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Development of FE model for simulating electrical resistivity survey to predict mixed ground ahead of a tunnel face

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ABSTRACT

Accurate prediction of mixed ground conditions ahead of a tunnel face is of vital importance to safely excavate a TBM tunnel. Previous studies have mainly focused on electrical resistivity surveys from the ground surface as a geotechnical investigation. In this study, an FE numerical model for simulating electrical resistivity surveys was developed to predict risky mixed ground conditions in front of a tunnel face. The FE model is validated by comparing with the apparent electrical resistivity values obtained from the analytical solution corresponding to a vertical fault on the ground surface (i.e., simplified model). A series of parametric studies was performed with the FE model to analyze the effect of the interface slope (between two different ground formations) on the electrical resistivity surveys. The parametric study revealed that as the interface slope of the mixed ground decreases, the numerical analysis exhibited the similar trend to the analytical solution. It is concluded that the developed FE numerical model can successfully predict the presence of a mixed ground zone, which enables optimum management of potential risks.

1. INTRODUCTION

Due to steeply rising population density in urban areas, it is essential to develop underground structures such as traffic and utility tunnels (Broere, 2016). A shield TBM is considered a promising method to excavate tunnels in urban areas with less noise and vibration, and securing adjacent structures' stability (Jeong, 2018). However, when excavating TBM tunnels, unexpected geological risks can endanger construction safety and significantly reduce the efficiency of tunnel excavation, such as undesirable water inflow into the tunnel face, surface collapse, etc. (Chang, 2006).

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A mixed ground condition is one of the most hazardous geological risks in shield TBM tunnelling (Toth, 2013). Soil-rock mixed ground conditions can cause side wear of cutters around rock formations resulting in excessive cutter consumption (Park, 2017). In addition, the choice of the soil conditioning methods depends on the geotechnical characteristics of excavation sites. Inappropriate additives for soil conditioning may result in a reduction in penetration rate in mixed ground conditions (Kim, 2018).
Therefore, the accurate prediction of mixed ground conditions ahead of a tunnel face can minimize potential risks in advance.

However, few studies on the prediction of mixed ground conditions have been conducted owing to the difficulty in simulating such conditions in front of a tunnel face. Thus, in this study, an FE numerical model for simulating electrical resistivity surveys was developed to predict risky mixed ground conditions ahead of a tunnel face. The FE model was validated by comparing the numerical analysis results with the analytical solution corresponding to a vertical fault and the experimental results. In addition, a parametric study to analyze the effect of the interface slope on electrical resistivity was conducted.

2. ANALYTICAL SOLUTION

A well-known analytical solution with the Wenner array was achieved to simulate electrical resistivity surveys from the ground surface. The electrical resistivity survey to predict mixed ground conditions ahead of a tunnel face is similar to conducting the electrical resistivity survey to detect a vertical fault from the ground surface (Fig. 1).

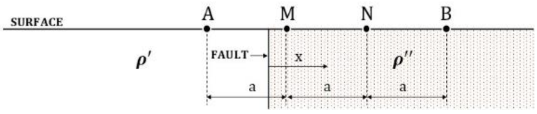


Fig. 1 Front view of Wenner configuration to a vertical fault

The apparent electrical resistivity corresponding to a vertical fault (ρ_a) from the ground surface can be represented in Eq. (1), (Van Nostrand and Cook, 1966):

$$\frac{\rho_a}{\rho'} = 1 + \frac{3ka^3x}{(x^2-a^2)(4x^2-a^2)}\ ,\ x < \frac{-3a}{2} \quad , \quad \frac{\rho_a}{\rho'} = 1 - \frac{kx(2x-3a)}{2(x-a)(2x-a)}\ ,\quad \frac{-3a}{2} < x < \frac{-a}{2}$$

$$\frac{\rho_a}{\rho'} = \frac{1}{1+k}\left[1 + k^2 + \frac{ka(x+ak)}{(x^2-a^2)}\right],\quad \frac{-a}{2} < x < \frac{a}{2} \quad , \quad \frac{\rho_a}{\rho'} = \frac{1-k}{1+k}\left[1 + \frac{kx(2x+3a)}{2(x+a)(2x+a)}\right],\quad \frac{a}{2} < x < \frac{3a}{2}$$

$$\frac{\rho_a}{\rho'} = \frac{1-k}{1+k}\left[1 + \frac{3ka^3x}{(x^2-a^2)(4x^2-a^2)}\right]\ ,\quad \frac{3a}{2} < x \qquad (1)$$

where ρ', ρ'' are the electrical resistivity values of the left and right ground formation, a is the distance between the electrodes and x is the distance from the fault to the center of the electrode array as shown in Fig 1. k is the reflection factor expressed in Eq. (2).

$$k = \frac{\rho''-\rho'}{\rho''+\rho'} \qquad (2)$$

When conducting the electrical resistivity survey by shifting the electrode array, $\frac{\rho_a}{\rho'}$ in Eq. (1) should be differently expressed according to the location of the electrode array relative to the vertical fault (i.e., $x = \frac{\pm 3a}{2}, \frac{\pm a}{2}$ in Eq. (1)).

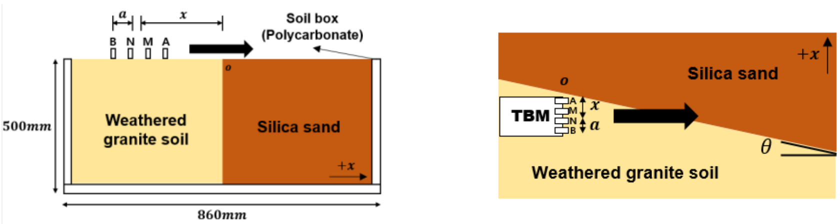
3. FE NUMERICAL SIMULATION

3.1 Verification of developed FE model

A 3D finite element model was developed using a commercial 3D FE numerical analysis program, COMSOL Multiphysics. A simplified model was devised to show the applicability of numerical simulation for electrical resistivity surveys to predict mixed ground conditions ahead of a tunnel face (Fig. 2). In the numerical model, the governing equation (Eq. (3)) for the electrical resistivity survey is originated from the principle of Poisson's equation and is formulated by the Gauss law and the equation of continuity.

$$-\nabla \cdot (\sigma \nabla V - J^e) = Q_j \tag{3}$$

The developed FE model was validated by comparing the numerical results with not only the laboratory experimental results, but also the analytical solution (i.e., Eq. (1)). The laboratory experiment was conducted to measure electrical resistivity with Supersting R8 (Advanced Geosciences, Inc) while moving the electrodes in a soil chamber (i.e., simplified model in Fig. 2(a)). The movement of the electrodes was arranged to resemble approximately the electrical resistivity survey on a tunnel face being excavated behind mixed ground conditions, as shown in Fig. 2(a) and 2(b). The dimensions of the FE model were identical to the soil chamber system as described in Fig. 3. The material properties applied in the numerical analysis were measured from the laboratory experiment and are represented in Table 1.



(a) Simplified model (b) Tunnel excavation model
Fig. 2 Modeling for simulating mixed ground condition ahead of tunnel face

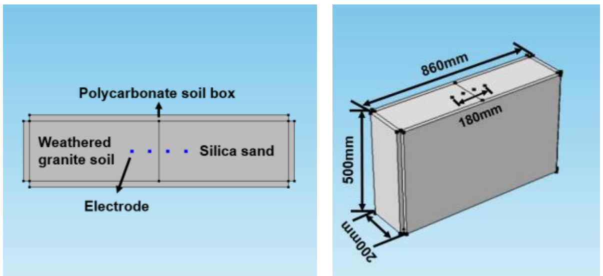


Fig. 3 FE model for simulating laboratory experiment of the electrical resistivity survey (Simplified model)

Table 1. Material properties adopted in FE numerical analysis

Type	USCS	Porosity (%)	Electrical resistivity ($\boldsymbol{\Omega \cdot m}$)
Weathered granite soil	SW	37	469.88
Silica sand	SP	42	231.31
Kaolinite	CH	51	34.38

The numerical analysis results are compared with the laboratory experimental results and the analytical solution for the simplified model as shown in Fig. 4. With respect to the analytical solution, the numerical analysis results showed the root mean square error (RMSE) and the average error of 19.7$\Omega \cdot \mathrm{m}$ and 6.7%, respectively. Thus, it is concluded that the developed FE model can simulate the electrical resistivity survey with sufficient accuracy.

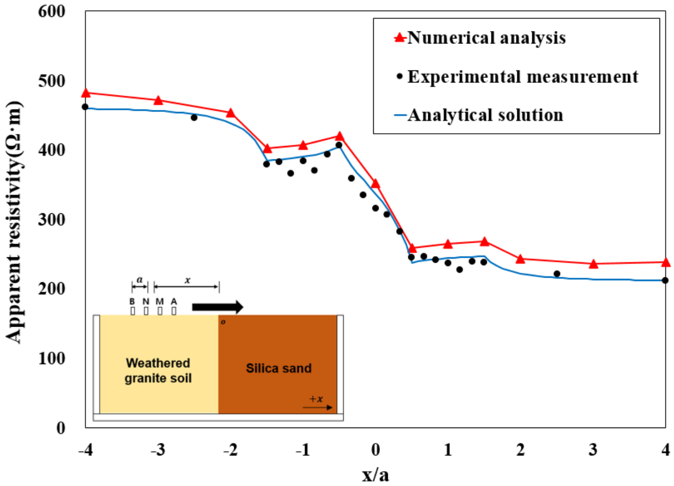


Fig. 4 Comparison of numerical analysis results with laboratory experimental results and analytical solution for simplified model

3.2 Effect of tunnel geometry

The verified FE numerical model was applied to the tunnel excavation model (Fig. 2(b)) to simulate electrical resistivity surveys for predicting mixed ground conditions ahead of a tunnel face. In order to estimate the effect of real tunnel geometry, the tunnel excavation model was compared with the simplified model in case of three mixed ground conditions as summarized in Table 2. Instead of using a and x (in Fig. 2 and 4) as the variables during tunnel excavation, the tunnel diameter (D) and the distance (L) between the tunnel face and the mixed ground interface were adopted as the variables as shown in Fig. 5.

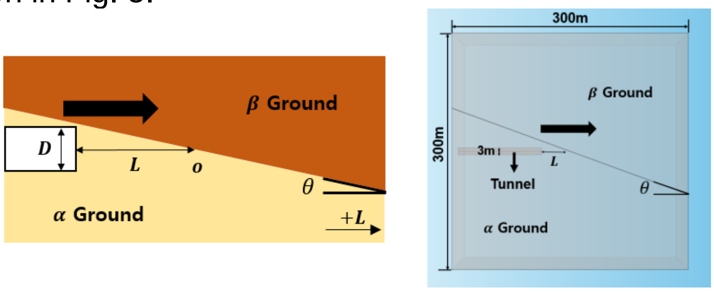


Fig. 5 Numerical modeling of simulating mixed ground condition in front of tunnel face (Tunnel excavation model)

Table 2. Numerical analysis cases of mixed ground conditions

	α ground	**β** ground
Case 1	Weathered granite soil	Silica sand
Case 2	Weathered granite soil	Kaolinite
Case 3	Silica sand	Kaolinite

The numerical results for the tunnel excavation model were compared with the analytical solution to the simplified model, to estimate the effect of real tunnel geometry on electrical resistivity surveys, as shown in Fig. 6 and Table 3. The tunnel excavation model resulted in smaller apparent electrical resistivity values than the simplified model by 13.06 ~ 25.80%. In addition, the large difference of electrical resistivity between the two ground formations (i.e., Case 2) showed the more dramatic effect of the tunnel geometry comparing to the simplified model. The smaller electrical resistivity in the tunnel excavation model is attributed to the boundary effect of the ground formation around the tunnel, which implies the importance of considering tunnel geometry. However, the trends of apparent electrical resistivity values corresponding to L/D during tunnel excavation were similar to that of the simplified model as shown in Fig. 6.

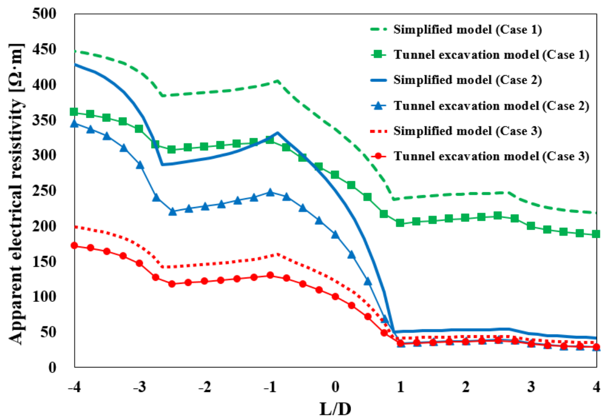


Fig. 6 Estimation on the effect of real tunnel geometry

Table 3. Average difference between tunnel excavation model and simplified model

	Average difference (%)
Case 1	16.75
Case 2	25.80
Case 3	13.06

3.3 Effect of mixed ground interface slope on electrical resistivity

The interface slopes (θ) between two different ground formations should be considered to simulate electrical resistivity surveys during tunneling through mixed ground conditions (refer to Fig. 5). A parametric study was carried out to estimate the effect of the interface slopes on electrical resistivity for Case 2 in Table 2.

The results of the numerical analysis are shown in Fig. 7. As the interface slope became smaller (or flatter), the electrical resistivity values followed the similar trend of the simplified model because the tunnel excavation model in this case exhibits the similar geometry to the simplified model. On the other hand, the higher interface slopes (i.e., steeper) showed rather drastic reduction in the electrical resistivity values when the tunnel face approaches the interface, which is somewhat different from the simplified model. Note that it is of importance to figure out the variation of electrical resistivity measurements corresponding to the interface slopes during performing electrical resistivity surveys under mixed ground conditions.

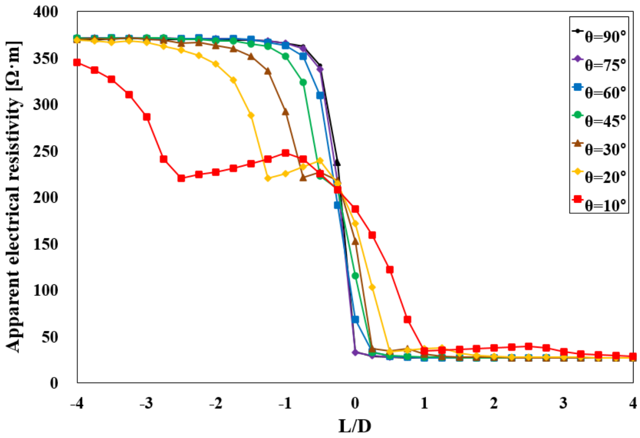


Fig. 7 Effect of interface slopes on electrical resistivity survey

4. SUMMARY

In this study, a FE numerical model was developed for simulating electrical resistivity surveys to predict mixed ground conditions. The FE model was validated by comparing with the electrical resistivity values obtained from the analytical solution corresponding to the simplified model, which represents a vertical fault on the ground surface. Compared to the analytical solution, the RMSE and average error of the numerical results were estimated to be 19.7$\Omega \cdot \mathrm{m}$ and 6.7%.

The effect of real tunnel geometry was examined by comparing the tunnel excavation model with the simplified model for three mixed ground conditions. The tunnel excavation model resulted in smaller apparent electrical resistivity values than the simplified model by 13.06 ~ 25.80% because of the boundary effect of the ground formation around the tunnel.

The effect of interface slopes (θ) between two different ground formations was considered in the parametric study. As the interface slope became smaller, the electrical resistivity values followed the similar trend of the simplified model because of the similar geometry to the simplified model. However, the higher interface slopes showed rather drastic reduction in the electrical resistivity values when the tunnel face approaches the interface.

ACKNOWLEDGMENTS

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