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Experimental verification for prediction method of anomaly ahead of tunnel face by using electrical resistivity tomography

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Abstract. The prediction of the ground conditions ahead of a tunnel face is very important, especially for tunnel boring machine (TBM) tunneling, because encountering unexpected anomalies during tunnel excavation can cause a considerable loss of time and money. Several prediction techniques, such as BEAM, TSP, and GPR, have been suggested. However, these methods have various shortcomings, such as low accuracy and low resolution. Most studies on electrical resistivity tomography surveys have been conducted using numerical simulation programs, but laboratory experiments were just a few. Furthermore, most studies of scaled model tests on electrical resistivity tomography were conducted only on the ground surface, which is a different environment as compared to that of mechanized tunneling. This study performed a laboratory experimental test to extend and verify a prediction method proposed by Lee *et al*., which used electrical resistivity tomography to predict the ground conditions ahead of a tunnel face in TBM tunneling environments. The results showed that the modified dipole-dipole array is better than the other arrays in terms of predicting the location and shape of the anomalies ahead of the tunnel face. Having longer upper and lower borehole lengths led to better accuracy of the survey. However, the number and length of boreholes should be properly controlled according to the field environments in practice. Finally, a modified and verified technique to predict the ground conditions ahead of a tunnel face during TBM tunneling is proposed.

Keywords: electrical resistivity tomography; experimental test; electrode array; prediction method; tunnel boring machine

1. Introduction

In general, surface geophysical and geological surveys during the design stage, before the tunnel excavation process, focus on covering wide areas and evaluating the overall ground properties of the construction area. This is important because encountering an unexpected anomaly or a series of anomalies during the tunnel excavation process, without a proper response, can cause a considerable loss of time and money (Chen *et al*. 2011, Khezri *et al*. 2016)). Since having an understanding of the ground conditions ahead of a tunnel face is extremely important, a technique to predict the front of the tunnel face for a tunnel boring machine (TBM), in which the tunnel face is not visible with the naked eye, has been needed. Several studies on the prediction techniques, which can be applicable in mechanized tunneling, have been conducted (Kneib *et al* 2000, Kaus and Boening 2008, Dowden and Robinson 2001, Li *et al*. 2017, Liu *et al*. 2017). Currently, most prediction techniques used at TBM construction sites, such as bore-tunneling electrical ahead monitoring (BEAM), tunnel seismic profiling (TSP), and ground penetrating radar (GPR), are designed with a sensor installed in the cutter head for regular measurements. However, these methods have various shortcomings, such as low accuracy and low resolution for the prediction of ground conditions ahead of a tunnel face. Considering these disadvantages, Richter (2011) and Schmidt *et al*. (2017) conducted a study of predicting the ground conditions ahead of a tunnel face through an irregular borehole radar exploration in a karst topography, where the stability is very low.

Most studies on the electrical resistivity and electrical resistivity tomography surveys have been conducted using numerical simulation programs (Chong *et al*. 2017), but laboratory experiments are just a few. Hong (1999) conducted scaled model tests using a pole-pole array in electrical resistivity tomography under the assumption of the occurrence of two- and three-dimensional anomalies. Oh (2001) carried out scaled model tests to compare vertical and horizontal resolutions depending on the electrode array in electrical resistivity tomography. However, most studies of scaled model tests on the electrical resistivity tomography survey were conducted only on the ground surface, which is a different environment as compared to that of mechanized tunneling.

Through numerical simulations, Lee *et al*. (2019) investigated the possibility of using the electrical resistivity tomography survey for predicting the ground conditions ahead of the tunnel face at a TBM tunneling site. The electrical resistivity tomography survey was assumed to be

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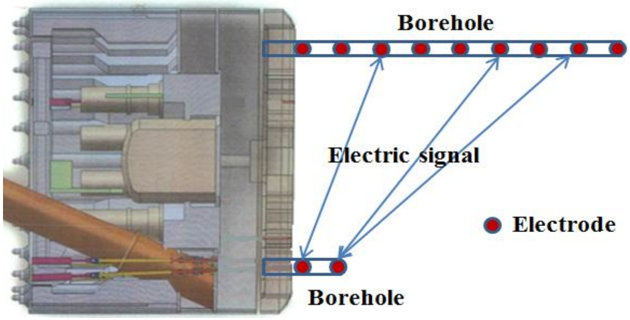
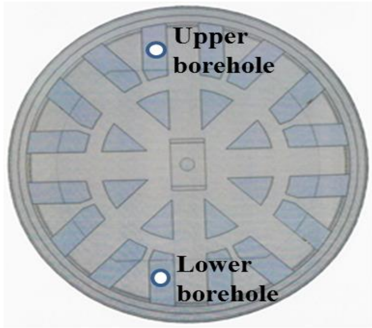


(a) Side view



(b) Front view

Fig. 1 Schematic diagram of prediction method considered in this study (Lee *et al*. 2019)

performed by excavating a borehole and inserting an electrode into the borehole using the probe drilling equipment loaded in the main body of the TBM. Based on their numerical results, they confirmed the applicability of using the electrical resistivity tomography survey and proposed a method to predict the ground conditions ahead of a tunnel face in TBM tunneling. This study is conducted to extend and verify the above-mentioned prediction method proposed by Lee *et al*. (2019) using laboratory experimental tests. The laboratory experiment simulates the TBM construction environment, in which anomalies are located ahead of the tunnel face. The tests are performed by changing the electrode array and borehole length to determine an optimal value for both these parameters, in which the anomalies ahead of the tunnel face can be predicted during TBM tunneling. Finally, a modified and verified technique to predict the ground conditions ahead of the tunnel face during TBM tunneling is proposed.

2. Electrical characteristics

Electrical resistivity is a property that quantifies how strongly a given material opposes the flow of an electric current. It is a constant that indicates the electrical properties of a material, regardless of its shape and size. The unit is ohm meter (Ω m). While electrical resistance indicates how hardly a material passes an electric current, the electrical resistivity represents an electrical resistance of a unit volume material. Electrical resistivity in rock mass changes by porosity, degree of saturation, electrical conductivity of ground water, and content of clay (Ryu *et al*. 2008, Oh *et al*. 2014, 2015). The newer a bedrock is, the higher the electrical resistivity is induced. On the contrary, rock mass with many fractured zones and joints has low electrical resistivity.

The electrical resistivity tomography (electrical resistivity cross-sectional imaging) survey performs measurement and analysis under the same principle as that in the electrical resistivity survey. The electrical resistivity tomography survey has a high resolving power as it installs electrodes in the boreholes adjacent to the targeted area for survey, which is different from the process followed in the surface electrical resistivity survey. In the electrical resistivity tomography survey, a borehole is drilled from the ground surface; multiple electrodes are installed inside the borehole, letting the object for survey to be surrounded by the electrodes; and a direct current is artificially transmitted into the borehole to measure the potential difference in multiple measuring electrodes. This is one of the electrical resistivity survey methods to identify geological features, such as the presence of underground resources and faults, by analyzing the electrical resistivity distribution obtained from the potential. More details on electrical characteristics can be found in the study conducted by Lee (2014).

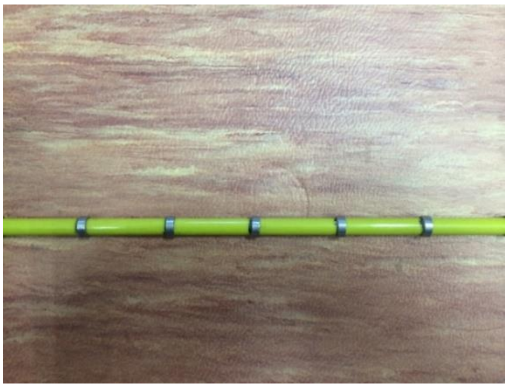
3. Prediction method using electrical resistivity tomography

Fig. 1 shows the schematic diagram of the electrical resistivity tomography survey applicable to TBM, which is considered in this study. The prediction method performs an electrical resistivity tomography survey through boreholes, which are excavated using the probe drilling equipment usually installed in TBM when the tunneling line's ground condition is not good. It considers two cases; one has a probe drilling equipment installed on only the top of the TBM main body and the other has the probe drilling equipment installed on both the top and bottom of TBM, as shown in Fig. 1. The laboratory experiment targets two cases. One with borehole length of 20 m for the top of the TBM main body, on which a probe drilling equipment is usually loaded, and the other with borehole lengths of 1 m and 20 m for the bottom of the TBM main body, on which the probe drilling equipment is selectively loaded depending on the ground condition of the TBM construction site. The 20 m borehole length is determined based on the result from a questionnaire survey targeting TBM site operators. Its result concluded that the optimal survey depth ahead of the tunnel face, for them to offer a proper auxiliary construction technique and countermeasure, would be 10–20 m approximately (Lee *et al*. 2011).

4. Experimental test program

In the TBM tunneling method, various facilities and mechanical and/or electrical equipment, such as a chamber, pressure cell, conveyor, and cylinder, are placed at the back of the cutter head. Despite the use of a probe drilling equipment for the electrical resistivity tomography survey,

(a) Water tank



(b) Electrode

(c) Brass block for anomaly

(d) Aluminum disk for cutter head

Fig. 2 Laboratory experimental test apparatus

the survey result may not be reliable because of the influence from the TBM main body and cutter head (Lee 2014). The main purpose of the laboratory experiments conducted in this study is to find a proper electrode array and borehole length for the electrical resistivity tomography survey, that is compatible with the TBM tunneling environments. Therefore, experimental scaled model tests are performed by varying the electrode array and borehole lengths.

4.1 Test apparatus

In a laboratory scaled model test using a water tank, it is possible to set the location and shape of the ground model. Therefore, there is no uncertainty by the surrounding geographic features and conditions, which can occur in a field test. However, measurement errors may occur due to the boundary effect stemming from the limited size of a water tank, electric noises surrounding the laboratory, changes in medium electrical conductivity by evaporation, and difficulty in the remote ground electrode installation. The laboratory experiment, similar to the experiment at a field site, may also experience errors according to the borehole effect and electrode status.

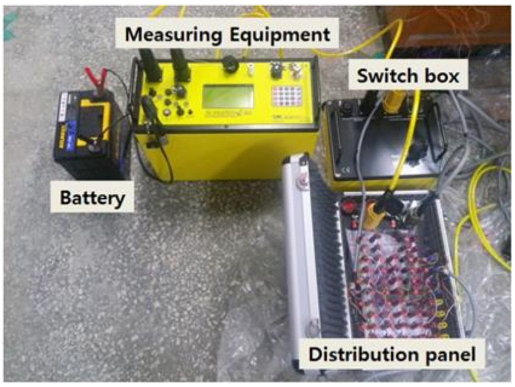
A 100 × 100 × 100 cm acrylic hexahedron water tank was manufactured for the scaled model tests. As there was a risk of damage to the tank by the excessive weight when the tank is filled with soil and water, the tank outside was reinforced with a metallic frame, as shown in Fig. 2(a).

Generally, platinum and stainless steel are widely used for electrodes. The tests herein used anti-rust stainless steel electrodes. The electrode interval and length were determined based on the electrode similarity rule, which would be used for the field construction site. The interval was set at 2 cm and, for an accurate measurement, the electrode was made in the form of a very thin ring with 0.2 cm length because the interval set is short, as shown in Fig. 2(b). A round bar was manufactured with fiber reinforced plastics (FRP) to fix electrodes and place them properly inside the water tank. To minimize the boundary effect on the bottom of the water tank, the distance between the lowest electrode and the bottom floor of the tank was kept at least 30 cm or more and 21 electrodes were attached at every 2 cm in the FRP round bar, as shown in Fig. 2(b). Considering the space between electrodes, electrode length, and water tank size, the distance between boreholes was set at 16 cm. A remote ground electrode was installed on the central wall of the water tank, which is the farthest spot from the borehole cross section. The distance from the boreholes to the remote ground electrode is 42 cm, 21 times longer than that of the electrode interval.

A bedrock was simulated with tap water, and water was filled in the tank up to 83 cm height from the bottom floor. The tests were performed in more than 72 h after the water was filled for stabilization to boost the measurement accuracy in the end. The anomalies were simulated with a 14 × 14 × 6 cm brass block, as shown in Fig. 2(c). The TBM cutter head was simulated using a 14 cm diameter aluminum disc, as shown in Fig. 2(d).

The equipment for measuring the electrical resistivity for this study was SuperSting R8/IP/SP, as shown in Fig. 3(a), a survey instrument sold by the American AGI, and it

(a) SuperSting R8/IP/SP



(b) Measurement system

Fig. 3 Electrical resistivity measurement system

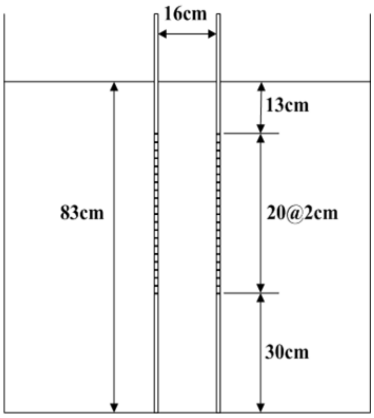
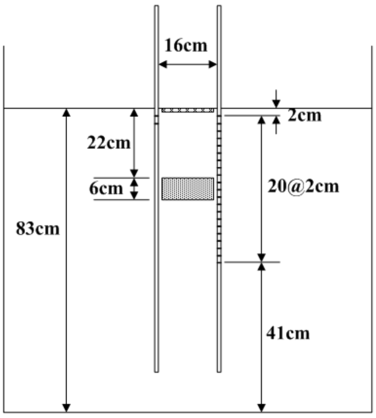
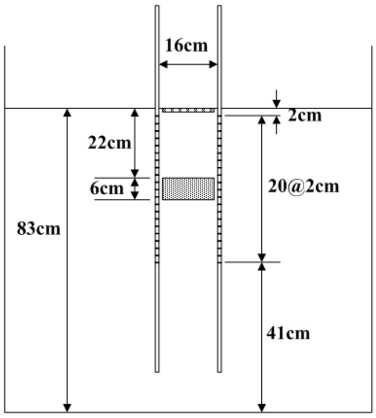


Fig. 4 Schematic diagram of the blank test



(a) 20 m upper borehole and 1 m lower borehole



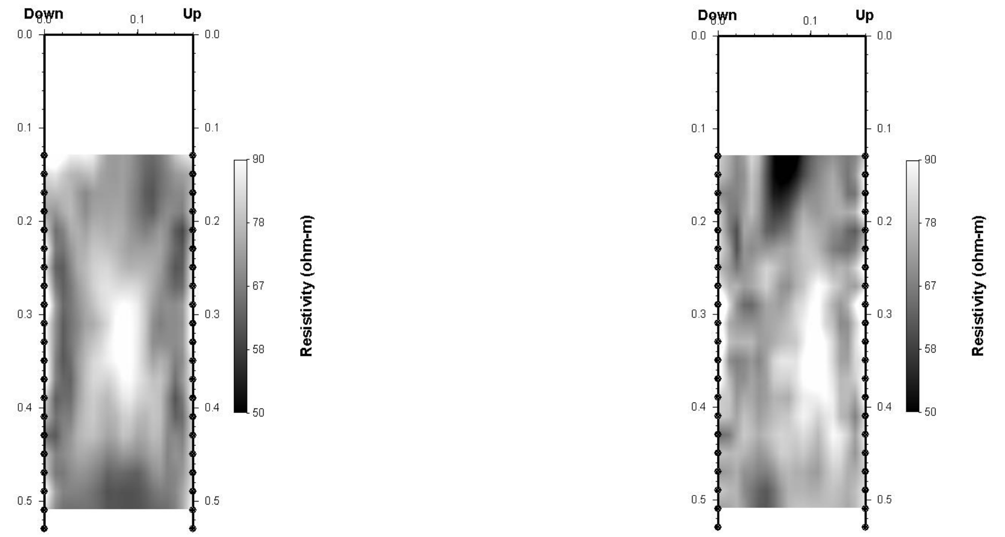
(b) 20 m upper borehole and 20m lower borehole

Fig. 5 Schematic diagram of the anomaly simulation test

is possible to carry out the electrical resistivity survey, self-potential (SP) survey, and induced polarization (IP) survey. The equipment's output current is ranging between 1–1,250 mA and the output voltage is ±10 V. As they executed the survey using 42 electrodes, the switch box and distribution panel were connected to establish the measurement system, in which an automatic measurement was possible, as shown in Fig. 3(b). The analysis was conducted using TomoDC ver. 1.2, which is a resistivity tomography analysis and numerical simulation program developed by the Korea Institute of Geoscience and Mineral Resources.

4.2 Test setup

This study performed a blank test first to identify the experiment's accuracy and influence of errors and noises, and then executed an anomaly simulation test to find an appropriate electrode array and borehole length, in which the anomalies are well predicted under the TBM cutter head simulation environment. At the TBM construction field site, a horizontal borehole ahead of the tunnel face can be excavated using a probe drilling equipment. However, there was a difficulty in simulating a horizontal borehole in the



(a) Maximum input current 35 mA (b) Maximum input current 2 mA

Fig. 6 Results of the blank test

laboratory water tank environment. Thus, the TBM cutter head and boreholes were turned by 90°, the cutter head was installed on the water surface, and the electrodes were placed in a vertical direction to perform the laboratory tests.

Fig. 4 shows the schematic diagram of the blank test setup. A cross-hole survey, reverse cross-hole survey, and inline survey were performed with the dipole-dipole array. To find the maximum input current for a laboratory experiment, the test was conducted by changing the maximum input current from 2 mA to 70 mA. Electrodes were placed at every 2 cm from the 13 cm point below the water surface. The electrode installed at the lowest point was located at the 30 cm point above the bottom floor of the water tank.

Fig. 5 shows the schematic diagram of the anomaly simulation test setup. A cross-hole survey, reverse cross-hole survey, and inline survey were performed with the pole-pole, pole-dipole, dipole-dipole, modified dipole-dipole, and modified pole-pole arrays. The tests targeted borehole lengths of 20 m and 1 m (Fig. 5(a)) as well as two boreholes with 20 m length (Fig. 5(b)). Electrodes were placed at every 2 cm from the 2 cm point below the water surface. The electrode installed at the lowest point was located at the 41 cm point above the bottom floor of the water tank. The brass block (simulating anomaly) was located at about 22–28 cm below the water surface.

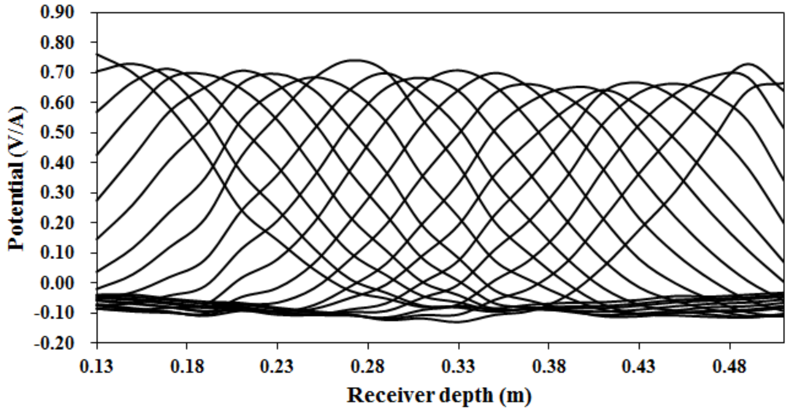
5. Test results and analyses

5.1 Blank test results

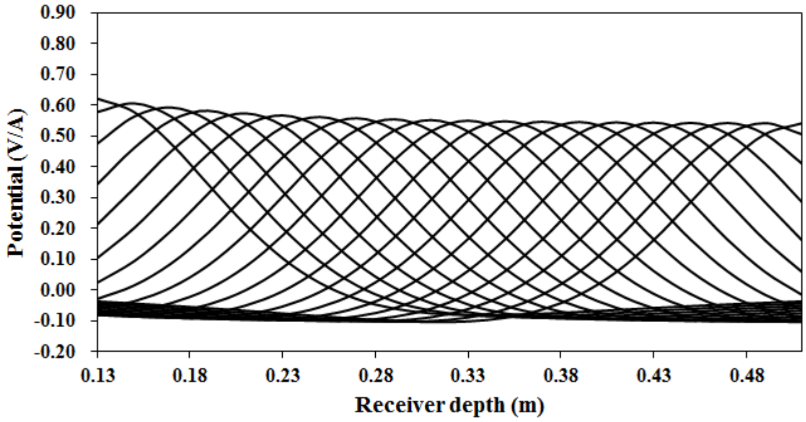
Prior to the blank test, the electrical conductivity of tap water, which is the medium inside the water tank, was measured using the conductivity meter. The electrical conductivity of the tap water was estimated to be approximately 137.4 μS/cm, which is approximately 70 Ω m after converting it into electrical resistivity. The electrical resistivity of tap water, measured by Hong (1999) and Song *et al*. (2000), was about 47 Ω m and 58–62 Ω m, respectively. The difference, around 10–20 Ω m, was considered to occur due to the regionally different properties of tap water caused by different water source, water quality and purifying methods, and time spent to stabilize the water in the water tank. Therefore, the electrical resistivity of tap water suggested in this study, 70 Ω m, is considered appropriate.

Fig. 6 shows the test result of the blank test, which was conducted to identify the appropriateness of the ground medium (tap water) inserted in the water tank. With 35 mA of the maximum input current, the electrical resistivity distribution was about 50–90 Ω m, as shown in Fig. 6(a). The overall pattern of the electrical resistivity distribution was similar to the tap water electrical resistivity measured by the conductivity meter, i.e., 70 Ω m. Considering the equipment measurement errors, the ground medium inserted in the water tank and the test method are considered to be adequate. With 2 mA of the maximum input current, the electrical resistivity distribution was about 43–107 Ω m, as shown in Fig. 6(b). The overall pattern of the electrical resistivity distribution was almost 70 Ω m. In addition, when the maximum input current was 10 mA, a similar result was obtained. Therefore, it seems that the change in the maximum input current does not have a big influence on the test result. However, the value that the overall electrical resistivity distribution showed to be closest to that of the tap water in the water tank, 35 mA, is considered to be used in the anomaly simulation tests as the maximum input current.

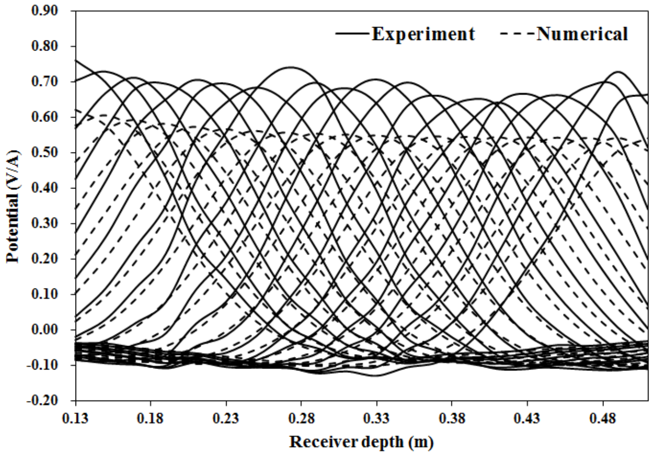
Fig. 7 shows the potentials measured in 21 electrodes when the maximum input current is 35 mA. Fig. 7(a) represents the potential curve obtained from the blank test and Fig. 7(b) represents the potential curve obtained from the numerical analysis under the same condition with the blank test. Comparing the two curves, it is observed that the potentials obtained from the blank test are bigger than those obtained from the numerical analysis, as shown in Fig. 7(c). This is because the solder and epoxy, which were used to connect the electrodes to the wires, obstruct the electric



(a) Potential curve obtained from blank test



(b) Potential curve obtained from numerical analysis



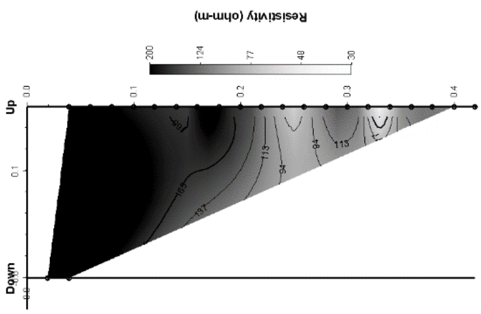
(c) Comparison of potential curves

Fig. 7 Potential curves obtained from blank test and numerical analysis

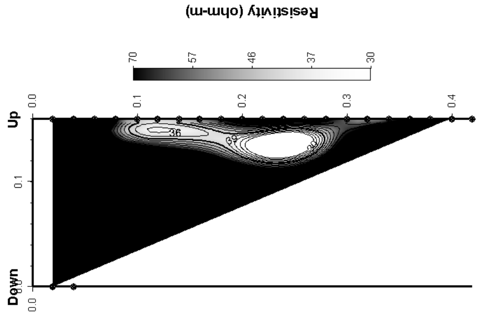
current flow. Further, the boundary effect shown in the side and bottom floor of the water tank seems to have an influence on the result, as the test was carried out in a limited space. Apparently, the potential decreases or increases when the location of electrodes is not correct, and this phenomenon seems reflected as well. However, the overall pattern of the potential curve was similar. Therefore, the ground medium (tap water) inserted in the water tank and the test method are considered appropriate when the equipment measurement errors are considered.

5.2 Anomaly simulation test results

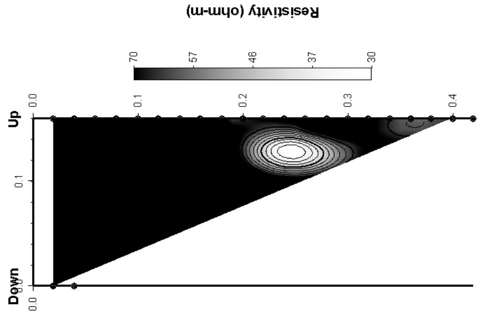
Considering the expected prediction depth ahead of the tunnel face, which this study targets, and the TBM tunneling environments, the laboratory scaled model tests were performed on two cases of excavation: 20 m upper borehole length and 1 m lower borehole length, and 20 m length for both upper and lower boreholes, as shown in Fig. 1. The pole-pole, pole-dipole, dipole-dipole, modified pole-pole, and modified dipole-dipole arrays were used for the laboratory tests. The modified dipole-dipole array was tested only when the sum of array constants k and l is 8 and 10 (Lee *et al*. 2019). Fig. 8 shows the test results of the excavated ground model of 20 m upper borehole and 1 m



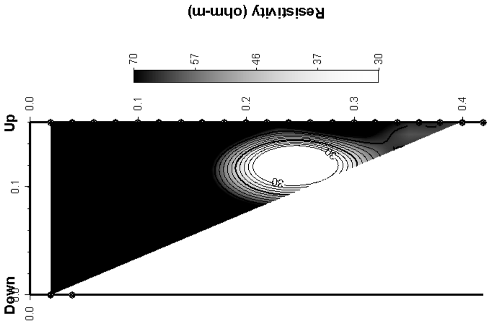
(a) Pole-dipole array



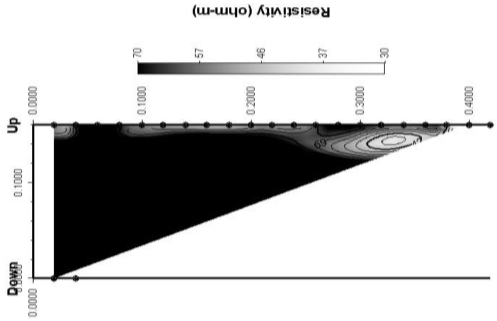
(b) Dipole-dipole array



(c) Modified dipole-dipole array (k+l=8)



(d) Modified dipole-dipole array (k+l=10)



(e) Modified pole-pole array

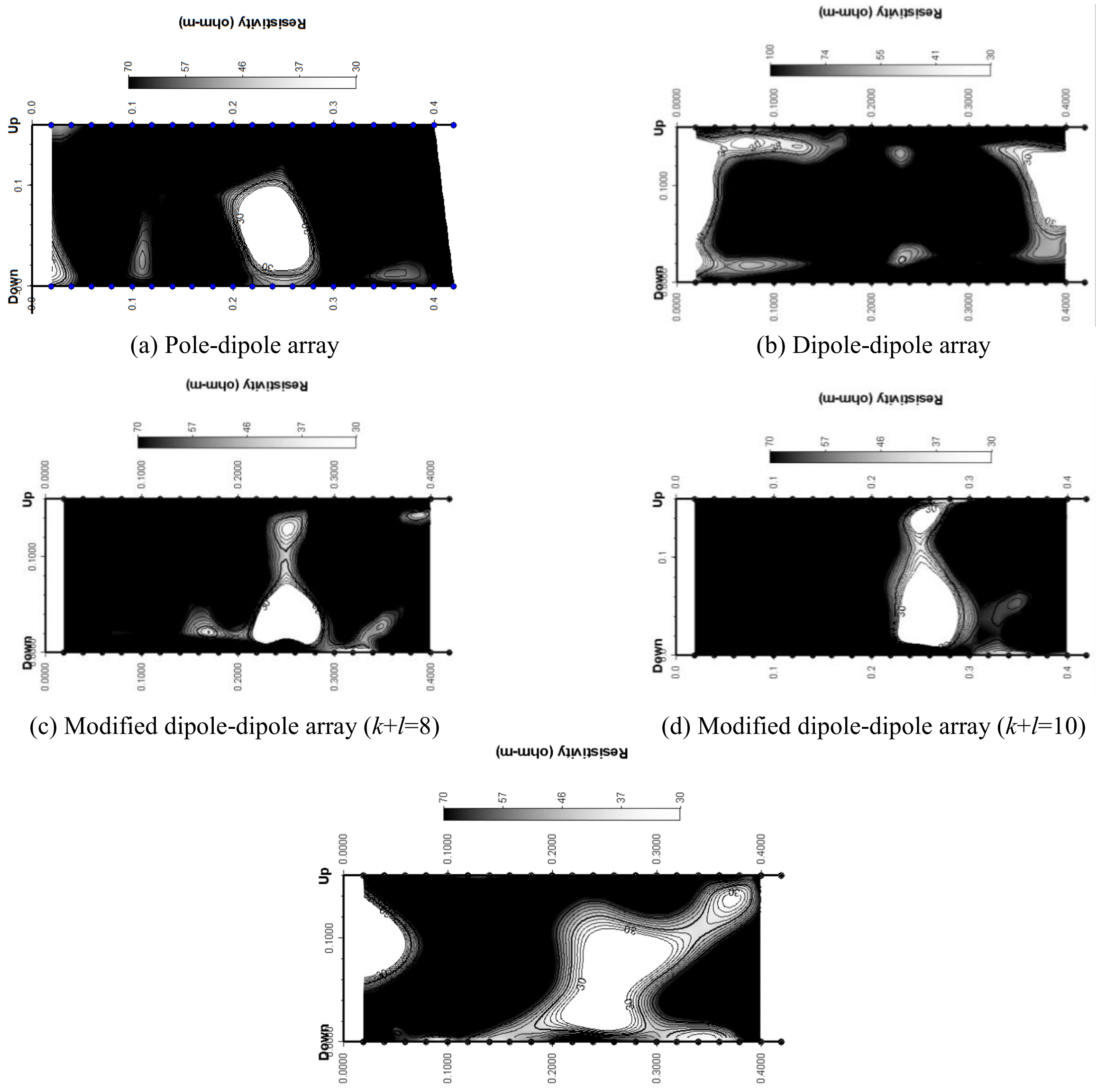
Fig. 8 Laboratory experimental test results with each electrode array (upper borehole length is 20 m and lower borehole length is 1 m)

lower borehole. The pole-pole array and pole-dipole array were excluded from the result analysis due to the following problems that occurred during the measurement or analysis process. For a pole-pole array, it is necessary to input the correct coordinate of remote electrode into an analysis program; however, the TomoDC program used in this study does not allow this type of input. Therefore, the coordinate of the remote electrode was included in the surface electrode for analysis. Consequently, cross-section analyses had to be conducted between the remote and borehole electrodes, leading to the problem of an over capacity of analysis.

For a pole-dipole array, it is not possible to inject a current into the medium during a reverse cross-hole survey and during the inline survey for the upper borehole because of the remote electrode installation problem. Thus, data only from the cross-hole survey was used for the analysis, and the shape or location of the anomaly was not correctly identified due to the lack of measured data, as shown in Fig. 8(a). Apart from these problems, the pole-pole and pole-dipole arrays have difficulty in installing a remote electrode in TBM field site, so that it is hard to apply them to TBM tunneling environment.

The dipole-dipole array has very low potentials on its characteristic; thus, high potentials took place only around the current dipole-dipole array. For both the cross-hole survey and the reverse cross hole survey, the distance between the current dipole-dipole and potential dipole-dipole arrays was at least eight times more than that between the electrodes, and a very low potential was detected. As the current dipole-dipole and potential dipole-dipole arrays were closely located to each other in the inline survey, somewhat higher potential was measured. Thus, the location of anomaly is roughly observed only in sections near the upper borehole as shown in Fig. 8(b).

For a modified dipole-dipole array, the location and shape of the anomaly were more accurate and identifiable than those for the other electrode arrays. The resolution decreases with an increase in the sum of array constants k and l. When the sum of the array constants is 10, the anomaly was widely covered, as shown in Fig. 8(d). When the sum of the array constants is 8, the anomaly size was approximately 10 cm, as shown in Fig. 8(c). This is not so much different from the thickness (6 cm) of the brass block,



(a) Pole-dipole array

(b) Dipole-dipole array

(c) Modified dipole-dipole array (k+l=8)

(d) Modified dipole-dipole array (k+l=10)

(e) Modified pole-pole array

Fig. 9 Laboratory experimental test results with each electrode array (upper borehole length is 20 m and lower borehole length is 20 m)

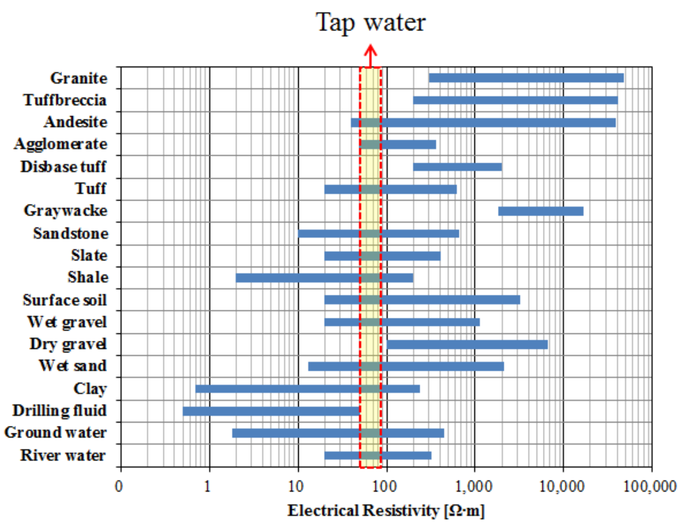


Fig. 10 Distribution of electrical resistivity of geomaterials

which was simulated as the anomaly. In an 8 m diameter TBM, which is usually used for subway tunneling, if the survey technique suggested in this study is adopted for the ground with a 3 m thick anomaly ahead of the tunnel face, the thickness of the anomaly will be assumed as approximately 5 m. Considering the longitudinal length of segment, this is an overestimated result by about 1–2 rings.

For a modified pole-pole array, the survey is performed after fixing negative currents and potential electrodes. In this test, the fixed negative currents and potential electrodes are located very close to the aluminum disc, which was simulated as the TBM cutter head. Thus, a distorted result, which is very different from that of the initially simulated ground model, is obtained because of the noises, as shown in Fig. 8(e).

Fig. 9 shows the test result when the upper and lower borehole lengths are 20 m. As the 20 m length of the lower borehole is long enough, the measured data are abundant. Therefore, its result is more reliable than the case in which the lower borehole length is 1 m. For a pole-dipole array, it is not possible to inject a current into the medium because of the remote electrode installation problem during a reverse cross-hole survey and during an inline survey for the upper borehole. Therefore, the analysis was conducted by combining the data from the cross-hole survey with the data from the inline survey for the lower borehole. As a result, the location and shape of the anomaly were approximately identifiable. However, due to lack of inline survey data for the upper borehole, no anomalies were detected in sections adjacent to the upper borehole, as shown in Fig. 9(a).

The dipole-dipole array has a very low potential; thus, the signal-to-noise ratio (S/N) is observed to be accordingly low. Multiple negative electrical resistivities were observed from the measured data. A low electrical resistivity in an extremely narrow region, where the location of the anomaly was hardly found, turned up because of the analysis. Further, multiple data went through filtering and showed distorted results, which are different from that of the initially simulated ground model, as shown in Fig. 9(b).

For a modified dipole-dipole array, the correct location and shape of the anomaly were more accurate and identifiable than those for the other electrode arrays, as shown in Figs. 9(c)-(d). It was analyzed that the location of the anomalies, located at around 22–28 cm, was consistent with the brass block simulated as the anomaly. The shape of a vertical anomaly was also identifiable. It can be concluded that the modified dipole-dipole array is the best array for predicting the location and shape of the anomaly ahead of the tunnel face in TBM tunneling environments.

For a modified pole-pole array, the location and shape of the anomaly were found widely across the broad sections because its resolution is poorer than that of the modified dipole-dipole array. Although the location of the anomaly was roughly identifiable, the size of the anomaly was overestimated (nearly 1.5–2.0 times in thickness to that of the 6 cm brass block simulated as the anomaly), as shown in Fig. 9(e). In conclusion, it is hard to perform an accurate survey.

Like previous studies, the ground was simulated with water and brass block was used to simulate the anomaly zone in the experimental tests. Fig. 10 shows a typical distribution of electrical resistivity of geomaterials, including tap water. The tap water used in this study has an electrical resistivity of about 70 Ω m as described above. The purpose of this study is to predict the anomaly zone with poor ground conditions when excavating a section with good ground conditions. Therefore, applicability of predicting anomaly zone conducted in this study can be limited in soft clay ground having low electrical resistivity.

The purpose of this study was to predict the anomaly over 3m thickness that could affect the safety of TBM tunnel excavation. Numerical analysis (Lee *et al*. 2019) and experimental test results showed that the electrode distance is appropriate for 1m.

6. Conclusions

This study performed a laboratory experimental test to extend and verify a prediction method proposed by Lee *et al*. (2019), which used the electrical resistivity tomography survey to predict the ground conditions ahead of a tunnel face in TBM tunneling. The laboratory tests were performed by changing the electrode array and borehole length to determine an optimal value for both, in which the anomalies ahead of the tunnel face can be predicted during TBM tunneling. Finally, a modified and verified technique to predict the ground conditions ahead of the tunnel face during TBM tunneling is proposed. The results obtained in this study are as follows:

• A blank test was performed to identify the accuracy of laboratory scaled model test and the influence of errors and noises. The electrical resistivity distribution obtained from the resistivity tomography survey was about 50–90 Ω m, and the overall pattern of the electrical resistivity distribution was similar to the tap water electrical resistivity measured by the conductivity meter, i.e., 70 Ω m. In addition, the potential curves obtained from the numerical analysis and the potential curves measured from the resistivity tomography survey were similar. The ground medium (tap water) constructed in the water tank and the test method proposed in this study are therefore considered appropriate when the equipment measurement errors are considered.

• An anomaly simulation test was conducted by changing the electrode array to find the best electrode array for predicting the anomalies ahead of the tunnel face under the TBM tunneling environment. The dipole-dipole array has very low potentials on its characteristic; thus, high potentials took place only around the current dipole-dipole. The modified pole-pole array showed a very different result from that of the initially simulated ground model since the fixed current and potential electrode are adjacent to the TBM cutter head. The modified dipole-dipole array proved better than the other arrays in terms of predicting the location and shape of the anomalies ahead of the tunnel face.

• It was verified that the modified dipole-dipole array predicted the location and shape of the anomaly well, and it was predicted approximately 60% thicker than the real scenario. In the case that a 3 m thick anomaly is located ahead of the tunnel face in TBM with an 8 m diameter, about 5 m anomaly will be predicted using the technique suggested in this study. Considering the longitudinal length of the segment generally used for the 8 m diameter TBM, this is a gap by about 1–2 rings. The fact that the modified dipole-dipole array predicts a thicker anomaly would help TBM tunneling to predict the presence of an anomaly in advance.

• When the lower borehole is 20 m long, there are various measured data obtained; thus, it predicts the location and shape of an anomaly better than 1 m long lower borehole for most electrode arrays. It is considered that the number and length of boreholes should be properly controlled according to the construction field site environments, such as the location of probe drilling equipment and the borehole excavation time, despite the fact that longer upper and lower borehole lengths lead to better accuracy of the survey.

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