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Key Technologies for Intelligent Construction of Tunnels on Beijing-Zhangjiakou High-speed Railway

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Abstract: The following key innovative technologies adopted for Beijing-Zhangjiakou high-speed railway are introduced: (1) In the construction of Qinghuayuan tunnel, the prefabrication and assembly technology is adopted for the under-track structure of the tunnel and assembly robots are developed and applied, which ensures the construction schedule, meets the safety requirements, saves labor costs, and has achieved significant economic and social benefits. (2) A visualized and intelligent construction management and monitoring platform is built during the construction of the shield-bored Qinghuayuan tunnel, which realizes visualized and real-time prediction and analysis of risks and ensures the safety of tunnel construction. (3) Automatic coatingtechnology is adopted for the outside enveloping waterproofing of Donghuayuan tunnel, which greatly improves the working efficiency and reduces the danger of the operators. (4) Cross-section quality management system based on 3D laser scanning technology is adopted for New Badaling tunnel and Zhengpantai tunnel, which meets the needs of process control and early warning for tunnel cross-section measurement.

Keywords: Beijing-Zhangjiakou high-speed railway; tunnel; intelligent construction; prefabrication and assembly technology; BIM technology; automatic construction

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京张高铁隧道智能建造技术

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摘要: 为实现高速铁路向信息化、智能化方向发展,以京张高铁为背景,介绍京张高铁隧道智能建造采用的关键技术: 1)清华园隧道建设过程中采用轨下结构全预制拼装技术,利用自研拼装机器人,实现了智能化拼装,极大地节约了人力成本,保证了施工的进度及安全要求; 2)清华园盾构隧道建设过程中,搭建可视化智慧施工管理监控平台,实现对风险的可视化实时预测和分析,保障隧道建设安全; 3)东花园隧道外包防水采用自动化喷涂防水技术,极大地提升了作业效率,降低了作业人员的危险性; 4)新八达岭隧道项目和正盘台隧道项目中采用基于三维激光扫描技术的隧道断面质量管理系统,满足了对隧道断面量测进行过程控制和预警处理的需求。

关键词: 京张高铁; 隧道; 智能建造; 预制拼装技术; BIM 技术; 自动化施工

0 Introduction

As an important transportation infrastructure, railway is the backbone of a country's comprehensive transportation system. Under the background of upgrading and transformation from conventional manufacturing industry to industry 4.0 era[1-5], efficient, green, intelligent and information-based construction of railways has become an inevitable trend of the development of the railway transportation industry[6].

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On December 30, 2019, the world's first intelligent high-speed railway, Beijing-Zhangjiakou high-speed railway, was officially put into operation. Beijing-Zhangjiakou high-speed railway, as the traffic support line of the 2022 Beijing Winter Olympic Games, the economic service line promoting the integrated and coordinated development of Beijing-Tianjin-Hebei region, and the example line of China's high-speed railway construction, fully follows the concept of "intelligent and green Beijing-Zhangjiakou high-speed railway" and a number of intelligent key technologies have been applied[7-11], which ensures the smooth opening of Beijing-Zhangjiakou high-speed railway.

Intelligent construction technology is the focus of tunnel research, and also the direction of future development[12]. With the construction of Sichuan-Tibet railway in China, due to the influence of oxygen deficiency and permafrostin high plateau, as well as the aging and sharp reduction of labor force in China, intelligent tunnel construction has become an inevitable trend. In this paper, the principle, core technology and application effect of several key intelligent construction technologies adopted for tunnels on Beijing-Zhangjiakou high-speed railway are presented, which can provide reference for the construction of tunnels on Sichuan-Tibet railway and other tunnel projects.

1 Intelligent under-track structure assembly technology adopted for Qinghuayuan tunnel

At present, there are two common structural types for the under-track structure of large-diameter shield-bored railway tunnels: full cast-in-place under-track structure; under-track structure composed of partial precast structure and partial cast-in-place structure. Under-track structure composed of fully-precast components is to be developed. The lining structure, under-track structure and auxiliary trenches of Qinghuayuan tunnel are prefabricated and assembled, which is the first time that fully prefabricated and assembled structure is adopted for tunnels in China[13]. According to the structural characteristics of the tunnel, a mechanized automatic assembly robot is developed. Standardization, automation, specialization and intelligence is realized in the construction of the under-track structure, the construction progress is accelerated, the construction period is shortened, damages to the segments caused byre-bar installing is avoided, the durability and reliability of the tunnel structure is improved, the interference of the external environment on the construction operation is reduced, the working environment is improved and the impact of vibration on the surrounding environment is reduced. Due to the flexible construction sequence and the high efficiency, the full prefabrication and assembly technology for the under-track structure of shield-bored tunnel has achieved remarkable economic and social benefits, which is a great innovation in the construction of the under-track structure of shield-bored tunnel in China.

1.1 Control principle of intelligent assembly of under-track structure

The under-track structure is composed of one middle box culvert and two side box culverts. The key of the intelligent assembly lies the research and development of the assembly robot. The assembly robot is mainly composed of gantry, walking wheels, power supply system, transverse moving system, balancing system, rotation system, U-shaped hoisting system, box culvert adjusting and positioning systemetc, as shown in Fig. 1. The equipment can lift the culvert components from the transporting vehicle, and put them into the designated installation position after transverse movement and adjustment. Finally, the box culvert components can be accurately installed in the tunnel, thus rapid mechanized assembly of the box culvert can be realized.

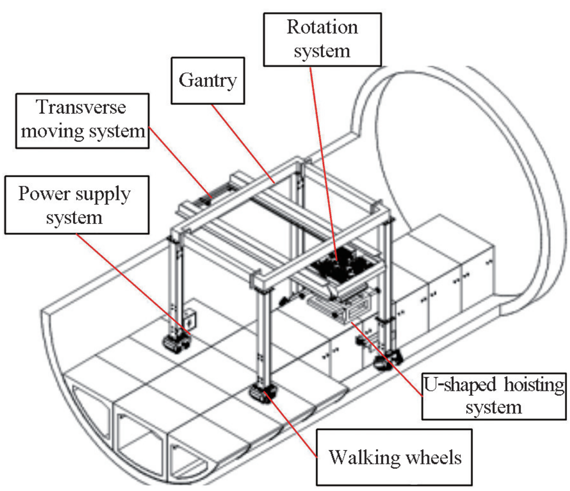


Fig. 1 Assembly machine for under-track structure of tunnel

The box culvert components adjustment and positioning structure adopts 2D/3D robot visual positioning technology. The visual image is acquired through camera, and transferred to the central control system to conduct image recognition and analysis and obtain position error of box culvert using inverse kinematics, thus adjusting the position and posture of box culvert, eliminating error and realizing accurate positioning and adjustment.

1.2 Assembly precision control

The middle box culvert is assembled first, and then the box culvert on both sides are assembled. The side box culverts are connected with the middle box culvert by bolts, therefore the positioning of the side box culverts is based on the middle box culvert, and no additional setting-out is needed. The overall assembly accuracy of the under-track structure is controlled within 5 mm. When the bolts are connected and tightened, the whole assembly process is completed. After the completion of the assembly, caulking is carried out to block the gap between the box culverts, and then the gap between the prefabricated under-track structure and the tunnel segments is filled with M10 micro expansion cement mortar. The bottom structure is monitored. The main monitoring items include the internal stress and strain of the components and the displacement of the integrated component structure, including settlement and sliding along the arc surface.

In order to speed up the construction of Qinghuayuan tunnel, the middle box culvert is assembled along with the shield boring, while the side box culverts are assembled after a long time lag. With such assembly mode, the synchronous fine adjustment of the middle box culvert and the side box culverts cannot be realized, which leads to the large dislocation of the side box culvertsin the later stage. Therefore, it is suggested that the box culvert and the side box culverts should be assembled simultaneously in future projects.

2 Visualized construction technology adopted for Qinghuayuan tunnel

A visualized and information-based intelligent construction management and monitoring platform based on 3D BIM model, VR technology and GIS roaming[14] is established for Qinghuayuan tunnel, which realizes the whole-process management and monitoring of construction steps such as excavation, componentassembly and grouting, and realizes the visualized and real-time prediction and analysis of risks.

2.1 Visualized monitoring system for shield tunnel construction

The shield tunnel construction monitoring system is anintelligent construction monitoring system that can process and analyze massive construction data including construction monitoring data, construction information and construction management information, and realize different functions by means of digital and visualization technology.

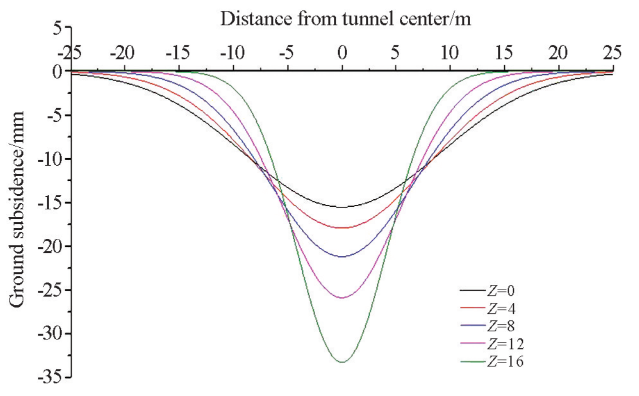
The intelligent construction monitoring system includes seven modules: home page, engineering GIS, shield monitoring, monitoring data, prediction and early warning, system management, and information upload. Different modules can achieve different system functions, and there are mutual connections and data exchange among the modules, which together constitute the intelligent construction system. The Engineting GIS module includes a satellite map, which shows the geographical location of the railway line in the interval and the adjacent relationship with the surrounding buildings, municipal roads and Metros in detail. At the same time, it also shows the important risk source information near the railwayline in detail. The shield monitoring module shows the tunnel details, grouting pipeline, grouting pressure, speed and displacement information of the current segment ring of the tunnel in detail, which can realize the real-time monitoring of shield boring posture and important parameters. It also shows the construction progress management chart, including the curve of comparison between the preset progressand actual progress of the shield and the cakechart showing the progress of the completed shield tunnel. This can facilitate managers to intuitively see the progress of the tunnel excavation and the difference between the preset progressrate and the actual rate, and help timely adjust the construction progress.

The prediction and early warning module shows the detailed geological information of surrounding buildings, municipal roads and subway lines and the important risk sources encountered in the construction of the tunnel. Then it analyzes and predicts the stratum response caused by shield tunnel construction and the response of surrounding buildings. At the same time, the location, risk level, predicted settlement value and control value of the risk sources are listed in detail, and the safety status is evaluated accordingly, thus realizing the real-time prediction of the risks of important buildings and main risk sources.

2.2 Key technologies of visualized construction

(1) A visualized management platform for tunnel construction based on BIM, GIS, and Internet technology is built. The whole process of shield tunnel construction is intelligentized, visualized and dynamically monitored and managed to realize the real-time prediction of the danger of adjacent buildings.

(2) The empirical method (such as the empirical method based on Peck theory) and artificial intelligence (ANN, GEP, and WPM) are used to comprehensively predict the ground surface settlement and the horizontal deformation of the buildings (structures) within the influence range of the construction in real time, and the optimal shield tunnel construction parameters corresponding to different stratum conditions and tunnel geometry parameters are obtained so as to guide the tunnel construction. The settlement trough obtained by Peck prediction model and the 3D view of settlement trough obtained by Peck prediction model are shown in Figs. 2 and 3, respectively.



Z is the distance between tunnel face and point along tunneling direction.

Fig. 2 Settlement trough obtained by Peck prediction model

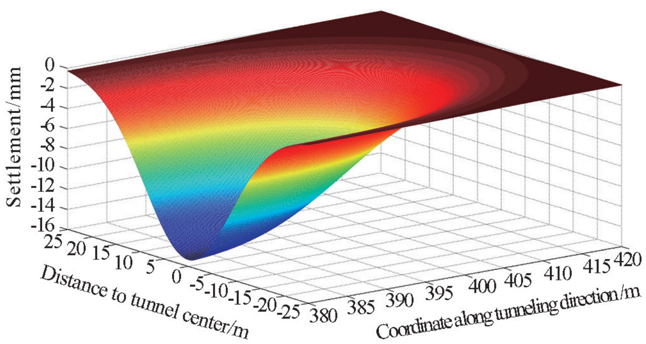


Fig. 3 3D view of settlement trough obtained by Peck prediction model

(3) The shield monitoring platform can digitize the geological conditions, surrounding buildings and engineering measures in shield tunneling, including the shield machine parameters, such as the shield's attitude parameters, pressure parameters, slurry inflow/outflow and grouting parameters, which are acquired from the shield machine's sensors and uploaded to the monitoring platform for quantitative digital processing.

2.3 Application and effect of visualized construction technology

At present, the application of the system in Qinghuayuan tunnel of Beijing-Zhangjiakou high-speed railway is very reliable, and the scientific and fine construction goal of Qinghuayuan tunnel based on modern advanced technologies such as informatization, intelligence, and visualization has been successfully realized. When the shield passesclose to multiple risk sources, the relationship between the tunnel and the surrounding environment can be displayed in advance by means of 3D model, and the influence of the shield tunneling process on the surrounding environment can be analyzed by means of software simulation, and then the shield tunneling parameters such as cutterhead rotation speed, excavation chamber pressure, and thrust cylinder forceand screw conveyor rotation speed are recommended. In the process of shield advancing, the ground surface settlement is monitored and timely fed back, the shield operators are warned in advance, and the tunneling parameters are dynamically adjusted. In the conventional mode, however, the statistics of shield tunneling parameters and monitoring data need to be analyzed artificially before corresponding countermeasures are taken. The visualized shield tunnel construction monitoring system greatly simplifies the process of human intervention, can send early warning information and perform automatic identification, thus accelerate the response speed and treatment efficiency of risks, reduce the probability of accidents, and improve the risk management and control ability of the tunnel construction. In this way, the visualized and dynamic management of the whole process of shield tunnel construction is preliminarily realized.

3 Automatic coating waterproofing technology adopted for Donghuayuan tunnel

Donghuayuan tunnel is the first cut-and-cover tunnel located in deep foundation pit withrich water in China for which quick-setting rubber asphalt coating water proofing material is adopted[15]. The new quick-setting rubber asphalt coating waterproofing material[16] is a kind of environmental protective water-based coating, which does not produce harmful substances in the cycle from production to application. It has the outstanding advantages of seamless overlap, perfect fit, low working environment requirements, high construction efficiency, strong adhesion, puncture resistance, acid alkali salt resistance, energy saving and consumption reduction, and can solve problems such as corner leakage, cracks and irregular structure joints. An automatic coating robot has been developed for the construction of Donghuayuan tunnel, which effectively improves the quality, efficiency and intelligence of coating construction. The robot can perform coating accurately, making the coating material adhere to the base surface with high strength, and the coating layer uniform and smooth. It effectively reduces the material loss, greatly improves the working efficiency and the safety and reliability of the construction.

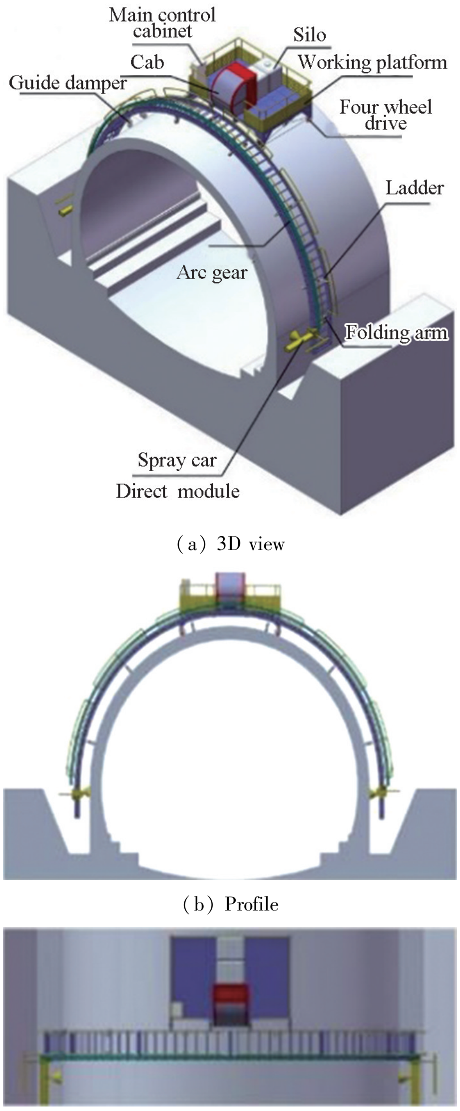
3.1 Intelligent control system of automatic coating

The automatic quick-setting rubber asphalt coating system consists of six parts: working platform, control system, feeding system, support system, walking system and coating trolley, as shown in Fig. 4.

(1) Working platform: It is customized according to the external dimension of the tunnel structure. It is equipped with the control system and the feeding system, with guardrails around.

(2) Control system: It mainly includes main controller, main electric control cabinet and frequency converter control cabinet. The main controller is controlled by PLC controller, and two kinds of control are set: touch screen + button. The values can be put in by means of the touch screen to set the basic parameters of the equipment. The control system has one-button start function, and automatic coating, climbing and returning can be performed automatically. The walking of the support system is controlled by electrical means. The system also has its own deviation correction function.

PLC controller is the intelligent control center of the automatic coating system. The built-in micro-processing chip can calculate, analyze and control the speed of the walking system and the supply of the feeding system, as well as the coating speed of the coating gun on the coating trolley, so as to accurately control the coating thickness.



(a) 3D view

(b) Profile

(c) Top view

Fig. 4 Automatic coating system for quick-setting rubber asphalt waterproofing material

(3) Feeding system: The quick-setting rubber asphalt coating waterproofing material is a kind of two-component coating material. The main agent of the coating waterproofing material is a kind of brown and viscous water-borne rubber asphalt emulsion, while the curing agent B is a kind of colorless transparent demulsifier. These two components are loaded into 2 containers of the operation platform respectively. The components are pumped by means of the booster pump, which is controlled by the main controller. Chain is arranged on the support system to protect the hose, which is connected to the coatingtrolley and moved along with the coating

trolley.

(4) Support system: The support system is customized according to the external dimensions of the tunnel structure. It takes the form of ladder with guardrails, on which the workers can walk. Its outside is composed of upper U-shaped channel steel and lower U-shaped channel steel. Two grooves are installed on the lower U-shaped channel steel and used as the walking track of the coating trolley; the upper U-shaped channel steel is used as the walking track of the chain.

(5) Walking system: Four driving wheels are installed under the working platform; each driving wheel is driven by a motor and can walk under the control of the main controller, and can be corrected. Under the support system, adjustable one-way damping wheel is installed, which moves together with the driving wheels of the working platform.

(6) Coating trolley: Cantilever beam is installed on the support system, four gears are installed to connect with the two grooves of the support system, transmission chain and coating gun are installed on the cantilever beam, one motor is installed todrive the coating trolley to walk along the support system, and the other motor is installed to drive the coating gun to walk along the cantilever beam.

The new automatic rapid-setting rubber asphalt waterproofing material coating system realizes the intelligent management of the construction stages and the construction teams.

3.2 Key technology and innovation of automatic coating system

(1) Considering the characteristics of the coating of the two-component liquid waterproofing material and the uniform dimension of the tunnel structure, coating robot made of steel structureis customized according to the geometric dimension of the tunnel structure (as shown in Fig. 5). The waterproofing material is fed automatically, and the coating and walking of the system can be performed automatically.

(2) The control of the coating thickness is one of the core technologies of this intelligent equipment. By means of theoretical calculation, the coating pressure is fixed, the moving rate of the coating gun is controlled, and the design coating thickness can be realized.

Fig. 5 Coating robot in operation

3.3 Application effect of automatic coating technology

The above-mentioned automatic coating technology is used for the construction of Donghuayuan tunnel. The efficiency of the automatic coating robot is 4 times that of manual coating. 22 000 m^2 coating is to be performed for Donghuayuan tunnel. In the case of manual coating, 500 m^2 coating can beachieved per day, and 44 day sare needed; in the case of robot coating, 2 000 m^2 coating can be achieved per day, and 11 days are needed. Due to the application of the robot coating for Donghuayuan tunnel, 33 day sare saved. Automatic coating robot only needs two persons in a group, while manual coating needs six persons in a group, reducing the number of field workers by 66.7%.

Conventional manual coating requires hand-held coating gun for operation, and high-altitude operation on the inverted arc imposes high risks. The automatic coating system has automatic coating gun, which does not require operators to work at height, effectively reducing the safety risks of the operators.

The automatic coating robot can control the coating dosage accurately, and it is easy to operate, and the coating thickness is perfect and uniform. Therefore, the error of different coating thicknesses and the improper overlap coating, which are common in manual coating, are avoided effectively. The qualification rate of the coating performed by the automatic coating system is 100%. The automatic coating robot has better control over the quantity of the waterproofing coating material needed. Due to the large error, the conventional manual coating cannot achieve the waterproofing effect when the quantity of the waterproofing coating material used is less than the design quantity; the cost of the coating materials increases when the quantity of the waterproofing coating material used is more than the design quantity. Due to the application of the coating robot in Donghuayuan tunnel, the water leakage of the tunnel is avoided effectively, the damage and influence of the water leakage on the equipment and vehicles in the tunnel are reduced, and the high cost to deal with the water leakage in the future is avoided.

The application of the automatic coating robot effectively reduces the workload of the site management personnel. According to the acceptance standard, the needle thickness gauge is used for real-time monitoring of the waterproofing coating layer, and one random checking will be made for every 100 m^2 coating. In the case of the conventional manual coating, in order to control the coating quality, the construction contractor needs to do more checking, treat the unqualified parts and perform monitoring after the treatment.

A coating robot and corresponding control system are developed for Donghuayuan tunnel in order to achieve the automatic coating. Due to the high requirements on the coating equipment, the automatic coating system may have some difficulties in the future promotion.

4 Tunnel cross-section quality management system based on 3D laser scanning technology

The tunnel cross-section quality management system based on 3D laser scanning technology, with BIM as the core, is a new generation of information management platform for railway tunnel construction. By means of the automatic 3D laser scanning acquisition terminal, the system uses professional analysis software to analyze the smoothness of the point cloud data according to the corresponding specification requirements, and the analysis results are automatically uploaded to the early warning platform for display, early warning and disposal. The tunnel cross-section quality management system is convenient for the construction contractor and the supervision contractor to manage the tunnel cross-section quality on the platform, and improves the management level and efficiency of the project quality, to achieve the goal of "rapid identification of risks, timely prediction of risks, display image of risks, and effective control of risk".

4.1 Introduction

The functional structure of the tunnel cross-section quality management system based on 3D laser scanning technology includes field data acquisition end, front-end processing end, and system analysis end.

(1) Data acquisition end: Due to the application of the new technology of 3D laser scanner and automatic total station, the single point operation mode from point to line and then from line to surface in the conventional survey is broken through. By means of high-speed laser scanning survey, we can quickly obtain the massive 3D point cloud data of the scanned object surface, realize the span from point survey to surface survey, thus quickly establish the 3D model of the object.

(2) Front end processing: Clean up and optimize the collected point cloud data to achieve comparative analysis of specific requirements such as overbreak and underbreak analysis, smoothness calculation, cross-section analysis, deformation calculation, volume analysis, roundness analysis, centerline deviation calculation, etc. The point cloud data is processed to form a solid project simulation image. By using the color, reflection intensity and other information contained in the point cloud data, the water seepage and cracks of the tunnel are analyzed, thus realizing the visualized management of tunnel quality and promote the quality management of tunnel projects.

(3) System analysis end: The system analysis end is the core of thetunnel cross-section quality management system. By means of the processing of the point cloud data and the correlation comparison with BIM model of the tunnel, the function of analysis on the excavation, primary support, secondary lining overbreak, underbreak, smoothness, cross-section, deformation, volume, true roundness, and center line deviation are realized. According to the overbreak and underbreak analysis data, smoothness analysis data, volume comparison data, deformation data and other information, the tunnel construction process and the tunnel profile quality can be comprehensively analyzed and a comprehensive evaluation index can be formed. Not only the quality of thecompleted works can be evaluated, but also improvement measures can be recommended for the subsequent construction, so as to avoid overbreak, underbreak or smoothness deficiency. The function structure of tunnel cross-section quality management system based on 3D laser scanning technology is shown in Fig. 6.

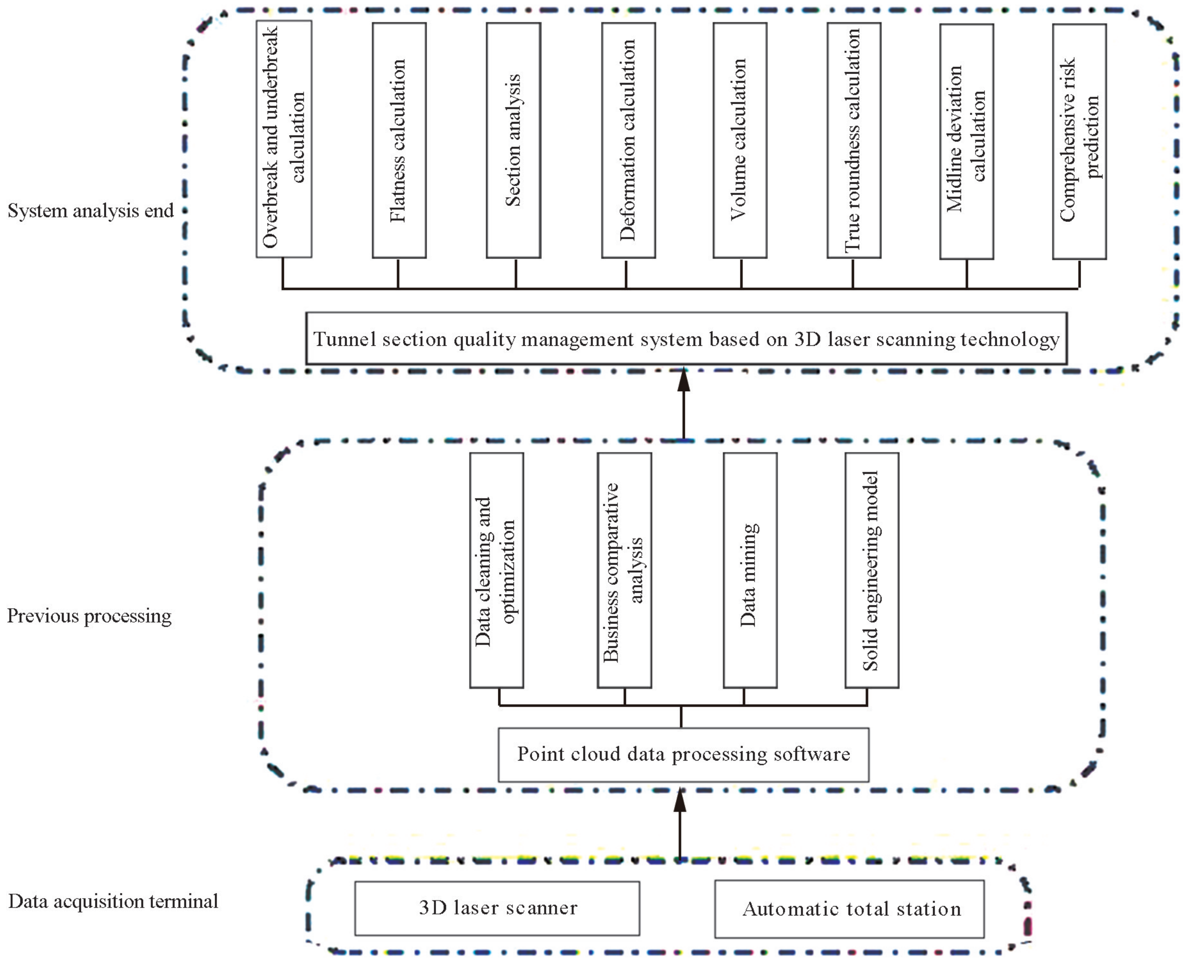


Fig. 6 Function structure of tunnel cross-section quality management system based on 3D laser scanning technology

4.2 Key technologies and innovations of tunnel cross-section quality management system

(1) The three-dimensional coordinates of the contour of the scanning target can be obtained in a short time, with long distance and high precision by means of the automatic, high-precision and three-dimensional scanning function of the three-dimensional laser scanning technology. The complex condition of the construction site can be recorded efficiently and completely and can be compared with the design BIM model, thus bringing great help for the works quality inspection and works acceptance.

(2) The 3D laser scanning technology processing software and BIM model belong to different metadata. The tunnel cross-section quality management system realizes the automatic and real-time transmission of the two kinds of metadata, and "assimilates" all different metadata into a unified type of data, which is stored in the cloud database. After the transmission of different metadata is completed, the real-time analysis of different data is carried out, and the functions of cross-section sketch package download and analysis result and analysis report download are provided, thus realizing the synchronization and efficient collaboration of the overall metadata.

(3) It is the first time to realize the digital integration of the control point cloud data generated by 3D laser scanning technology and BIM model coding data, realize the real-time association between the dynamically reconstructed point cloud model and BIM model, and grasp the construction status in real time. It further realizes the analysis on excavation, primary support, overbreak/underbreak and secondary lining, as well as tunnel clearance calculation and tunnel cavity monitoring, etc., and achieves the visualized three-dimensional quality control in terms of overbreak/underbreak, tunnel clearance and tunnel cavity based on BIM.

(4) It is the first time that 3D laser scanning technology, BIM-based visualization technology, mobile internet technology and other new information technologies are used to optimize and improve the existing

calculation rules and standards for the contour smoothness of high-speed railway tunnels. The developed calculation principle and mathematical analysis model for the contour smoothness of railway tunnels form a new technical standard for the contour smoothness of high-speed railway tunnels, which can improve the speed and accuracy of analysis on the contour smoothness and can be displayed and released in the early warning system in time, thus realizing timely feedback and closed-loop solution for problems.

4.3 Effect of application of tunnel cross-section quality management system

In New Badaling tunnel and Zhengpantai tunnel, the application of the tunnel cross-section quality management system based on 3D laser scanning technology has greatly improved the accuracy and timeliness of tunnel cross-section quality management, and greatly improved the working efficiency of all parties involved in the construction[17].

In the data acquisition end, according to incomplete statistics, the application of the tunnel cross-section quality management system has reduced the labor cost by 20%, improved the data acquisition efficiency by 30% and improved the accuracy by 25%. In the front-end analysis, the BIM model, analysis report and cross-section sketch are automatically generated by professional analysis on the point cloud data in terms of cross-section segmentation, overbreak/underbreak analysis, contour smoothness analysis, cavity volume analysis and deformation analysis, which provide guidance for the field operators in real time. At the same time, all kinds of analysis results can be transmitted to the early warning system in real time for early warning control, and realize the monitoring of IOT transmission, centralized storage, professional analysis and early warning release, realize the effective control of key parts and key quality issues in the construction of tunnels, comprehensively improve the management of the whole process of tunnel construction, improve the management efficiency and accuracy of construction management personnel, and facilitate the timely elimination of construction safety hazards.

Due to the application of the tunnel cross-section quality management system, the timeliness and accuracy of data acquisition, data processing, data feedback and early warning are ensured, and the automation of data transmission, data processing, data feedback and early warning is realized. At the same time, the system has the function of traceability and supervision, which plays the role of checking and guidance. Compared with the conventional methods, the tunnel cross-section quality management system based on 3D laser scanning technology can meet the needs of process control and early warning dealing for tunnel cross-section measurement, strengthen the supervision on the site operation behavior, realize timely and rapid response and treatment for abnormal deformation, timely elimination of potential safety hazards, reduce the probability of accidents, improve the ability of tunnel construction risk management and control, and get good feedback from many users.

5 Conclusions and discussions

(1) Full component prefabrication and assembly technology is adopted and assembly robot is developed for the under-track structure of Qinghuayuan tunnel, which realizes intelligent assembly and greatly improves the construction efficiency and assembly accuracy.

(2) The visualization system applied in the construction of shield-bored Qinghuayuan tunnel can display the shield working conditions in real time, analyze the risks automatically according to the real-time state of the shield, and give suggestions on thrust parameters, which effectively improves the tunnel construction quality and management efficiency.

(3) Automatic coating waterproofing technology is adopted for Donghuayuan tunnel and customized automatic coating robot is used, which realizes the automatic material feeding, automatic positioning and automatic coating. Compared with the conventional manual coating technology, the automatic coating waterproofing technology has significant advantages in construction quality, safety, efficiency and progress.

(4) In the construction of New Badaling tunnel and Zhengpantai tunnel, the tunnel cross-section quality management system based on 3D laser scanning

technology is applied, which deeply integrates the BIM refined model and the 3D laser scanning point cloud model to further realize the visualization of tunnel construction.

However, there are still some shortcomings in the application of intelligent technology in Beijing-Zhangjiakou high-speed railway tunnels, which need to be overcome step by step. For example, regarding the full component prefabrication and assembly technology, assembly error will inevitably occur and the adaptability of the assembly machine is to be further improved. Regarding the application of the visualized construction system, it is necessary to further improve the convenience of the human-computer interaction, optimize the system interface, strengthen the promotion of the system and improve the quality of the employees.

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京张高铁隧道智能建造技术

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摘要：为实现高速铁路向信息化、智能化方向发展，以京张高铁为背景，介绍京张高铁隧道智能建造采用的关键技术：1)清华园隧道建设过程中采用轨下结构全预制拼装技术，利用自研拼装机器人，实现了智能化拼装，极大地节约了人力成本，保证了施工的进度及安全要求；2)清华园盾构隧道建设过程中，搭建可视化智慧施工管理监控平台，实现对风险的可视化实时预测和分析，保障隧道建设安全；3)东花园隧道外包防水采用自动化喷涂防水技术，极大地提升了作业效率，降低了作业人员的危险性；4)新八达岭隧道项目和正盘台隧道项目中采用基于三维激光扫描技术的隧道断面质量管理系统，满足了对隧道断面量测进行过程控制和预警处理的需求。

关键词：京张高铁；隧道；智能建造；预制拼装技术；BIM 技术；自动化施工

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Key Technologies for Intelligent Construction of Tunnels on Beijing-Zhangjiakou High-speed Railway

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Abstract：The following key innovative technologies adopted for Beijing-Zhangjiakou high-speed railway are introduced：(1) In the construction of Qinghuayuan tunnel，the prefabrication and assembly technology is adopted for the under-track structure of the tunnel and assembly robots are developed and applied，which ensures the construction schedule，meets the safety requirements，saves labor costs，and has achieved significant economic and social benefits. (2) A visualized and intelligent construction management and monitoring platform is built during the construction of the shield-

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bored Qinghuayuan tunnel, which realizes visualized and real-time prediction and analysis of risks and ensures the safety of tunnel construction. (3) Automatic coatingtechnology is adopted for the outside enveloping waterproofing of Donghuayuan tunnel, which greatly improves the working efficiency and reduces the danger of the operators. (4) Cross-section quality management system based on 3D laser scanning technology is adopted for New Badaling tunnel and Zhengpantai tunnel, which meets the needs of process control and early warning for tunnel cross-section measurement.

Keywords: Beijing-Zhangjiakou high-speed railway; tunnel; intelligent construction; prefabrication and assembly technology; BIM technology; automatic construction

0 引言

铁路作为重要的交通基础设施,是一个国家综合运输体系的骨干力量,在传统制造业向工业 4.0 时代升级转型的大背景下[1-5],建设高效、绿色、智能化、信息化的铁路工程已成为铁路运输行业发展的必然趋势[6]。

2019 年 12 月 30 日全球首条智能化高速铁路京张高铁正式开通运行,京张高铁作为 2022 年北京冬奥会的交通保障线,促进京津冀地区一体化协同发展的经济服务线,中国高铁建设的示范线,在建造过程中充分发扬“智能京张,绿色京张”理念,应用多项智能化关键技术[7-11],保障了京张高铁的顺利开通。

智能建造技术是当今隧道研究的热点,也是今后发展的方向[12]。随着我国川藏铁路的开工建设,受高原缺氧、高寒冻土等因素的影响,同时我国劳动力高龄化并急剧减少,隧道智能化建造成为必然选择。本文将系统地介绍京张高铁隧道建设过程中多项智能建造关键技术的原理、核心技术及应用效果,可为川藏铁路等隧道工程的建设提供参考。

1 清华园隧道轨下结构智能拼装技术

目前大直径盾构铁路隧道轨下结构常用的结构形式有全部现浇与部分预制、部分现浇 2 种,但轨下结构采用全预制构件拼装的施工方法尚属空白。清华园隧道的支护结构、轨下结构和附属沟槽均进行预制机械化拼装建造,在国内首次实现了隧道结构全预制拼装施工[13],并针对隧道结构特点,研制了机械化自动拼装机器人,实现了隧道轨下结构建造的标准化、自动化、专业化、智能化,加快了施工进度,节约了工期,避免了大量植筋损坏盾构管片,提高了结构耐久性和可靠性,减少了外界环境对施工作业的干扰,改善了作业环境,降低了振动对周边环境的影响。盾构隧道轨下结构全预制工艺,由于其具有施工灵活、效率高等特点,取得了显著的经济效益和社会效益,是国内盾构隧道轨下结构施工的革命性创举。

1.1 轨下结构智能化拼装的控制原理

轨下结构由 1 个中箱涵和 2 个边箱涵组成,其拼装智能化的关键在于拼装机器人的研发。拼装机器人主要由车架、行走车轮组、小车供电、横移机构、平衡机构、旋转机构、U 型吊具、箱涵件调整定位机构等组成。隧道箱涵

预制件拼装机如图 1 所示。该设备可以将箱涵件从运输车吊起，并平移调整后放到指定安装位置，最终将箱涵件精确安装于隧道内，实现箱涵快速机械化拼装。

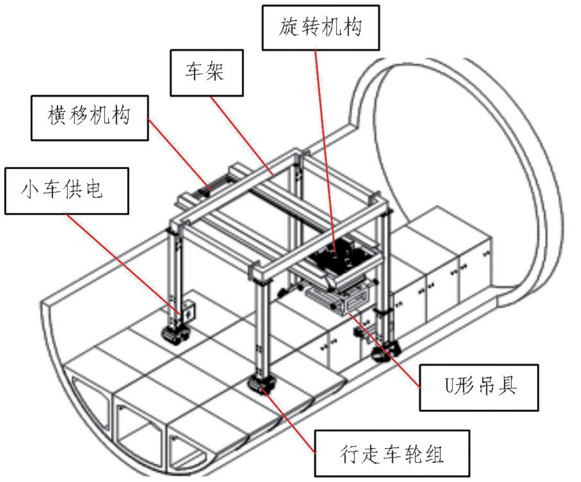


图 1　隧道箱涵预制件拼装机

Fig. 1　Assembly machine for under-track structure of tunnel

箱涵件调整定位机构采用 2D/3D 机器视觉定位技术，通过摄像机采集视觉图像，并传输给中央控制系统进行图像识别分析、利用逆运动学求解得到箱涵位置误差值，并调整箱涵的位置和姿态位姿，消除误差，实现精准定位和调整。

1.2　拼装精度控制

轨下结构拼装时先拼装中箱涵，之后拼装两侧边箱涵。由于边箱涵构件与中箱涵采用螺栓连接，其定位以中箱涵为基准，不再单独进行放样，整体拼装精度控制为 5 mm 以内。当各构件之间螺栓连接并紧固完毕后，即完成整个构件拼装工序。拼装完成后进行嵌缝施工，将箱涵之间的空隙堵住形成密闭空间，然后对预制结构与盾构管片之间的空隙采用 M10 微膨胀水泥砂浆充填，最后对底部结构进行监测。主要监测内容为构件内部应力应变和构件整体性的位移，包括沉降及沿弧面滑移。

清华园隧道轨下结构拼装时，为了加快拼装进度，中箱涵随盾构掘进先拼装，而边箱涵滞后很长时间才开始拼装，这种先后拼装的模式无法实现中箱涵和边箱涵的同步精调，导致后期边箱涵拼装的错台较大。因此，后续工程建议中箱涵和边箱涵同步拼装。

2　清华园隧道可视化施工技术

清华园隧道搭建了基于三维 BIM 模型、VR 技术和 GIS 漫游的可视化、信息化的智慧施工管理监控平台[14]，实现对掘进、拼装、注浆等施工环节的全过程管理和监控，同时实现了对风险的可视化实时预测和分析。

2.1　盾构可视化施工监控系统

盾构施工监控系统是一个集施工监测数据、施工信息以及施工管理信息于一体，能对海量施工数据进行处理分析，并通过数字化、可视化技术实现不同功能的智慧施工监控系统。

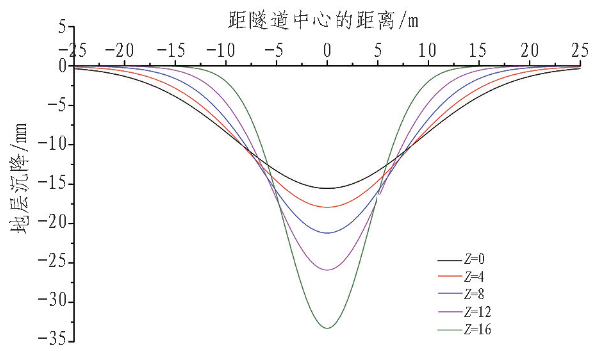
智慧施工监控系统共包括首页、工程 GIS、盾构监控、监测数据、预测预警、系统管理以及信息上传 7 大模块。不同模块可以实现不同的系统功能，各模块之间也存在相互联系和数据交换，共同作用构成智慧施工系统。工程 GIS 模块包含了工程的卫星地图，详细显示区间线路的地理位置关系以及和周边建筑物、市政道路和地铁的毗邻关系，同时还详细显示线路附近重要的风险源信息。盾构监测模块详细显示隧道掘进当前环的隧道详情、注浆管道、注浆压力和速度与位移信息，可实现对盾构掘进姿态和重要参数的实时监控，同时还显示了施工进度管理图，包括盾构预设与实际进度比较曲线图和盾构完成进度饼状图，可以方便管理人员直观地看到隧道掘进的完成情况以及与预设进度的差别，帮助及时进行调整施工进度。

预测预警模块中展示了详细的周边建筑物、市政道路以及地铁线路的地质信息,同时详细列举了线路施工过程中遇到的重要风险源信息,还可对盾构隧道施工引起的地层响应和周边建筑物响应进行分析预测。风险信息列表详细列出了风险源的位置、风险等级以及沉降预测值和控制值,并据此判别安全状态,实现了重要建(构)筑物和主要风险源危险性的实时预测预报功能。

2.2 可视化施工关键技术

1)搭建了基于 BIM、GIS 和互联网技术的隧道施工可视化管理平台,采用盾构施工全过程智能化、可视化动态监控与管理,实现对临近建(构)筑物危险性的实时预测预报。

2)采用经验方法(如基于 Peck 理论的经验方法)和人工智能(ANN、GEP 及 WPM)等方法多角度综合实时预测地表及施工影响范围内的建(构)筑物的沉降及水平变形,推导出不同地层条件和隧道几何参数对应的最优盾构施工参数指导施工。Peck 预测模型横断面沉降槽如图 2 所示。Peck 预测模型三维视图如图 3 所示。



Z 为隧道开挖方向与掌子面的距离。

图 2 Peck 预测模型横断面沉降槽

Fig. 2 Settlement trough obtained by Peck prediction model

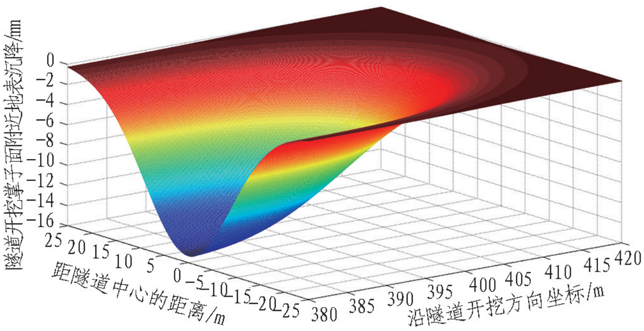


图 3 Peck 预测模型三维视图

Fig. 3 3D view of settlement trough obtained by Peck prediction model

3)盾构监控平台要求将盾构掘进中的地质条件、周边建筑物、工程措施等信息数字化,并且能够从盾构的传感设备中自动采集盾构的姿态参数、压力参数、进出浆和注浆量参数等,实现各种信息的数字化处理。

2.3 可视化施工技术的应用及其效果

目前该系统在京张高铁清华园隧道的应用十分可靠,基于信息化、智能化、可视化等现代先进技术成功实现了科学化、精细化的施工目标。在盾构穿越多个风险源的时候,通过 3D 模型提前展示隧道与周边环境的关系,并且能够通过软件模拟分析盾构掘进过程对周边环境的影响值进而推荐刀盘转速、土舱压力、油缸推力、螺旋输送机转速等盾构掘进参数;在盾构推进过程中结合地面测量数据,及时反馈地面沉降量提前预警盾构操作人员,动态调整掘进参数。传统的盾构掘进参数和监测数据的统计,大部分需要人为分析数据并进行相应的对策处理。盾构可视化施工监控系统大大地简化了人为干预的流程,不仅能够预警信息并进行自动判别,加快了应对风险的响应速度和处理效率,降低了安全事故的概率,提高了隧道施工的风险管控能力,初步实现了盾构施工全过程的可视化动态管理。

3　东花园隧道自动化喷涂防水技术

东花园隧道是国内首次采用速凝橡胶沥青喷涂防水材料的强富水深基坑明挖隧道[15]，新型喷涂速凝橡胶沥青防水材料[16]是一种绿色环保的水性涂料，从生产到使用均不产生有害物质，具有无缝搭接、完美贴合、工作环境要求低、施工效率高、附着力强、耐穿刺、抗酸碱盐、节能降耗等突出优势，能解决边角、裂缝、不规则结构的连接处渗漏等技术难题。东花园隧道专门研制了自动喷涂机器人，有效提高了喷涂施工的质量、效率和智能程度。该机器人能精确地按照设定轨迹自动准确喷涂，使材料与基面全面高强粘附、喷层均一平整。有效减小了损耗量，极大地提高了工效，大幅度提升了施工的安全可靠性。

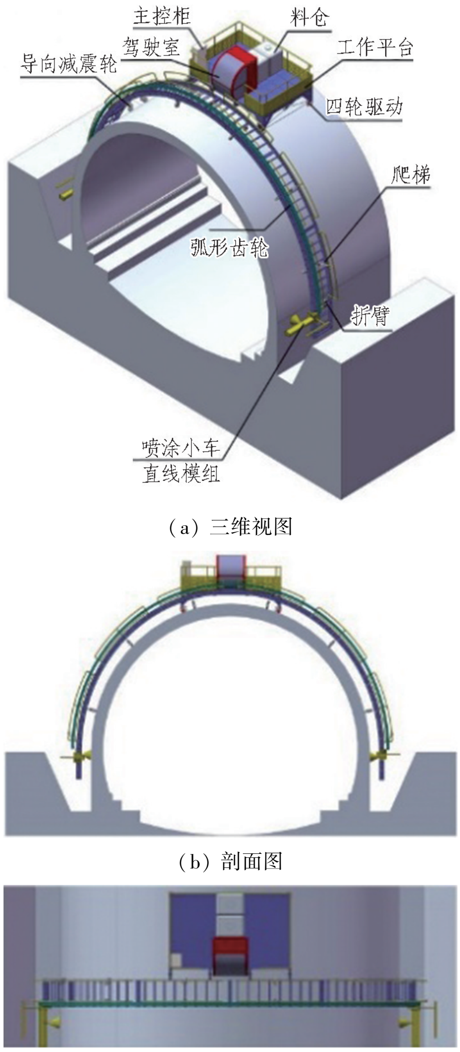
3.1　自动化喷涂的智控系统

新型速凝橡胶沥青防水材料的自动化喷涂系统包括工作平台、控制系统、供料系统、支撑系统、走行系统和喷涂小车 6 部分，如图 4 所示。

1）工作平台。根据结构外观尺寸进行定制，是存放控制系统和供料系统的操作平台，周围设置护栏。

2）控制系统。主要包括主控制器、主电控制柜和变频器控制柜，主控制器采用 PLC 控制器控制，设置触摸屏+按钮 2 种控制，触摸屏可以实时输入数值进行设备基本参数设置，一键启动功能，自动运行喷涂、爬升、回位，支撑系统行走电动控制，自带纠偏功能。

PLC 控制器是自动化喷涂的智控中心，其内置的微处理芯片可以计算分析并控制行走系统的速度和供料系统的供应量，以及喷涂小车上喷枪的喷速，从而精准控制喷层厚度。



（a）三维视图

（b）剖面图

（c）顶视图

图 4　速凝橡胶沥青防水自动化喷涂系统

Fig. 4　Automatic coating system for quick-setting rubber asphalt waterproofing material

3）供料系统。新型喷涂速凝橡胶沥青防水材料为双组份涂料，防水涂料主剂 A 组份为棕褐色黏稠状的水性橡胶沥青乳液，固化剂 B 组份为无色透明的破乳剂，分别装入操作平台的 2 个容器中。通过增压泵泵送涂料，增压泵由主控制器进行控制，在支撑系统上设置坦克链对管道进行保护，直达喷涂小车，并跟随小车采用回卷式移动。

4)支撑系统。根据结构外观尺寸进行定制,采用爬梯形式,可供工作人员行走,并设置护栏。外侧采用上、下双层 U 型槽钢,在下层 U 型槽钢上设置 2 道齿槽作为喷涂小车的行走轨道,上层 U 型槽钢作为坦克链的行走轨道。

5)走行系统。在工作平台下设置 4 个驱动轮,每个驱动轮由 1 个电机驱动,在主控制器控制下行走,并可进行纠偏,在支撑系统下设置可调节单向减震轮随工作平台的驱动轮进行移动。

6)喷涂小车。在支撑系统上设悬挑梁,设置 4 个齿轮与支撑系统的 2 道齿槽进行连接,在悬挑梁上安装传动链和喷枪,设置 2 个电机进行驱动,1 个电机驱动喷涂小车沿支撑系统行走,1 个电机驱动喷枪沿悬挑梁行走。

自动化喷涂系统实现了新型速凝橡胶沥青防水施工的智能化。

3.2 自动化喷涂关键技术及创新

1)根据防水材料双组份液体喷涂方式的特性和结构物的外轮廓结构尺寸一致的特点,创新提出了按照结构物的几何尺寸采用钢结构定制喷涂机器人,该机器人自动上料、自动喷涂、自动行走,填补了铁路明挖隧道自动喷涂防水施工的行业空白。

2)新型速凝橡胶沥青防水自动化喷涂对喷涂厚度的控制,是本智能化设备的核心技术,通过理论计算,固定喷涂压力,控制喷枪移动速率,实现设计喷涂厚度。喷涂机器人现场作业如图 5 所示。

图 5 喷涂机器人现场作业

Fig. 5 Coating robot in operation

3.3 自动化喷涂技术应用效果

东花园隧道采用了自动化喷涂技术,自动化喷涂机器人的施工工效是人工喷涂施工工效的 4 倍。按照东花园隧道喷涂 22 000 m^2 进行计算,人工喷涂每日喷涂 500 m^2,需要 44 d; 机器人喷涂每日喷涂 2 000 m^2,需要 11 d,节约工期 33 d。自动化喷涂机器人只需 2 人 1 组,人工喷涂需要 6 人 1 组,减少现场作业人员 66.7%。

传统人工喷涂需要人工手持喷枪进行作业,在倒弧形上高空作业,作业人员危险性极高,属于高危作业; 自动化喷涂采用自动喷枪,无需作业人员高空作业,有效降低了作业人员的危险性。

自动化喷涂机器人能够精确地控制喷涂用量,操作简单,喷涂厚度完美均一,有效地避免了人工喷涂存在的喷涂厚度不一、搭接面处理不到位等(合格率为 100%),对防水涂料的使用量控制更好。而传统人工喷涂误差较大,使用量低于设计量达不到防水效果;使用量高于设计量喷涂材料成本增加。采用自动化喷涂机器人,有效避免了隧道渗漏水情况的发生,降低了洞内渗漏水对洞内设备和运营车辆产生破坏和影响的程度,同时减少了后期对隧道渗漏水进行处理产生的高额费用。

自动化喷涂机器人的应用有效地降低了现场管理

人员的工作量,按照验收标准采用针测法测厚仪对喷涂防水层进行实时监测,每 100 m^2 抽查 1 处。而传统人工喷涂施工单位为了控制喷涂质量都是进行加密监测,同时需要对不合格部位进行加强处理,处理完成后还需要进行监测。

东花园隧道在自动化喷涂实现的过程中设计了专门的喷涂机器人及相应的控制系统,对装备的要求较高,在后续的推广过程中可能存在一定的困难。

4　基于三维激光扫描技术的隧道断面质量管理系统

基于三维激光扫描技术的隧道断面质量管理系统是以 BIM 为核心,面向铁路工程隧道建设的新一代信息化管理平台。该系统通过三维激光扫描自动采集终端,利用专业分析软件对点云数据的平整度按照相应规范要求进行分析,分析结果自动上传至预警平台进行展示和预警发布处置,方便铁路工程施工单位及监理单位在平台上对隧道施工断面质量进行管理,提高了工程质量的管理水平与效率,达到了“快速辨识风险、及时预报风险、形象展示风险、有效控制风险”的目标。

4.1　三维激光扫描隧道断面质量管理系统

基于三维激光扫描技术的隧道断面质量管理系统功能架构包括现场数据采集端、前端处理和系统分析端。

1)数据采集端。通过利用三维激光扫描仪与全自动全站仪相结合的新技术,突破了传统测量中由点到线、再由线到面的单点作业模式,通过高速激光扫描测量的方法,能快速获取被扫描物表面的海量三维点云数据,实现了从点测量到面测量的跨越,从而能快速建立物体的三维模型。

2)前端处理。将收集而来的点云数据进行清理、优化,实现超欠挖、平整度、直圆度、断面、变形、方量、中线偏差等指标的分析计算。对点云数据进行处理,形成实体的工程模拟影像,并通过运用点云数据中所包含的色彩、反射强度等信息,分析隧道的渗水、裂缝等情况,实现隧道质量的可视化管理,推动隧道工程的质量管理。

3)系统分析端。系统分析端是隧道断面质量管理系统的核心,通过对点云数据进行处理,并与隧道 BIM 模型进行关联比对,实现断面步距对开挖、初期支护和二次衬砌超欠挖分析、平整度计算、断面分析、变形计算、方量计算、真圆度计算、中线偏差计算等功能;并能根据超欠挖分析数据、平整度分析数据、方量对比数据、变形数据等信息,综合分析每段里程内的施工过程数据、成型质量数据,形成综合评判指标。既能对已完工程进行质量评判,又能对后续施工提出改进措施,避免出现超欠挖、平整度超限的情况。基于三维激光扫描技术的隧道断面质量管理系统功能架构如图 6 所示。

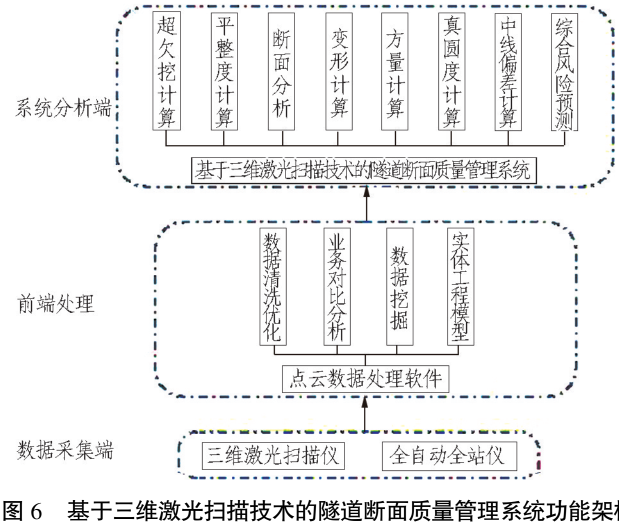


图 6　基于三维激光扫描技术的隧道断面质量管理系统功能架构

Fig. 6　Function structure of tunnel cross-section quality management system based on 3D laser scanning technology

4.2 隧道断面质量管理系统关键技术及创新

1)通过三维激光扫描技术全自动、高精度、立体扫描手段,短时间、远距离、高精度地获得扫描目标的表面三维坐标,高效、完整地记录施工现场的复杂情况,与设计BIM模型进行对比关联,为工程质量检查、工程验收带来巨大帮助。

2)三维激光扫描技术处理软件与BIM模型属于不同元数据,本系统实现两者的自动和实时传输,把所有异类数据"同化"为统一类型数据,存储在云端数据库。不同元数据传输完成之后,按需求里程段进行不同数据的实时解析,提供断面图打包下载、分析结果及报告下载等功能,实现整体多元数据的同步和高效协同。

3)首次实现隧道三维激光扫描技术生成的控制点点云数据与BIM模型编码数据数字化集成,实现动态重构点云模型与BIM模型实时关联,实时掌握施工状态,进一步实现对隧道进行施工作业过程开挖、初期支护、二次衬砌的超欠挖分析、隧道净空计算、隧道空洞监测等,实现基于BIM的隧道超欠挖、净空及空洞方量等三维可视化质量管控。

4)首次采用三维激光扫描技术、BIM可视化技术以及移动互联技术等信息化新技术手段,对现有高铁隧道工程平整度计算规则和标准进行优化提升,制定的铁路隧道工程平整度计算原理和数学分析模型,形成高铁隧道工程平整度新的技术标准,能够提高平整度分析的速度和精度,并可以及时在预警系统进行展示和预警发布,实现问题及时反馈和闭环处置。

4.3 隧道断面质量管理系统技术应用效果

在新八达岭隧道项目和正盘台隧道项目中,通过应用基于三维激光扫描技术的隧道断面质量管理系统,极大地提高了隧道断面质量管理准确性与及时性,较大程度提高了参建各方的工作效率[17]。在数据采集端,据不完全统计,该系统的应用已节省人工成本20%,提高采集效率30%,提高准确率25%。在前端分析中,通过对点云数据进行断面切分、超欠挖、平整度、方量、变形等指标的专业分析,自动生成BIM模型、分析报表和断面图实时指导现场作业人员。与此同时,各类分析结果能够实时传输到预警系统中进行预警管控,实现监测物联传输、集中存储、专业分析、预警发布,实现对隧道工程建设过程关键部位、关键质量问题的有效管控,全面提升所建隧道项目施工全过程的精益管理,提高了建设管理人员的管理效率及准确性,便于及时消除施工安全隐患。

通过应用该系统,解决了数据采集、处理、反馈、预警的及时性和准确性问题,实现了数据传输、处理、反馈和预警自动化,同时具有溯源监管功能,起到了检查和指导的作用。与传统方法相比,应用基于三维激光扫描技术的隧道断面质量管理系统,满足了对隧道断面量测进行过程控制和预警处理的需求,加强了对现场作业行为的监管力度,保证隧道施工及周边环境施工安全的及时性、真实性,实现对变形异常及时、快速地响应和处理,及时消除安全隐患,降低了安全事故的概率,提升了隧道施工风险管控能力,得到了多家使用单位的良好反馈。

5 结论与讨论

1)清华园隧道轨下结构采用全预制拼装技术,并研发了拼装机器人,实现了智能化拼装,极大地提高了施工效率与拼装精度。

2)清华园盾构隧道应用可视化施工系统施工,能够实时展示盾构工作情况,并能根据盾构实时状态自

动分析风险情况并给予推进参数建议，有效地提升了施工质量和管理效率。

3）东花园隧道防水工程创新性地采用了自动化喷涂防水技术，利用钢结构定制自动喷涂机器人，实现了防水材料的自动上料、自动定位、自动喷涂。与传统人工喷涂技术相比，在施工质量、安全、工效和进度上有显著优势。

4）新八达岭隧道和正盘台隧道在建设过程中应用了基于三维激光扫描技术的隧道断面质量管理系统，将 BIM 精细化模型与三维激光扫描点云模型进行深度融合，进一步实现对隧道施工作业过程的可视化。

在京张高铁隧道智能技术应用的过程中仍存在一些不足需要改进，例如采用全预制拼装技术进行施工时不可避免会产生拼接误差，同时拼装机也存在适应性不强的问题；在可视化施工系统应用的过程中需要进一步加深人机互动的便利性，优化系统界面，同时加强推广，提高从业人员的素质。

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