Prediction of ground conditions ahead of the TBM face using electromagnetic waves

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ABSTRACT

The usage of TBM is growing gradually in South Korea with an increase in tunnel constructions in urban areas. TBM is suitable for tunneling in urban areas, while below the surface of the streets, unexpected anomaly zones exist, such as core stones, weak, mixed, fault and fractured zone, along with numerous obstacles such as water and sewage tunnels, deep foundations, cable tunnels, and metro lines. Therefore, it is important to predict ground conditions ahead of the TBM face for safe and economic tunnel construction. In this study, we developed a method to predict ground conditions ahead of the TBM face using electromagnetic waves. Unknown parameters such as ground conditions (size, state, location of anomaly) can be predicted from multiple measurements via back analyses. The developed method was verified through field tests.

Keywords: Ground prediction, TBM, Anomaly zone, Electromagnetic waves

1. INTRODUCTION

Construction of underground tunnels in urban areas is gradually increasing in order to provide efficient transportation without the need for overhead cables, which obstruct the views. The TBM method is utilized for urban tunnelling with its low excavation vibration and noise compared to the blasting method. The subsurfaces of urban areas have numerous obstacles such as deep foundations, cables, and water tunnels that affect the new TBM tunnel. In some cases, TBM damages unseen tunnels and causes water/sewage leakages and/or blackout. Downtime also happens due to ground conditions such as boulders, faults, and fractured zones. In this study, a geophysical method is suggested to predict ground conditions of ahead of TBM face using electromagnetic waves.

2 THEORETICAL BACKGROUND

The basic concept of this method is that the electromagnetic wave is transmitted through an electrode sensor and the wave is received using the other sensors. Electrical resistances are obtained using that process. Back analysis is performed based on several measurements of electrical resistance.

2.1 Electrical field analysis for homogeneous rock mass

The electric current density ($\vec{J}$) and the electric current ($I$) have the following relationship:

$$I = \int \vec{J} \cdot dS.$$  \hspace{1cm} (1)

$S$ is the surface area of electromagnetic wave flows. The electric current ($I_e$) flowing in an ideal semi-infinite intact rock can be expressed as

$$I_e = \int (\sigma E_\infty \cdot \vec{n}) da,$$  \hspace{1cm} (2)

where $E_\infty$ is the electric field at an arbitrary point in an intact rock, $\sigma$ is the electrical conductivity of an intact rock, $da$ is the infinitesimal area of the surface ($S$), and $\vec{n}$ is a unit vector normal to the infinitesimal area $da$. The electrical resistivity ($\rho_e$) in an ideal intact rock of half space given as (Choi et al., 2006; Ryu, 2010)

$$\rho_e = R_e \cdot \pi \cdot a$$  \hspace{1cm} (3)

by rewriting Eq. (2). $R_e$ is the electrical resistance measured by two electrodes, and $a$ is the equivalent radius of the electrodes.

2.2 Electrical field analysis for joint rock mass

Let’s consider a regularly patterned rock mass with two electrodes on the surface, consisting of a homogeneous intact rock block and discontinuities (e.g., joints) that are orthogonal to each other in three directions (Fig. 1a). The electric current in the rock...
mass induced by the electric field is dependent on the electrical conductivity of the homogeneous intact rock and joints (Reitz et al., 1979). At a semi-infinite y-z plane including an MN section that is the plane that includes the middle point between the two electrodes, the electric field of the joints (\(E'_j\)) or the electric field of the intact material (\(E'_\text{ir}\)) at an arbitrary point (\(U\) in Fig. 1b) can be expressed using Coulomb’s law and Gauss’s law, given that the center of electrode \(P\) is placed as the origin, and assuming that the two electrodes are point electrodes:

\[
\frac{E_{j \text{ or} \ ir}}{4\pi e_o} = \frac{Q}{U^2} \cdot \mathbf{r}
\]  

(4)

Here, \(e_o\) is the dielectric permittivity of the joints, \(Q\) is the electric charge, \(L\) is the distance between two electrodes \(+q\) and \(-q\), \(\mathbf{r}\) is the direction vector of the x-axis, and \(U\) is the length between a sensor and an arbitrary point on the MN section \(U(L/2, y_i, z_i)\). The electric current \(I_{rm}\), which flows (through the x-axis) perpendicular to a semi-infinite y-z plane including the MN section, can be calculated by vector summation of the electric current \(I_{jw}\) flowing through the joints on the x-z plane, the electric current \(I_{jy}\) flowing through the joints on the y-z plane, and the electric current \(I_j\) through the intact rock (in the case of \(d_t > t\), the intersection areas between the x-z plane and x-y plane can be ignored, as shown in Fig. 1(c)):

\[
I_{rm} = I_{jw} + I_{jy} + I_j,
\]

(5)

In this equation, \(I_{jw}, I_{jy},\) and \(I_j\) can be expressed as follows using Eq. (2):

\[
I_{jw} = \frac{1}{2} \sum_{p=1}^{\infty} \sum_{k=-\infty}^{\infty} \int_{y_{1\text{w}}}^{y_{2\text{w}}} \left( \int_{z_{1\text{w}}}^{z_{2\text{w}}} g(z) \cdot g(z) \right) \frac{Q}{2\pi e_o} f_1
\]

\[
I_{jy} = \frac{1}{2} \sum_{p=1}^{\infty} \sum_{k=-\infty}^{\infty} \int_{x_{1\text{y}}}^{x_{2\text{y}}} \left( \int_{z_{1\text{y}}}^{z_{2\text{y}}} g(z) \cdot g(z) \right) \frac{Q}{2\pi e_o} f_2
\]

\[
I_j = \frac{1}{2} \sum_{p=1}^{\infty} \sum_{k=-\infty}^{\infty} \int_{x_{1\text{y}}}^{x_{2\text{y}}} \left( \int_{z_{1\text{y}}}^{z_{2\text{y}}} g(z) \cdot g(z) \right) \frac{Q}{8\pi e_o} f_3
\]

\[
= \frac{Q}{8\pi e_o} \left[ \tan^{-1} \left( \frac{2k(d_z + t_z) + t_z}{L} \right) - \tan^{-1} \left( \frac{2k(d_z + t_z) - t_z}{L} \right) \right]
\]

(6)

Finally, we obtain

\[
f_2 = \sum_{k=-\infty}^{\infty} \left( \tan^{-1} \left( \frac{2p(d_z + t_z) + t_z}{L} \right) - \tan^{-1} \left( \frac{2p(d_z + t_z) - t_z}{L} \right) \right)
\]

\[
f_2 = \sum_{k=-\infty}^{\infty} \sum_{p=-\infty}^{\infty} \int \left( \int_{z_{1\text{ir}}}^{z_{2\text{ir}}} g(z) \cdot g(z) \right) \frac{Q}{(L/2)^2 + z_U^2} dz
\]

\[
g(z)_1 = \sin \left( \frac{k(d_z + t_z) + t_z}{2} \right)
\]

\[
g(z)_2 = \sin \left( \frac{k(d_z + t_z) + t_z}{2} \right)
\]

(7)

The electrical resistance \((R_{rm})\) equation of a rock mass can be expressed as

\[
R_{rm} = \frac{1}{a} \left( \frac{\sigma_j (f_1 + f_2) + \sigma_{\text{ir}} L}{4} f_3 \right)
\]

(11)

using Eqs. (5) and (6).

The electrical resistivity \((\rho_{rm})\) equation of a rock mass can be expressed as follows using Eq. (3) (Choi et al., 2006; Ryu, 2010):

\[
\rho_{rm} = \frac{\pi}{\sigma_j (f_1 + f_2) + \sigma_{\text{ir}} L}
\]

(12)

### 2.3 Electrical field analysis for rock mass with a spherical weak zone

The electric field of rock mass with spherical weak zone mass can be expressed in terms of relative permittivity (the ratio between the permittivity of the spherical weak zone \((\varepsilon_{sw})\) and the permittivity of the rock mass \((\varepsilon_{rm})\)), \(K_{sw} = \varepsilon_{sw}/\varepsilon_{rm}\) and the electric field of the rock mass. The relationship can be written as

\[
E_{sw} = \frac{K_{sw} + 2}{3} E_{ir}
\]

(13)

Finally, we obtain

\[
\rho_{\text{sw}} = \frac{2\pi}{\pi \sigma_{\text{sw}} f_4 + \frac{3\alpha \sigma_{\text{sw}}}{K_{sw} + 2} + (\pi - \alpha) \sigma_{\text{sw}} f_5}
\]

(14)

Where \(\sigma_{\text{sw}}\) is the electrical conductivity of the spherical weak zone, \(\sigma_{\text{sw}}\) is the electrical resistivity of the jointed rock mass, \(r_{sw}\) is the radius of the spherical weak zone, and \(\alpha\) is the angle between \(l\) and the tangent line (Fig. 2). \(f_4\) and \(f_5\) are as follows:

\[
f_4 = \sum_{k=-\infty}^{\infty} \left( \frac{2k(d_z + t_z) + t_z}{L} \right)
\]

\[
f_5 = \sum_{k=-\infty}^{\infty} \sum_{p=-\infty}^{\infty} \int \left( \int_{z_{1\text{ir}}}^{z_{2\text{ir}}} g(z) \cdot g(z) \right) \frac{Q}{(L/2)^2 + z_U^2} dz
\]
\[
f_4 = 2 + \cos \left( \tan^{-1} \frac{L + r_{sw}}{X_{mn-wsw}} \right) + \cos \left( \tan^{-1} \frac{L - r_{sw}}{X_{mn-wsw}} \right) - \cos \left( \tan^{-1} \frac{L - r_{sw}}{L - X_{mn-wsw}} \right) - \cos \left( \tan^{-1} \frac{L + r_{sw}}{L - X_{mn-wsw}} \right)
\]

(15)

\[
f_5 = \cos \left( \tan^{-1} \frac{L - r_{sw}}{X_{mn-wsw}} \right) + \cos \left( \tan^{-1} \frac{L - r_{sw}}{L - X_{mn-wsw}} \right) - \cos \left( \tan^{-1} \frac{L + r_{sw}}{X_{mn-wsw}} \right) - \cos \left( \tan^{-1} \frac{L - r_{sw}}{L - X_{mn-wsw}} \right)
\]

(16)

3 FIELD TEST

The verification of electromagnetic wave theory is performed in NATM tunnels and on the surface. The influence of disc cutter shielding is shown in TBM tunnels.

3.1 Verification of theory in NATM tunnels (Yangji Tunnel)

The crown of the Yangji Tunnel in a national road between Singal and Hobup, South Korea is collapsed because an unseen fault was located above the tunnel crown. Pre-core data represented that the fault was 50 m above the tunnel crown. The electromagnetic survey developed in this study predicted the fault location quite accurately, as shown in Fig. 3.

3.2 Verification of theory in NATM tunnels (on the surface)

A cable tunnel buried beneath the surface is precisely estimated using the electromagnetic survey developed in this study. The cable tunnel is located 4 m below the surface (Figs. 4(a), (b)).
flows through the EPB TBM machine itself.

4 CONCLUSIONS

The electromagnetic survey is developed in this study. Several field tests are performed. The main conclusions of this study are listed as follows:
- The theoretic derivation of the survey is obtained from basic electromagnetic equations (Maxwell’s equations).
- The theoretic derivation of the survey is verified using field tests. This survey predicts the location of the buried cable tunnel with about 0.5 m error.
- The measurement in EPB TBM shows that the TBM machine itself affects the electromagnetic survey. Therefore, it is necessary to prepare the method that prevents the electrical current from flowing the TBM machine.

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