Geomechanics and Engineering, *Vol. 19, No. 1 (2019) 93-104*
DOI: https://doi.org/10.12989/gae.2019.19.1.093

Electrical resistivity tomography survey for prediction of anomaly in mechanized tunneling

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(Received February 22, 2018, Revised September 9, 2019, Accepted September 10, 2019)

Abstract. Anomalies and/or fractured grounds not detected by the surface geophysical and geological survey performed during design stage may cause significant problems during tunnel excavation. Many studies on prediction methods of the ground condition ahead of the tunnel face have been conducted and applied in tunneling construction sites, such as tunnel seismic profiling and probe drilling. However, most such applications have focused on the drill and blast tunneling method. Few studies have been conducted for mechanized tunneling because of the limitation in the available space to perform prediction tests. This study aims to predict the ground condition ahead of the tunnel face in TBM tunneling by using an electrical resistivity tomography survey. It compared the characteristics of each electrode array and performed an investigation on in-situ tunnel boring machine TBM construction site environments. Numerical simulations for each electrode array were performed, to determine the proper electrode array to predict anomalies ahead of the tunnel face. The results showed that the modified dipole–dipole array is, compared to other arrays, the best for predicting the location and condition of an anomaly. As the borehole becomes longer, the measured data increase accordingly. Therefore, longer boreholes allow a more accurate prediction of the location and status of anomalies and complex grounds.

Keywords: electrical resistivity tomography; electrode array; prediction of anomaly; tunnel boring machine; tunnel face

1. Introduction

In general, during the design stage before the excavation of a tunnel, a surface geophysical and geological survey is performed to determine the ground condition and to identify anomalies such as faults, fractured zones, and weakened zones. The ground survey during the design stage mainly focuses on covering broad areas and determining the overall material properties along construction lines. This is important because if unpredicted anomalies are encountered during the tunnel excavation, without a proper response, they can cause significant time and financial losses (Khezri *et al*. 2016, Chong *et al*. 2017). Because, as stated above, understanding the ground condition ahead of the tunnel face is extremely important, a technology is needed to predict the front of the tunnel face in the case of the tunnel boring machine (TBM), in which the ground ahead of the tunnel face is not visible to the naked eye. Many studies on prediction technologies, which can be applicable to mechanized tunneling, have been conducted (Kneib *et al*. 2000, Dowden and Robinson 2001, Li *et al*. 2017, Liu *et al*. 2017).

Kaus and Boening (2008) studied how to predict the ground condition ahead of the tunnel face from electrical resistance measurements and induced polarization by installing an array of electrodes in the cutter head and the side of the main body of a TBM. Most prediction techniques currently used with TBM tunneling, such as bore-tunneling electrical ahead monitoring (BEAM), tunnel seismic profiling (TSP), and ground penetrating radar (GPR), are based on the installation of a sensor in the cutter head for periodic measurements. However, these methods have shortcomings such as low accuracy and low resolution to predict accurately the ground condition ahead of the tunnel face. Considering these disadvantages, Richter (2011) and Schmidt *et al*. (2017) conducted a study on predicting the front of the tunnel face through an irregular borehole radar exploration in a karst topography, where stability is very low.

Because borehole excavation is possible by using a probe drilling equipment installed in the TBM, this study investigates the characteristics of a variety of electrode arrays and analyzes the TBM construction site environments in order to apply the electrical resistivity tomography, which has been used in geophysical surveys, to TBM construction sites. In addition, through a numerical modeling of various arrays of electrodes, considering the conditions in TBM construction sites, an appropriate array of electrodes for predicting anomalies ahead of the tunnel face during TBM construction is proposed. Finally, a new electrical resistivity tomography survey for prediction of ground conditions ahead of the tunnel face in TBM tunneling is proposed.

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http://www.techno-press.org/?journal=gae&subpage=7
ISSN: 2005-307X (Print), 2092-6219 (Online)

2. Electrical resistivity

2.1 Characteristics of electrical resistivity

Electrical resistivity is the material property that quantifies how much a given material resists the flow of an electric current, and a constant indicates that electrical property in a material, regardless of its shape and size. The unit of the constant is ohm-meter (Ωm). While the electrical resistance indicates the degree of difficulty with which a material allows an electric current to pass through, the electrical resistivity represents the electrical resistance of a unit volume of material. The relationship between electrical resistivity (ρ) and electrical resistance (R) can be expressed as in Eq. (1). Here, F_s is the shape factor, which changes along with the shape of a spot where a current flow. F_s in a cylindrical wire is the result of dividing the material length by the cross section.

$$R = \rho F_s \tag{1}$$

The electrical resistivity in rocks changes by porosity, degree of saturation, electrical conductivity of groundwater, content of clay, and other factors (Oh *et al*. 2014). Because a fresher rock has lower porosity and lower level of clay content, higher electrical resistivity is induced. On the contrary, a weathered rock, with lots of fractured zones and joints filled with materials such as clay, has larger porosity, and thus, lower electrical resistivity is induced. A soil has lower electrical resistivity than rock, while a harder rock tends to show higher electrical resistivity. In general, granite, which has higher uniaxial compression strength, shows higher electrical resistivity.

2.2 Electrical resistivity survey and electrical resistivity tomography

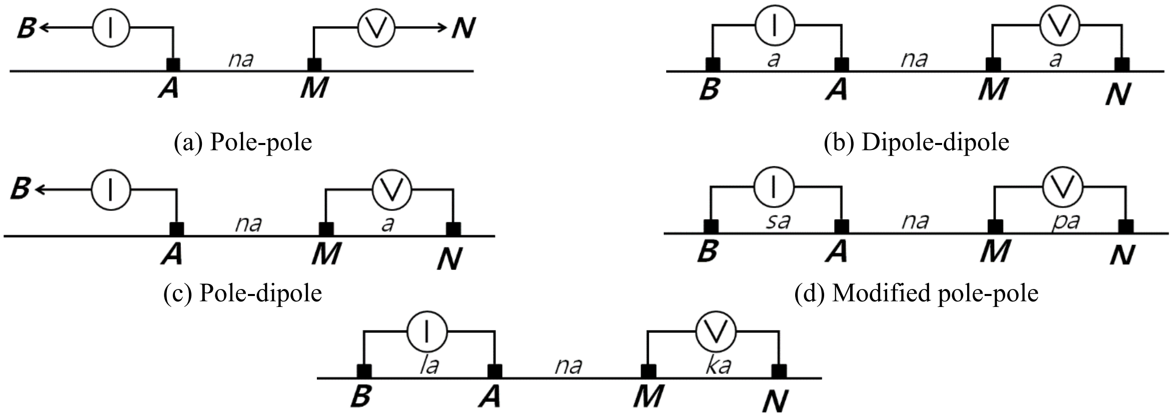
Several types of electrical resistivity surveys have been performed to assess the ground condition using the property of electrical resistivity (Chen *et al*. 2011, Kim *et al*. 2011, Oh *et al*. 2015). Generally, geophysical surveys have been carried out, such as electrical resistivity surveys to investigate the ground conditions of a broad area, borehole loggings of electrical resistivity to identify the ground properties surrounding the boreholes, and electrical resistivity borehole tomography to assess the ground conditions between boreholes. The purpose of the electrical resistivity survey is to ascertain the ground conditions by using the electrical resistivity distribution and has been widely adopted in civil engineering (Ryu *et al*. 2008). It is a method to examine the subsurface condition by installing multiple electrodes on the surface in line with a series of arrays depending on the object to be explored. It measures the electrical resistivity that is produced by artificially letting the current to flow into the underground. The electrical resistivity is influenced by rock properties such as porosity, degree of saturation, groundwater properties inside gaps, types of rock-forming minerals, and particle properties, and by external factors such as fractured zones and faults. Currently, the two-dimensional survey is mainly being used, among the horizontal, vertical, two- and three-dimensional types of surveys. The electrical resistivity survey, as an economical and efficient method, allows a comprehension of geological features, including the comprehensive geological distribution, existence of fractured zones, weathering or alteration degree of strata, and ground water condition.

The electrical resistivity tomography also performs measurements and analyses under the same principle of the electrical resistivity survey. In the electrical resistivity tomography, a borehole is drilled from the ground surface, multiple electrodes are installed inside the borehole letting the survey object to be covered by the electrodes, and a direct current is artificially flowed into the hole to measure the potential difference in the multiple measuring electrodes. This is a type of electrical resistivity survey, which identifies the underground geological characteristics by analyzing the electrical resistivity distribution obtained from the potential differences. The electrical resistivity tomography is different from the surface electrical resistivity survey wherein the resolving power is enhanced by installing electrodes inside the borehole.

2.3 Characteristics of the electrode array

The surface electrical resistivity survey is generally performed using pole-pole, pole-dipole, dipole-dipole, Wenner, or Schlumberger arrays. The electrical resistivity tomography, which requires the installation of electrodes in a borehole for the survey, uses pole-pole, pole-dipole, or dipole-dipole arrays, as shown in Fig. 1. The pole-pole array has the highest signal to noise ratio (S/N ratio) among the three array types, but its resolving power is low. The dipole-dipole array is the best in terms of resolving power; however, its S/N ratio is the lowest (Sasaki 1992). In general, among the three possible arrays, the electrical resistivity tomography mostly uses the pole-pole method. While the dipole-dipole array is frequently adopted in surface surveys, it is very difficult to use it in electrical resistivity tomography. The reason is that not only exists an unmeasurable shadow zone caused by the geometric limitations stemming from the installation of a current and a potential electrode in the subsurface but also a significant negative apparent resistivity occurs (Cho *et al*. 1997).

Kim *et al*. (2001) proposed a modified pole-pole and modified dipole-dipole arrays to compensate the problems of using pole or dipole in electrode arrays as shown in Fig. 1. The modified dipole-dipole array was designed to compensate the low S/N ratio of the existing dipole-dipole array, and it is based on the principle that the potential difference increases as the interval between an electric current and a potential dipole grows. This array is the same as that of the dipole-dipole in pattern, but unlike that array, the distance between the current source dipole and the potential dipole is an integer ratio of the measuring interval (a). The modified pole-pole array is the transformed version of the existing pole-pole array. Under the modified arrangement, a negative current and a potential electrode are fixed at each side of the measurement line, instead of at a remote grounding, but a positive current and a potential electrode move to make measurements, just the same as with the existing pole-pole method. This method is especially useful for a site where a remote grounding is not

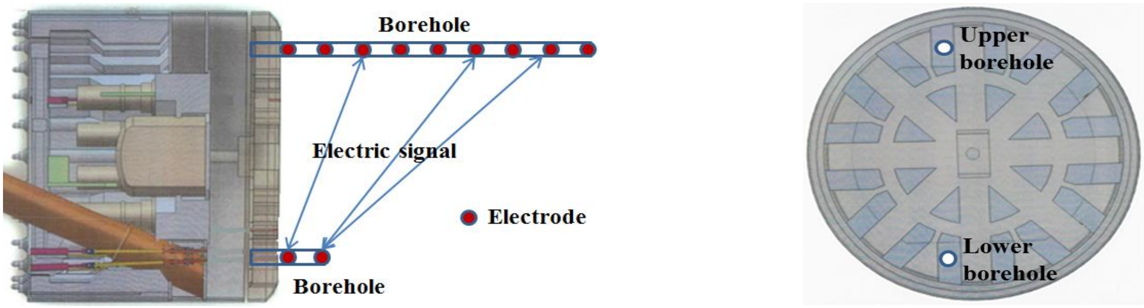


(a) Pole-pole (b) Dipole-dipole

(c) Pole-dipole (d) Modified pole-pole

(e) Modified dipole-dipole

Fig. 1 Electrode format according to electrode array (Lee *et al*. 2011)



(a) Side view (b) Front view

Fig. 2 Schematic diagram of resistivity tomography applicable to TBM

possible. However, because of the fixation of the negative current and potential electrode at each side of the measurement line, the potential measured from both sides of the measurement line displays lower values than that of the pole-pole array. A higher value of potential, which is nearly that of the pole-pole array, is measured at the central area of the measurement line (Kim *et al*. 2001).

By normalizing the potential or potential difference measured at each array into the potential (V_{pp}) measured at the pole-pole array using the electrode interval (a) and electrode separation index (n), Eqs. (2) to (6) indicate that a normalized potential can be induced. The potential measured during the survey consists of electric response and electric noise on the ground. Under the assumption that the electric noise is consistent, the potential level and S/N ratio are directly proportional. If the electrode separation index or/and the electric conductivity on the ground increases, the potential decreases leading to a low S/N ratio. In the modified electrode array, the greater the values of the array constants, s, p, l, and k grow, the higher the S/N ratio becomes.

$$\text{Pole–Pole Array} \;:\; V_{pp} \tag{2}$$

$$\text{Pole–Dipole Array} \;:\; \frac{1}{n+1}V_{pp} \tag{3}$$

$$\text{Dipole–Dipole Array} \;:\; \frac{2}{(n+1)(n+2)}V_{pp} \tag{4}$$

$$\text{Modified Pole–Pole Array} \;:\; \frac{sp\,(s+2n+p)}{(s+n)\,(n+p)\,(s+n+p)}V_{pp} \tag{5}$$

$$\text{Modified Dipole–Dipole Array} \;:\; \frac{kl\,(l+2n+k)}{(l+n)\,(n+k)\,(l+n+k)}V_{pp} \tag{6}$$

3. Suggestion of new electrical resistivity tomography survey

At TBM construction sites, the ground of the tunnel face contacts the cutter head. At the backside of the cutter head, various facilities and mechanical and/or electrical equipment such as a chamber, pressure cell, conveyor, and cylinder, are put in place. Therefore, not only the electrical effect caused by the metallic cutter head during the measurement of electrical resistivity but also noise from multiple electrical equipment can occur. That is, when the electrical resistivity is measured only around the cutter head, it is highly likely that unreliable outcomes will be obtained.

In many TBMs, the probe drilling equipment is installed on the top of the machine. The ground condition determines whether the probe drilling equipment is necessary or not. When the ground condition is poor, the equipment is mostly installed. In the case of measuring electrical resistivity through the electrical resistivity tomography survey, two boreholes ahead of the tunnel face should be excavated. But it is difficult to install the probe drilling equipment on both the top and bottom of the TBM because various facilities and equipment are put in place at the back of the cutter head.

Thus, this study assumes that a 20 m borehole is excavated from the top of a TBM, considering the situation where the probe drill was installed at that position in the TBM. At the same time, it is assumed that a 1 m borehole is excavated from the bottom of the TBM, considering the poor circumstances for excavating a borehole at the bottom of the TBM, as shown in Fig. 2. However, if a space is secured in the early stage of the TBM design for installing a probe drilling equipment at the bottom of the TBM equipment, loading a probe drilling equipment at that position can be possible. Although a probe drilling equipment is installed at the bottom of the TBM, the possible length for the excavation ahead of the tunnel face will be limited when the time constraint for borehole drilling and the multiple equipment facilities or components on the bottom of the TBM main body are considered. Based on these circumstances, a total of five cases are assumed in terms of borehole length drilled on the bottom of the TBM: 1 m, 5 m, 10 m, 15 m, and 20 m. Fig. 2 represents the overview of the new electrical resistivity tomography survey proposed in this study, which is applicable to TBM.

4. Determination of electrode array for new tomography survey

In the TBM construction method, a variety of metallic material and equipment components such as a chamber, pressure cell, conveyor, and cylinder are located at the back of the cutter head. In such an environment, despite the use of a probe drilling equipment for the electrical resistivity survey, the survey result may not be reliable because of the influence from the TBM body and cutter head (Lee 2014). Therefore, this research conducted a numerical simulation considering the TBM environment to determine an appropriate electrode array for the new electrical resistivity tomography survey here suggested.

4.1 Conditions for numerical analysis

This study conducted a numerical simulation 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. As shown in Fig. 3, the interval between an upper and a bottom borehole was determined as 8 m, considering the TBM diameter mainly used for cross sections of roads and subway tunnels. In principle, the cutter head of the TBM should be circle-shaped, but that used for this study was square shaped since TomoDC is a 2.0D analysis program. In this study, the anomaly was vertically aligned to the direction of the tunnel excavation, as shown in Fig. 3. The resistivity of the bedrock was set at 1,000 Ωm and that of the anomaly, which has less strength than a bedrock and many discontinuous planes, was set at 100 Ωm. The

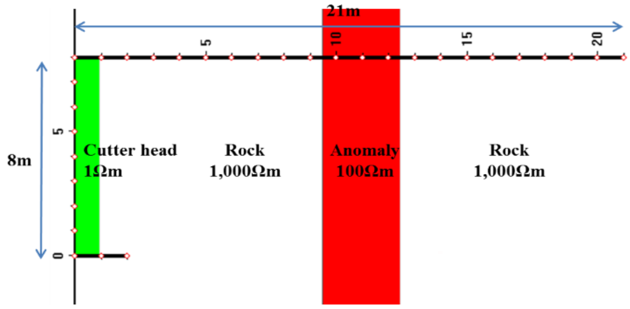


Fig. 3 Conditions for numerical simulation

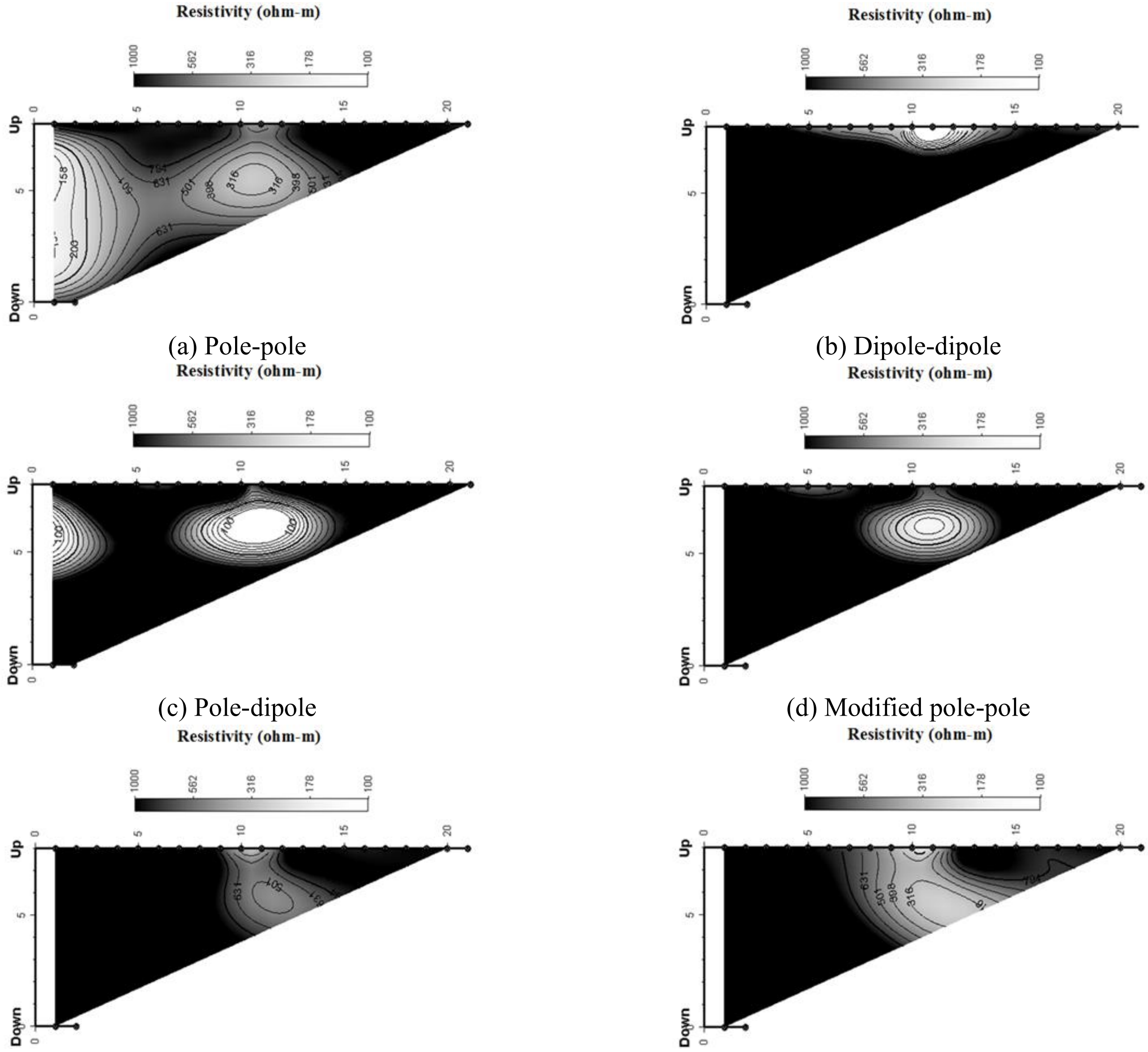
thickness of the anomaly was modeled at 3 m and the distance between the cutter head and the center of the anomaly was modeled at 10 m. The resistivity of cutter head was assumed at 1.0 Ωm as shown in Fig. 3.

The electrode space was set at 1 m, and the electrode arrays used for the numerical simulation were pole-pole, pole-dipole, dipole-dipole, modified pole-pole, and modified dipole-dipole. As the array characteristics of the modified dipole-dipole method change according to the sum of the array constants, the sum of k and l array constants was classified into seven cases: 4, 6, 8, 10, 12, 14, and 16.

The data with extremely low potentials or rapid changing electrical resistivity obtained from the numerical simulation were edited and then analyzed. The data with levels higher than ±5 mV/A according to the variation of the potential were edited for analysis. While this study displayed a high value of potential because it conducted a simulation under the assumption of a bedrock resistivity of 1,000 Ωm, the potential value in the case of a bedrock with low resistivity and/or an anomaly will be very small. In the case of the survey conducted on the ground whose bedrock is composed of weak soil or composite ground with a low resistivity, the potential value can be smaller than ±5 mV/A. In this case, the data with potential lower than ±5 mV/A should be selectively used depending on the construction site environment, and particular care should be taken when the data is edited. TomoDC allows a smooth change in the simulated electrical resistivity distribution by using the smoothness-constrained inversion method, which limits a rapid change in electrical resistivity. Therefore, the data from sections where the electrical resistivity sharply changed (tens of times in a short period of time) were deleted because of the possibility of producing a result that did not reflect the actual ground condition. As a result of executing the inversion analysis without data editing, the electrical resistivity of the anomaly obtained from the analysis was much lower than that of the input in an anomaly model.

4.2 Results of numerical analysis according to electrode array

The results of the numerical simulation according to the electrode array are presented in Fig. 4. Here, the maximum contour line is set at 1,000 Ωm, because the bedrock electrical resistivity is 1,000 Ωm, and the minimum contour line is set at 100 Ωm, as the anomaly electrical resistivity is 100 Ωm. Because the pole-pole array has low resolving



(a) Pole-pole (b) Dipole-dipole

(c) Pole-dipole (d) Modified pole-pole

(e) Modified dipole-dipole (k+l=8) (f) Modified dipole-dipole (k+l=10)

Fig. 4 Numerical analysis results according to electrode array

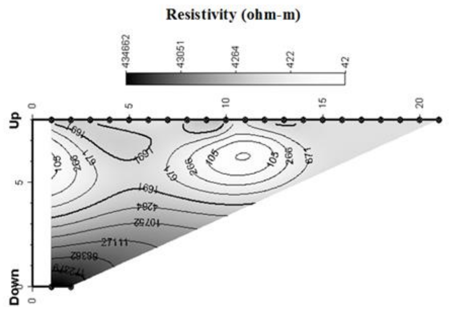
power, the effect of the cutter head and anomaly is widely seen, as shown in Fig. 4(a). The result shows a very different form from that of the modeled situation, and the anomaly appears connected to the cutter head. Although the electrical resistivity of the modeled anomaly was 100 Ωm, the analyzed anomaly's resistivity was about 300 Ωm. The problem for the dipole-dipole array is that its potential is so low that the S/N ratio is accordingly too low.

In the dipole-dipole array, the high potential is located only around the current dipole-dipole and the remaining areas have not only extremely low potentials but also shadow zones where the potential difference is nearly zero (Cho *et al*. 1997). Therefore, proper measurements will be possible only in the inline survey in which the current dipole-dipole is located, near the potential dipole-dipole. As shown in Fig. 4(b), the location of the anomaly is roughly observed only in sections near the upper borehole. In conclusion, it is considered that with the dipole-dipole array it is difficult to predict the accurate form or location of an anomaly.

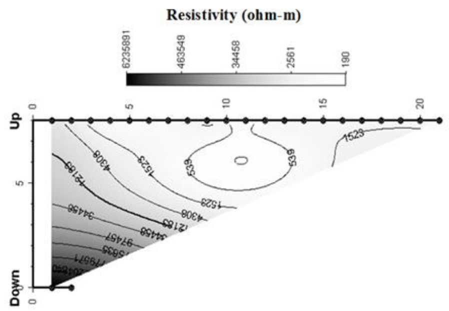
Just as in the pole-pole case, the pole-dipole array faces low resistivity around the cutter head, owing to its effect, as shown in Fig. 4(c). In terms of resolving power, this case is among the low-level electrode arrays, although it ranks higher than the pole-pole array. With respect to the anomaly, the thickness of the pole-dipole array is smaller than that of the pole-pole array but the anomaly horizontally spanned approximately 6 m because its resolving power is low. The electrical resistivity is similar to that of the modeled anomalies. The modified pole-pole array shows almost the same result but has a thinner anomaly than the pole-dipole array, as shown in Fig. 4(d).

When the sum is 8 or 10, the vertical anomaly appears as modeled in the simulation, as shown in Figs. 4(e) and (f). A relatively accurate prediction of the anomaly is possible, compared to the other arrays, and the anomaly thickness is about 5 m. The shape of the anomaly is somewhat dented because the borehole and electrode array are asymmetrical. The modified dipole-dipole array is better than the pole-pole array in terms of resolving power; nonetheless, the anomaly resistivity is 200-500 Ωm.

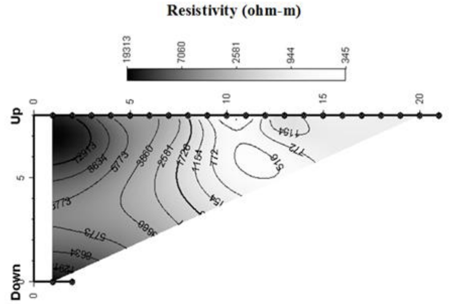
The electrical resistivity of the bedrock was analyzed to be 1,000 Ωm, as shown in Fig. 4, because the minimum and maximum values of the contour lines were set at 100 Ωm



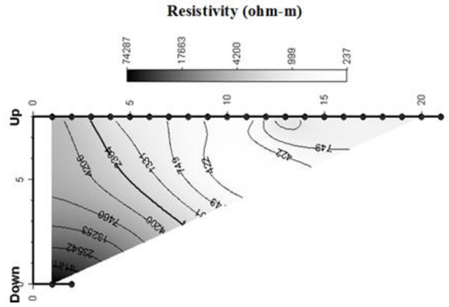
(a) Pole-dipole



(b) Modified pole-pole

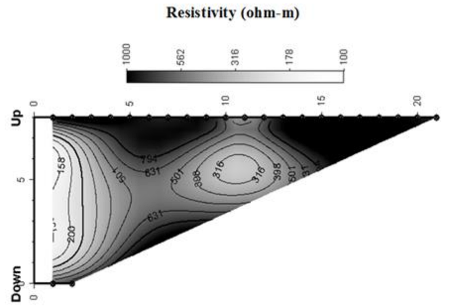


(c) Modified dipole-dipole (k+l=8)

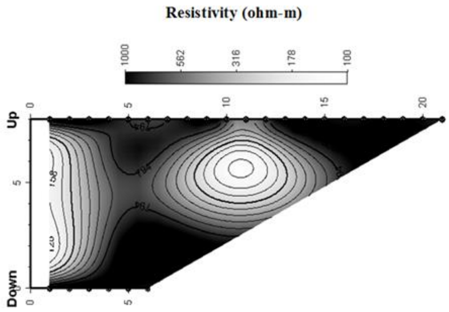


(d) Modified dipole-dipole (k+l=10)

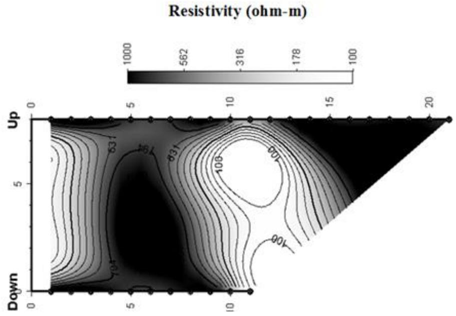
Fig. 5 Numerical analysis results according to electrode array (no limit contour case)



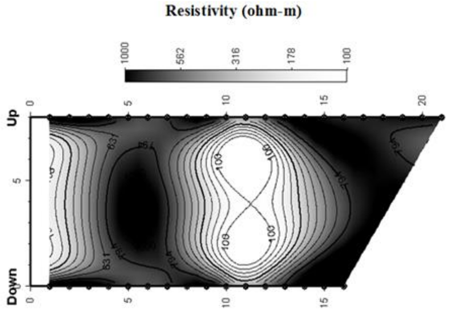
(a) Lower borehole length 1 m



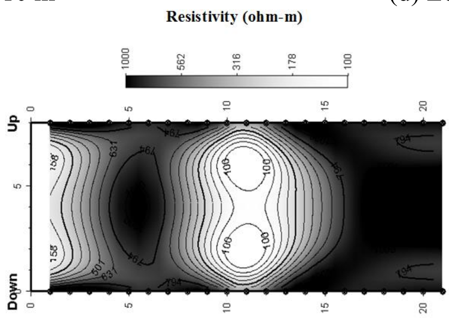
(b) Lower borehole length 5 m



(c) Lower borehole length 10 m

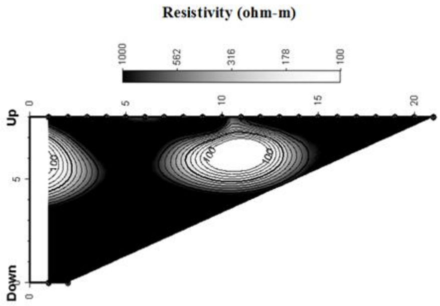


(d) Lower borehole length 15 m

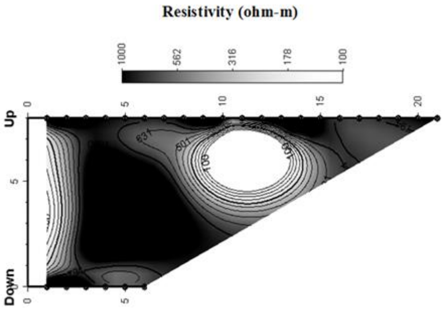


(e) Lower borehole length 20 m

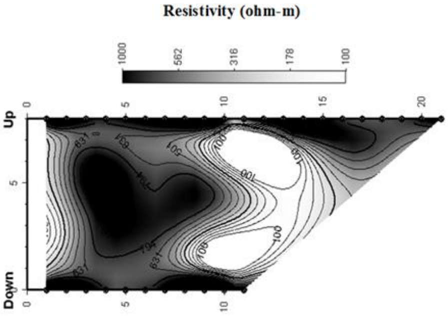
Fig. 6 Results of pole-pole array according to borehole length



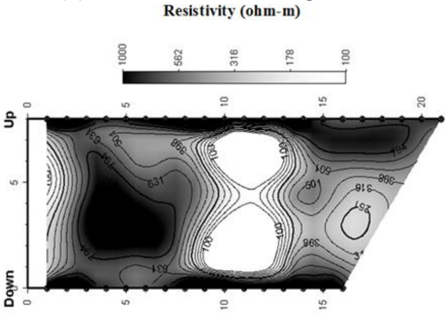
(a) Lower borehole length 1 m



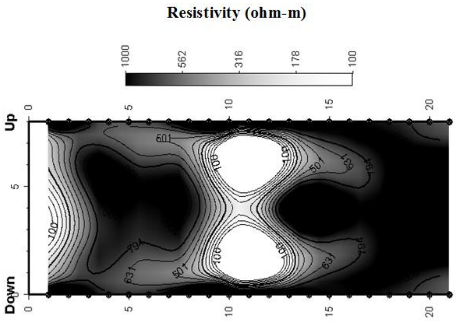
(b) Lower borehole length 5 m



(c) Lower borehole length 10 m

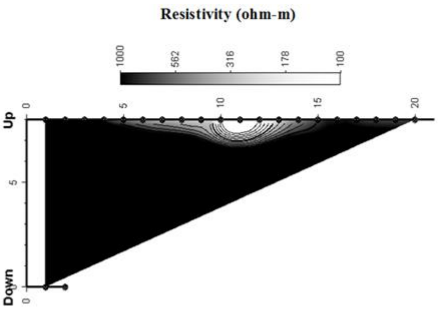


(d) Lower borehole length 15 m

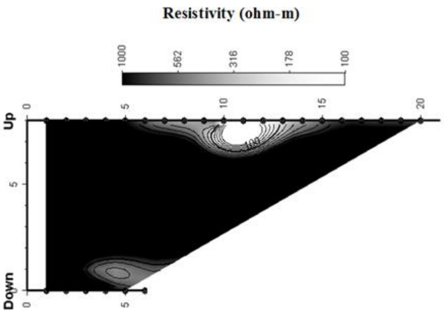


(e) Lower borehole length 20 m

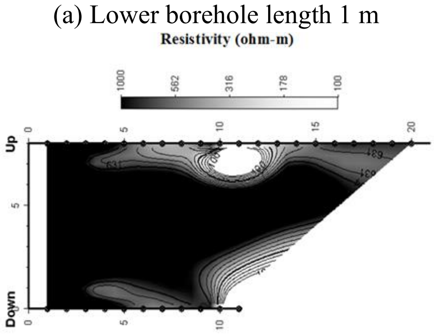
Fig. 7 Results of pole-dipole array according to borehole length



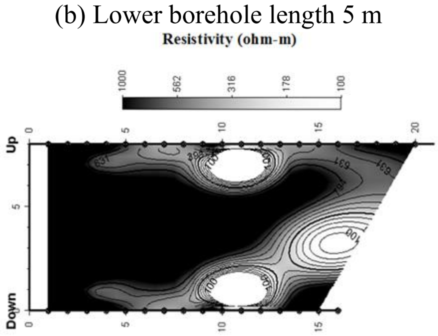
(a) Lower borehole length 1 m



(b) Lower borehole length 5 m

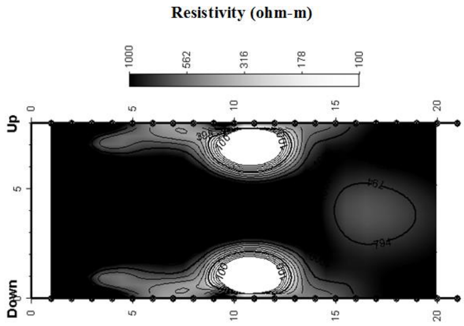


(c) Lower borehole length 10 m



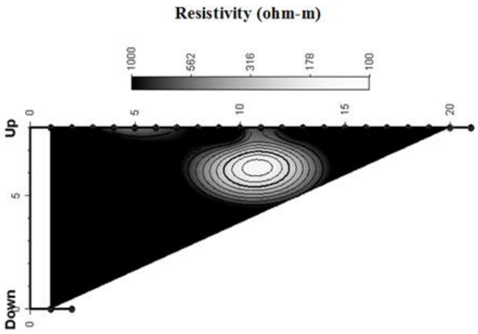
(d) Lower borehole length 15 m

Fig. 8 Results of dipole-dipole array according to borehole length (continued)

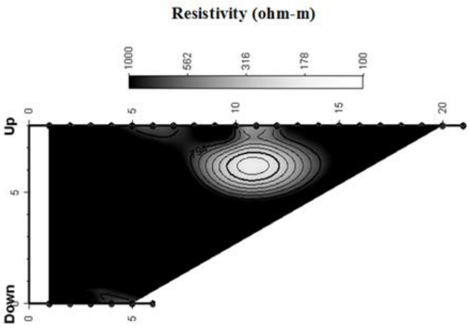


(e) Lower borehole length 20 m

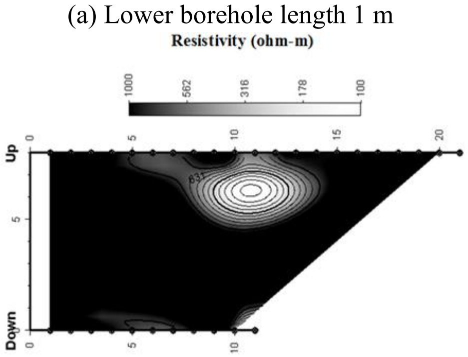
Fig. 8 Results of dipole-dipole array according to borehole length



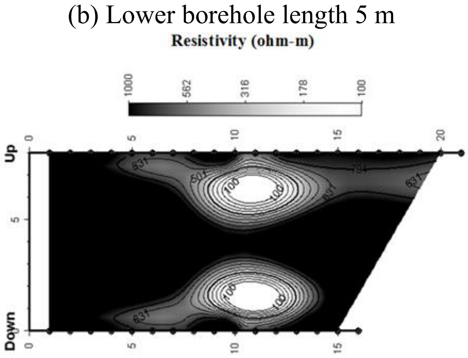
(a) Lower borehole length 1 m



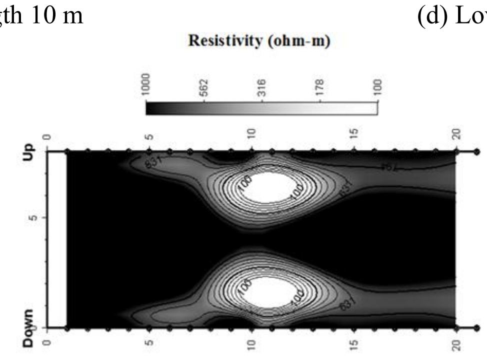
(b) Lower borehole length 5 m



(c) Lower borehole length 10 m



(d) Lower borehole length 15 m

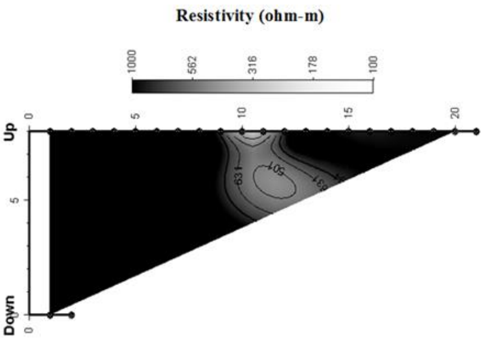


(e) Lower borehole length 20 m

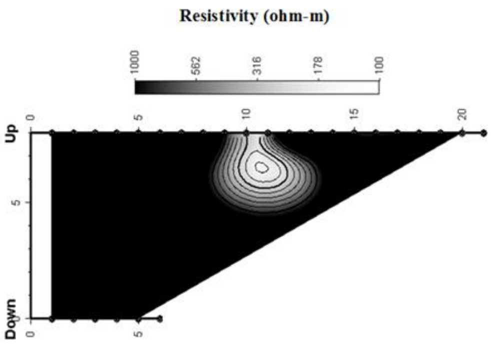
Fig. 9 Results of modified pole-pole array according to borehole length

and 1,000 Ωm, respectively. However, considering a case without a limit value of the contour line, excepting the pole-pole and pole-dipole arrays, the rest of them tend to show high electrical resistivity in the sections adjacent to the cutter head and from the tunnel face to about 5-8 m further ahead at the bottom borehole, as shown in Fig. 5.

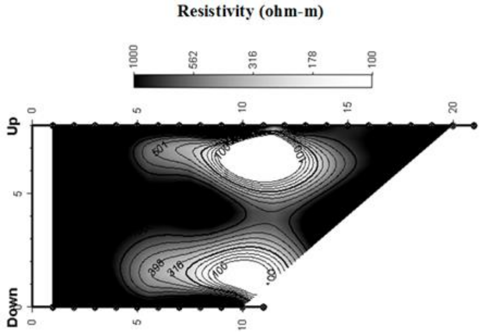
As a result of the numerical simulation using various electrode arrays, the location and status of the anomaly seems to be properly predicted if the electrical resistivity tomography survey is executed using the pole-dipole array in the TBM site. In addition, if the interval between the potential electrodes increases, the resolution becomes even higher. However, in the TBM site, there are a cutter head and a variety of equipment in the backside of the chamber, and various supporting materials in the tunnel cross section are installed (shotcrete and wire mesh for the open TBM



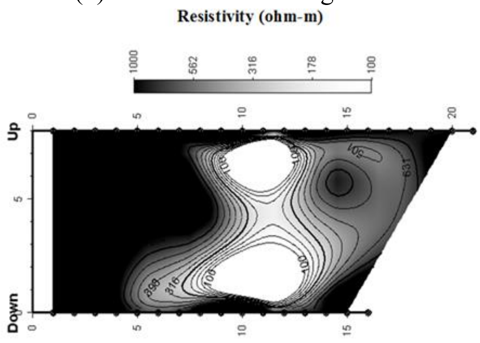
(a) Lower borehole length 1 m



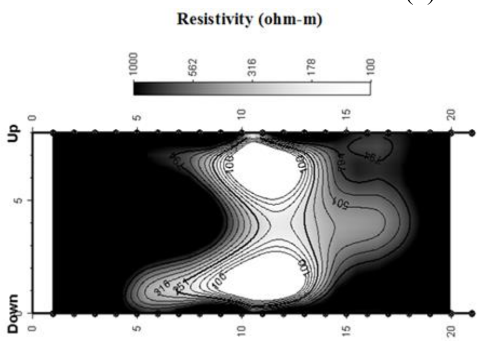
(b) Lower borehole length 5 m



(c) Lower borehole length 10 m



(d) Lower borehole length 15 m



(e) Lower borehole length 20 m

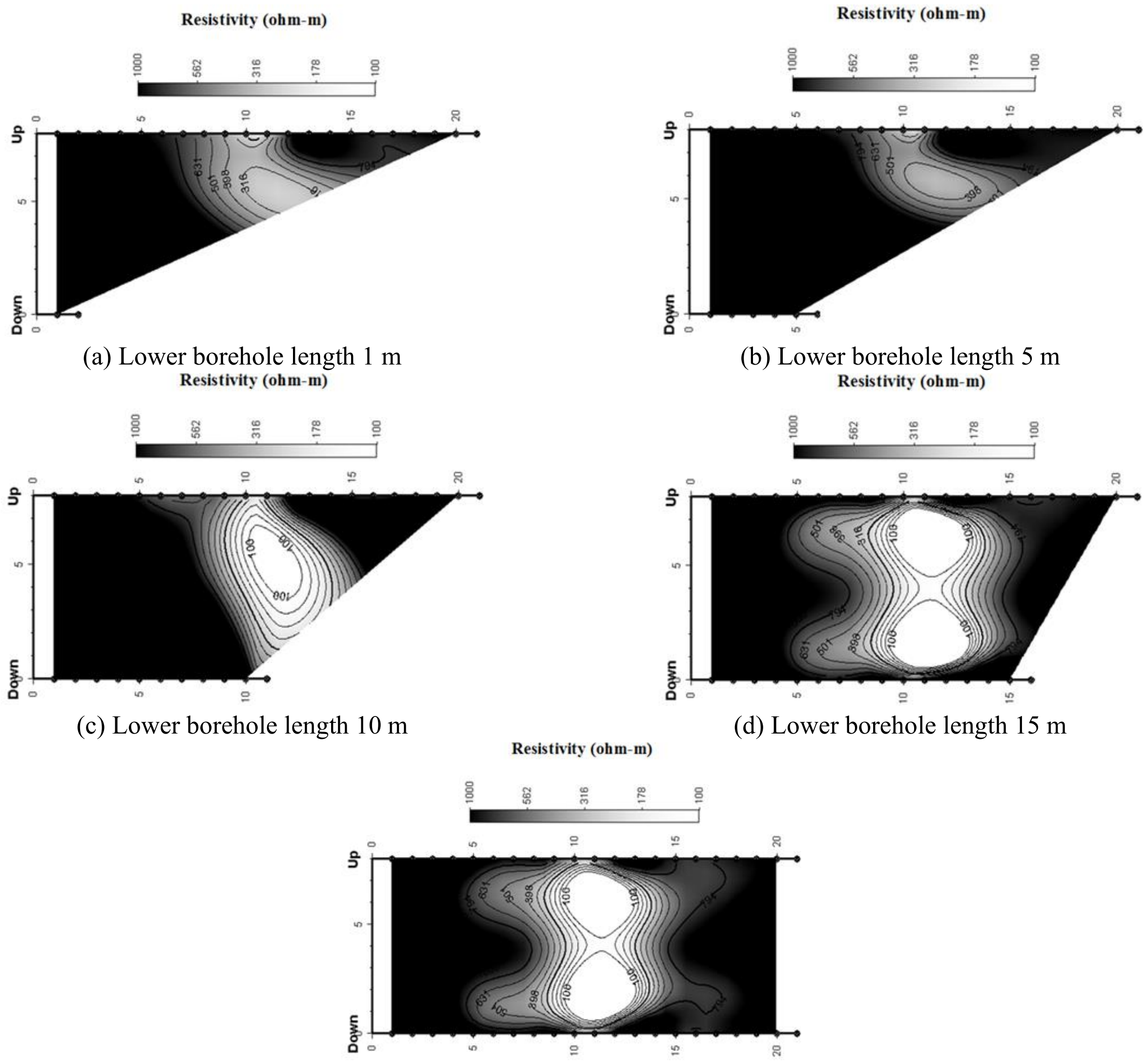
Fig. 10 Results of modified dipole-dipole array (k+l=8) according to borehole length

and segments for the shield TBM). Therefore, no adequate place to install a remote ground electrode far from the electrical influence can be found. If the remote ground electrode is in a wrong place, the entire data may cast doubts in terms of their reliability. Among the various electrode arrays, the modified dipole-dipole array in which the sum of array constants k and l is 8 or 10 best predicted the location and form of the anomaly. In addition, the modified dipole-dipole array does not require remote ground electrode installation. Therefore, it is concluded that an accurate prediction of the ground condition ahead of the tunnel face is possible by performing the electrical resistivity tomography survey by using the modified dipole-dipole array. Furthermore, this is the most appropriate method for the TBM site. Note that a specific care should be taken, as there is a quite significant difference between the true and the analyzed values of electrical resistivity of the anomaly.

4.3 Results of numerical analysis according to lower borehole length

Numerical simulations with each electrode array along with changes in the lower borehole length were performed. If the lower borehole gets longer, the amount of measured data sharply increases. This is true for all the electrode arrays, and therefore, it is possible to predict accurately the zone and status of the anomaly. For the pole-pole array, a 1 m borehole length leads to 208 pieces of data, while 10 m and 20 m lengths lead to 451 and 771 data points, respectively, with a maximum difference of four times. Therefore, the longer the lower borehole length gets, the more reliable the produced results and a better prediction of shape and location of the anomaly is possible.

Figs. 6-11 present the results of the numerical analysis with each electrode array along with the changes in lower borehole lengths. For the case of the pole-pole array, the cutter head and the anomaly are distributed across wide areas, despite the longer lower boreholes, as shown in Fig. 6. When the lower borehole length was longer than 10 m, the analyzed electrical resistivity of the anomaly displayed a very similar result to that of the modeled, i.e., 100 Ωm. The pole-dipole array shows a horizontal anomaly when the lower borehole is short, but the anomaly shape becomes more vertically shaped, as the modeled anomaly, when the



(a) Lower borehole length 1 m

(b) Lower borehole length 5 m

(c) Lower borehole length 10 m

(d) Lower borehole length 15 m

(e) Lower borehole length 20 m

Fig. 11 Results of modified dipole-dipole array (k+l=10) according to borehole length

lower borehole becomes longer, as shown in Fig. 7. Because the pole-pole and pole-dipole arrays have low resolution, the anomaly thickness is large, and the remaining area away from the modeled anomaly also shows low electrical resistivity.

As shown in Fig. 8, the dipole-dipole array does not show a vertical anomaly, even if the borehole length becomes longer, as it has a low potential. In addition, it shows two anomalies located around the boreholes, which was not expected. However, owing to the high resolution of the dipole-dipole array, the electrical resistivity of the analyzed anomaly was the same as that of the modeled anomaly, 100 Ωm, even when the lower borehole is 1 m long. In the modified pole-pole array, as the borehole gets longer, the anomaly appears only around the borehole because its potential becomes lower from a certain point, as shown in Fig. 9. This result is similar to that of the dipole-dipole array.

As shown in Figs. 10-11, in the modified dipole-dipole array where the sum of the array constants k and l is 8 or 10, the anomaly is vertically located from the point where the lower borehole is 1 m long or longer. The longer the borehole length becomes, the better prediction for the shape of the anomaly is possible. However, the anomaly thickness is about 4-5 m, somewhat thick, because the resolution gets poorer as the sum of the array constants becomes larger. In the analysis of underground electrical resistivity distribution, the smoothness-constrained inversion method was used to allow a smooth change in the electrical resistivity distribution. Because of that, it was not possible to predict accurately the modeled anomaly thickness, 3 m. Nonetheless, the electrode array that best predicts the location, shape, and thickness of the anomaly is the modified dipole-dipole array. Besides, as the lower borehole gets longer, the electrical resistivity of the analyzed anomalies was similar to that of the modeled anomalies, 100 Ωm.

5. Conclusions

The purpose of this study was to predict the ground condition ahead of the tunnel face in a TBM tunneling site by using the electrical resistivity tomography survey. This study compared the characteristics of each electrode array and performed an investigation on in-situ TBM construction site environments. Numerical simulations for each electrode array were carried out in order to determine the proper electrode array to predict anomalies ahead of the tunnel face. The results obtained in this study are as follows:

• The TBM site is faced with electrical noises because various mechanical and electrical equipment components are located there. Thus, it is highly unlikely that reliable results will be obtained when estimating the electrical resistivity of the ground, because the metallic cutter head contacts the ground. Against this backdrop, this study proposed a new method in which an electrical resistivity tomography survey can be executed by excavating boreholes and inserting electrodes, using the probe drilling equipment installed in the TBM.

• For the case of the pole-pole array, during the electrical resistivity tomography survey in the TBM, it was very difficult to identify the ground condition ahead of the tunnel face owing to the influence of the cutter head, compounded by the fact that its resolving power is low. It seems practically impossible to apply the resistivity tomography survey with the dipole-dipole array, owing to its very low S/N ratio, which is one of the properties of this array.

• The pole-dipole and modified dipole-dipole arrays predicted well the location and status of anomaly. However, the pole-dipole array is difficult to use in TBM tunneling, as it requires remote ground electrode installation. Therefore, it is considered appropriate to carry out the electrical resistivity tomography survey in TBM tunneling using the modified dipole-dipole array.

• For the case of the modified dipole-dipole array, it was possible to make an accurate prediction of the shape and location of the anomaly when the sum of the array constants k and l is 8 or 10. However, it was hard to predict the true value of the ground electrical resistivity. Therefore, considerate care for this issue should be taken during the electrical resistivity tomography survey in TBM tunneling.

• As the lower borehole length becomes longer, the amount of measured data increases accordingly. Therefore, a longer lower borehole allows a more accurate prediction of the location and status of anomalies and complex grounds. It is recommended that the number and length of boreholes should be properly controlled according to the TBM site environments, despite the fact that longer upper and lower boreholes lead to better accuracy of the survey.

Acknowledgements

This research was supported by a grant (Project number: 13SCIP-B066321-01 (Development of Key Subsea Tunnelling Technology)) from the Infrastructure and Transportation Technology Promotion Research Program funded by the Ministry of Land, Infrastructure, and Transport of the Korean government.

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