dangers</td><td>Taking emergency measures</td></tr>
<tr><td>A1</td><td>Performance reducing due to ongoing changes, or performance losing due to heavy rain, water seepage, earthquake, etc.</td><td>Taking prompt actions</td></tr>
<tr><td>A2</td><td>Performance reducing in the future due to possible changes</td><td>Taking measures when necessary</td></tr>
<tr><td colspan="2">B</td><td>Changes that might lead to integrity A</td><td>Taking measures such as monitoring as necessary</td></tr>
<tr><td colspan="2">C</td><td>Minor changes</td><td>Prioritizing the inspection thereof next time</td></tr>
<tr><td colspan="2">S</td><td>Fine integrity</td><td>N/A</td></tr>
</table>

In accordance with Japanese tunnel inspection standards, if the tunnel lining integrity is rated as A, individual inspection shall be carried out in the process of comprehensive inspection once every two years, to achieve the itemized assessment of integrity (AA, A1, A2).

Crack is a common tunnel disease, and the criteria for assessing the degree of crack deterioration are shown in Figure 3. The integrity assessment of mountain tunnels with cracks is detailed in Table 4. The development status depends on the ratio between the lining deformation u and the development time t. In case of 10 mm/year<u/t or 2 mm/month<u/t, it is deemed as very fast development; in case of 3 mm/year<u/t<10 mm/year, it is regarded as fast development; in case of 1 mm/year<u/t< 3 mm/year, it is determined as slow development.

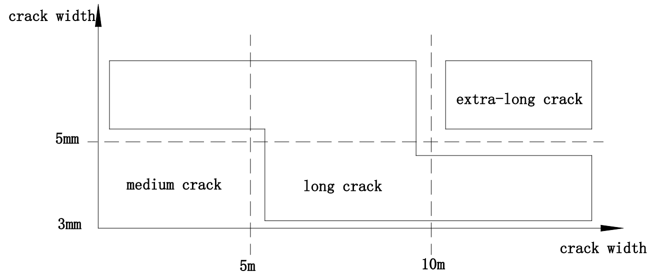


Figure 3
Criteria for distinguishing extra-long cracks, long cracks and medium cracks

Table 4
Integrity assessment of mountain tunnels with cracks

Degree of deterioration	Development status	Deterioration prediction	Integrity
Extra-long cracks, or shear cracks, serious crushing	Yes	Instability of current tunnel	AA
	No	Being unable to identify its stability before next inspection	A1
Long cracks, crushing	Very fast development	Instability of current tunnel	AA
	Fast	Being unable to identify its stability before next inspection	A1
Medium cracks	Very fast development	Instability of current tunnel	AA
	Fast	Being unable to identify its stability before next inspection	A1
	Slow development	High possibility of reduced stability before next inspection	A2
No obvious cracks	Very fast development	Instability of current tunnel	AA
	Fast	Being unable to identify its stability before next inspection	A1
	Slow development	High possibility of reduced stability before next inspection	A2
	No	Stability of current tunnel	B~C

The deterioration location, initial defect, and structural form shall also be taken into account for the purpose of integrity rating. In addition, assessment results shall be corrected if necessary. In the case of vertical pressure, landslide and other circumstances caused by any mountain movement, the integrity rating will be reduced by one grade. If the depth of cracks in a masonry tunnel made of bricks or concrete blocks exceeds 100 mm, the tunnel lining thickness, location and scope, and deterioration degree shall be taken into account, and the integrity may be reduced accordingly by one grade. If the tunnel lining has initial defects such as material deterioration and insufficient thickness, the bearing capacity of lining will be undermined. In this case, the integrity will be assessed based on the effective thickness (the thickness with an intensity greater than 15 MPa), and assessment results can be appropriately corrected, as shown in Table 5.

Table 5
Correction of assessment results for initial defects of lining

Effective thickness γ, effective thickness t_s	Correction of assessment results
γ<1/3, or effective thickness t_s<250mm	Integrity reducing by 2 grades
1/3≤γ<2/3	Integrity reducing by 1 grade

Note: Effective thickness γ=t_s/design thickness;
t_s=thickness with an intensity greater than 15 MPa

2.2 European Tunnel Condition Assessment

In some European countries, tunnel conditions are assessed by I-IV grades. The overall conditions of and corresponding repair measures for each grade of tunnels are shown in Table 6.

Table 6
Tunnel condition rating and repair measures

Grade	Overall condition	Description	Repair measures
I	Favorable	No problem, or insignificant problem	Maintaining the current conditions
II	Reasonable	Existence of some non-structural problems (diseases)	Minor maintenance to avoid deterioration
III	Poor	Structural diseases, serious or massive deformation or cracking, large-scale water seepage	Repair required within 5 years
IV	Very poor	Severe structural diseases, risks of collapse in important structure areas	Dealing with as soon as possible to stabilize the conditions within one year, with regular special inspection required for special monitoring of hazardous areas

2.3 Chinese Tunnel Condition Assessment

In accordance with the Assessment Standard for Structure Deterioration of Railway Bridges and Tunnels [23] (Q/CR405.2-2019), tunnel deterioration can be rated as A, B, C, and D according to the impact on structural functions and traffic safety, and grade A can be further divided into AA and A1. Different repair measures for different tunnel deterioration grades are shown in Table 7, and the deterioration rating depends on the highest deterioration level of a single disease. In accordance with the Interim Regulations on the Safety Rating of Railway Tunnel Linings [24] (TYH [2004] No. 174), lining defects and diseases shall be quantitatively graded. In particular, the severity of lining defects and diseases of segmented tunnels shall depend on the highest level of single quantitative indicators. In addition, the lining safety level shall rest with surrounding rock level, groundwater condition, impact on traffic safety, and other factors. The safety level of tunnel lining shall depend on the safety level of the tunnel segment with most severe diseases.

Table 7
Tunnel deterioration rating and repair measures

Deterioration grade		Impact on structural functions and traffic safety	Measures
A	AA (very severe)	Serious deterioration, endangering traffic safety	Taking measures immediately
	A1 (Severe)	Serious deterioration, which might endanger traffic safety	Taking measures as soon as possible
B (relatively severe)		Possibility to become very severe	Strengthening monitoring and taking measures if necessary
C (moderate)		Minor impact	Strengthening inspection, keeping normal maintenance
D (minor)		No impact	Normal maintenance and inspection

2.4 Comparison of Tunnel Condition Assessment Standards

Japanese tunnel condition assessment standards focus on implying and predicting the causes of changes in tunnel performance. Tunnel integrity assessment is based on the severity of tunnel diseases, deterioration degree, development status, and impact on structural stability. In addition, the deterioration location, initial defect, and structural form shall also be taken into account to correct assessment results. Japanese standards are more hierarchical and systematic in the integrated application related to lining damages, deformations and defects, but are insufficient in the assessment of serious internal lining defects. In contrast, European standards focus on the impact of diseases on the overall performance of the tunnel structure. In addition, convenient Chinese standards highlight the single-indicator assessment, but ignore the correction of assessment results in case of multiple deterioration types.

3 Tunnel Inspection Devices

With the growing scale of tunnels in operation, traditional inspection modes gradually become outdated due to their high subjectivity, low efficiency, and certain risks. Just in this context, Japan and China respectively developed special rail-mounted tunnel lining inspection devices.

3.1 Japanese Tunnel Inspection Devices

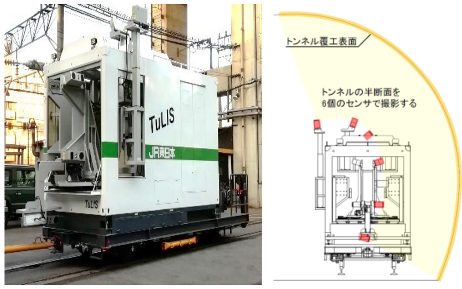
In 2001, East Japan Railway Company (JR East) [25] and Mitsui Engineering & Shipbuilding (MES) jointly developed a self-powered tunnel lining inspection vehicle installed with radar antennas. Relying on two radar antennas on the crank arm, and one radar antenna on the straight arm, the inspection device can detect the lining within a range above the arched line, having the function of three-dimensional inspection of lining cavity within a range of 40 cm [26, 27]. The working condition of inspection is shown in Figure 4.

Figure4

Working condition of JR East's geological radar inspection vehicle

In order to realize the fine inspection of surface conditions of normal-speed railway tunnels, JR East introduced the vehicle for detecting surface conditions of lining using the laser scanner (1# vehicle) in 1999. In 2010, JR East successively introduced the 2# and 3# inspection vehicles. Currently, the three inspection vehicles are still used to detect the surface conditions of normal-speed railway tunnel lining at a speed of 8.5 km/h. The general view of the inspection vehicles is shown in Figure 5 (a). In order to detect the JR East upgraded the original tunnel inspection system used for nearly 20 years in 2020. The upgraded version of inspection vehicle is equipped with 12 sensors (lasers + cameras), which can realize the continuous inspection of surface conditions and 3D shapes of linings at a speed of up to 20 km/h. Currently, new inspection vehicles were put in to use for the Shinkansen tunnels in February 2020 [28]. A inspection vehicle for Shinkansen tunnels is shown in Figure 5 (b).

(a) A inspection vehicle for normal-speed railway tunnels



(b) A inspection vehicle for Shinkansen tunnels put into use in 2020

Figure 5

Japanese vehicles for detecting surface conditions of railway tunnel linings

3.2 Chinese Tunnel Inspection Devices

In 2012, China Academy of Railway Sciences developed a inspection vehicle for normal-speed railway tunnels [29, 30]. This vehicle with the 25T passenger train body is equipped with 5 sets of medium-and-high-frequency geological radar antennas. With a maximum antenna inspection depth of 1.5 m, and a inspection speed of 3~5 km/h, it is used to detect normal-speed railway tunnels. An inspection vehicle for normal-speed railway tunnels is shown in Figure 6.

Based on the inspection technology for normal-speed railway tunnels, China Academy of Railway Sciences developed a inspection vehicle for high-speed railway tunnels in 2018 [31, 32]. This vehicle is equipped with 9 sets of high-and-low-frequency radar antennas, and a CCD imaging system. With 8 industrial cameras, the CCD imaging system achieves a crack recognition accuracy of 1mm. In addition, its geological radar inspection speed is 3 km/h, and its imaging inspection speed is 50 km/h [33]. Figure 7 shows the general view of a inspection vehicle for high-speed railway tunnels, as well as the distribution of imaging systems.

Figure 6

An inspection vehicle for normal-speed railway tunnels

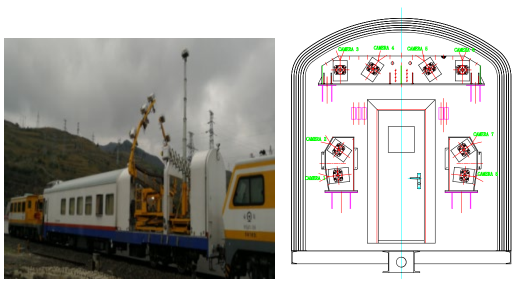


Figure 7

An inspection vehicle for high-speed railway tunnels

3.3 Comparison of Inspection Devices

Japanese tunnel inspection vehicles are all self-powered, with geological radars and cameras mounted on different vehicles. In contrast, Chinese tunnel inspection vehicles refitted from the 25 T passenger train body are not self-powered, but are towed by other vehicles. In addition, geological radars and cameras are mounted on the same vehicle. It’s worth noting that in terms of the imaging inspection speed, Chinese vehicles for detecting surface conditions of tunnel linings are superior to Japanese ones.

4 Suggestions on Improvement of Railway Tunnel Inspection System

It is important to effectively detect and conduct quantitative and scientific assessment of railway tunnel defects and diseases developing constantly. However, the current railway tunnel inspection system is hard to meet such needs. In consideration of the actual conditions, scale and development law of China's railway tunnels, China should establish a sound system of railway tunnel inspection throughout the process of management.

4.1 Establishing a Railway Tunnel Inspection System

The overall framework of the railway tunnel inspection system composed of four modules (inspection items, inspection system, inspection technology and devices, data analysis and evaluation) is shown in Figure 8.

4.2 Establishing a System of Railway Tunnel Inspection Throughout the Process of Management

With reference to foreign railway tunnel inspection systems, relevant tunnel inspection systems should be further optimized based on existing tunnel inspection systems according to the scale of China's railway tunnels and the actual conditions in application of new technology and devices, so as to realize the whole-process management of tunnel diseases. Tunnel inspections mainly include routine inspection, cyclic inspection, temporary inspection, special inspection, and key tunnel calibration and monitoring. Different types of inspections vary greatly in the inspection objects, frequency, operation requirements, data accuracy, personnel (organization), etc. Details are shown in Table 8.

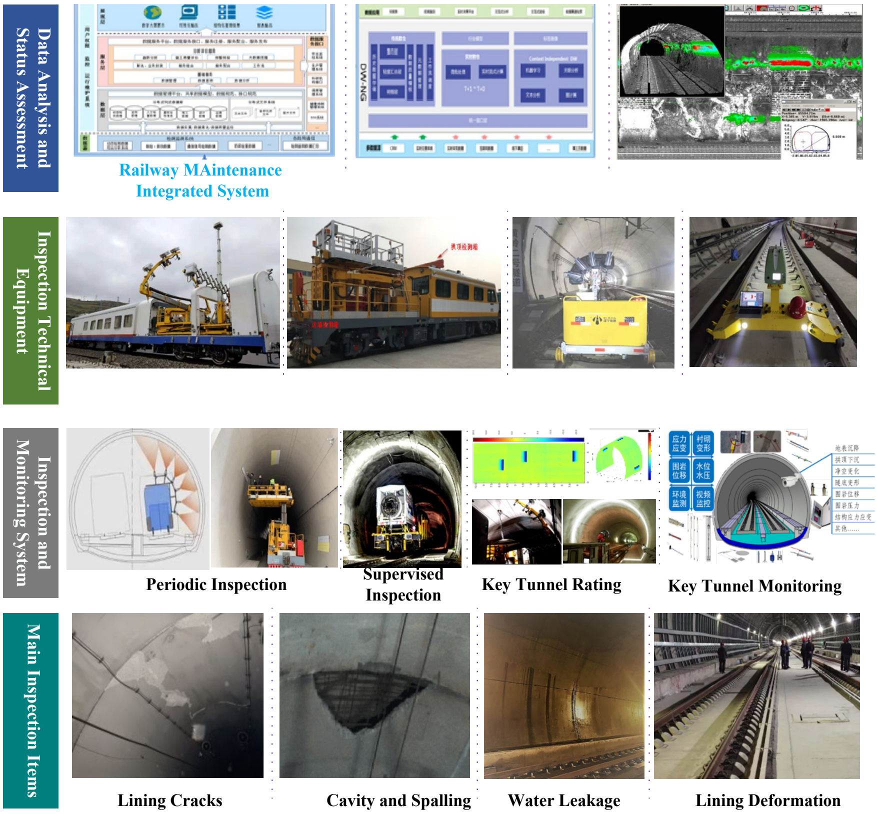


Figure 8
Framework of railway tunnel inspection system

Table 8
Attributes of different inspections

Inspection type	Object	Frequency	Operation requirement	Personnel/organization
Routine inspection	Surrounding environment; Overall condition seen visually; Diseases that need special attention;	Daily	Simple tools	Trackwalker
Cyclic inspection	Full contact	Cyclic (4~6 years)	Professional auxiliary inspection devices	Inspector
Temporary inspection	Key parts	After a natural disaster;	Professional auxiliary	Inspection engineer

		Adjacent engineering; Affecting third-party safety	inspection devices	
Special inspection	Uncertain defects and diseases	As required	Professional technology or devices	Inspection engineer Testing agency
	External environment\tunnel boundaries	As required		
Key calibration and monitoring	Complex geological tunnel; Rapid disease development; Occurrence of geological disasters	Cycle (≤10 years) or real-time online	Professional technology and devices	Inspection engineer Analytical engineer Testing agency

Routine inspection shall refer to the ordinary inspection of accessible parts along the ground or rail surface in the visual manner or by using simple tools without the help of professional auxiliary facilities. The objects of routine inspection mainly include the surrounding environment, overall tunnel condition in a visual range, and diseases that need special attention as indicated in the cyclic inspection list.

Cyclic inspection shall refer to a comprehensive and detailed contact inspection of tunnels according to the inspection plan. It is necessary to issue a detailed inspection report, update and distribute the disease records to all the parties of maintenance management, and clarify the maintenance work recommendations and their urgency in the report.

Temporary inspection shall refer to the inspection of exceptions after the occurrence of any natural disaster. A random inspection is required if concrete spalling might seriously affect the safety of any third party or adjacent engineering might affect the target structure.

Special inspection shall refer to the special inspection of structural condition, material performance, defects and diseases, and external environment of a tunnel in operation with the help of professional technology or devices. The inspection objects include the safety condition of tunnel lining, and tunnel boundaries. A special inspection is required if the distribution and impact of defects and diseases are uncertain. Supervisory tunnel inspection belongs to the scope of special inspection.

Calibration and monitoring of important tunnels shall refer to the comprehensive calibration and assessment of surrounding environments of complex geological tunnels, to assess their safety levels. If the diseases develop rapidly and geological disasters may affect the traffic safety, the monitoring system is required for real-time monitoring, forecasting and warning.

Conclusions

This paper compares and analyzes the status quo and practical experience of Japan, Europe, the United States, and China in terms of railway tunnel inspection. Results show that Japanese tunnel condition assessment standards focus on inplying and predicting the causes of changes in tunnel performance. In addition, they are more hierarchical and systematic in the integrated application related to lining damages, deformations and defects, but are insufficient in the assessment of serious internal lining defects. In contrast, European standards focus on the impacts of diseases on the overall performance of the tunnel structure, and the review of discovered diseases, regarding inspection as an important part of tunnel maintenance. In accordance with American standards, the inspection cycle shall depend on the service time of the tunnel in operation. Because American railways are privately owned, currently there are no uniform rating methods for railway tunnel structures. In accordance with Chinese standards, the inspection cycle shall depend on the operating speed of the railway in operation. Chinese standards highlight the single-indicator assessment, but ignore the correction of assessment results in case of multiple deterioration types. To overcome the deficiencies of manual inspection, Japan and China have respectively developed their own rail-mounted tunnel inspection devices.

In consideration of the operation characteristics, scale and development law of China's railway tunnels, this paper proposes to optimize the railway tunnel inspection system. The framework of a sound system of railway tunnel inspection throughout the process of management has been established. The railway tunnel inspection system is composed of four modules, namely inspection items, inspection system, inspection technology and devices, data analysis and evaluation. Railway tunnel inspections throughout the process of management mainly include routine inspection, cyclic inspection, temporary inspection, special inspection, and key tunnel calibration and monitoring. Different types of inspections vary greatly in the inspection objects, frequency, operation requirements, data accuracy, personnel (organization), etc.

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