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CONSTRUCTION METHOD AND APPLICATION OF A BASIC DIGITAL DATABASE FOR THE INTELLIGENT MANAGEMENT AND MAINTENANCE OF EXISTING RAILWAY TUNNELS

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Abstract
Introduction: China has an extensive network of tunnels requiring maintenance. An intelligent management and maintenance of these tunnels based on a digital information system can be useful. To this end, it is necessary to collect relevant digital information regarding the tunnel body and surrounding environment for long-term maintenance. **The purpose of the study** was to take an existing operational tunnel as the research subject; this study applied various information technology methods to construct a basic digital database for the intelligent management and maintenance of tunnels. **The following methods** were used: data statistics, drone aerial photography, ground penetrating radar, full-section laser scanning and theoretical analysis. As a **result,** the database can be used as a reference for similar projects.

Keywords: smart management and maintenance; digitization; basic database; aerial photography; full-section laser scanning; ground penetrating radar.

Introduction

According to statistics, as of 2022, China has operationalized a total of 17873 railway tunnels covering approximately 21987 km (Gong et al., 2023). With this, China has become a major country with a large number of tunnel maintenance tasks, and an intelligent management and maintenance of these tunnels based on the principles of digitization has become a necessary path. With the proposal of smart cities, smart management and maintenance technologies are gradually being developed. Currently, China mainly focuses on the development of new tunnels. For old tunnels, particularly those built before 2000 (a total of approximately 6887 tunnels with a total length of 3667 km) (Tian et al., 2021), the design drawings and other construction materials are mostly hand-drawn versions.

Establishing a basic database for digital smart management and maintenance of tunnels, and obtaining existing and historical data that can truly and comprehensively reflect the state of tunnels are key research directions, and these are discussed in this study. Conventional tunnel maintenance is largely based on the long-term understanding and tracking of tunnel diseases by maintenance personnel. This approach strongly relies on the skill and experience of the personnel, sense of responsibility, and business skills. Although there are qualitative and quantitative descriptions, such as in the form of maintenance records, they cannot help track and evaluate diseases or other anomalies appearing in the tunnel. Carrying out full lifecycle operation and maintenance based on digital monitoring can help objectively record the entire process of disease formation, development, and deterioration, and incorporate the experience of enterprise employees into an information system as long-term accumulated data, thus providing a strong support for decision-making (Dai, 2022). Hence, it is necessary to collect digital information regarding the tunnel body and surrounding environment for long-term maintenance.

Project Overview

An existing double-track tunnel with a total length of 5804 m was considered as the research subject in this work. The construction of this tunnel started in 1989 and was completed in 1993. It was operationalized in 1996. The tunnel has been designed using the principles of the new Austrian design method, with a curved wall composite lining. The construction method was drilling and blasting, with a spray anchor support.

The following issues have been noted in the current maintenance process of this tunnel: (1) Difficulty in terms of the engineering aspects. The tunnel is not only located in a complex loess hilly terrain but also passes through multiple gullies. In terms of the complex geological conditions, it mainly passes through layers of sand and mudstone interbedded with coal seams containing abundant groundwater. Since its completion, the tunnel has

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frequently seen diseases, mainly including lining damage and cracking, softening of the foundation bed, mud pouring from the base, blockage of drainage facilities, groundwater infiltration, and related issues. The tunnel underwent multiple disease treatments in 1997, 1998, 2000, 2001, and 2013. However, in recent years, tunnel diseases have continued to develop, and there is a further deterioration trend. (2) Insufficient information on the current state of the tunnel. After 30 years of operation, the surrounding environment has undergone significant changes; the tunnel now passes through multiple factories and roads and multiple coal mines below. The maintenance and testing data collected over the years are complex and inconsistent, and there is no systematic system in place, making it impossible to predict and identify the causes of existing diseases. (3) There is heavy traffic in the tunnel, and skylights are few. After the tunnel was opened, the operation of the line was busy, and the transportation pressure was very high. On average, a train passed every 8 min, and the transportation volume has increased year by year. Since 2012, the transportation volume has exceeded the 200 million ton mark for 11 consecutive years, with the highest annual transportation volume reaching 277 million tons. The difficulty and pressure in terms of transportation safety assurance, route maintenance, and equipment inspection and repair are enormous. There are few sunroof points for maintenance, and there can only be 2–3 sunroof points per week, with each sunroof point lasting 3–4 h.

In summary, to ensure the continuous safe operation of the line and ensure transportation capacity, it is necessary to establish a basic digital information system that can support operation and maintenance requirements and one that is convenient for maintenance comparison and decision-making. Furthermore, an intelligent management and maintenance technology characterized by either no personnel (unmanned) or minimal personnel and high efficiency should be developed.

Construction of a Basic Digital Database for Tunnels

Basic Database Objectives

To effectively control operational risks, ensure operational safety, and prevent tunnel diseases from affecting driving safety, it is necessary to conduct a comprehensive and systematic diagnosis of the tunnel and make necessary structural improvements. Before systematically rectifying tunnel diseases, a comprehensive and systematic digital database must be established. Based on this, analysis and diagnosis work should be performed, and the safety state of the tunnel should be evaluated to lay a solid foundation for disease treatment work.

The basic requirements in building a basic digital database (Fig. 1) for tunnels are the comprehensiveness and accuracy of the data. To ensure the comprehensiveness of the collected data, the data must contain information related to the entire life cycle of the tunnel, mainly including historical data and the current state of the tunnel. Historical data include all tunnel-related information during its construction and operation periods. The above information should be comprehensively collected, analyzed, and organized. The current state of the tunnel includes the comprehensive external environment and the internal environment and structure of the tunnel. The comprehensive digital collection of the current state of the tunnel mainly requires an environmental investigation of the external terrain, underground mining areas, and goaf, as well as sorting out of the internal environment, structural state, and disease database of the tunnel. Data collection methods are mainly employed for this process, such as drone photography, ground penetrating radar, and 3D scanning technology. The collected data are supplemented and verified using manual tapping verification, numerical simulation, comprehensive investigation and analysis, and other methods. To ensure the accuracy of the data collection, multiple self-verification tests and mutual verification of the results obtained using conventional manual testing and information technology testing were adopted.

Digitization of Historical Data

A comprehensive understanding of the state of a tunnel requires the collection of all historical data such as geological survey data, design documents, construction inspection reports, construction logs, design change data, supervision data, and completion documents from the construction period. Moreover, it is necessary to comprehensively collect all previous inspection and maintenance data and daily operation and maintenance data during the operation period of the tunnel. Finally, all the collected information should be converted into an electronic format, and then classified, organized, and archived.

The design materials and drawings for the tunnel were hand drawn versions, while the construction materials were handwritten versions. In conjunction with the construction of a digital archive, all the materials were scanned into digital electronic files. The collected materials were sorted by year and by category (Table 1). All the handwritten excavation process data were converted into digital tables, which can be equipped with 3D models in the later stage for 3D demonstrations and data analysis of the construction process. From the analysis and organization of the historical data, it is possible to have a better understanding of the tunnel and discover many potential diseases from the beginning of its construction. For example, at that time, the design standards were low, and waterproof boards

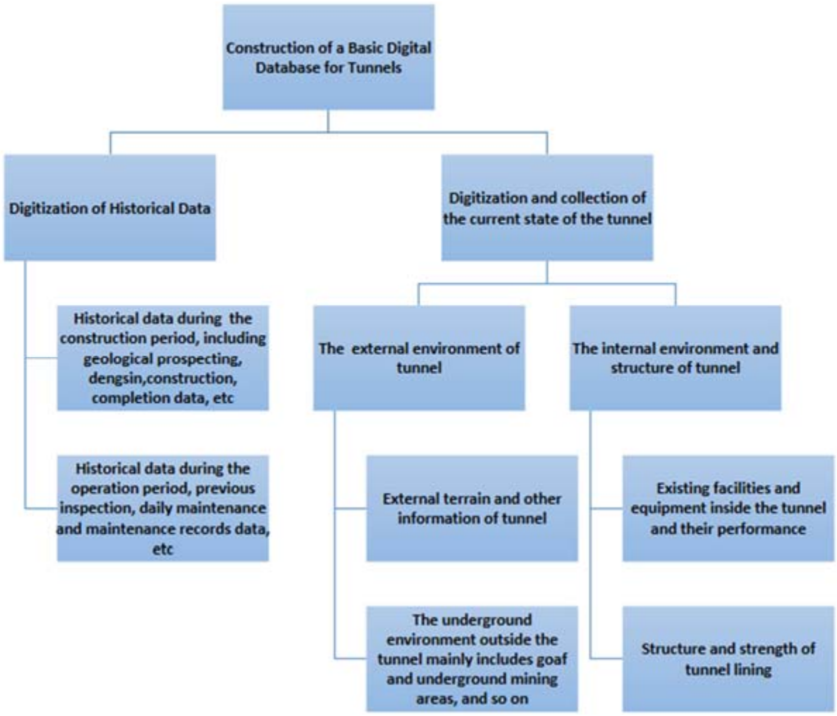

Fig. 1. Technical roadmap for the construction of a basic digital database

were not used in the lining. Waterproof measures were only used in some shallow buried trenches. The construction technology level for the lining was insufficient, and the construction conditions were limited, resulting in significant collapse and deformation during the construction process, which caused many voids behind the tunnel lining. The water temperature and geological conditions were poor, and a coal seam of 1987 m was present in the tunnel, accounting for 34.24 % of the total tunnel length. The tunnel contains abundant groundwater, including the presence of a loess tunnel groundwater layer, which led to more diseases at the bottom of the tunnel. Inadequate supervision and lack of a supervision system during construction were also noted. The digital historical data can be accessed and retrieved at any time through the building information modeling (BIM) platform in the later stage (Sun et al., 2020).

Digitalization and Analysis of Tunnel Environment

For the digital acquisition of the external environment of a tunnel, drone aerial photography technology, combined with completion data and manual on-site investigation and verification

Table 1. **General Catalogue of Historical Data Collection and Sorting for an Existing Operating Tunnel**

Number	File Overview	Number	File Overview
1	1990 Design Documents	12	Design documents for engineering and disease control in 2001
2	Tunnel excavation construction logs from 1990 to 1993	13	Tunnel clearance survey in 2005
3	Completion data for 1996	14	2012 non-destructive testing data
4	1996 Completion Drawing	15	2013 full line re survey
5	Data on disease control in 1997	16	Completion data for disease control in 2014
6	1998 drilling data	17	Disease control in the 2014 engineering year
7	Completion data for disease control in 1998	18	2016 Disease Settlement Data (2014)
8	1998 Engineering Information	19	Renovation of Drainage Ditches and Escape Caves in 2017
9	1999 Disease Control Engineering	20	2020 Flood Control and Renovation Design Documents
10	Completion data for disease control in 2000	21	Design Document for Rectification of Corrugated Plate Diseases in 2021
11	2000 Engineering Information		

methods, was mainly adopted (Li et al., 2005). The surface topography and terrain conditions of the entire line were comprehensively determined, and existing basic data were verified and revised, laying a good foundation for a comprehensive understanding of the current state of the tunnel from the perspective of an external comprehensive environment and for future intelligent operation and maintenance work.

A comprehensive aerial photography of the ground surface was conducted within a range of approximately 200 m on both sides of the tunnel centerline using drones. External environmental data were also collected, such as terrain and topography along the tunnel, gullies, nearby factory buildings, underground mining areas, current state of entrances and exits, and burial locations and conditions of auxiliary tunnels. Based on the collected basic image data, the key terrain and topography information within the survey area were modeled and processed. Based on the collected "Tunnel Completion Map" and other drawing materials, as well as the comprehensive external environment of the tunnel collected by drones, on-site surveys were conducted to compare and verify the collected data. Key environmental features, such as important gullies, nearby factories and mines, and tunnel auxiliary tunnels, were investigated and verified (Fig. 2), to discover possible and potential harmful environments. Through a comprehensive comparative analysis, the tunnel structure below the gully was found to be prone to severe water leakage, while the tunnel structure under the factory and mine was prone to more diseases. The internal structure of the auxiliary tunnel was also severely corroded by water leakage.

The digital assets collected mainly include a set of surface panoramic orthophoto data with a total width of 400 m on both sides of the tunnel centerline. A skewed model map (Fig. 3), displaying the current state of the tunnel surface from a full perspective, can be used as basic data for regular surface condition collection and terrain comparison measurement. In the later stage, it can be combined with the BIM to serve as basic digital data for relevant early warning systems to timely grasp the changing trends of surface diseases and to expand the digital assets of tunnels (Cheng et al., 2019). A topographic map of the tunnel was constructed as well. By combining the completed plan and longitudinal section, an electronic version of the topographic map and an electronic version of the longitudinal section can be formed.

In this inspection, the main focus was on surface data collection. Regarding underground mining areas and goafs, relevant information was mainly obtained through investigation and site visits. The relative position relationship between the tunnel and the mining area was obtained by analyzing data collected from government departments. In the later stage, special geological surveys can be conducted to address issues related to the goaf, in order to make the data more accurate and complete.

Collecting Data of the Ontology Information of Tunnel Structure

1) Vectorization of surface disease information inside the lining.

A full-section laser scanning technology was adopted for the digital acquisition of the internal surface of the tunnel. The purpose of using a full-section laser scanner to scan and image the tunnel lining was to collect data regarding the internal appearance and existing facilities and equipment of the tunnel, in order to meet the requirements of identifying tunnel surface diseases, detecting basic

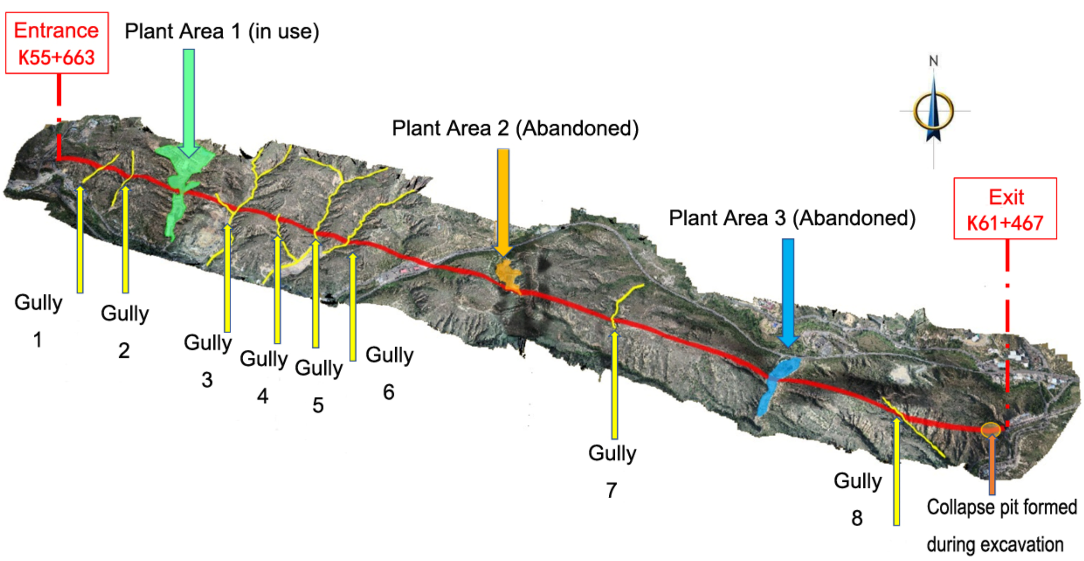

Fig. 2. Distribution of gully landform above the tunnel

Fig. 3. Skewed 3D model results

building limits, and recording intrusion locations in the later stage. Key findings include surface cracks, cracks, misalignment, falling blocks, water leakage, foreign objects, and other surface diseases in the lining, as well as the location of tunnel intrusion limits.

The GRP5000 tunnel scanning system (Fig. 4), which is currently one of the more advanced tunnel detection technologies, was used for the digital acquisition (Wen et al., 2014). The system meets the requirements of railway tunnel clearance, convergence deformation, and surface disease detection. It integrates a manually pushed rail inspection car and a high-speed laser scanning measurement technology. This makes it suitable to rapidly detect tunnels during tunnel operation, establish digital operation archives, guide maintenance operations, and improve operation and management levels.

A laser scanner was used to perform a full-section high-density scanning of the tunnel in a spiral shape (Fig. 5). The acquisition software gathers image information of the inner surface of the tunnel lining by analyzing the intensity of the emitted and received laser signals, forming a grayscale image (Fig. 6). By analyzing the phase difference between the emitted and received laser signals, the 2D coordinates of the scanning points on the surface of the tunnel lining can be obtained. Combined with the external absolute positioning of the total station or inertial navigation, the 3D absolute coordinates of all the measurement points can be obtained. The true unfolding map and cross-sectional contour information of the tunnel surface diseases can be

Fig. 4. GRP5000 tunnel scanning system

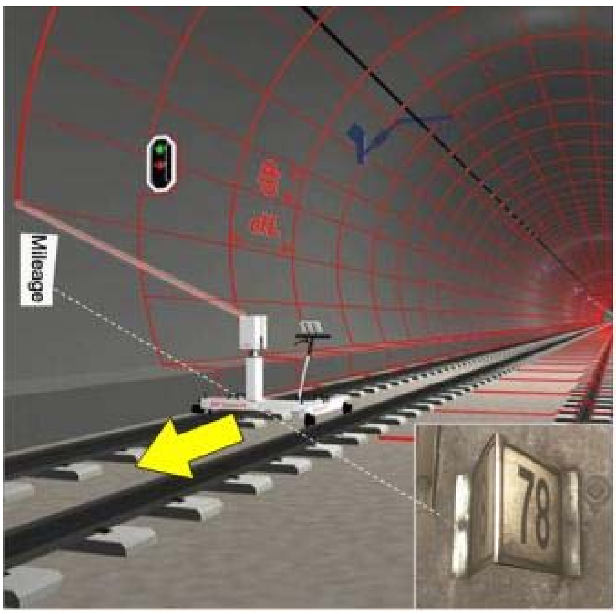

Fig. 5. Schematic of the full-section scanning of a tunnel

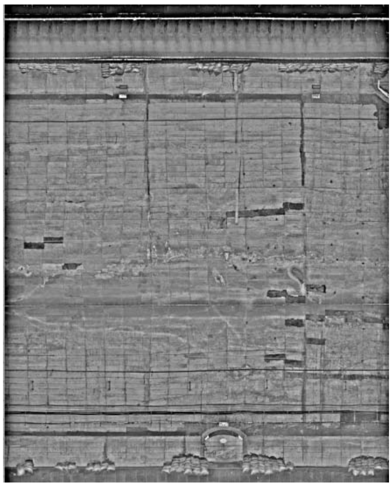

Fig. 6. Grayscale image

determined using professional post-processing analysis software (Fig. 7).

The main digital assets collected include a set of 3D point cloud data on the surface of the tunnel. This set was used for the later 3D modeling inside the tunnel, full tunnel high-definition grayscale imaging, and tunnel cross-section mapping (using a 2 m section for this project). Through a comprehensive analysis, a set of apparent disease display charts was formed.

2) Digital collection of tunnel lining structure and surrounding rock state.

In the digital acquisition of the current state of tunnel structures, the geological radar detection technology was mainly used for a comprehensive nondestructive testing of the tunnel lining structures (Shao et al., 2023). Diseases in the lining structure and surrounding rock, and other diseases, were mainly discovered.

Based on the current internal state of the tunnel, the SIR-3000 geological radar host and a 400 MHz shielded antenna were used for detection. This radar system host is lightweight, highly automated, has stable signals, high detection speed, and high resolution. It can display the detected profiles in real time, allowing for post-processing and interpretation of the data on a computer, thus integrating the data collection and processing steps. Ten survey lines were set up throughout the tunnel (Fig. 8), including two at the bottom of the tunnel, two on its side walls, and six on the arches. The lining inside the tunnel has a significant amount of fly ash, and the existing facilities and equipment are relatively outdated, and there is a need to avoid more interference. Therefore, the method used in this study was manual small carts (Fig. 9), which can adapt well to the characteristics of the coal transportation line in the tunnel. This method can not only closely adhere to the tunnel wall but also timely avoid old facilities,

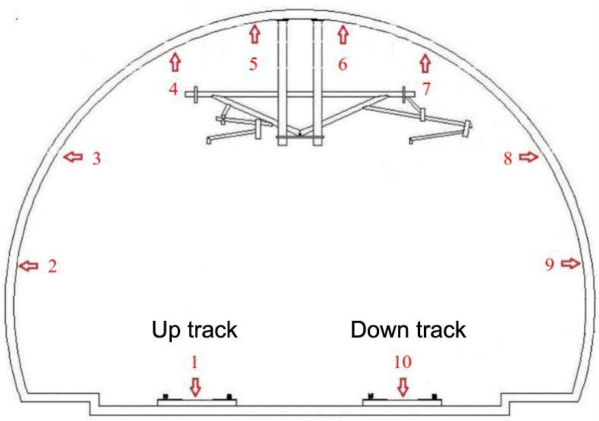

Fig. 8. Schematic of the geological radar

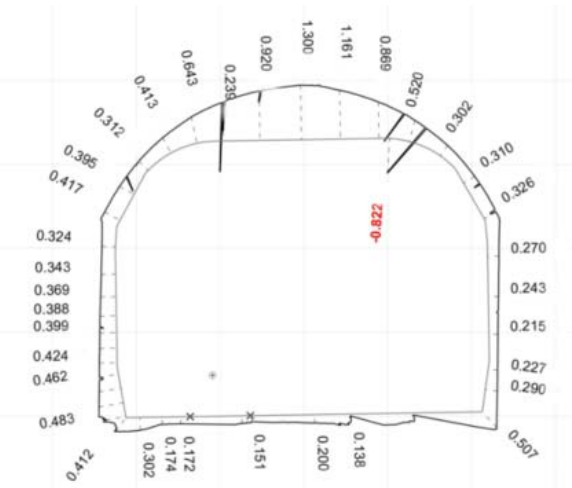

Fig. 7. Cross-sectional view Unit (m)

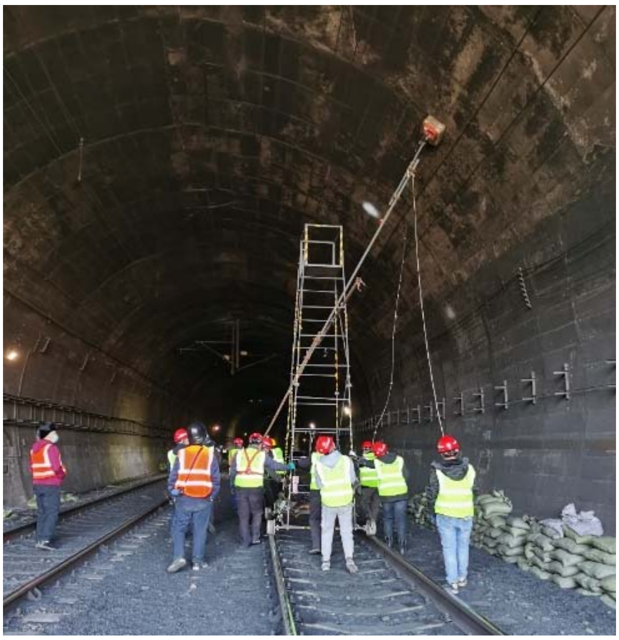

Fig. 9. Ground penetrating radar detection of tunnel lining

and the detected data are accurate and reliable. The detected contents mainly include the thickness of the tunnel secondary lining, void and non-dense distribution inside and behind the secondary lining, cracks and water accumulation on the tunnel floor, and other issues.

A set of ground penetrating radar data was obtained, including information related to the position, shape, structure, and size of the detected target body. Clear and interpretable geological radar image profiles were generated through data processing. A search for areas in the radar wave spectrum where the reflection wave has discontinuous in-phase axes produced bending, strong reflection wave energy, and strong echo amplitude response. Based on the phase, frequency, and amplitude changes of the radar waves, a comprehensive qualitative judgment was made, and the density of the backfill (or grouting) behind the lining, the thickness of the lining, and the distribution of steel frames and steel bars inside the lining were ultimately determined.

The digital assets collected include a set of geological radar data, clear and interpretable geological radar image profiles, and typical disease images inside (behind) the lining (Fig. 10).

3) Concrete strength data collection at a typical section.

A digital collection of the concrete strength data for tunnel lining was performed using a concrete rebound meter for testing. In accordance with the standard, each detection point was located 50 m away, and 234 detection areas were tested along the entire line. By revising, a table of the concrete strength for the entire tunnel was formed, and areas with insufficient concrete strength were identified. A total of 60 tested areas were found to have insufficient concrete strength (Fig. 11), including 29 upstream side walls and 31 downstream side walls.

The HT-225A concrete rebound tester was used. It complies with the relevant provisions of the national standard GBT9138-2015 “Rebound Tester,” JJG817-2011 “Rebound Tester Verification Technical Regulations,” and TB10426-2019 “Railway Engineering Structure Concrete Strength Testing Regulations.” This tester is suitable for testing the strength of general building components, bridges, and various concrete components (slabs, beams, columns, and bridges)

Information integration

Tunnel Disease Statistics

The main focus of the inspection was tunnel lining diseases, and the types of tunnel diseases detected are summarized as follows.

1) Apparent diseases of tunnel arch walls include cracking, falling blocks, cracking, and moisture accumulation in the tunnel lining.

Diseases such as lining corrosion and damage

2) The diseases of the tunnel arch wall structure include insufficient lining thickness, insufficient strength, non-dense lining cavities, lining corrosion, intrusion, and other diseases.

3) The main diseases at the bottom of the tunnel include cracking, non-compaction, water filling, sinking, mud pouring, and insufficient thickness of the tunnel bottom.

4) The diseases of the drainage system include broken blind pipes, water leakage, broken ditches, blockage and paralysis of the drainage system, and paralysis of the drainage system of the dewatering well.

5) The main diseases inside the car shelter include water leakage, deformation, peeling, and other diseases.

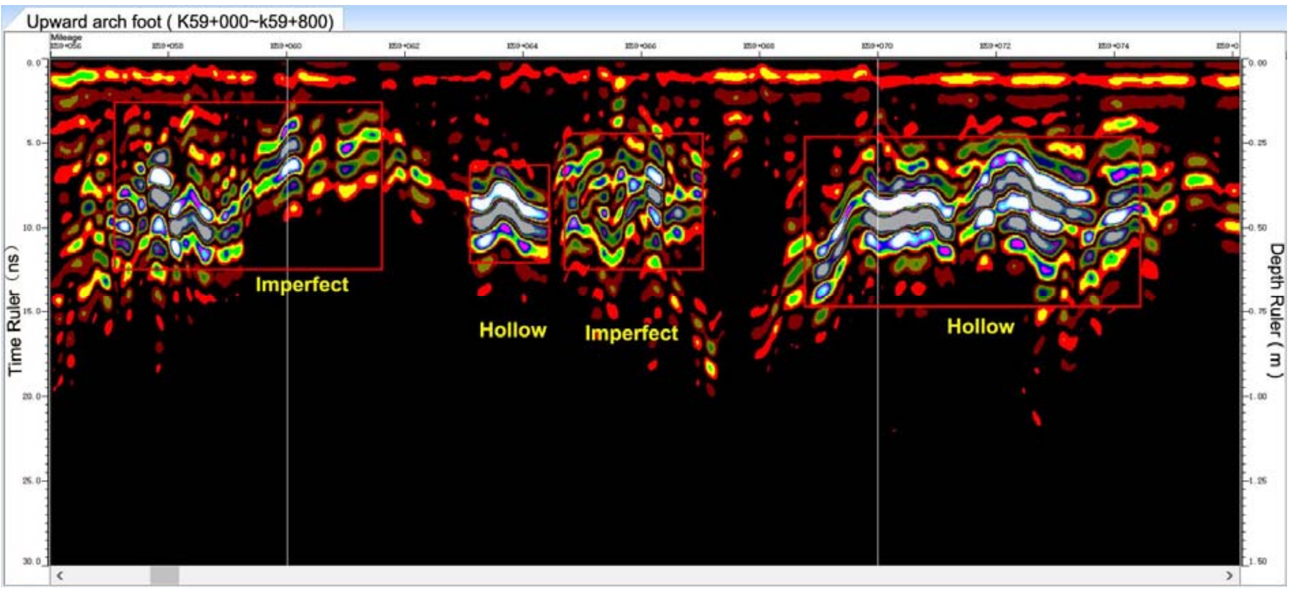

Fig. 10. Typical image of voids and non-compact areas inside (behind) the lining

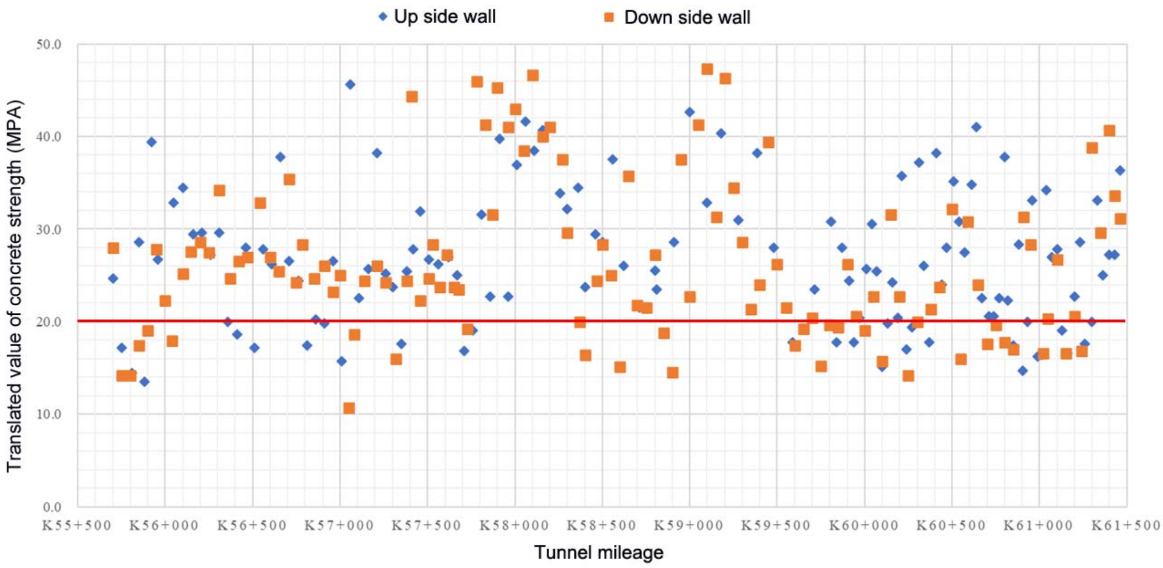

Fig. 11. Distribution of the concrete strength of existing tunnel lining side walls by mileage

6) Other diseases include a large number of missing stakes in the line, severe water accumulation in ventilation openings, and the proximity of other underground mining tunnels to the tunnels.

The results of all the diseases detected in this test are summarized in the table 2. For a detailed display, please refer to the "Comprehensive Disease Display Diagram of a Certain Tunnel".

Comprehensive display diagram of tunnel diseases

By integrating all the historical data and inspecting the disease data, a comprehensive disease display chart for a certain tunnel was drawn, aiming to fully display the current state and existing disease state of the tunnel. This map is based on the longitudinal section map measured this time, and three parts were collected: historical data statistics, detection results, and historical disease treatment statistics. The first part of the tunnel longitudinal section diagram collects information from the completion data, including the type of surrounding rock, lining section (design thickness, changes, and reference drawings), geological conditions (overall overview and coal seam statistics), geomorphology, steel support statistics, construction collapse statistics (construction length, collapse amount, maximum arch cavity height, and single linear meter collapse amount), ground elevation, inner rail top surface elevation, design slope, construction auxiliary tunnels, and ground changes. This section fully reflects the original structure of the tunnel. The second part shows the disease state identified by all the information tested in this test, including the distribution of arch wall diseases, tunnel bottom diseases, arch wall lining inspection thickness, tunnel bottom inspection thickness, and side-wall concrete inspection strength, all of which are shown in the figure. In the longitudinal section, the positions of the gullies, factory buildings, and terrain change points detected in the comprehensive environment, as well as the auxiliary tunnels are shown. From the graph, all the detected diseases at any cross-section can be read. The third part is the layout diagram of previous disease rectification and reinforcement, from which we can see which reinforcement measures have been taken in these areas.

For example, the K56+830–57+000 mileage section is located below the third gully, and its developed small gully is consistent with the direction of the line here. During construction, this section experienced significant collapse, with a maximum collapse of 34.38 cubic meters per linear meter and a maximum void height of 3 m. There is also a ventilation shaft outside this site, which is well exposed and has a significant amount of internal water accumulation. The lining inside the tunnel has serious water leakage, and the lining surface has a large area of corrosion. The arch crown is cracked and falls seriously, and the concrete strength (17.4 MPa) is relatively low. The right arch waist is limited, and there are serious cavities and non-compact diseases behind the lining. The bottom plate of the tunnel is not compact, filled with water, and cracked severely, and there is serious mud pouring. There has been a history of arch crown anchor rod reinforcement. It is recommended to perform rectification as soon as possible.

The K60+790–K60+970 mileage section is located below the eighth gully. There are two longitudinal cracks that run through the arch waist, with many cracks, severe water leakage, and limited penetration. Other issues are the insufficient lining thickness and low concrete strength. The arch crown contains coal seams, voids, etc. The arch crown has

Table 2. **Disease Detection Results**

Number	Project	Unit	Nondestructive testing	Manual tapping and investigation	External environmental investigation	Remarks
1	Lining chipping	place		43		
2	Invasion limit	place	267			
3	Insufficient lining thickness	place	4942			
4	Insufficient concrete strength	place	60			
5	Cracks (0.3–0.5 mm)	place	151			
6	Cracks (>0.5 mm)	place	2752	37		Cracking of lining
7	Cracking	place	3			
8	Yin dampness	place	1698	91		Leakage water
9	Lining corrosion	place	3			
10	Damaged lining	place	284			
11	Interior panel	place	96			
12	Empty	place	1073	164		
13	Not dense	place	1046			
14	Bottom plate cracking	place	22			
15	Bottom of the tunnel is not dense enough	place	120			
16	Tunnel bottom is not compacted and filled with water	place	82			
17	Tunnel bottom churning and mud seepage	place		19		
18	Gully fracture	place		13		
19	Avoiding tunnel diseases	quantity		239		
20	Investigation of the water level in the side ditches	place		32		
21	Investigation of the water level in precipitation wells	quantity		64		
22	Gully	quantity			8	Outside the tunnel
23	Auxiliary tunnel	quantity			11	Outside the tunnel
24	Coal mine roadway	quantity			2	underground
Total		place	13301		21	

been reinforced with anchor rods. It is recommended to perform rectification as soon as possible.

Evaluation of tunnel disease level

The tunnel was graded in sections of 100 m, and all the sections were graded based on nondestructive testing results. The results of each section were rated as AA level, and combined with manual tapping and observation results, according to the Provisional Regulations on Safety Level Evaluation of Railway Operation Tunnel Lining, the safety level of the tunnel lining is extremely severe, i.e., AA level. The tunnel should be renovated as soon as possible and 24 h monitoring work be conducted to ensure driving safety.

Verification and supplementation of digital collection results

The above digital achievements in the rapid machine inspection of information technology were verified and supplemented through methods such as manual tapping, numerical simulation, and comprehensive investigation and analysis.

(1) Tunnel manual tapping detection technology: The method of manually tapping the tunnel wall (Fig. 12) was used to investigate hidden dangers in the tunnel lining (Bao et al., 2023). The main factors to be investigated include concrete cracks, falling blocks, voids, water leakage, water accumulation in ditches, diseases in car shelters, and mud pouring from the tunnel. The main results are various disease tables, including data on voids and cracks, which are mutually verified with nondestructive testing results. A comparative analysis showed that the results of nondestructive testing and manual testing mostly overlap with each other, proving the high accuracy of the nondestructive testing data in this study.

(2) Numerical simulation: By comprehensively analyzing all the detection results, weak links and typical sections of tunnel structures and diseases

Fig. 12. Tunnel manual tapping detection

were identified, modeling was done with measured data, a numerical simulation analysis was conducted on the tunnel, the trend in the tunnel deterioration was identified, and preparations were made for later operation and maintenance of the tunnel. The MIDAS-GTS software was used in the numerical simulation calculation of this tunnel. Based on all the detection results, 76 typical cross-sections in areas with severe diseases were selected and subjected to 2D and 3D numerical simulations (Fig. 13) to determine the bearing capacity of the tunnel lining and the safety of the tunnel structure, and to analyze and predict the further deterioration trend of the tunnel. After using the load structure method to calculate and analyze the tunnel lining structure with different thicknesses and strengths, it was found that the safety factor at the intersection of the arch and the side walls on both sides did not meet the regulatory requirements in all 76 sections, and the safety factor at the arch crown, arch waist, and arch foot of some sections did not meet the requirements. The calculation results obtained using the geological structure method and the load structure method exhibited consistent trends.

(3) Comprehensive investigation and analysis method: By investigating the daily regular inspection data in tunnel engineering, combined with historical data, tunnel interior surveys, nondestructive testing results of tunnel lining diseases, and manual testing results, special investigations and research were conducted on tunnel boundaries, water damage inside the tunnel, tunnel bottom diseases, and water quality. The intrusion limit inside the tunnel was mostly caused by historical reinforcement measures and the increase in the amount of ballast at the bottom of the tunnel. The water quality inside the tunnel was good and noncorrosive. Due to the poor geological conditions, unclear inverted arch structure, paralyzed drainage system, increased transportation volume, repeated action of heavy-duty trains, and untimely operation and maintenance, the tunnel bottom exhibited serious diseases.

Conclusions

(1) Basic working methods were established. By digitizing historical tunnel data and applying information collection technologies, such as drone aerial photography, ground penetrating radar, and full-section laser scanning, a basic database for the intelligent management and maintenance of existing operational tunnels was established.

(2) A comprehensive analysis method was established. Through methods, such as manual tapping, numerical simulation, and comprehensive investigation and analysis, the results of the information technology testing were reviewed, verified, and supplemented. The database established for the information technology testing results was found to be accurate and reliable.

(3) All the data were digitized and connected. By conducting comprehensive research and drawing a comprehensive disease display chart, all the data can be integrated and displayed for a comprehensive analysis.

(4) The 3D display software platform inside and outside the cave requires further improvement. Drone aerial photography technology was used to conduct a 3D modeling of the external environment of the tunnel, and the full-section laser scanning technology was applied to collect 3D data inside the tunnel. All the digital collection results can be

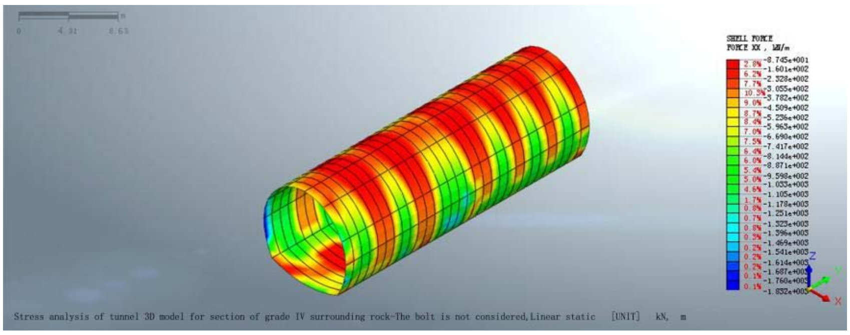

Fig. 13. Modeling results of the stress acting at typical sections of the tunnel lining

incorporated into the BIM platform to achieve a 3D integrated visualization display in the later stage. By studying the visualized 3D model, the causes of diseases can be identified and analyzed efficiently and intuitively.

(5) The next step is to strengthen research on rapid inspection equipment to better adapt to the rapid detection of various operating tunnels with heavy traffic.

(6) Regular inspections can be combined with targeted rapid inspections to improve the level of facility security. The tunnel can be combined with regular inspections and targeted rapid inspections during operation and maintenance. By comparing and analyzing multiple detection results from different periods, it is possible to quickly identify the causes and trends in the changes in the tunnel structure, providing assurance for later operation and maintenance.

References

Bao, X. Z., Da, Z. H., Zhang, C. B., Chai, X. S., Kang, Z. X., Zhou, Y., and Dai. X. J. (2023). Knocking Echo Characteristics of Tunnel Lining Cavity. *China Railway Science*, No 4, pp. 144–152.

Cheng, F. Y., Yao, G. M., Kui, Y. C., Wang, J. H., and Zhao, X. Q. (2019). GIS/BIM-Integrated Digital Management of Highway Tunnel and Its Application. *Tunnel Construction,* Vol. 39, Issue 12, pp. 1973–1980. DOI: 10.3973/j.issn.2096-4498.2019.12.007.

Dai, C. P. (2022). Life Cycle Management of Heavy Haul Railway Track Infrastructure Based on Digital Model. *Railway Engineering*, No 8, pp. 37–41.

Gong, J. F., Wang, W., Li, X., and Zhu, Y. (2023). Statistics of Railway Tunnels in China by the End of 2022 and overview of key tunnels of project newly put into operation in 2022. *Tunnel Construction*, Vol. 43, Issue 4, pp. 721–736.

Li, F., Chu, M. H., Dai, Q. H., and Zhang, L. P. (2005). Research on key technique of aerophotogrammetry flight management system based on GPS and GIS. *Science of Surveying and Mapping*, Issue 6, pp. 38–39.

Shao, W. W., Cheng, Y., Li, H. Y., and Ma, W. G. (2023). Analysis and Remediation Methods of Tunnel Lining Defects Based on Geological Radar. *Journal of Engineering Geophysics,* No, 01, pp. 1–10.

Sun, Y. M., Li, Y., and Nie, Z. G. (2020). Integration technology of 3DGIS and BIM and its application in highway tunnel intelligent management and maintenance system. *Bulletin of Surveying and Mapping*, Issue 10, pp. 127-130. DOI: 10.13474/j.cnki.11-2246.2020.0334.

Tian, S. M., Wang, W., and Gong, J. F. (2021). Development and Prospect of Railway Tunnels in China (Including statistics of Railway Tunnels in china by the End of 2020). *Tunnel Construction*, Vol. 41, Issue 2, pp. 308–325. DOI: 10.3973/j.issn.2096-4498.2021.02.018.

Wen, Z. B., Duan, Q., and Li, Z. Z. (2014). Application of laser holographic scanning technology in tunnel disease investigation. *Traffic Standard*, No 23, pp. 115–118.

МЕТОД ПОСТРОЕНИЯ И ПРИМЕНЕНИЕ ОСНОВНОЙ ЦИФРОВОЙ БАЗЫ ДАННЫХ ДЛЯ ИНТЕЛЛЕКТУАЛЬНОГО УПРАВЛЕНИЯ И ОБСЛУЖИВАНИЯ СУЩЕСТВУЮЩИХ ЖЕЛЕЗНОДОРОЖНЫХ ТОННЕЛЕЙ

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Аннотация
Введение. В Китае имеется обширная сеть туннелей, требующих обслуживания. Интеллектуальное управление и обслуживание этих туннелей на основе цифровой информационной системы может быть полезным. Для этого необходимо собирать соответствующую цифровую информацию о кожухе тоннеля и окружающей среде для долгосрочного обслуживания. **Целью** было взять в качестве объекта исследования существующий действующий туннель. В данном исследовании применяются различные методы информационных технологий для построения основной цифровой базы данных для интеллектуального управления и обслуживания туннелей. **Используемые методы**: статистические данные, беспилотная аэрофотосъемка, данные малоглубинного радиолокационного зондирования, данные полнопрофильного лазерного сканирования и теоретический анализ. **Результаты**. База данных может быть использована в качестве справочного пособия для аналогичных проектов.

Ключевые слова: интеллектуальное управление и обслуживание; цифровизация; основная база данных; аэрофотосъемка; полнопрофильное лазерное сканирования; малоглубинное радиолокационное зондирование.