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Review

Detecting and monitoring of water inrush in tunnels and coal mines using direct current resistivity method: A review

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A B S T R A C T

Detecting, real-time monitoring and early warning of underground water-bearing structures are critically important issues in prevention and mitigation of water inrush hazards in underground engineering. Direct current (DC) resistivity method is a widely used method for routine detection, advanced detection and real-time monitoring of water-bearing structures, due to its high sensitivity to groundwater. In this study, the DC resistivity method applied to underground engineering is reviewed and discussed, including the observation mode, multiple inversions, and real-time monitoring. It is shown that a priori information constrained inversion is desirable to reduce the non-uniqueness of inversion, with which the accuracy of detection can be significantly improved. The focused resistivity method is prospective for advanced detection; with this method, the flanking interference can be reduced and the detection distance is increased subsequently. The time-lapse resistivity inversion method is suitable for the regions with continuous conductivity changes, and it can be used to monitor water inrush in those regions. Based on above-mentioned features of various methods in terms of benefits and limitations, we propose a three-dimensional (3D) induced polarization method characterized with multi-electrode array, and introduce it into tunnels and mines combining with real-time monitoring with time-lapse inversion and cross-hole resistivity method. At last, the prospective applications of DC resistivity method are discussed as follows: (1) available advanced detection technology and instrument in tunnel excavated by tunnel boring machine (TBM), (2) high-resolution detection method in holes, (3) four-dimensional (4D) monitoring technology for water inrush sources, and (4) estimation of water volume in water-bearing structures.

1. Introduction

A large number of infrastructures including railways, water conservancy and hydropower projects are being constructed in karst areas in Western China. Deep tunnels are also increasingly used for those projects, and the depth of some coal mines reaches up to 1000 m. However, the geological conditions in these areas are quite complex, thus it is very difficult to fully understand the geological setting of the project area during the stage of engineering survey. Meanwhile, adverse geological conditions are sometimes difficult to be investigated, including fault, karst cave, fractured rock mass, etc., which have the potential to induce geological hazards unexpectedly. Water inrush is one of the most serious geological hazards in underground engineering, causing equipment damage, project delay, and even casualties. Therefore, construction safety of underground engineering is a challenging issue in association with geological hazards (Li et al., 2007, 2008, 2014; Qian, 2012).

To the authors' knowledge, the main sources of water and mud inrush in underground construction are the adverse geological bodies filled with groundwater, which include faults, karst caves, coal mine collapse column and goaf. In order to effectively control or avoid water inrush, the adverse geological body should be precisely determined prior to construction and its evolution process must be real-time monitored for the early warning purpose. The existence and migration of groundwater are the main factors controlling the conductivity of subsurface media (except conductive rocks). For the direct current (DC) resistivity method is sensitive to groundwater, it is widely used in underground engineering, such as mines and tunnels, with advantage of easy interpretation. The DC resistivity method is basically used in the following three aspects: (1) routine detection of water-bearing structures in different

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locations; (2) advanced detection of water-bearing structures ahead of working face; and (3) real-time monitoring of evolution process of water inrush in order to obtain groundwater migration information for early warning purpose (see Fig. 1).

However, the geo-environments of underground engineering are more complex than those of ground surface. Underground engineering is a whole space environment but characterized with a narrow observation space. In this circumstance, it is rather difficult to lay out the survey lines as schemed due to the interference of a large number of metal structures. Consequently, it is difficult to acquire effective and detailed information of water-bearing structures, which often results in positioning error, non-uniqueness of inversion, and false anomaly. To solve above problems, various studies have been carried out on DC resistivity detection in underground engineering, such as effective observation mode, interference removal method, and inversion theory. In this paper, the DC resistivity method used in underground engineering is reviewed, and the main issues concerning technical problems and development trends are discussed. Also, recent work on DC resistivity method and water inrush monitoring by our research group is introduced.

2. Technical issues of DC resistivity method in tunnels and coal mines

DC resistivity method is one of the important geophysical methods, which is interpreted based on conductivity difference between rock and water. In recent years, this method is widely used for detection and real-time monitoring of water-bearing structures in tunnels and coal mines.

2.1. Routine detection

The safety of working face basically has close relation with adverse geological structures around the excavation, especially when these structures are filled with water. Due to the high sensitivity to water, the DC resistivity method can be used by laying out survey lines on the bottom or sidewall of tunnel, with which the resistivity information can be provided. However, underground resistivity detection is rather different from traditional ground detection because of the relatively narrow detection space, thus underground detection is easy to be interfered by metal components in tunnels and mines. In addition, as the depth of excavation increases, the geological conditions are more complex, which is usually encountered during resistivity detection in tunnels and coal mines.

The traditional ground resistivity methods are used to detect the water-bearing structures in mines, including electrical section method and high-density electrical method in a single tunnel (Maillol et al., 1999; van Schoor, 2005; Martínez-López et al., 2013; Martínez-Pagán et al., 2013). These methods belong to electrical sounding method, with which two-dimensional (2D) vertical geo-electrical information is acquired in a single tunnel to identify the water-bearing structures. However, the non-uniqueness of inversion is a challenging issue for resistivity inversion under the conditions of serious interference. Meanwhile, the false anomalies are frequently reported in terms of resistivity inversion results. As a result, the water-bearing structure cannot be precisely identified due to the complex electrical structure, as shown in Fig. 2.

The computed tomography (CT) in medical science is considered to be a good method to solve the non-uniqueness of electrical sounding method. Electrical penetration mode with high resolution is used to acquire numerous observation data in different directions. Hence, electrical penetration detection method (Han and Shi, 2000; Spitzer and Chouteau, 2003; Eso and Oldenburg, 2006; Li et al., 2010) and three-dimensional (3D) parallel electrical method (Liu et al., 2009a; Wu et al., 2009, 2010; Zhang et al., 2009) using electrical penetration mode are frequently applied in tunnels and mines. In the electrical penetration detection method, the current and measuring electrodes are installed respectively in the working face of the two adjacent tunnels, as shown in Fig. 3. In the 3D parallel electrical method, besides the two parallel roadways, there is an open-off cut that can be used to detect the water-bearing structure, as shown in Fig. 4. The parallel electrical method has the function of multi-point parallel measurement, with which the efficiency and quality of data collection could be improved.

Two parallel roadways or open-off cut are used as detection space in the electrical penetration mode. Current is emitted by the current electrodes from a roadway or hole, and the measuring electrodes can receive potential difference in another roadway or hole. The detection angle is added in the electrical penetration mode to obtain multi-angle information, which increases positioning accuracy and resolution of detection result. The electrical penetration mode is the on-going research trend in accurate detection, in which the non-uniqueness of inversion is significantly reduced.

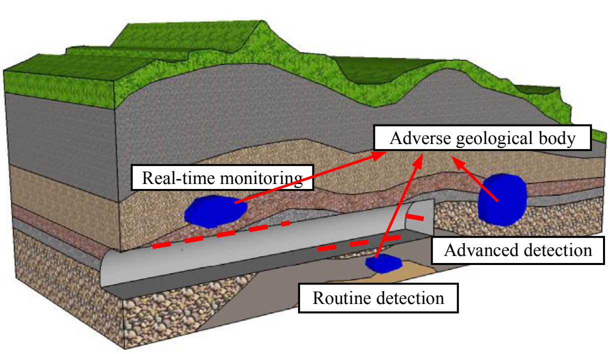

Fig. 1. Schematic diagram of application of DC resistivity method.

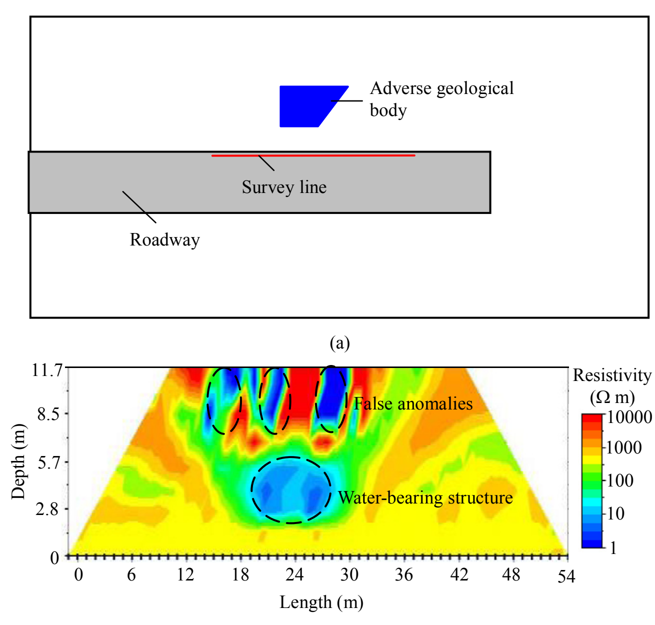

Fig. 2. Detection results of water-bearing structure. (a) Water-bearing structure over the roof. (b) Inversion result.