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Development of Tunnel Electrical Resistivity Prospecting System and its Applicaton

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Abstract

The detailed knowledge of ground conditions ahead of the tunnel face is necessary for safe and economical tunnel construction. The Tunnel Electrical resistivity Prospecting System (TEPS) has been developed to accurately detect the geological, hydro-geological, and geotechnical conditions such as the location, the size, the state of anomalies, cavities, weak zones, improved zones, high permeability water or gas bearing zones, or faults/fractures existing ahead of the tunnel face by measuring a series of electrical resistances and performing back analyses. The TEPS are composed of several electric sensors (electrodes), an in-situ resistance measurement system, an automated data acquisition system, inversion programs for back analyses, and closed form solutions for electric field analyses of jointed rock masses. Although the detectability of the TEPS is dependent upon the size and state of an irregular zone, its reliable penetration depth ranges in about 4~5 times of the tunnel size. It takes about 30 minutes to complete a test for one section of a tunnel. As practical applications, this paper presents several case studies for the ground condition estimation of collapsed tunnel zones using the TEPS. Overall, the ground conditions predicted by the TEPS are in accordance with the ground conditions measured during construction, verifying the TEPS.

Introduction

Rapid urbanization has increased the necessity of new spaces such as underground structures and long tunnels. For successful underground and long tunnel construction, it is very important to have a detailed understanding of the ground conditions at the design stage. As such, a site investigation such as boring and geophysical exploration surveys must be performed in order to ascertain the conditions of ground around the tunnel scheduled for construction. Nevertheless, there have been many reports of tunnel accidents that are caused by unexpected occurrence of anomalies, such as weak zones, fault zones, and cavities (CHO et al., 1999; KIM et al., 2000; HASEGAWA et al., 1993). So, technology that can be used to attain an accurate understanding of the ground conditions ahead of tunnel face and to predict even minute anomalies existing ahead of tunnel face is needed.

Measurement of electrical resistivity, used to attain information on the ground conditions of a tunnel region, facilitates understanding of the electrical characteristics and configuration of media (BOYCE, 1968; CHOI et al., 2004). In practice, electrical resistivity based exploration techniques are widely used in a variety of fields, from predicting the particle size in a discrete medium at a small scale to detecting anomalies or geological structures under the ground at a large scale (JACKSON et al., 1978; KIM et al., 2005). The conventional nondestructive method of using apparent electrical resistivity at a large scale is suitable for understanding the general ground conditions, but is not suitable for close-range exploration within a range of 3 times the tunnel diameter ahead of tunnel face, where the stability of the tunnel is most significantly affected and most tunnel accidents occur. In this paper, a method to predict ground conditions in the area ahead of tunnel face using electrical resistivity (Tunnel Electrical resistivity Prospecting System: TEPS) is developed in order to improve the reliability and efficiency of site investigations under tunnel construction (Figure 1).

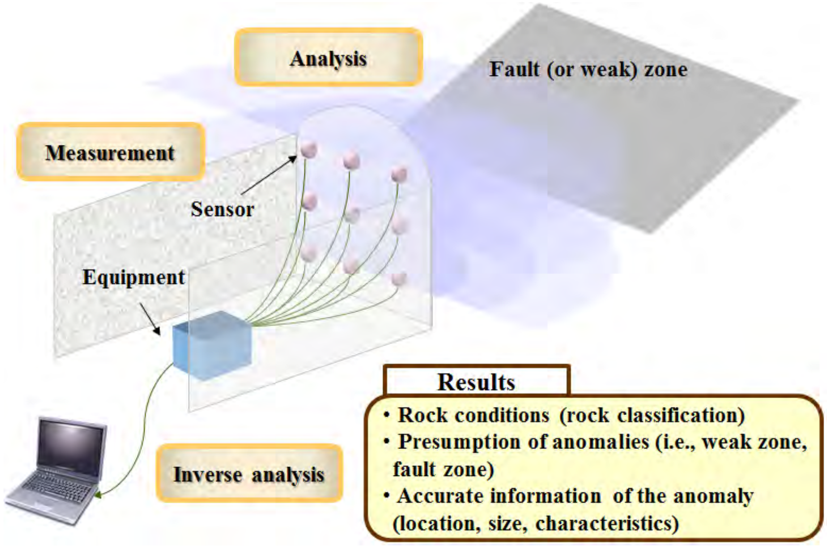

Fig. 1: Tunnel Electrical resistivity Prospecting System (TEPS).

TEPS

A TEPS consists of the analytical equation, the rock mass classification system, the inverse program, the control system, and the measurement system (RYU, 2010).

Analytical equations

Analytical equations are obtained by the electric field analysis using Gauss' law and Laplace equation. Those consists of the electrical resistance equation (R_{rm}) at jointed rock mass, the electrical resistance equation (R_{rm-sa}) at jointed rock mass with a spherical anomaly, and the electrical resistance equation (R_{rm-pa}) at jointed rock mass with a platy anomaly, as follows:

$$R_{rm} = f(\sigma_{ir}, \sigma_{j}, d, t, a) \tag{1}$$

$$R_{rm-sa} = f(\sigma_{rm}, \sigma_{sa}, x_{sa}, y_{sa}, z_{sa}, x_{s}, y_{s}, x_{r}, y_{r}, r_{sa}, K_{sa}, a) \tag{2}$$

$$R_{rm-pa} = f(\sigma_{rm}, \sigma_{pa}, A, B, C, D, x_{s}, y_{s}, x_{r}, y_{r}, t_{pa}, K_{pa}, a) \tag{3}$$

where σ_{ir} is the electrical conductivity of joints, σ_{j} is the electrical conductivity of intact rock, *d* is the thickness of intact rock, *t* is the thickness of joints, *a* is the radius of sensors, σ_{rm} is the electrical conductivity f surroundings possible to obtain from Equation (1), σ_{sa} is the electrical conductivity of a spherical anomaly, (x_{sa}, y_{sa}, z_{sa}) is the locational coordinate of a spherical anomaly, (x_{s}, y_{s}) is locational coordinate of source sensor, (x_{r}, y_{r}) is locational coordinate of receiver sensor, r_{sa} is the radius of a spherical anomaly, K_{sa} is the ratio of dielectric permittivity, σ_{pa} is the electrical conductivity of a platy anomaly, ($Ax+By+Cz=D$) is the plane equation of a platy anomaly, t_{pf} is the thickness of a platy anomaly, and K_{pa} is the ratio of dielectric permittivity.

Rock mass classification system

In order to estimate the rock conditions by using electrical resistivity, the Q-system and RMR, used as the rock mass classification, were correlated with electrical resistivity (CHOI et al., 2006; RYU, 2010). The parameters of Q-system and RMR are correlated with the electrical resistivity by using the equation (1), and the specific relationship between rock mass classification and electrical resistivity could be obtained using the certain field information (Figure 2).

Inverse programs

The inverse programs of TEPS can predict the location, size, and characteristics of anomalies that exist ahead of tunnel face by using the developed analytical equation and electrical resistance values measured in the fields. The inverse procedures consist of the Monte Carlo method and the Genetic Algorithm method.

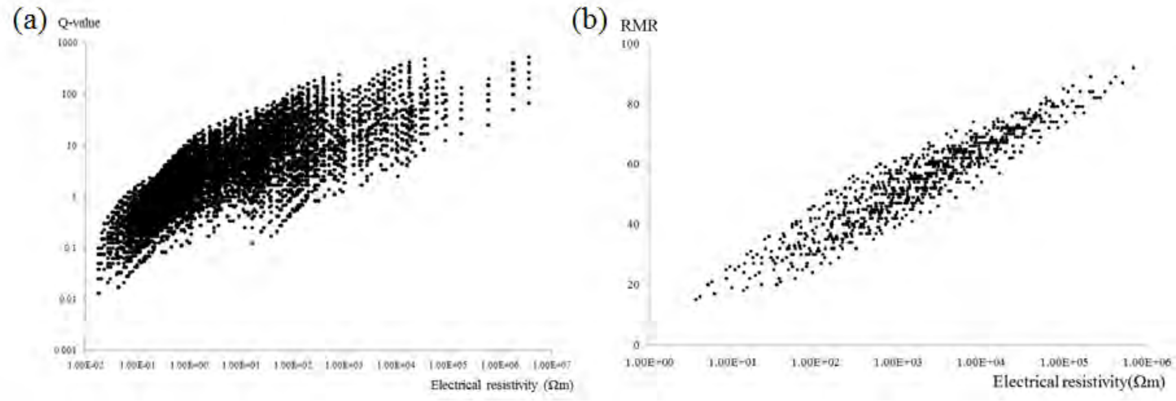

Fig. 2: The relationship between rock mass classification and electrical resistivity. (a) Q-system and electrical resistivity. (b) RMR and electrical resistivity.

Control system and measurement system

The control system can control the measurement of electrical resistance values in the fields, and the measurement system is organized for measuring the electrical resistance values in the fields. The measurement system consists of a data acquisition (DAQ), a digital multimeter (DMM), a power supply, a switch controller, a terminal block, and sensors.

Field applications

In order to verify the applications of Tunnel Electrical resistivity Prospecting System (TEPS), the field tests are performed at several field sites. The representative field tests are like followings:

○○ western detour roads (○○ tunnel)

Field experiments were performed in order to distinguish the existence of anomaly ahead of tunnel face, predict the possibility of the adding collapse, and estimate the rock condition around a collapsing section, in regards to the collapse of side wall under construction. In prediction results of tests, the weak zone (the height is 5m ~ 10m, the radius is about 2.6m, the depth is

0.5m, and electrical resistivity values are 0.2 times than one of surroundings) was predicted at the location near to the tunnel face (Figure 3a). This means that the larger region than the collapsed zone is put as the reinforcement region in order to prevent the adding collapse. Also, the strong zone (electrical resistivity values are relatively 3 times than one of surroundings) is predicted at 1m ~ 1.5m ahead of tunnel face and the left of tunnel face. The field mapping data in ○○ tunnel shows the accuracy of predicted results.

<u>○○ national highway – zone 2 (○○ tunnel)</u>

Field experiments were performed in order to distinguish the existence of anomaly ahead of tunnel face, predict the possibility of the adding collapse, and estimate the rock condition around the collapsing section, in regards to the collapse of tunnel face under tunnel construction. Prediction results are shown in Figure 3(b). Based on predicted results, the excavation work was performed after fixing the rock-bolt and the anchor at the bedrock for no more collapsing at ceiling part of tunnel. The adding collapse didn't happen.

All things taken together, although the detectability of the TEPS is dependent upon the size and state of an irregular zone, its reliable penetration depth ranges in about 4~5 times of the tunnel size. It takes about 30 minutes to complete a test for one section of a tunnel.

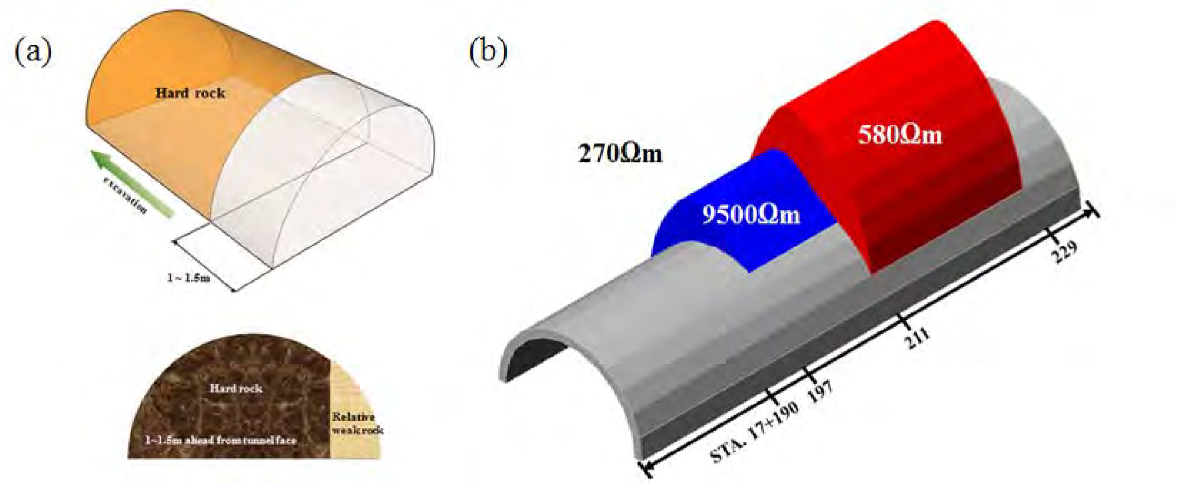

Fig. 3: Field test results. (a) ○○ western detour roads (○○ tunnel). (b) ○○ national highway – zone 2 (○○ tunnel).

Conclusions

A TEPS (Tunnel Electrical resistivity Prospecting System), which was developed as a tunnel-ahead prediction technology for preventing previously economic and social damage caused by the unexpected occurrence of anomalies under tunnel construction, consists of the analytical equation, the rock mass classification system, the inverse program, the control system, and the measurement system. Field tests were performed for field applications of the TEPS and field test results show the accuracy and reliability of TEPS.

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