KSCE Journal of Civil Engineering (2020) 24(4):1318-1329
DOI 10.1007/s12205-020-1833-0

pISSN 1226-7988, eISSN 1976-3808
www.springer.com/12205

Surveying and Geo-Spatial Engineering
TECHNICAL NOTE

Development Status of Digital Detection Technology for Unfavorable Geological Structures in Deep Tunnels

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ARTICLE HISTORY

Received 10 October 2019
Revised 21 December 2019
Accepted 12 January 2020
Published Online 11 March 2020

KEYWORDS

Long tunnel
Unfavorable geological structures
Digital detection technology
Exposed structure
Implicit structure

ABSTRACT

The geological conditions of long tunnels are complex and changeable. Potential structural planes or unfavorable geological structures are random and unpredictable. Sudden geological disasters can easily cause delays in construction periods, economic losses, and even serious casualties. Tunnel monitoring measurement and advanced geological forecast research have always been two major guarantees for safe tunnel construction. However, the current research lacks a clear explanation of the classification of rock mass structural surfaces and the hazard-causing mechanism. Many recent instabilities of surrounding rock structures and The block loss accident has made it a hot issue for research. First, combining the past work of the team, the structural surfaces in the rock mass are mainly divided into two types: exposed and hidden structural surfaces, and different detection methods are summarized for their different occurrence states. Among them, digital compass contact measurement, near Range photogrammetry and laser scanning have become the three major means to support the development of the geological survey of the tunnel structural surface. Secondly, it systematically summarizes the comprehensive detection methods of bad geological structures in the rock mass structure, and introduces the specific application of geophysical technology in tunnel engineering. Finally, the development trends of the above two rock mass structure detection technologies are discussed. Based on the two parts of rock mass structural surface and unfavorable geological structure, it systematically expounds the development status of the existing typical disaster-causing structure detection technology, which can provide important references for researchers in this field, especially field engineers.

1. Introduction

China has a vast territory, but its per capita resources are relatively scarce, moreover, the economic development of various regions is very uneven. To the needs of national growth and integrate domestic superior resources, China has always regarded transportation infrastructure as the strategic focus of national economic development since the reform and opening. During the "11th Five-Year" and "12th Five-Year" period, under the major strategic support of the "West-East Gas Transmission", "South-to-North Water Transfer" and "One Belt, One Road", the transportation and hydropower projects in China, especially tunnel construction, have achieved long-term development. By the end of 2018, China had been operating 15,117 railway tunnels with a total length of 16,331 km, and there had been 3,477 railway tunnels under construction, with a total length of 7,465 km. Besides, there had been 6,327 railway tunnels under planning, with a total length of 15,634 km (Zhao and Tian, 2018). Xiamen Xiang'an Subsea Tunnel is the first submarine tunnel built in the mainland of China. The immersed tunnel is also used in some sections of the Hong Kong-Zhuhai-Macao Bridge and is currently open to traffic. In the next few years, China will also put a large number of undersea tunnels under construction planning. Right now, China has already become the country with the largest number of tunnels in the world. Taking the "13th Five-Year" Plan as an opportunity, the transportation and hydropower tunnel construction in China has ushered in a new growth point. There will be more and larger-scale tunnel

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projects, especially transportation, municipal and water conservancy tunnels, in the future. However, tunnel development has also brought more challenges to the construction technologies of tunnels in China.

As we all know, the geological structures along the tunnels often develop abnormally, especially the hidden structural planes or bad geological structures, and they have the characteristics of random and unpredictable development process. At present, tunnel monitoring measurement and advanced geological forecast are two major guarantees for safe construction of tunnels. Monitoring measurement is used to obtain information about the force field and displacement field of surrounding rocks, and advanced geological prediction is used to obtain the geophysical field anomaly information in front of the palm face. The two complement each other as a escort for tunnel construction. However, after participating in the construction monitoring and forecasting work of more than a dozen tunnels, it was found that the type, location and scale of the unfavorable geological bodies in front of the forecast can play a good role in guiding the site construction and can effectively avoid the occurrence of water gush Mud and other major geological disasters. However, many major geological hazards (landslides, instability of surrounding rock structures, dropped blocks, etc.) are sudden and no warning signs. Monitoring and measurement and advanced geological forecast cannot accurately predict such hazards in advance. Larger casualties and economic losses. In recent years, disaster accidents caused by tunnel structure instability have gradually attracted people's attention. From the author's team about the mechanism of the influence of the structure in the tunnel rock mass on the stability of surrounding rock, it is found that the structural surface is the key factor leading to the instability of surrounding rock. The detection of structural planes is of great significance for the effective prevention and control of surrounding rock instability.

Through the study of related literatures, it is found that the current research lacks a clear explanation of the classification and hazard-causing mechanism of rock mass structural planes, and there are few articles that comprehensively and systematically introduce the detection techniques of structural planes. And understanding to promote the continuous development of the prediction technology of rock mass structural surface. This article introduces the current status of structural surface detection technology in detail. At the same time, combined with the author's team's nearly ten years of advanced geological forecasting work, the detection technology of bad geological bodies in tunnel structures A more detailed introduction was also made. It is hoped that a large number of researchers, especially engineers, will pay great attention to the special structure of rock mass structural surface, to avoid tunnel safety accidents caused by such geological factors to the greatest extent, and to ensure the safe construction of tunnels and underground engineering.

2. Typical Disaster-Causing Structure Types

In the formation and existence process of a rock mass, it is subjected to various complex and unbalanced geological and tectonic effects, resulting in various discontinuities and defects of the rock mass, such as joints, fissures, faults, folds, contact zones and shear zones, etc. These structural planes form a complex fracture network, whose impact on the mechanical properties of the rock mass is much greater than that of the rock mass itself on its mechanical properties. The deformation and stability of a rock mass is often determined by the structural characteristics of the rock mass rather than the rock strength. To study the stability of a rock mass, we must not underestimate the impacts of structural planes, which has been a common understanding in both the academic and the engineering fields.

In the 1950s, an Austrian school represented by L. Muller proposed that structural planes play a controlling role in the mechanical properties of rock masses and the engineering stability, thus opening up the age of rock mechanics centered on the study of structural planes and rock mass structures. In 1978, the International Society for Rock Mechanics (1978) proposed the “Recommended Method for Quantitative Description of Structural Planes in Rock Masses”, which gave 10 descriptive indicators such as occurrence of structural plane and spacing. In the 1980s, Gu (1979) and Sun (1980) further proposed the “rock mass structure control theory”, which believes that the rock mass structure restricts the physical and mechanical properties and also the deformation and failure mechanism of the rock mass and controls the stability of the rock mass. To study the laws governing the deformations and failures of rock masses, fractal geometry has been widely used in geotechnical mechanics. Xie (1992) was the most representative one who studied rock fissures and joint distribution. They mainly used two-dimensional fractal indicators to express the features and geometries of materials. Accurate and comprehensive acquisition of the geometric parameters of structural planes is the basis of the fractal study on rock mass structures, and is also another major application branch of structural plane geometry.

2.1 The Investigation Methods for Rock Mass Structural Planes Exposed in Tunnels

The structural plane features of the rock masses exposed after tunnel excavation have important reference values for predicting the unconstructed rock mass structural planes, at the same time it is the most visual (Yang et al., 2014). The orientations of structures I and II in the rock masses are clear, but it is difficult to identify and extract Level III structural planes. The distribution, to a certain extent, constitutes the geometric and mechanical boundaries of the rock mass instability; therefore it is the main object of the investigation on rock mass structural planes. Guan (2003) extracted the main control structural planes of the main structures I and II by image processing to predict the extension direction of the main control structural planes in front of the tunnel face. Besides, there are many related researches for the Level III structural planes at home and abroad (Xie et al., 2006; Lemy and Hadjigeorgiou, 2003; Leu and Chang, 2005; Song et al., 2019).

The advancement of the information acquisition technology for rock mass structural planes relies on the rapid development of geological technologies and other related technologies. Many of its achievements have been made based on the application and intersection of different technologies in this field. The current information acquisition technologies for structural planes are expanded as follows:

The acquisition of structural plane information by the drilling technology or in-hole photographic technology is mainly to obtain a complete core by using the in-situ core-taking technology, and then calculate the spatial distribution information of the structural plane by referring to the hole inclination data. However, this method is expensive and requires high hole forming process quality. In addition, the structural plane information obtained by this technology is not representative enough, and it is difficult to obtain the scale information. However, under the condition where it is impossible to directly collect large-scale structural plane information, this technology is still the main method. At present, it is convenient to manually collect the structural information of the core, especially in the automatic extraction of structural plane information, where there are already fully automated core scanning instruments at home and abroad. The German company DMT has launched core scanners long before. In 2006, China launched the YXCJ-VI core scanners, but they are only able to obtain the mineral elements of the rocks instead of the information on structural planes (Zheng, 2010). Based on the existing digital panoramic drilling camera technology, the method proposed by Wang et al. (2015) is to reduce the error by improving the survey speed, which can obtain the high-resolution appearances and gap widths of the structural planes from the photographic images.

Contact measurement method is also called the compass measurement method. In the field survey of structural surface, the contact measurement based on geological compasses has been used for hundreds of years. It is still the mainstream method for the collection of rock surface structural occurrences. However, the mechanical pointer measurement has significant disadvantages such as large error and inconvenient operation. Because the information is recorded manually, it is still inefficient to extract various parameters from the rock mass information at a later stage. At the same time, it is severely affected by the weather. With the improvement of science and technology, the development of digital geological compass has become an emerging subject.

With the development of the laser and electronic technologies, laser measurement has evolved from static point measurement to dynamic tracking measurement and three-dimensional (3D)_ measurement. CYRA company in American and MENSI company in French are two laser technology companies. They are the first to apply laser technology to 3D detection. Among them, CYRA company can achieve accurate measurement of medium and long distance targets with a measurement accuracy of 6 mm to 4 cm; MENSI company focuses on high-precision 3D measurement at short distances. The measurement accuracy can reach 0.25 mm. Means of measurement. The traditional 3D data acquisition methods mainly include: single-point acquisition of 3D coordinates, such as GPS high-precision positioning, 3D coordinate measuring machine and total station system; close-range photogrammetry and aerial photogrammetry based on the optical photogrammetry principle. The single-point acquisition of 3D coordinates is inefficient. It takes a long time to analyze a complex site, and it is impossible to detail the structural planes and entity descriptions. The method of making inferences from data and images using software by the principle of optical photography to obtain physical 3D data models is also complicated and instable and produces large errors. Due to the restriction of data acquisition hardware equipment and the complex posterior data processing. The 3D laser scanning technology is, however, quite different from the traditional technical means. It breaks through the traditional single-point measurement methods and can quickly acquire massive 3D coordinate data of the surfaces of objects. These 3D coordinate data are also called “point cloud”. However, the complexity of the surfaces of the ground objects determines the difficult original data acquisition for 3D spatial data modeling. Studies have found that when 3D laser scanning is adopted, there are many loopholes in the point cloud data collected from complex parts.

The 3D-laser-measurement technology has been developed with higher measurement accuracy and longer working distance at present, which can be applied in more fields in the future. Konica Minolta's Vivid910 3D laser scanner has a maximum precision of 0.008 mm; the Canadian company Optech's ILRIS 3DER scanner can scan up to 1,500 m. The 3D laser measurement has also been applied to the field of aeronautical measurement, i.e., Lidar. The 3D laser scanning device can perform accurate 3D data measurement on ground targets at low altitudes with an accuracy of 5 cm. Due to its low cost and flexibility, it has extended the aerial survey technology to a wider range. The 3D laser scanning technology also has a very wide application prospect in military, water conservancy, electric power, transportation, flood control, landslide monitoring, forestry and other fields. However, the ground laser scanning technology is still in the development stage, it has not been applied in the field of geotechnical engineering investigation until at present. In 2001, Feng and Röshoff (2015) proposed the theory of measuring the exposed surfaces of rock masses by using the 3D laser scanning technology. The method, which was applied to structural plane roughness and trace measurement of rock masses in 2003, pioneered the application of this technology in practical engineering.

In China, some explorations have been carried out in the application of the 3D laser scanning technology to measure the exposed surfaces of rock masses. Luo et al. (2017) introduced the 3D laser scanner and its geological survey work on high and steep rock slopes. He et al. (2007) conducted a more in-depth study on the measurement of structural planes by using the 3D laser scanning technology, and realized the measurement of structural planes by triangulation of point cloud data. However, due to the large amount of point cloud data, it takes a long time to perform the triangulation and statistical calculation. So, there is still room for improvement if it is to be applied in actual engineering.

Most of the researches on the application of the photogrammetry technology to obtain structural plane information are in the preliminary experimental stage. A prominent problem is that the interpretation accuracy of the structural plane is not high. There are many systems for measuring the information of rock mass structural planes. In China, Academician Zhang Zuxun presided over the development of the VirtuoZO digital photogrammetry workstation in the 1990s (Zhang, 2000). Since then, researchers have done a lot of applied research based on the VirtuoZO system. Based on the reinforcement project of Guangzhou Poly Linyu Mountain Slope, the digital photogrammetric workstation, VirtuoZo, is used to quickly acquire the geometric information of rock mass structure surface (Wang et al., 2008). On the basis of the ShapeMetrix3D system, Wang et al. (2011) proposed a method for cutting rock mass structural planes based on virtual grid, and constructed the GeoSMA-3D system and applied the close-range photogrammetry in the key block analysis. GPS-RTK technology is a real-time differential GPS measurement technology that combines the data transmission technology and the GPS measurement technology based on carrier phase observation. It has such advantages as high positioning accuracy, strong comprehensive mapping ability and easy operation. Now this technology has been widely used in geological exploration and mapping at home and abroad.

After the structural plane trace coordinates are obtained by the GPS-RTK technology, it is still remains a challenging task as how to obtain the regionalized parameter information of structural planes. Wang et al. (2013) used the arcgis platform to store and analyze the fracture measurement data, and used the geostatistical method considering the spatial variability theory to predict the fracture surface density, which constituted certain progress in the extraction of fracture density. However, how to efficiently manage and make full use of the coordinate information of structural planes obtained by the GPS-RTK technology still remains to be studied, which is also one of the researches focuses in this paper.

2.2 The Detection Method for Rock Mass Structures inside Tunnels

The contact method and the close-range 3D laser scanning measures the appearances of structural planes based on the exposed rock mass traces. However, rock masses may not be fully exposed in actual engineering, so it will be difficult to ascertain the structural plane information in this case. To explore the information on drilling structures inside the rock masses, the conventional methods include drilling core method, borehole TV imaging and drilling ultrasonic and optical imaging.

In the 1950s, the wellbore camera technology was first developed based on optical principles. Its biggest advantage is that it can directly observe the internal conditions of the wellbore, which provides ideas for solving related problems. However, the borehole camera technology has remained in the borehole television mode, which is mainly observation in the analog mode, and the development of the camera angle of view has gone through several stages from tens to 360 degrees (Beyer and Jocebs, 1986; Yu et al., 1989; Yu et al., 1990). In the mid-to-late 1990s, the digital panoramic borehole camera system was successfully developed, that is, the panoramic technology in digital mode, which rid itself of the traditional measurement method based on observation. This system not only has Panoramic observation capabilities, as well as measurement, calculation, and analysis capabilities (Wang et al., 2002). It is represented by the panoramic digital borehole camera developed by Wuhan Institute of Geotechnical Engineering, Chinese Academy of Sciences. Now there are two representative digital optical imaging systems in the world, the first of which is the digital optical television (OPTV and OBI–40), and the second is the digital panoramic drilling camera system, whose detection range has developed from vertical, horizontal and tilt detection to the current full-azimuth detection. In the early 1970s, borehole television images were first used to study the characteristics of fissures, and analyze the development of the joints exposed by boreholes and their distributions with depth. Later, based on the borehole camera technology, fracture occurrence, fracture width, and fracture filling characteristics (Wang et al., 2017) of the pore wall structure were studied in depth so that more accurately evaluation of rock mass integrity can be gained, which is of great value for the geological characteristics and the engineering conditions of the research area. Fig. 1 shows the borehole images obtained by the author using the panoramic digital borehole camera system. The borehole camera has a certain effect in the structural plane exploration. Based on the structural plane parameters obtained by the advanced drilling imaging of the tunnel face, Sun et al. (2019) proposed a multi-structure plane geometric recognition method based on angle, and the spatial distribution of large structural planes in the unexcavated rock mass is identified by effective auxiliary technology.

Drilling ultrasonic imaging is an in-situ imaging method that

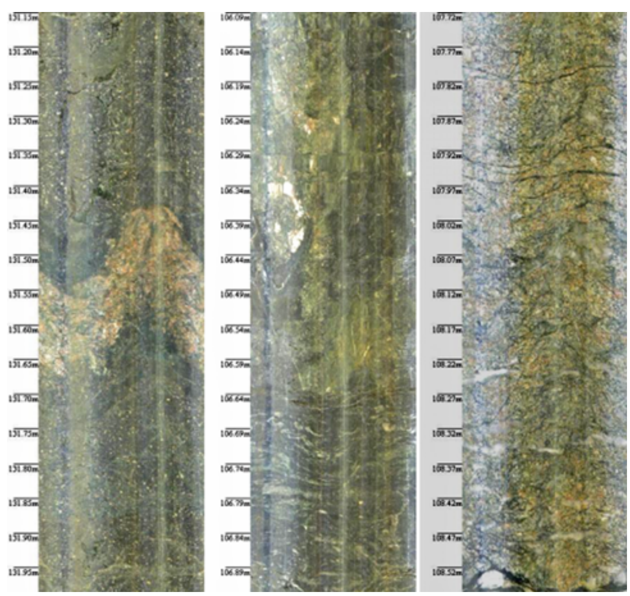

Fig. 1. Borehole Image

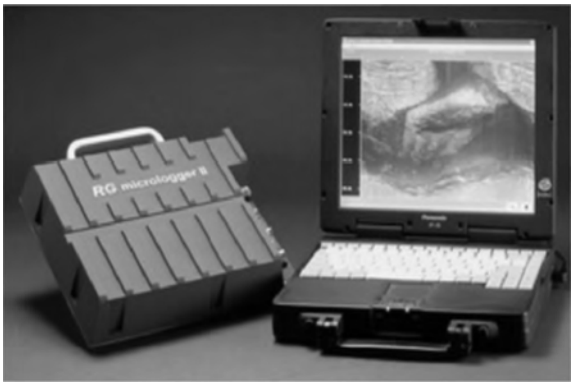

Fig. 2. High Resolution Acoustic Televiewer

has the advantages of intuitiveness, high precision, and high definition, and has been widely accepted by the engineering community. It should be emphasized that the color of the travel time and amplitude image of the ultrasound imaging is different from the visual color of the actual rock sample under natural light. It reflects the smoothness of the well wall as determined by the hardness of the rock. A 360° rotation scan by the probe forms a rock mass image of the bore wall, and as the probe goes deeper, a complete image of the rock wall is formed. A representative ultrasonic imaging device is the high resolution acoustic televiewer of the borehole acoustic imaging system of Robertson Geologging, UK, as shown in Fig. 2. Due to its sonic orientation and wave velocity focusing, it is especially suitable for the classification of rock weathering degree, Structural surface, spacing and RQD (Kong, 2005; Shi et al., 2010). A high-resolution synthetic aperture SAFT imaging technique was proposed to comprehensively process a large number of cross-section scanning echo signals to enhance the reflected signal and suppress the interference signal, so that the echoes of the corresponding rock wall feature regions are more prominent (Wang et al., 2019). Based on the sound amplitude and sound time parameters of the scanned cross-section echo signal.

3. Development of the Detection Technology for Unfavorable Geological Bodies in Tunnels

3.1 Comprehensive Advanced Geological Prediction Technology

There are many types of disasters in tunnels, such as inrush waters, large deformations and faults. Disasters are always accompanied by disaster sources, which are the various types of unfavorable geological bodies that exist in tunnels. Geological exploration is the fundamental work and plays a leading role in tunnel design, but it is regional macroscopic, in other words, it can clearly distinguish regional lithologies and structures by geological knowledge and experience. However, for small regional rock masses (such as the front faces), it is only possible to speculate on the unfavorable geological bodies from the exposed rock masses, which is too subjective and also depends on the competency of geological personnel. The comprehensive tunnel prediction methods are mainly divided into two aspects: geological exploration and geophysical exploration. High-risk sections of the tunnels are often drilled with the support of advanced drilling methods. Usually three holes are laid on the tunnel face. Then the drilling speed, drilling pressure and flushing fluid are recorded and analyzed in real time to directly obtain the front rock mass structure information. However, this method has the inevitable “one hole view” problem, and as a result, only the rock mass information around the borehole can be obtained. If you need to fully understand the regional rock mass structure information, a lot of drilling will be required, which is laborious and time-consuming and strongly affects the construction progress. Geophysical exploration is an indirect detection method based on the discontinuity of rock masses. The principle is to solve the problem of the source body based on the measured data or the observed geophysical field. The core is inversion, whose result is uncertain. Therefore, geophysical exploration is multi-dissolving. At present, through the improvement of geological technologies, the optimization of drilling schemes and the improvement of inversion algorithms, the prediction and detection accuracy of unfavorable geological bodies in tunnels are improved to a certain extent, but fundamentally, the results are still ambiguous and uncertain.

Because the karst area has unique hydrological characteristics and geomorphological features, the commonly used tunnel cavity detection techniques include drilling methods and geophysical detection methods. Among them, the geophysical methods mainly include the resistivity method, the transient electromagnetic method, the seismic wave method, the ground penetrating radar method and the land sonar method, etc.

In the tunnel construction process, the drilling method is the most routine and direct geological survey method, especially for the high-risk sections of tunnels. In order to ensure the safety and reliability of the tunnel construction, the drilling method is necessary even if the geophysical survey has been implemented. The drilling method can be used in the detection of underground goaf to determine the thickness and height of the goaf roof at the drilling point, and determine the horizontal range of the goaf in the range of drilling. However, for a cavity in a tunnel, the drilling layout is limited, and it is impossible to confirm visual phenomena such as a surface collapse caused by the goaf. Therefore, the drilling method is quite blind and often the accuracy of the geophysical results is verified by drilling. Moreover, this method is also costly and time-consuming. Its essence is the single-point detection. The connection between holes can only be based on experience and related algorithms.

Geological prediction is usually divided into long-term and short-term predictions. The infrared detection technology is one of the short-term geological prediction methods. This technology is mostly used in coal mines for water exploration and fire detection. In recent years, it has been applied to tunnel geological prospecting. It can detect the hidden water-bearing structure in front of the tunnel without obtaining information such as water volume, water pressure, and water quality. So that it is also impossible to directly forecast the unfavorable geological bodies such as faults and fracture zones (Lv and Chen, 2010).

The principle of the transient electromagnetic method is to use a non-grounded return line or a grounding conductor as a field source to emit a pulsed magnetic field into the geological body, and then use the return line or the dipole to receive a secondary fault formed in the underground half space during the interval. In the flow field, the spatial position and shape of the goaf are determined by observing the change of the secondary flow field. This method is similar to the high-density resistivity method, where the spatial information of the underground goaf is obtained according to the electrical difference between the goaf and the surrounding rock. Compared with other electrical methods, the transient electromagnetic method is the most sensitive detection method for finding low-resistance targets in high-resistance geological bodies. Its main advantages include small detection blind zone, high SNR, obvious abnormal response, large detection depth and higher detection efficiency. In the field of transient electromagnetic theory, the one-dimensional forward and inversion technologies are relatively mature, but it is still necessary to conduct further studies on 2D and 3D forward and inversion, 3D inversion is the only way to improve the interpretation of TEM data. The 3D model forward is the basis of the inversion. Therefore, improving and perfecting the TEM 3D model forward is of significant for theoretical and practical significance to further improve the application level of TEM data interpretation and methods. At present, the transient electromagnetic method (TEM) data is basically based on the inversion interpretation of an isotropic model, which will cause a large inversion interpretation error for exploration areas with significant electrical anisotropy. Liu et al. (2019) solved the discretized full tensor conductivity time domain Helmholtz equation, and realized the TEM arbitrary anisotropy 3D forward algorithm based on the finite volume method, which is in accordance with the actual geological conditions.

The high-density resistivity method is an array-based method of exploration, and the basic principle is still based on the difference in conductivity between the cavity and the surrounding rock. Currently, it is widely used in underground mine projects. (Bernatekjakiel and Kondracka, 2016; Sun et al., 2017). However, this method still has difficulty in accurately detecting the boundaries of unfavorable geological bodies. The accuracy largely depends on the reliability of the inversion algorithm.

The ground penetrating radar method is the most commonly used method for detecting unfavorable geological structures such as caves and faults in tunnels. The principle is to determine the distribution law of rock mass media by transmitting pulsed electromagnetic waves in a certain frequency range. It is widely used in the initial support of tunnels and the detection of voids after the secondary lining. The sub-surface geological prediction, especially in the early stage of tunnel construction, can obtain various characteristic parameters of the disaster sources through comprehensive analysis and processing of radar data and complex signal analysis. Comprehensive evaluation of information of unfavorable geological bodies can greatly improve detection accuracy (Flor et al., 2016; Baek et al., 2017). At present, the ground penetrating radar method still has the following problems when being applied in tunnel cavity detection:

1. Improving the resolution of the ground penetrating radar method requires a larger frequency band, but the signal-to-noise ratio is affected by factors such as complex rock mass characteristics, high signal attenuation and high frequency and increased signal dispersion effects;
2. When the ground penetrating radar uses a low frequency antenna, the accuracy of the acquired data is not sufficient to identify any unfavorable geological body in front face;
3. The interference of external signal sources severely limits the frequency range of the ground penetrating radar method;
4. The original data inversion method largely depends on the skill level of the operator. For more reliable analysis results, a priori information is necessary;
5. The wave velocity is difficult to measure as the formation layers are inhomogenous and the water contents and densities of various media are very different, having certain impacts on the wave velocity.

The problem of radar wave velocity measurement is mainly solved in the following way: collect the drilling data of the previous exploration and ground geological survey to obtain the positions of several known geological bodies below the detection area, and inversely calculate the wave velocity to make the calculated value as close as possible to the real wave velocity distribution.

The basic principle of the elastic wave reflection method is as follows: the seismic wave is artificially excited by the source device, when a seismic wave propagates in a medium and encounters a wave impedance difference at the interface of the medium, reflection, transmission, etc. occur. By judging the kinematics and dynamics of seismic waves, the purpose of distinguishing geological body characteristics is achieved. When the seismic wave propagating in the local plastid encounters the physical interface or wave impedance, emission, refraction and transmission will occur. Seismic wave signals can be received by high-precision seismographs, and geological structures in front of the tunnel face (Xiao and Xie, 2012), such as karst caves, weak rock formations, faults and water-rich conditions, are predicted based on the above data. Representative methods are: tunnel seismic prediction (TSP), tunnel reflection tomography and land sonar, etc. Among them, TSP is a linear observation method, which is better for large-scale discontinuous detection perpendicular to the tunnel axis (Zhao et al., 2006; Alimoradi et al., 2008; Xu et al., 2008). The layout of TSP measuring points is shown in Fig. 3(a). The TRT technology developed by American research institutes and the tunnel seismic tomography technology developed by Chinese research institutes are belong to the three-dimensional space observation mode, and the positioning accuracy of unfavorable geological bodies is higher than that of the two-dimensional observation mode. The layout of TRT

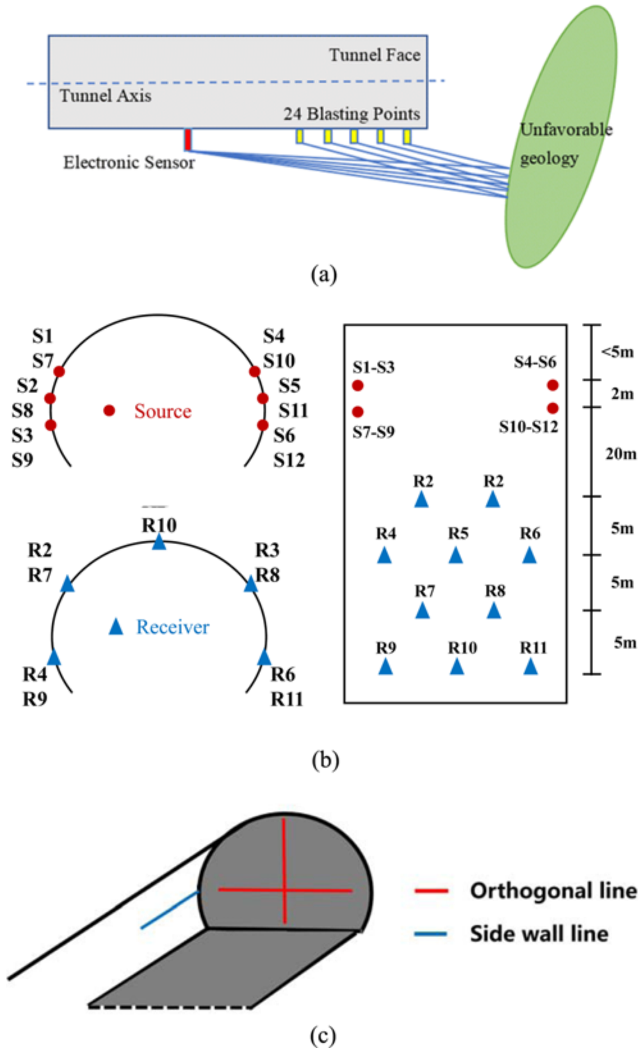

Fig. 3. Layout of Several Elastic Wave Reflection Methods: (a) TSP Measuring Point Layout (Bu et al., 2018), (b) TRT Measuring Point Layout, (c) Land Sonar Method Line Layout

measuring points is shown in Fig. 3(b). The land sonar method invented by Zhong et al. (2012) is a zero-offset elastic wave reflection method. Because of the optimal offset design, it has a good detection effect on small and medium-sized caves and anomalous bodies crossing small axes. The line layout of the land sonar method is shown in Fig. 3(c).

The application of geophysical methods is described below. Since the 1980s, geophysical exploration technology has been introduced into the tunnel's advanced geological forecast, but it was initially carried out as an experiment (Xue, 1993). The advanced geological forecast is still mainly based on the guidance construction and palm surface geological sketch methods. With the continuous improvement of the understanding of geophysical prospecting technology, the geophysical prospecting technology gradually emerged in the field of tunnel construction in China in the 1990s. Advance geological forecast in geoscience research have increased rapidly due to technological developments, lower costs, simpler field procedures and more rapid inversion and interpretation of data. The negative apparent velocity coincidence axis obtained from the vertical seismic profile of the tunnel is used as a reflection wave mark to identify the front interface of the palm face (Zeng, 1994).

Through the practice of tunnel advance geological prediction to detect karst caves and faults, tsp interpretation technology has been developed (Liu and Liu, 2003; Zhu et al., 2003; Deng, 2004). The tsp method has entered a period of rapid development in the field of advanced geological prediction. Li et al. (2006) has introduced a new method for advanced geological prediction of tunnels-the transient electromagnetic method. This method is sensitive to bad geological bodies such as low-resistance water-containing faults, mud-filled water-filled caves, and water-containing mud-containing broken zones. Li et al. (2009) proposed a principle of comprehensive prediction that takes the geological analysis as the target, combining geological analysis and geophysical exploration, considering the condition inside and outside of the tunnel, employing long-term and short-term prediction methods, and adopting mutual geophysical parameters. The system and organization of comprehensive geological prediction in tunnels are established. Mukherjee et al. (2010) analysised the GPR's potential in exploring and identifying shallow water-saturated zones (WSZs) in carbonates and found that it is constrained by the geoelectrical properties of carbonate soils as a function of moisture content. Sun et al. (2012) developed a method for multi-component and multi-array TEM which can be applied in tunneling, especially for identifying the spatial distribution of karst water and karst pipes. Park et al. (2013) examined the spatial distribution and shape of underground cavities using ERT in a karst area in Korea, and the field ERT results show that cavity areas filled with clay or groundwater appeared as low-resistivity anomalies in the limestone formation. Kilic and Eren (2018) introduced fundamental role played by Ground Penetrating Radar (GPR), during the tunnel boring project, and identified the presence of karst conduits and voids from collected GPR data. Geophysical exploration technology escorts tunnel safety construction.

In terms of 3D exploration techniques, with the large-scale construction of tunnel engineering and the advancement of science and technology, after 2010, 3D detection techniques have gradually been promoted and applied in tunnel prediction, including seismic wave reflection method, electromagnetic method and resistivity method. Among them, Zhu et al. (2010) used the three-dimensional elastic wave reflection method for advanced geological prediction in tunnel, and achieved good detection results. Biger and Tronicke (2010) and Jiang et al. (2017) have carried out high-resolution 3D geological radar detection work, proving that attribute-based analysis has great potential for more comprehensive 3D GPR data interpretation. Liu et al. (2012) obtained the exact location of the water-bearing geological structure in front of the palm face through three-dimensional resistivity inversion. Sun (2015) studied the 3D transient electromagnetic response characteristics of the water-containing structure in the tunnel, and proposed an effective method to accurately predict the water-bearing body ahead. In general, due to the certain limitations of the tunnel space, the detection technology of the long survey line arrangement is severely limited, and methods that do not require much detection space and do not affect the construction progress can be well adapted to the special detection environment of the tunnel. In summary, the method of single-point rapid detection is the future development direction of tunnel geological prediction.

No matter which kind of geophysical exploration technology is adopted, its principle is based on the inversion of the measured data. To some extent, ambiguity, multiplicity and uncertainty are inevitable. The inference of the inversion results must be based on the discontinuity of the rock mass, that is, the difference in the properties between the rock and the structural. The use of multiple inversions to reduce multiplicity is the eternal goal of geophysical prospecting and the unremitting pursuit of engineering staff.

3.2 Rock Mass Information Acquisition Technology: Laser Point Cloud Imaging

Borehole laser scanning is to insert a probe with the integrated laser scanning function into the cavity to obtain the 3D surface point cloud data of the inner walls of the cavity. The principle is the same as that of the vertical laser scanning, but its biggest advantage is that the laser probe is miniaturized, which can adapt to a variety of narrow passages and spaces, and even help obtain data of deep rock masses. At present, mature borehole scanning equipments on the market include Noranda produced by the Canadian Technical Research Center and CMS produced by Optech from Canada, and Cavity Auto-scanning Laser System produced by Measurement Devices Ltd from the United Kingdom. The Cavity Auto-scanning Laser System is shown in Fig. 4. A comparison of the parameters between C-ALS and CMS is shown in Table 1. In China, borehole laser scanning related research started quite late. In 2007, the School of Resources and Safety Engineering, Central South University, introduced the first cavity scanning equipment C-ALS in China. Wang et al. (2016) summarized the main methods for detection of goafs. That paper proposed the corresponding treatment and monitoring schemes and studied the safety evaluation method for goaf

Fig. 4. Schematic Diagram of the C-ALS Device

Table 1. Comparison Table of Parameters between C-ALS and CMS (Ma and Peng, 2013)

Parameters	CMS	C-ALS
Horizontal scanning (°)	280	360
Vertical scanning (°)	360	360
Drilling hole diameter (cm)	> 24.7	> 6.5
Probe size	270 mm × 247 mm × 175 mm	5 cm dia
Laser types	FDA 21 CFR 1010	Class 1: FDA IEC
Range resolution (cm)	1	1
Angle precision (°)	0.2	0.2

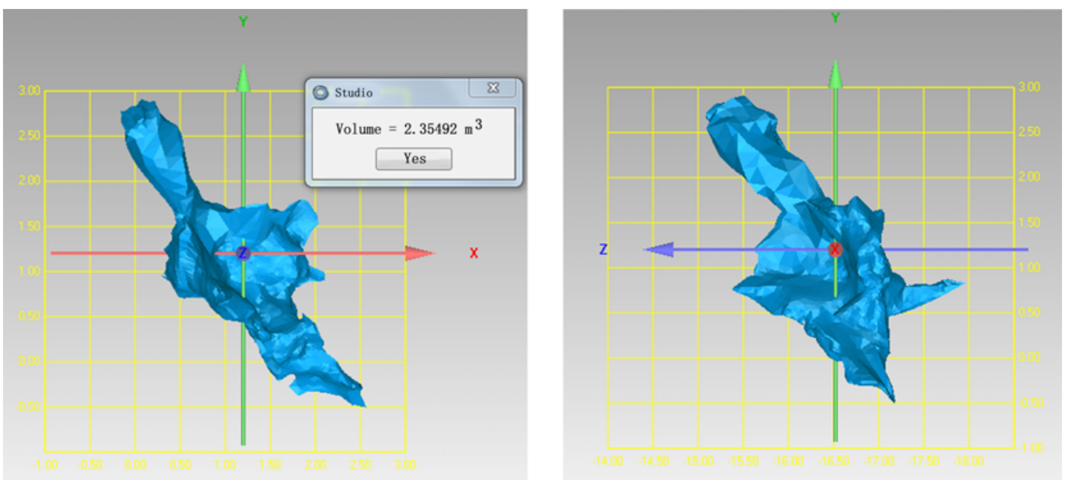

Fig. 5. D Solid Model of Cave: (a) Top View, (b) Side View

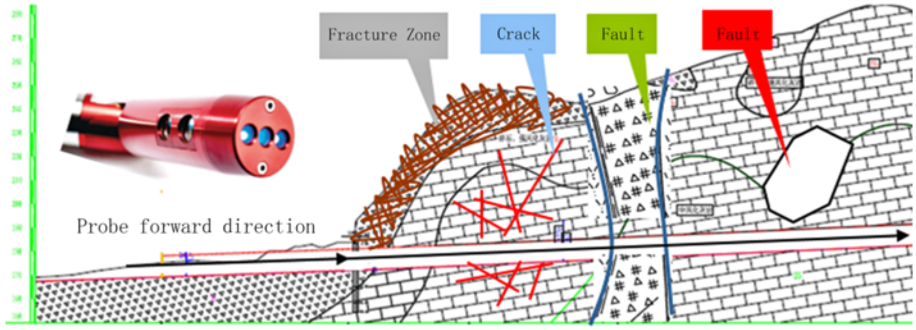

Fig. 6. Schematic Diagram of Rock Mass Internal Structure Information Detection

stability by analyzing examples of metal mines. Liu (2008) and Liu (2012) used C-ALS to obtain the surface point cloud model for complex goaf, and studied the Surpac-FLAC3D coupling technology to carry out numerical analysis of the real goaf stability.

At present, the drilling scanning equipment has been widely used in the detection of coal mine goaf, and is mainly used to detect the key information of the thickness of the overlying rock mass in the goaf, the volume, shape and filling state of the goaf. Fig. 5 shows the imaging results of the detected caves with C-ALS in a tunnel. It can obtain quantitative information such as the size, shape and filling state of a cave. So, it is a particularly effective means of obtaining structural information. In the construction of tunnels, this method should be vigorously promoted.

In summary, the cavity laser scanning device has the following advantages:

1. It can quantitatively obtain the position and filling state of the tunnel cavity to provide key information for fine construction;
2. It can provide point cloud information for establishing a refined geological model, which is helpful for carrying out the analysis of the stability of unfavorable geological bodies.

In the tunnel construction, for the unfavorable geological structures inside rock masses, the unexposed structures can only be detected through geological exploration, advanced drilling and geophysical characterization, and no specific prediction method can be selected in advance. With the rapid expansion of computer, mechanical, image processing, laser measurement and other technologies, more and more technologies are introduced and applied to the detection of unfavorable geological bodies in tunnels, which also provide technical means to detect and display the original appearances of unfavorable geological bodies. The rock mass image contains rich joint information, and the laser scan contains the point cloud data of the rock mass. Combining them together is no longer a problem. The vertical and vehicle-mounted 3D laser scanners of Leica, Z + F, Faro and other brands have already been able to board images and point cloud data. For the exposed rock mass, it is easier to obtain rock mass information by means of imaging and point cloud scanning, but for the unexposed rock mass, the structural information can only be acquired by inserting the probe integrated with CCD camera, laser scanning and other technologies into the rock through the hole. The schematic diagram is shown in Fig. 6. Therefore, in addition to acquire both rock mass images and laser point cloud data, the probe hardware must also be miniaturized.

1. The probe enters the cavity to acquire images, from which we can extract structural features and analyze the structural plane of the rock borehole wall, it is the function of borehole imaging.
2. When the probe is placed in the cavity, a dynamic video of the entering process can be obtained at any time to get the condition of the cavity, and it is necessary to prevent accidents such as pinching and damages of the probe.
3. The probe smoothly enters the detection area, which can be 360° adjusted by the 3D servo machine to realize the acquisition, processing and modeling of the point cloud data in the cavity, and finally realize the quantitative detection of the position, shape and volume of the cavity.
4. In addition to acquiring the point cloud data of the cavity wall, the probe in the cavity is also equipped with a certain light-filling device to acquire the images of the rock wall in the cavity. Finally, the static image and the point cloud data are combined together to establish the pixel-point cloud data model.

4. Discussion and Development Trend

1. In the aspect of structural surface detection, the prior art mostly starts with the surface information of the palm surface and the exposed information of the borehole wall. It uses program algorithms to predict the development of the internal structural surface, but it has some blindness and uncertainty. Moreover, the limited amount of information and large construction costs cannot meet the needs for safe and efficient construction of tunnels. Therefore, the development of fully automated intelligent structural surface recognition robots and high-resolution internal structural surface detection technology is the future development trend.
2. In terms of the existing detection technology of bad geological bodies, multiplicity has always been an inherent problem in geophysical detection methods. A variety of advanced forecasting technologies combine with each other, verify each

other, complement each other, and restrain each other. They can play a role in reducing multiplicity and improving detection reliability. Therefore, many scholars are committed to the research of comprehensive advanced geological forecasting methods. The current comprehensive advanced geological forecast is a simple combination and combination of a variety of different methods. The detection results of each forecast method are artificially compared, analyzed and checked to make comprehensive judgments and interpretations. The information of each type of geophysical exploration is still isolated. The research on the joint inversion of multiple geophysical information is an effective way to suppress the multiple solutions, but the related research is still in its infancy. Therefore, constrained joint inversion has a good application prospect.

3. In terms of the latest technology of bad geological bodies, with the help of vibration with a certain energy generated during blasting or advanced drilling construction, advanced geological forecasting by arranging sensors on the palm face or side wall is an emerging technology that can reduce detection. It takes up construction time, saves labor and economic cost of detection, and has broad application prospects.
4. In terms of three-dimensional laser scanning, the existing technology can obtain the morphological and scale information of bad geological bodies, which we call contour information, and seeing the true internal appearance of geological structures has broader application prospects. True-color imaging technology can Obtaining the most authentic information of rock mass information, combining laser point cloud information with true color imaging technology can achieve multi-dimensional and multi-parameter acquisition of rock mass information, which will greatly promote the progress of 3D laser scanning technology.

5. Conclusions

1. The rock mass structure has a non-negligible effect on the stability of the overall structure of the tunnel. The existing research lacks a clear explanation of the classification of the rock mass structural surface and the hazard-causing mechanism. Many recent instabilities of surrounding rock structure occurred. And block accidents make it a difficult problem for research. Based on the research work of the team, starting from the difference in the existence of the two types of structural planes, it is pointed out that the research focus and trend of structural planes of rock masses should be a “surface-internal” simultaneous detection method.
2. The obvious differences between the poor geological structure of the tunnel and the surrounding rocks can provide a physical basis for accurate detection of geophysical detection technology. Each detection method has its natural advantages and certain shortcomings. The use of multiple inversions to reduce multiplicity is the eternal goal of geophysical prospecting and the unremitting pursuit of engineering staff.
3. The detection methods for structural planes and bad geological bodies have basically become a system. With the advancement of science and technology and the need for interdisciplinary studies, many new methods will continue to emerge, forming a good complement to existing technologies. But the general development trend should be based on the detection technology of automation and intelligence.

Acknowledgements

The authors gratefully acknowledge the financial support from the National Science Fund for Excellent Young Scholars (NO. 51722904), National Natural Science Foundation of China (NO.51679131). The authors are grateful for the reviewers for their valuable comments and suggestions that helped to improve the quality of the paper.

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