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ZhangJiHuai Railway Project – The use of a new innovative system for scanning in a drill & blast excavation

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ABSTRACT: The Zhangjiajie-Jishou-Huaihua (hereinafter referred to as ZhangJiHuai) highspeed railway project has started its construction since 12th December 2016. The Jishou Tunnel, as an early start section and key control project of the line, first introduced tunnel scan system which has been widely used on the entire project. Tunnel scan system integrates 3D laser scanner and smart computer software, which makes it possible to collect, process and output scan data in real-time on the job-site. The system provides a comprehensive solution of survey, data analysis and documentation for tunnel construction works. The principle of the system is collecting high-precision, high-density spatial and image data of point clouds on the tunnel surface of complex objects geometry through non-contact high-speed laser scanning measurements. With intelligent software "Amberg Tunnel", the data acquisition and analysis can be streamlined and standardized, functions cover a variety of complex applications of tunnel measurements, including control survey of profile over-/under-break, undulation analysis of shotcrete lining, layer thickness analysis of inner lining concrete and tunnel imaging etc.. This paper introduces the background of the project and the application of Tunnel 3D Laser Scanning System on the project.

KEYWORDS: Tunneling, 3D laser scan, Over-/underbreak, Volume of concrete lining, Thickness analysis

1. INTRODUCTION

The 246 km long ZhangJiHuai high speed railway project has started its construction since 12 Dec. 2016, and expected to be operational in 2021. The 12.16 km long Jishou Tunnel is the longest tunnel of the ZhangJiHuai highspeed rail project and the key control project of the line. A new innovative tunnel scan system has been introduced to this tunnel project at the very beginning of its excavation for comprehensive tunnel construction survey and quality control of tunnel excavation and tunnel lining layer thickness analysis and documentation. The principle of tunnel scan system is collecting high-precision, high-density spatial and image data of point cloud on the surface of complex objects through non-contact high-speed laser scanning measurement. With the help of "Amberg Tunnel" software, the laser data acquired can be quickly processed for excavation quality check such as control survey of profile over-/underbreak, undulation analysis of shotcrete lining, layer thickness measurement of inner lining as well as tunnel excavation perimeter blast-holes contour analysis based on laser scanning images etc..

2. BACKGROUND OF THE PROJECT

The ZhangJiHuai Railway project locates in Hunan province of China, has a total length of 246.6 km, total investment of 38.24 billion Chinese yuan, design speed of 350 km/hour. It has 7 stations. The construction period is 5 years. It will be completed and opened in 2021. The time from Huaihua to Zhangjiajie will be shortened from 3.5 hours to 1 hour after completion. There are 168 bridges and 124 tunnels in the line, which length account for 91.3% of the whole line. Most of areas that railway runs through are scenic spots with complex geological conditions. The requirement of environmental protection is extremely high. Figure 1 shows the layout of ZhangJiHuai railway project.

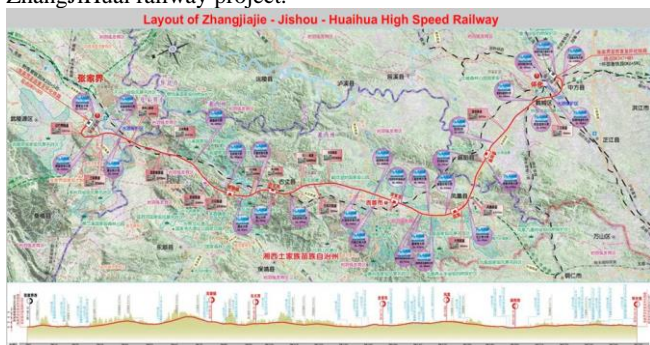


Figure 1. Layout of ZhangJiHuai railway

The 12.16 km long Jishou Tunnel is the longest double-track tunnel on the entire project. It is located in a complex geological environment with many faults and a large amount of water inflow. The tunnel is constructed by drill and blast method. The design excavation area of typical section reaches 120 m². The typical profile is shown in the following Figure 2:

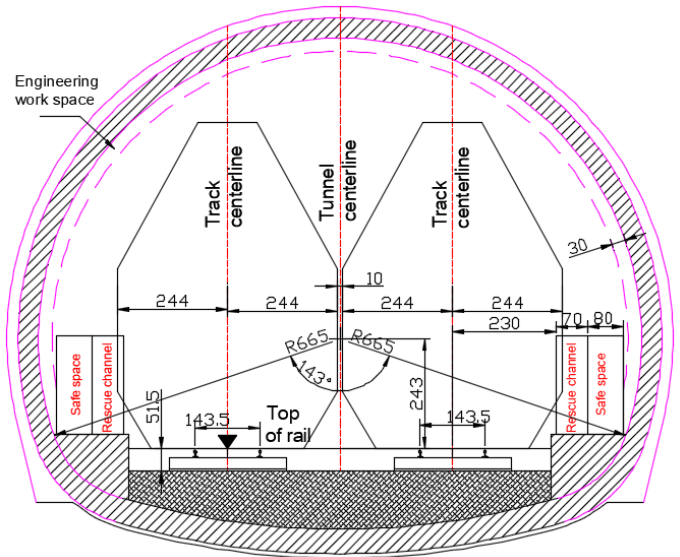


Figure 2. Typical profile

3. REQUIREMENT OF USER

China Railway Tunnel Group is responsible for construction of Jishou Tunnel. Based on their many years of tunnel construction experience, following problems should be solved in the excavation process through use of tunnel scan system:

- 1) Quantity statistics of concrete;
- 2) Inspection of concrete lining thickness;
- 3) Image of tunnel surface;
- 4) 3D tunnel navigation based on scan point cloud.

The analysis of full-coverage over- and underbreak after every blast should be done on site, to help solving the owners requirement of "Zero Underbreak".

4. PRINCIPLE OF TUNNEL SCAN SYSTEM

Laser measurement technology is a kind of precision measurement technologies integrated with optical, mechanical, electronical and other technologies, which are developed with the appearance of

laser technology. Laser scanner consists of laser emission components, laser receiver components, signal processing devices, rotation control and electronic devices. The core task of laser scanner is getting the target distance and corresponding image information (grey scale value or RGB data) by emitting laser signal and receiving the diffuse reflection signal. According to the methods of measurement, the laser ranging is usually divided into time of flight method and phase-shift method. For time of flight method, the distance is calculated by measuring the time difference from the laser emission to return; For phase-shift method, the distance information is calculated by measuring the phase difference between modulated light that emitted by emitter and received light that reflected by object. Compared with the time of flight laser ranging method, phase-shift laser ranging method has advantage of high speed and high accuracy, but measurement range is short.

The work principle of 3D phase-shift scanner: Laser emitter emits a modulated laser beam outwardly through the high-speed rotated lens emitting, forms an annular laser beam. The laser will produce diffuse reflection when the laser beam encounters a target object, some of light will be received by the optical system of the scanner. The distance between scanner central point and reflected target will be determined by calculating the phase-shift between transmit and receive signals. Horizontal and vertical azimuth of every reflection point can be obtained by horizontal and vertical decoder (Encoder), thereby to obtain the coordinate values of X, Y and Z. Thanks to high-speed and high accuracy (millimeter accuracy), 3D Phase laser scanner is especially suitable for the measurements of tube axis structures, such as tunnels and other underground caverns.

5. DESIGN DATA OF TUNNEL

Tunnel scan system is a comprehensive tunnel measurement system based on real 3D coordinates, and design data plays a key role in the whole system. All calculation and analysis are closely related to the design data of tunnel projects, such as horizontal alignment, vertical alignment, theoretical profile and theoretical section definition. System provides a professional and user friendly interface for design data input, the user can also import other file formats such as .dxf, .txt and .xml. Normally, the preparation of design data is done at the office before entering the tunnel for the survey job, which makes data share possible at different jobsites.

6. ACQUISITION OF RAW DATA

The scan speed of laser scanner applied in tunnel is 1'000'000 points per second, depends on different requirements, several levels of scan resolutions are available. Scan survey will be done as soon as possible to minimize impact on tunnel face work. As Figure 3 shows, the documentation of the excavated tunnel is measured by a static method. The hardware for data acquisition consists of three parts: (1) Laser scanner and ruggedized computer system, computer is used to control scanner operation and storage of coordinates of X,Y and Z and reflection point, which is related to the scanner itself; (2) Sphere prism which is located within the scan range, and is used for an accurate positioning between the scan data acquired in different setups; (3) Total station which is used to determine the absolute position of scanner in every station and prism.

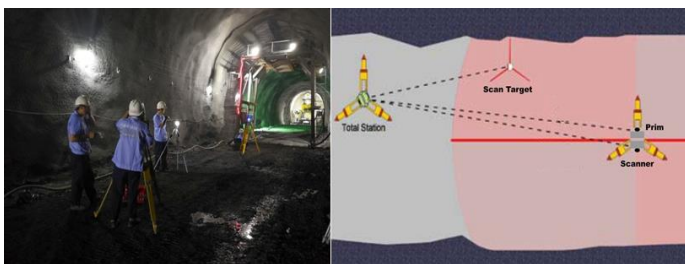


Figure 3. Scan Survey and setup on site

7. DATA ANALYSIS

Based on raw point cloud obtained by scanner, following analysis were completed according to requirements of user:

7.1 Over-/Underbreak Analysis

The coincidence between excavation profile and design profile has great influence on construction quality and cost control, which already has been realized by owner and contractor. Scan survey data processing should be completed quickly after the blasting procedure according to the "Zero Underbreak" requirement of ZhangJiHuai Railway's owner. The analysis results of over-/underbreak, unqualified area will be pointed out automatically by total station on site, which is a big help to tunnel crew treat with unqualified area immediately. Different from the traditional way, the hardware and software performance of tunnel scan system reaches a new level.

Scan parameters of tunnel over/underbreak measurement:

- ✓ Scan resolution: 6 mm/at 10m distance
- ✓ Analysis resolution: 50 mm
- ✓ Range of measurement: 30 m/station
- ✓ Measurement performance: 5 min/station
- ✓ Processing time on site: 15 min

As shown in Figure 4 left, the over-/underbreak of tunnel excavation is presented in the form of heatmap from scanning measurement original pointcloud. It shows the excavation work (grey and blue area) has just been completed within 10 meters from tunnel face, and the initial lining work (pink to purple area) follows up after 10 meters from tunnel face. The red area is underbreak area (50 - 100mm) depends on color level defined by user. On the right side of Figure 4, detailed analysis of tunnel profile is presented which is corresponding with the yellow line in the heatmap of Figure 4 left. There is a underbreak area obviously visible in bottom of right foot area of tunnel with a max. value of about 217mm.

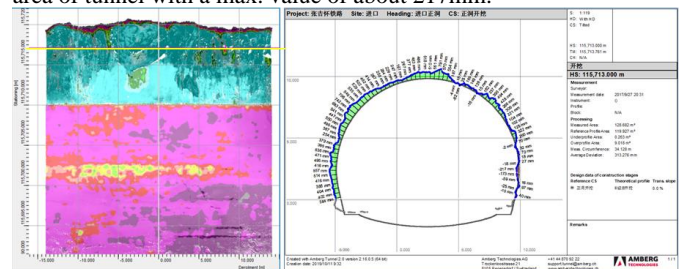


Figure 4. Heat map & Profile analysis graph output of scan system

7.2 Prediction Analysis of Initial Shotcrete Quantity

The profit margin of the construction industry is low now. For the contractor of long and large tunnels, the excessive consumption of concrete will directly affect the project income. Therefore, it is necessary to control effectively the amount of concrete used in tunnels. The application of tunnel scan system can not only accurately predict the amount of concrete to be used, but also accurately know the real amount of concrete lining. Managers can improve management measures by comparing actual consumption on site with prediction.

The system software calculates and analyses the amount of shotcrete needed for the initial rock support based on the point cloud after tunnel excavation and the design profile in stage of initial tunnel lining. Table 1 shows the volume statistics of a 10 m tunnel section with data listed in the red box as the theoretical amount of shotcrete lining to be consumed with 200 mm stationing interval. The processing resolution of point cloud selected is 50 mm instead of original point cloud resolution of 6 mm to balance the prediction accuracy of shotcrete quantity and scan data processing time.

Range		Description	HS diff [m]	Volume		
Start heading stationing [m]	End heading stationing [m]			Reference [m³]	Overprofile [m³]	Underprofile [m³]
115,710,000	115,710,200		0.200	22.603	3.016	0.000
115,710,200	115,710,400		0.200	22.603	3.016	0.000
115,710,400	115,710,600		0.200	22.603	3.095	0.000
115,710,600	115,710,800		0.200	22.603	3.173	0.000
115,710,800	115,711,000		0.200	22.603	3.173	0.000
115,711,000	115,711,200		0.200	22.603	3.173	0.000
115,711,200	115,711,400		0.200	22.603	3.173	0.000
115,711,400	115,711,600		0.200	22.603	3.127	0.000
115,711,600	115,711,800		0.200	22.603	3.081	0.000
115,711,800	115,712,000		0.200	22.603	3.081	0.000
115,719,000	115,719,200		0.200	22.603	1.850	0.169
115,719,200	115,719,400		0.200	22.603	1.850	0.169
115,719,400	115,719,600		0.200	22.603	0.932	4.995
115,719,600	115,719,800		0.200	22.603	0.014	9.024
115,719,800	115,720,000		0.200	22.603	0.014	9.024
Result			10.000	1,130.131	143.642	23.388

Table 1. Volume prediction of initial shotcrete support

7.3 Thickness Analysis of Tunnel Concrete Lining

Tunnel concrete lining is the most important part of tunnel structure in terms of tunnel operational safety and durability. In case of quality problems in the tunnel concrete lining, a series of damage will occur after tunnel operation, such as crack and water leakage, which would directly affect the long-term stability of tunnel operation and normal use of tunnel functions. To ensure the compliance of the tunnel lining dimensions with the tunnel design and to save construction and maintenance costs, it is imperative to measure and compare the thickness of initial and inner lining with high density and efficiency during the construction stages. Tunnel scan system provides a very effective solution for tunnel lining thickness analysis by comparing the scanning results at different stages of tunnel construction. System software processes first special relationship of 2 stages of point clouds which are registered in the same absolute coordinate system and then calculate thickness of concrete lining. As shown in Figure 5, lining thickness can be easily understood from the heat map outputted by system software.

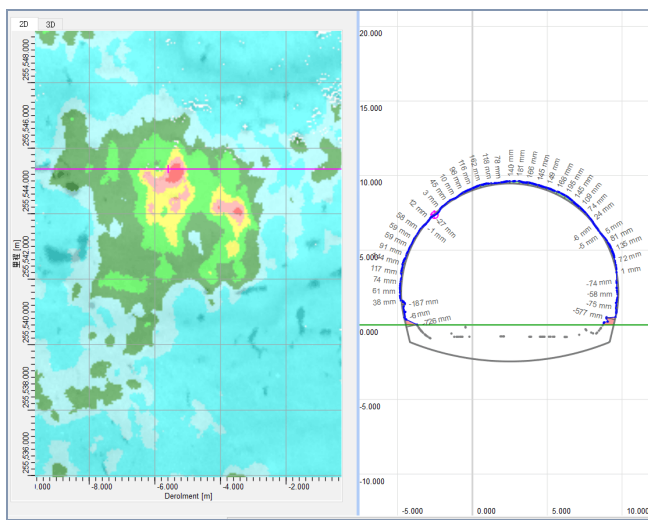


Figure 5 Profile analysis got in different time

Table 2 shows the comparison between the calculated and actual usage of concrete from ZhangJiHuai railway project, an average deviation is less than 1%.

No.	Start Stationing	End Stationing	Length	Act. usage (m³)	Cal. Volume (m³)	Deviation (m³)
1	DK330+342.50	DK330+330.60	11.90	198	197	1
2	DK330+294.90	DK330+283.00	11.90	172	170	2
3	DK330+283.00	DK330+271.10	11.90	170	167	3
4	DK330+271.10	DK330+259.20	11.90	160	159	1
5	DK330+259.20	DK330+247.30	11.90	173	171	2
6	DK330+247.30	DK330+235.40	11.90	176	173	3
7	DK330+223.50	DK330+215.50	8.00	112	110	2
8	DK330+207.50	DK330+198.50	9.00	117	116	1
9	DK330+153.10	DK330+141.20	11.90	183	181	2
10	DK330+141.20	DK330+129.30	11.90	173	172	1
11	DK330+129.30	DK330+117.40	11.90	175	172	3
12	DK330+117.40	DK330+105.50	11.90	181	179	2
13	DK330+081.70	DK330+069.80	11.90	177	175	2

Table 2. Calculated vs. Actual usage of concrete

7.4 Tunnel Surface Image

Retaining the image of excavation tunnel can not only provide evidence for future disputes, but also provide reference for geological mapping. By using processed reflectivity of each measured point cloud, tunnel scan system generates high resolution grey scale image of tunnel surface. The image is an orthophoto projection map from central line of the tunnel crown. As shown in Figure 6 left, half holes of perimeter blast-holes of tunnel wall are clearly visible from the scanned image, and Figure 6 right shows exemplarily tunnel face geology record based on scan image.

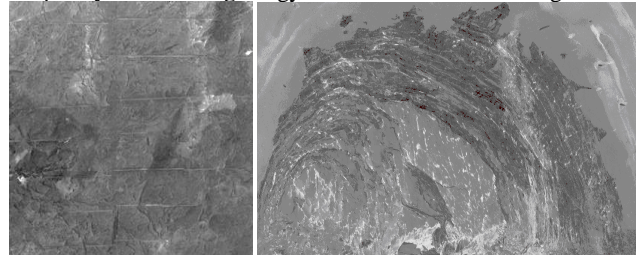


Figure 6. Scan image of tunnel wall & face after excavation

7.5 Undulation Analysis of Tunnel Surface

The durability of tunnel, especially for long tunnel is very high. Strict control and inspection in construction process requires fulfillment of technical specification at every construction stage. Before starting the construction of the inner lining, it is necessary to implement undulation analysis to check the shotcrete surface smoothness and its fulfillment of technical demand of the contract. It is impossible to complete the undulation inspection in limited time by conventional methods. The undulation analysis results may have big error due to less sample data if only a few profiles are measured. With the help of professional software and algorithm, tunnel scan system provides high density and high accuracy scan point cloud, and projection map of tunnel surface to check the tunnel lining surface smoothness. The undulation information will be presented in the form of projection map of tunnel surface by different color levels in another layer. By this way, the undulation of tunnel is expressed really fast, precisely and intuitively. The undulation inspection of algorithm used in tunnel scan system is bar method which is illustrated in Figure 7. The undulation index P is calculated as the depth to wavelength ratio measured with an assumed 1.50 meter virtual straight bar at any random location in any orientation with the formula defined as below:

$$\text{If } (L^* < L_{\min}), P = D/L_{\min} \quad (1)$$

$$\text{If } (L^* > L_{\min}), P = D/L^* \quad (2)$$

- With L: length of bar
- L*: Distance between two points
- A: Percentage defined by user (such as 50%)
- D: Distance to any point
- L_{min}: = A% × L
- P: Undulation index

According to Specification for Acceptance of Tunnel Works in Highspeed Railway (TB10753-2018 J1149-2018), the undulation index as shotcrete surface smoothness criteria shall not exceed 1/20. In Figure 8, the undulation index of more than 0.1 is marked in yellow and orange area.

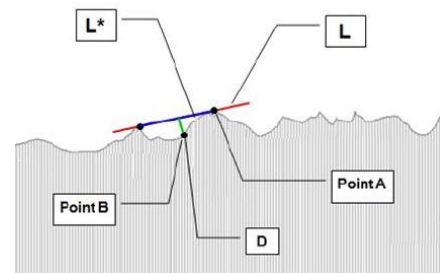


Figure 7. Principle of tunnel undulation calculation

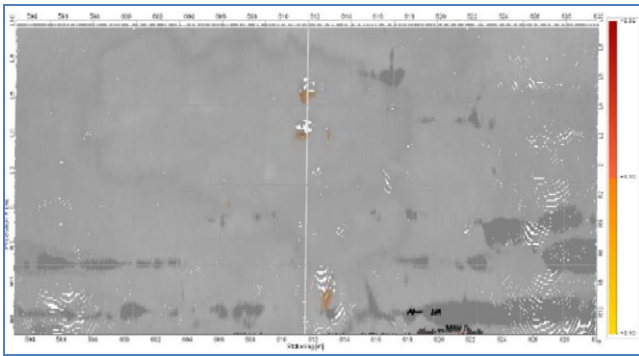


Figure 8. Result of undualtion calculation

7.6 Tunnel Point Cloud Navigation

In addition to providing analysis software for high-performance computers in the office, tunnel scan system also develops "Navigator" software based on tablet computer to process data quickly for field surveyor.

Surveyor can use "Navigator" software on the tablet to complete measurement, processing and analysis work on site after input design data and set the measurement task in the office. As well, "Navigator" support 3D tunnel scan results. Figure 9 shows the tunnel after the stage of initial shotcrete lining. 3D tunnel scan results can be staked out with a total station with clicking on the corresponding critical area in the 3D view.

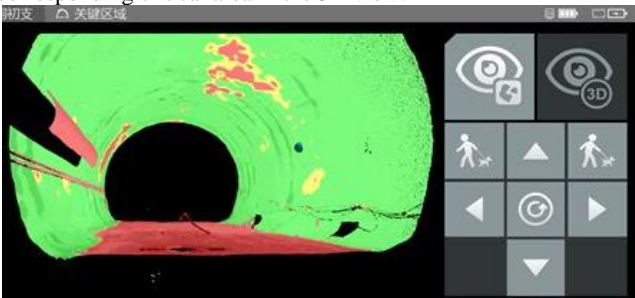


Figure 9. Tunnel critical area by "Navigator" software

8. EXTENSION APPLICATION FROM USER SIDE

With the increase of system application, users have accumulated a lot of experience and skills, as well as more data. Contractor and owner did not stay at the level of only use, but also developed some extended applications based on their own perspective and other management needs to achieve the maximum use of tunnel scan data.

8.1 Mobile APP

The contractor has developed "Tunnel Profile Information Management Platform" mobile app based on outputted profile data from Tunnel scan system. The user can see the profile graph, position of unqualified spot and detail information from intelligent mobile screen. This information can be pushed to relative person, such as project manager, person in charge of quality supervision and foreman on site etc..

8.2 Tunnel Profile Information Management Platform

In order to control quality of tunnel, the owner of ZhangJiHui railway project has put forward the requirement of "Zero Underbreak" as management target, which is impossible to fulfill with traditional measurement methods and management efficiency. A software "Tunnel Profile Information Management Platform" has been developed based on the output of tunnel scan system to facilitate management. Considering the bottleneck problem of large amount of data, difficulty of network upload, the data source of the platform is only profile points file with text format to be uploaded by contractors themselves.

The file has strict technical requirement, each profile has 400-600 measured points with stationing interval of 200mm. The platform uses technologies such as cloud computing and cloud database to

calculate the uploaded data in real time. According to the user's query requirements, display the information of over-/underbreak file, excavation volume and other information would be displayed. Relevant user knows the situation of tunnel excavation, which provides necessary technical means to realize management requirements.

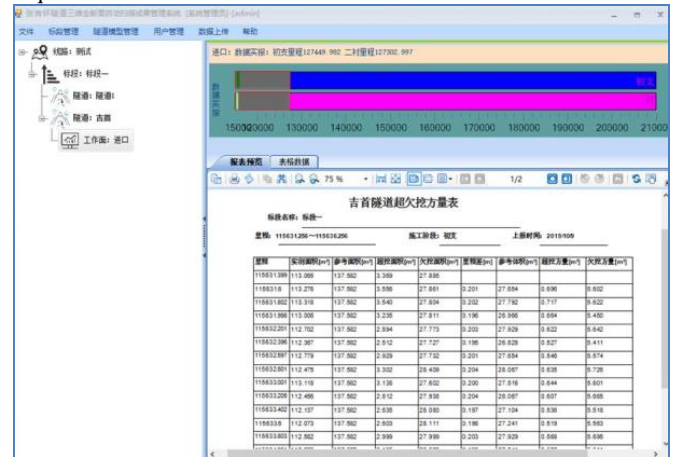


Figure 10. Platform of profile information management

9. CONCLUSION

It is a step forward in the field of underground engineering measurement technology that Tunnel Scan Technology is applied in underground projects. The precise equipment integrates with optical, mechanical, electrical technique replace the tedious manual method. The advantage of system hardware including: quick, high accurate and high density, providing reliable original measurement data for tunnel project; professional data process software provides various results including data report, grey scale map of tunnel surface and CAD models.

At present, China's tunnel construction is transforming from "vulgar" management to "fine" management. Tunnel engineering companies are increasingly motivated to apply advanced tunnel construction and management techniques to save cost and to be more competitive. It is expected that tunnel scanning technology will be widely applied in tunnel and underground engineering in near future in the Chinese tunneling industry.

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