Pitfalls in Three-Dimensional Numerical Modeling of Electrical Resistivity Method

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Abstract
Three-dimensional electrical resistivity surveys have been regarded as one of the best techniques to eliminate subsurface shallow targets, although, the method suffers from ambiguity in the data interpretation. Therefore, numerical modeling has been involved for more comprehensive data interpretation. Several numerical modeling software packages have been developed, for example, RES3DMODx64. In addition, to perform a three-dimensional resistivity survey, a set of electrodes should be deployed as a grid on the ground surface which might be as a rectangular or a square grid. The optimum survey grid and electrode arrays, however, have to be tested. A three-dimensional subsurface resistive target has been numerically modeled before multiple three-dimensional resistivity data sets were generated using both of the rectangular and the square grids, and by utilizing the most popular electrode arrays; dipole-dipole, pole-pole, and, Wenner arrays. The data sets are then, inverted using a robust inversion algorithm, to generate three-dimensional resistivity models. Results were used in a quantitative comparison, and it showed that the dipole-dipole array was the optimum array in delineating the target’s shape, position, and resistivity value using the square grid. On the second rank, the rectangular grid uses the dipole-dipole array, then, followed by the Wenner array on the third rank. The pole-pole array was the poorest in the reconstruction of the subsurface target.

Keywords: Electrical resistivity method; 2D modeling; 3D modeling; Electrode array

1. Introduction

The electrical resistivity method has been known as a non-destructive geophysical method and has a wide range of applications, for example, engineering (Abed et al., 2020), archaeological (Al-Hameedawi et al., 2021), environmental (Thabit and Khalid, 2016; Al-Menshed and Thabit, 2017), and natural cavities investigations (Thabit et al., 2015; Abed et al., 2021). Due to the sensitivity of the resistivity method to the ions concentration, therefore, the method has been applied for seawater intrusions in fresh groundwater (Abdulameer et al., 2018). Although, all the subsurface anomalies are distributed in three dimensions, two-dimensional surveys (2D surveys) are the most utilized. Due to recent developments in acquisition equipment and data interpretation software, three-dimensional surveys (3D surveys) get more popular. For the 2D surveys, the method is a more cost-effective and simple technique to be performed in the field, if it is compared with the 3D surveys (Loke et al., 2013).

DOI: 10.46717/igj.55.1C.11Ms-2022-03-30
However, some limitations such as ambiguity in the data interpretation might be the most challenging circumstance of the resistivity method. In addition, variations in the shallow subsurface resistivities might prevent imaging deeper targets, (Keary et al., 2002).

Variations in subsurface electrical resistivity can be imaged by applying an electrical current and then measuring the potential difference of the ground. Any contrast, from background hosting material, then can be represented by an anomaly, where the anomaly can have a higher or lower value of resistivity than the background’s resistivity value. To read a single resistivity value, a pair of metal electrodes are needed to inject the electrical current and another pair to measure the potential difference. To cover a survey profile, many electrodes connected by a multicore cable to a resistivity meter should be deployed, (Loke and Barker, 1995). The current and potential electrodes arrangement is named electrode configuration or, sometimes, electrode array. The most popular electrode configurations are Wenner, Wenner-Schlumberger, pole-pole; for more details about the electrode configurations, (Szalai and Szarka, 2008).

In many investigations, due to the ambiguity limitation of the method, data interpretation can be a difficult task to do. Therefore, two-dimensional (2D) and three-dimensional (3D) electrical resistivity modeling approaches have been engaged for more comprehensive data interpretation. RES2DMOD (Loke, 1999) and RES3DMODx64 (Loke, 2018a) are commonly used software packages for 2D and 3D numerical modeling, respectively. Bauer et al., (2006) applied the RES2DMOD to simulate soil and groundwater salinization problems. The RES3DMODx64 has been performed in different simulation studies, for example, seasonal monitoring of moisture content variation in river’s embankment and to determine possible seepage (Hojat et al., 2020), in a shallow landslide triggered by rainfall (Hojat et al., 2019), in monitoring leakage from underground storage tanks (Rucker et al., 2011).

The RES3DMODx64 calculates the apparent electrical resistivity by using the finite difference method or finite element method. This simulation package supports the most popular arrays, for example, Wenner (W), Wenner-Schlumberger (WS), pole-pole (PP), and dipole-dipole (DD) arrays. The electrodes should be arranged in a grid (in x and y directions) on the ground surface to achieve the 3D surveys. The grid might have a rectangular shape (the electrode spread in x direction longer than the electrode spread in the y direction) or the grid have a square shape (the electrodes have an equal separation in both x and y directions). In addition, the RES3DMODx64, supports three options to save the generated apparent resistivity data, these are 1) only save values in x direction, 2) only save values in y direction, and 3) save values in both x and y directions.

This study aims to qualitatively compare: 1) the rectangular and the square grids, and 2) the saved values in only x, in only y, and in both x and y directions. To verify these aims, the following objectives were obeyed, 1) to generate 3D resistivity data sets, of a subsurface target, using the rectangular and square grids, 2), to save the data sets in only x, in only y, and in x and y directions, 3) to replicate the data generation using three arrays (W, PP, and DD), 4) to invert the apparent resistivity data sets using the algorithm of robust inversion, and 5) to evaluate the inverted image and determine the optimum one in reconstruction the modelled subsurface target.

2. Materials and Methods

Two electrode grids (rectangular and square) were applied in the forward modeling phase of this study to image a resistive subsurface target by performing the finite difference method. The target has a resistivity value of 200 kΩ.m whilst the hosting background has 20 Ω.m resistivity value. The target dimensions were 2 m in the x and y directions and the upper boundary was at depth of 0.4 m and the lower boundary was at 1.6 m, therefore, the height of the target was 1.2 m. These dimensions were chosen to mimic a resistive anomaly for, almost, engineering applications, for example, a buried storage tank or a concrete foundation. The rectangular grid has 31 electrodes in the x direction and 15 electrodes...
in the y direction (Fig. 1a). The square grid has 31 electrodes in both of the x and y directions (Fig. 1b). The electrode spacing was kept 0.25 m in both of the grids and in both of x and y directions. Two nodes were utilized between any two adjacent electrodes. RES3DINx64 ver. 3.15 (Geotomo software) was used to invert all the generated data sets. As the subsurface target has a blocky shape and sharp boundaries, robust inversion algorithm, therefore, was used in the inversion process, (Claerbout and Muir, 1973). Throughout this study, 5th iteration was used.

![Fig. 1. Forward modeling using the RES3DMODx64 ver. 3.06, (a) rectangular grid survey theme, and (b) square grid survey theme. The high resistive block represents the target’s shape and location](image)

3. Results

3.1. Rectangular Grid

The inverted images of DD, PP, and W arrays are represented in Figs. 2, 3 and 4 respectively; where: a) for the values saved in the x direction, b) for the values saved in the y direction, and c) for the values saved in both of x and y directions. All the applied arrays were successful in recognizing the subsurface resistive target, although, the target was imaged in different resistivity values and in various shapes. For the DD array, the data set in the x direction, and the data set in both of the x and y directions, can reconstruct the target in a square shape that matches with the actual shape of the target. The data that is saved in the y direction shows the target elongated in the y direction more than the actual geometry (Fig. 2b). The target’s anomaly gets more elongated with depth, see layer 4 through layer 9.
Fig. 2. Inverted images of the DD array, a) for values saved in x direction; b) for values saved in y direction; and c) for values saved in both x and y directions

The PP array data sets are illustrated in Fig. 3. In x direction data set, the target looks stretched in the x direction of the grid whilst in the data set that is saved in the y direction, the target’s anomaly appears stretched in the y direction of the grid. The stretching phenomenon is represented more clearly
on deeper layers, see layers 7 through 9. In the third case, the data saved in both x and y directions, resolves the target in a shape that, almost, has the actual geometry of the target, less stretching, and the anomaly be more circular rather than elongated on a certain direction with depth. For the Wenner array data sets, the data saved in the only x direction, the data saved in the only y direction, and the data saved in both of x and y directions, were able to reconstruct the target in a quite similar anomaly. The target appears to have a square-like shape (matching the real geometry of the target) on layers 2 through 5. Then, on layers 6, 7, and 8 misfits the target actual shape where the anomaly appears more circular.

**Fig. 3.** Inverted images of the PP array, a) for values saved in x direction; b) for values saved in y direction; and c) for values saved in both x and y directions
In terms of the position of the target, the DD array does not resolve the target on shallower depth, if it is compared with its real depth, see layer two in Fig. 2. However, the inverted images from the pole-pole and the Wenner arrays produce the target’s anomaly on shallower depth, see layers number 2 in Figs. 3 and 4.

Fig. 4. Inverted images of the W array, a) for values saved in x direction; b) for values saved in y direction; and c) for values saved in both x and y directions.
For the PP and the W arrays, respectively. Another advantage of the DD array over the PP and W arrays is that the former was able to reconstruct the target with a resistivity value much closer to the real model compared with PP and W arrays. For the resistivity value of the target, the DD shows the target with more than 150 Ω.m, however, the PP and W arrays show the target with even less than 70 Ω.m. The better results of the DD array and the poorest results of the PP array might be related to the arrays sensitivities. The DD array is more sensitive to shallow targets and also has a good resolution in reconstruction the target; especially with the shallowest levels of investigations. Whilst the PP array has, almost, the poorest sensitivity and resolution; for more details about different arrays sensitivities, see, Loke (2018b).

3.2. Square grid

Inverted images of the DD array are represented in Fig. 5 through Figs. 6 and 7, data saved in x, in y, and in both of x and y directions, respectively. The shape of the target was equally and well resolved on all the saved data sets, and on all the layers where no obvious stretching can be seen on any one of them. The array was sensitive to the upper boundary of the target and it does not image it on shallower depth, see layers number 2 on Figs. 5 and 7. It, also, succeeded in imaging the target with a resistivity value of 150 Ω.m, which is closer to the real model resistivity value.

![Fig. 5. Inverted images of the DD array for values saved in x direction](image)

For the pole-pole array, the resistivity model of the x direction data set shows the target with a square shape on the third layer and on the fourth layer. After that, starching phenomenon starts to appear slightly and increases with deeper layers, where the misfit in imaging the target is obvious and oriented in the x direction of the electrodes grid (Fig.8), the saved data set in the y direction, displays the enlargement in the target’s anomaly and parallel to the y direction of the grid (Fig. 9). However, the data set that is saved in both of x and y directions, can overcome the target’s enlargement issue and represents it by a closer shape and dimension to the actual geometry. The target’s anomaly becomes more circular with depth (Fig. 10).
Resistivity images that generated from inverting data sets of the Wenner array resolved the target in a similar response where there is no difference among the data sets that saved in the x, in the y, and in both of x and y directions, as represented in Figs. 11, 12, 13, respectively. A square shape was generated for the target on layers 4, 5, and 6. On deeper layers, the anomaly was more circular. Both PP and W arrays image the target on shallower depth. The arrays underestimate the target’s resistivity value and resolve it with less than 70 Ω.m.

Fig. 6. Inverted images of the DD array for values saved in y direction

Fig. 7. Inverted images of the DD array for values saved in both x and y directions
Fig. 8. Inverted images of the PP array for values saved in x direction

Fig. 9. Inverted images of the PP array for values saved in y direction
Fig. 10. Inverted images of the PP array for values saved in x and y directions

Fig. 11. Inverted images of the Wenner array for values saved in x direction
Fig. 12. Inverted images of the Wenner array for values saved in y direction

Fig. 13. Inverted images of the Wenner array for values saved in x and y direction
In general, the square grid shows better results compared with the rectangular grid particularly for the data saved in both of x and y directions. That might be related to the survey profile in the x direction having the same length as the survey profile in the y direction, in the square grid surveys. Due to the fact that the investigation depth in the electrical resistivity surveys is profile length-dependent, where the longer profiles can investigate deeper, therefore, the profiles in x and y directions have the same investigated depth. Combining x and y direction data sets in one model, therefore, can be sounder and the data sets in the x and y directions can more constrain each other in the target reconstruction. The opposite might happen with surveys using the rectangular array where the surveys in the x direction are longer than those in the y direction, and ultimately, different investigated depth can be achieved which might influence the ultimate resistivity model when the surveys combined.

4. Conclusions

In this study, the reliability of rectangular and square electrode grids, and saving resistivity data sets by using the electrodes in x, in y, and in both of x and y directions, in three-dimensional modeling of the electrical resistivity method, were tested. Synthetic modeling of a resistive block was generated, where the finite difference method was performed. A qualitative comparison among the obtained inverted images then was undertaken based on the shape of the actual geometry of the subsurface target.

It can be concluded, for the rectangular grid and the data saved in x, in y, and in both of x and y directions, that the DD array was better than PP and W arrays in imaging the target’s depth and resistivity value, hence, the resistivity value was highly underestimated on the PP and W arrays. In addition, the DD array resolved the target with less dilation and more constrained to the actual geometry of the target. The PP array was the greatest in the elongation and dilation issues. The W array, although, does not show elongation on the target’s anomaly, but represented the target dilated more than the actual design. The tested arrays’ sensitivities might be the main reason for the variation in the target reconstruction.

In the case of the square grid and for all the saved data sets, the DD was able to resolve the target in terms of its shape, almost, without elongation effect and dilation in the target’s size. The PP array shows an elongated and dilated anomaly. The W array, although no elongation issue can be seen, it represented a dilated anomaly (i.e. much larger than the actual design). For the target’s resistivity value, the DD was the best and followed the PP and W. Overall, the results show that the square grid and saving data in any direction (in x, in y, and in both x and y) was the best case for numerically modelling a subsurface shallow target using the DD array. The W array comes on the second rank, followed by the PP array; where the data should be saved in both x and y directions. Interestingly, the data sets generated using the rectangular grid and the DD array were better than those generated using the square grid and the PP and W arrays. Ultimately, therefore, the ranking would be as follows: square grid and DD, rectangular grid and DD, square grid and W, rectangular grid and W, square and rectangular grid, in x and y directions, and PP arrays.

Acknowledgements

The authors are very grateful to the reviewers, Editor in Chief Prof. Dr. Salih M. Awadh, the Secretary of Journal Mr. Samir R. Hijab, and the Technical Editors for their great efforts and valuable comments.

References


