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The Resolution and Sensitivity Function of Electrode Arrays in 2D Resistivity Imaging Technique

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Abstract: Two synthetic models are employed to assess the relationship between resolution and sensitivity function of electrode arrays: Dipole-Dipole, Pole-Dipole, Wenner-Schlumberger, and Wenner arrays. Both models were designed with a survey line length of 100 m and minimum electrode spacing of 0.5 m. Each model includes two rectangular structures measuring 3 meters in length and 2 meters in width, positioned at depths from 4.44 meters to 6.44 meters. These structures are separated by 3 meters and 6 meters, respectively. After generating over 20 inverse models, the results indicated that electrode array resolution is not related to the sensitivity function but depends on the separation distance between subsurface structures rather than electrode spacing. Additionally, increased data coverage does not correlate with resolution, as higher measurement density failed to differentiate between separate structures. These factors cannot be considered significant or influential in developing a high-resolution model. Therefore, we recommend combining other geophysical methods with this technique when investigating subsurface structures separated by small distances.

Keywords: *Resolution, sensitivity function, electrode arrays, 2D resistivity imaging technique.*

1. Introduction

One of the greatest near-surface geophysical techniques is the electrical resistivity method, which is commonly applied to investigations in mining, hydrogeology, environmental science, geotechnical engineering, and civil engineering (Storz et al., 2000; Zhou et al., 2004; Al-Zubedi & Thabit, 2016). The best reviews of electrical resistivity tomography (ERT) are provided by Dahlin (2001), Auken et al. (2006), and Loke et al. (2013). This method includes several techniques typically conducted using more than ninety electrode arrays (Szalai & Szarka, 2008). However, the most commonly used electric arrays do not exceed ten arrays. This method encompasses various techniques; 2D and 3D resistivity techniques are valuable tools and provide crucial insights into subsurface imaging. Dipole-dipole, Schlumberger, Wenner, Pole-dipole, Pole-pole, Multiple gradient, and Wenner-Schlumberger arrays are most widely used in these techniques (Al-Zubedi, 2015). Various factors, including target depth, array sensitivity functions, and array resolution, influence the selection of the optimal array for electrical resistivity surveys (Roy & Apparao, 1971; Loke, 2012). Accurately determining the sensitivity function plays a crucial role in obtaining precise measurements of material resistivity, making it essential in 2D and 3D resistivity imaging techniques. The sensitivity function of electrode arrays in 2D and 3D resistivity imaging techniques depends on several factors, including electrode distribution, material type, and imaging technique (3D or 2D) (Neyamadpour, 2010; Aizebeokhai, 2009). Sensitivity is the smallest absolute change that a measurement can detect, making it an absolute quantity. The value indicates how much the resistivity of a subsurface portion will change, affecting the potential that the array measures. The effect of the subsurface zone on the measurement increases with sensitivity function value and depends on electrode placement (Loke, 2012). It reflects the resolution and investigation depth for each array (Chitea & Georgescu, 2009), while array resolution refers to their ability to distinguish and characterize subsurface features with clarity. Resolution varies significantly based on technique type, array used, subsurface material electrical properties, equipment, and data processing methods.The resolution enhancement plays a crucial role in enhancing the quality of resistivity imaging (Loke, et al., 2015). Modern electrode design optimization methods significantly improve the accuracy of 2D resistivity imaging surveys (Al Hagrey, 2012). These optimized arrays enable better differentiation of subsurface structures, such as groundwater flow paths, fractures, and rock layers.

Resolution enhancement works to maximize spatial resolution while minimizing data acquisition time. Thus, optimized datasets can achieve high resolution with fewer data points, particularly in the interwell region of borehole surveys. The sensitivity function indicates how changes in resistivity relate to environmental variables (e.g., soil type, moisture), and by optimizing electrode arrays, we enhance sensitivity to specific subsurface features. Consequently, this leads to more accurate imaging of geological structures and anomalies (Loke et al., 2007; Jiang et al., 2021). Some arrays provide better resolution for vertical changes in

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resistivity, while others provide better resolution for horizontal changes. If we understand the most important influencing factors, we should use the most appropriate array to obtain the best results. This study evaluates variables that directly affect electrode array sensitivity, resolution capability, and the ability to determine subsurface properties to enhance array resolution.

2. Theoretical Background

The application of resistivity imaging techniques has been increasing over the years in areas associated with environmental studies, groundwater prospection, mining, monitoring, and other applications which require better mapping of sites in a fast and efficient way (Giang et al., 2018; Loke et al., 2021; Al-Awsi & Abdulrazzaq, 2022). In particular, dual electrode arrays such as Dipole-Dipole have been most commonly used to perform surveys in 2D and 3D (Prakash et al., 2022). One of the main problems associated with Dipole-Dipole and any type of dual electrode arrays is their relatively low resolution and sensitivity function for certain separation values between electrodes used in data acquisition, resulting in degradation of the final image and considerable error in the estimated image (Abed et al., 2020).

To address the problem of low resolution and sensitivity function in images obtained from dipole-dipole electrode arrays, the research community has been studying and proposing alternatives with two or more steps for image reconstruction. One strategy uses electrodes with guarding configurations, such as pole-pole and pole-dipole in the first step and dipole-dipole in the second step. The cost and additional time required to perform these surveys are the main disadvantages in systems using pole-pole and pole-dipole configurations. Moreover, after implementing these configurations, the dipole-dipole still retains its main limitation. Other models proposed in the literature have resolution requirements compatible with dipole-dipole. However, shortcomings related to decreased accuracy remain present (Gharibi et al., 2005; Kiflu, et al., 2016; Simyrdanis, et al., 2021).

Several papers and studies conducted to determine factors affecting resolutions and array's sensitivity functions of 2D and 3D resistivity techniques in identifying subsurface targets were analyzed and discussed in this paper to identify the most significant factors. The spatial resolutions of these techniques in determining subsurface features were also analyzed and discussed.

Sensitivity Function

The array's sensitivity function is a numerical value that indicates how much a change in a survey area's resistivity affects the potential measured by the array, which means that the sensitivity function depends on the geometric factor of the electrode arrangement. In other words, it is based on the relative positions of the array electrodes. The Fréchet derivative is used to theoretically calculate this value for a homogeneous half-space (McGillivray & Oldenburg, 1990).

Referring to a conventional four-electrode array comprising two current electrodes and two potential electrodes, as shown in Figure (1), the sensitivity function can be computed using the straightforward equation provided by Roy and Apparao (1971):

$$F_{1D}(z) = \frac{2}{\pi} \times \frac{z}{\sqrt{(a^2+4z^2)}} \quad \text{..} (1)$$

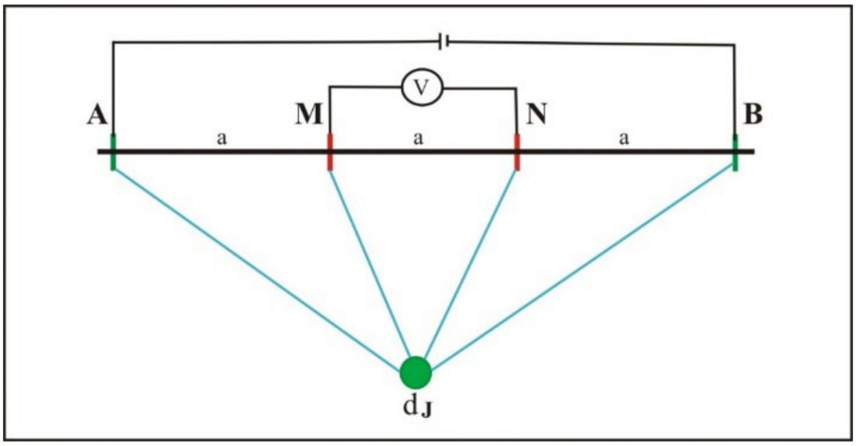

Figure 1. Calculate the sensitivity function for an array of four electrodes (Wiener array) at position ḑ(x,y,z) within a half-space.

In 2D resistivity imaging surveys, the sensitivity function of a homogenous half-space of the different arrays can be calculated by the equation given by Loke and Barker (1995) :

$$F_{2D}(x, z) = \pi\left[\frac{1}{2\alpha^3} - \frac{3a^2}{16\alpha^5}\right], \text{ with } \alpha = 0.25xa^2 + z^2 \quad \text{................}(2)$$

These equations, which are generally referred to as the depth-investigation characteristic, have been utilized by many researchers to determine the characteristics of diverse arrays in resistivity surveys, both 1D and 2D (Edwards 1977, Barker 1991, Merrick 1997). According to Parker (1991) and Edwards (1977), "median depth of investigation" provides a more reliable approximation. The sensitivity function and depth must be integrated to determine the median depth of investigation. With electrode spacing (a) equal to one meter, the Wenner array's sensitivity function and median depth of investigation equals 0.1730, as shown in Figure (2).

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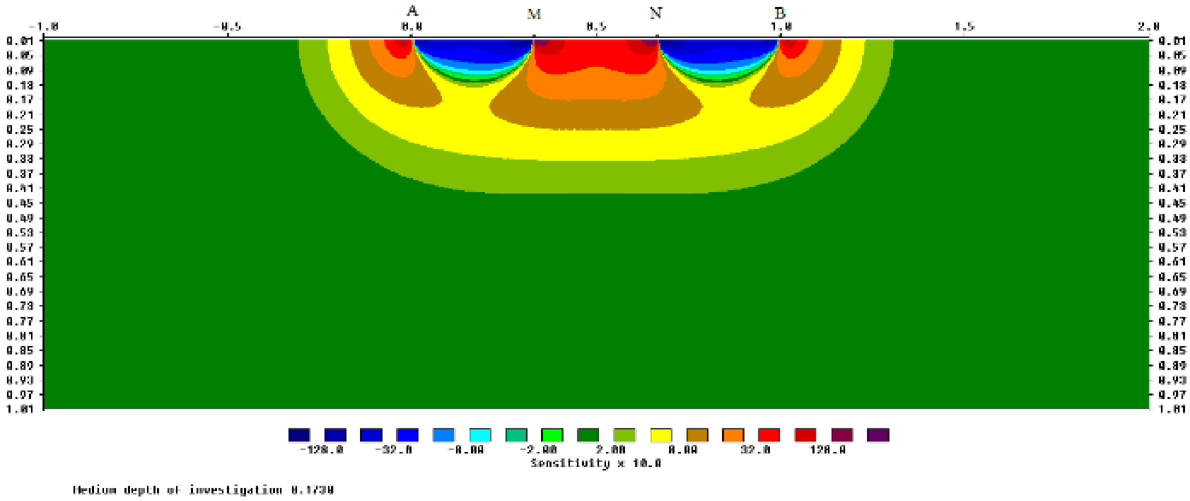

Figure 2. Showed the median depth of investigation and sensitivity function for a Wenner array with a one-meter electrode spacing (a).

The Resolution of Array

The resolution of electrical arrays can be described as the capacity of an array to distinguish two separated targets with a minimum distance between them, such that the two targets can be separately recognized instead of appearing as one target. The resolution can be classified into two types: vertical and horizontal resolution. The array's vertical resolution refers to its capacity to distinguish between two targets located at different depths. Conversely, horizontal resolution describes how two neighboring targets can be positioned horizontally and still be distinguished as two distinct targets rather than one (Kallweit & Wood, 1982).

In mathematics, the Fréchet derivative used in calculating the sensitivity function is defined as the derivative of a function between two Fréchet spaces. It is sometimes known as the strong derivative and can be seen as a generalization of the gradient to arbitrary vector spaces (Long, 2009). Loke (2012) provided an in-depth analysis of the sensitivity patterns of different arrays. According to Okpoli (2013), the sensitivity pattern is the crucial factor in determining the imaging capability of an electrode array. When comparing these arrays' sensitivity levels, the maximum sensitivity values are closest to the electrodes of the various arrays and decrease with depth. In other words, these arrays have lower resolution because the sensitivity function has a graduated value that depends on the distances between the electrodes, particularly the potential electrodes' distance from the nearest current electrode. The value gradually decreases as the distance between the electrodes increases. Since the final results of 2D and 3D resistivity imaging surveys are images or models reflecting the true subsurface resistivity value distribution, which is calculated based on the sensitivity values or Fréchet derivative for a homogeneous half-space (Loke, 2020), the resolution of this image depends significantly on the sensitivity function of the array used and the actual location of the measuring point subsurface.

3. Methodology

Two synthetic models generated more than 20 inverse models for Dipole-Dipole, Wenner-Schlumberger, Pole-Dipole, and Wenner arrays by simulating two 2D numerical models using RES2DMOD software version 2.14.22 (Geotomo software). This approach determined the relationship between resolution and sensitivity function for these arrays and their affecting factors. Both models featured a 100-m-long survey line with 1-m minimum electrode spacing. They contained two rectangular structures, each 3 m long and 2 m wide, located at a depth of 4.44 m and extending to 6.44 m. These structures possessed a resistivity of 30 Ωm within a homogeneous medium of 10 Ωm resistivity. In the first model, the structures were separated by 3 m, while in the second model, they were separated by 6 m, as shown in Figures (3 and 4).

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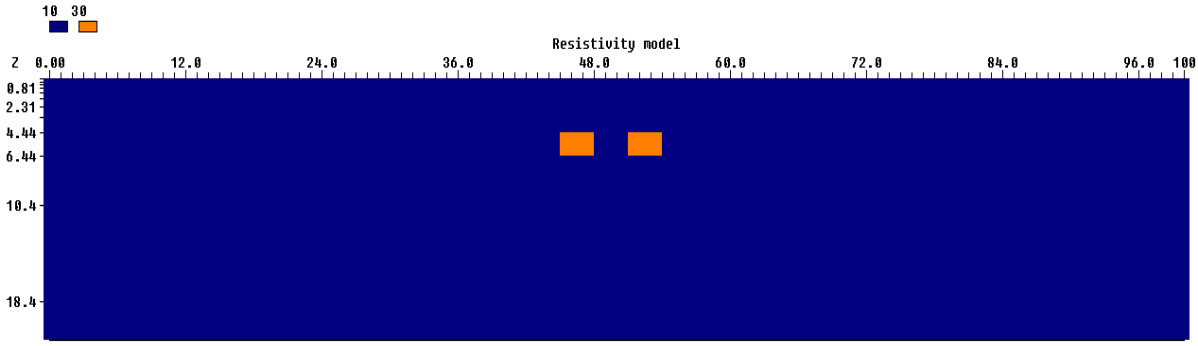

Figure 3. The 2D synthetic model of two structures separated by a distance of 3m.

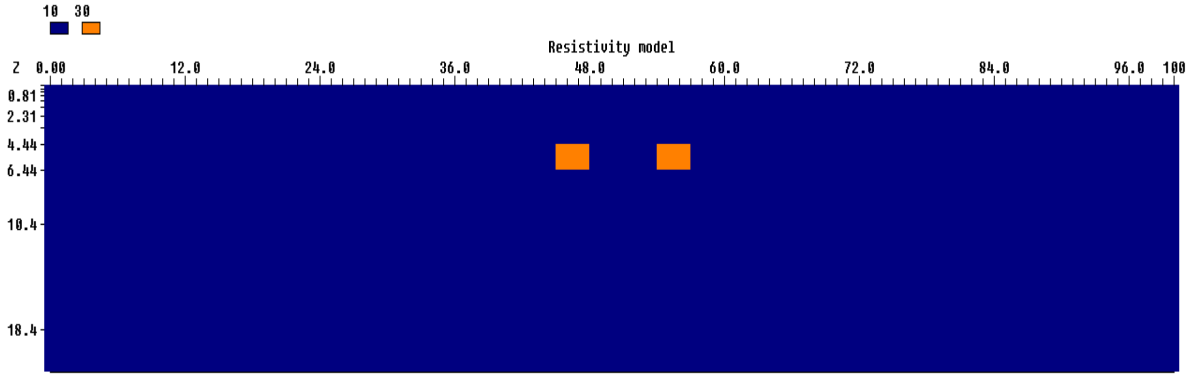

Figure 4. The 2D synthetic model of two structures separated by a distance of 6m.

4. Results and Discussion

After synthetic models are created, apparent resistivity measurements are collected for each model. These measurements are performed with an n-factor of 8a while a-spacing varies from 1a to a maximum of 4a, except for the Wenner array, which uses (33a). This procedure enables higher resolution and maximum investigation depth. The 2D inverse models are created using RES2DINV ver. 3.59 (Geotomo software) with L1 norm (robust) inversion method to obtain optimal boundaries between structures and host materials.

In the first model, where structures are separated by 3m, and after 2 to 5 iterations in generating inverse models for high-resolution imaging, all arrays successfully delineate the depth and extension of these structures. However, the arrays cannot separate them, making them appear as one structure. Therefore, data coverage was increased by raising the factor "n" values to provide overlapping data levels. Nevertheless, the two structures still appeared as a single structure, as shown in Figure (5). Subsequently, the synthetic model was redesigned with an electrode spacing of 0.5m. Yet, all inverse models of the arrays demonstrated difficulty in separating the two structures, as shown in Figure (6) as an example.

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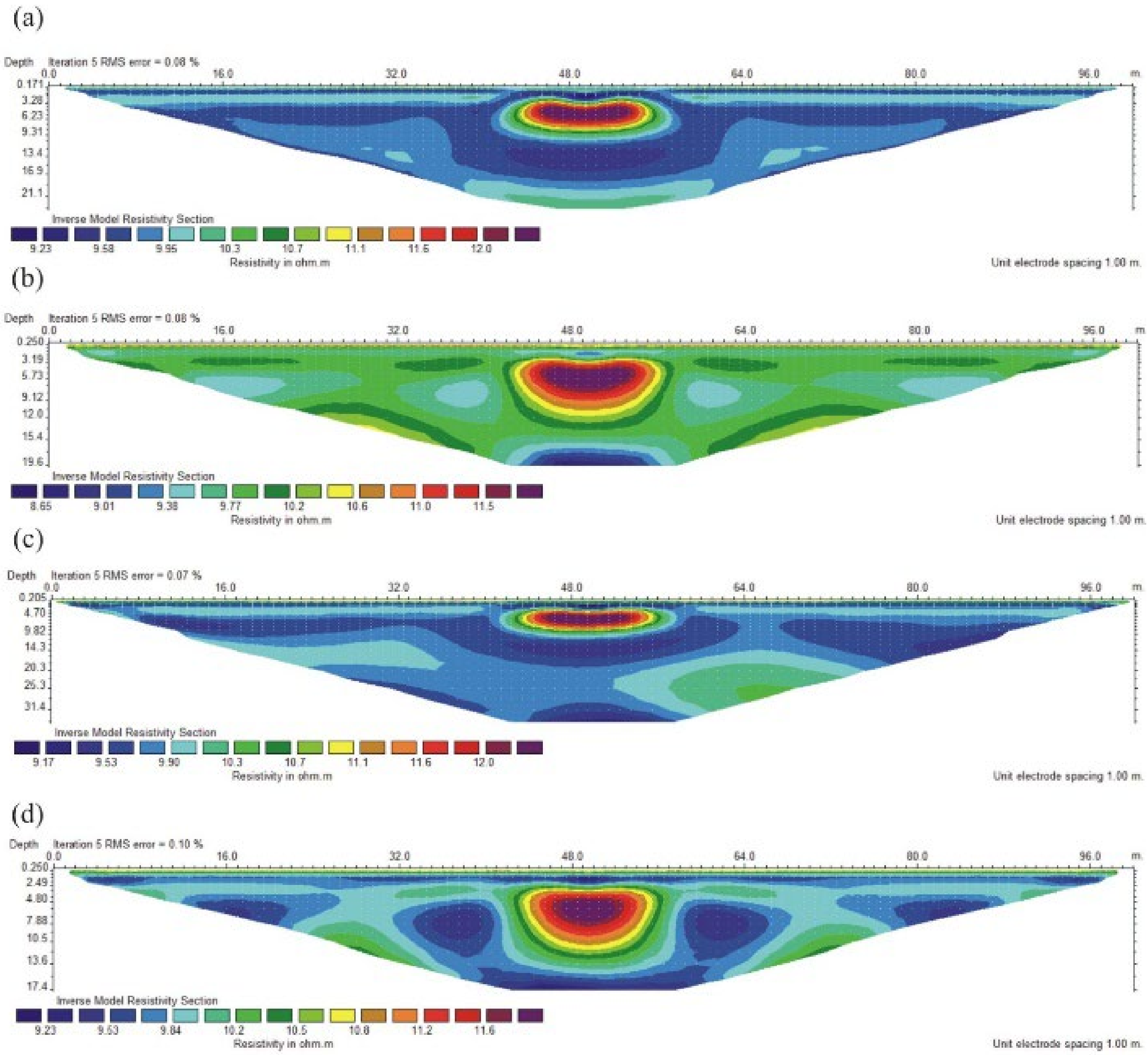

Figure 5. Inverse models of (a) Dipole-Dipole, (b) Wenner-Schlumberger (c) Pole-Dipole and (d) Wenner arrays.

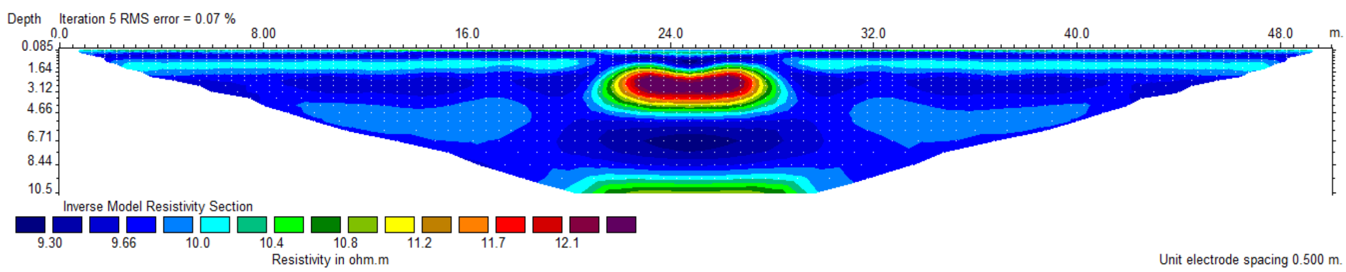

Figure 6. Inverse models of dipole-dipole array with 0.5m electrodes spacing for two structures separated by a distance of 3m.

At a distance of 6 meters between the two structures in the second synthetic model, the inverse models of all arrays successfully identified the structures and displayed them separately, with minor differences in their depth and extent definitions, as illustrated in Figure (7).

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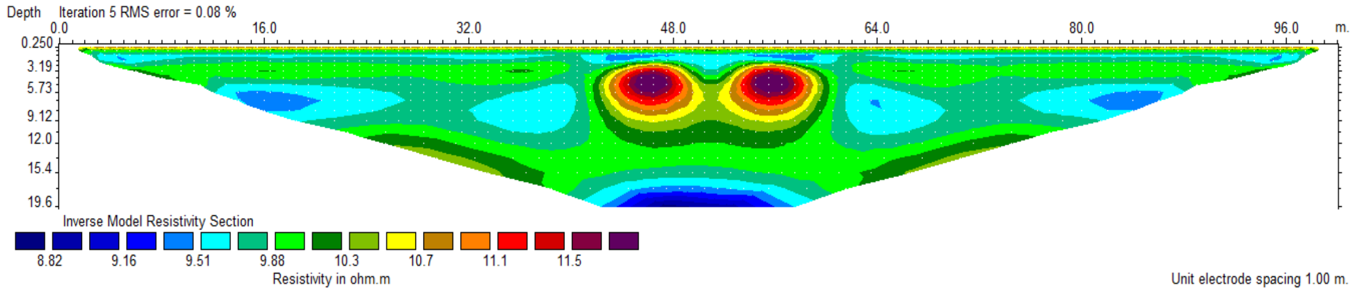

Figure 7. Inverse models of Wenner-Schlumberger array with for two structures separated by a distance of 6m.

In general, these results showed that electrode array resolution is not related to the sensitivity function but depends on the distance between subsurface structures rather than electrode spacing. Furthermore, increased data coverage has no relationship with resolution, as higher measurement density could not distinguish separate structures but showed them as one. Therefore, these factors are not crucial for obtaining a high-resolution model. However, to achieve high resolution, the most important step before electrical resistivity surveys is estimating target depth and geometry to select the optimal array. The distance between targets should be estimated carefully, and other geophysical methods should be integrated when investigating closely spaced subsurface structures.

5. Conclusion

In geophysical methods, including resistivity surveys, measurements are converted into images reflecting subsurface physical property changes. Image resolution depends on measurement accuracy. The sensitivity function and its influencing factors do not significantly affect measurement accuracy or final model resolution. The primary factor affecting electrode array resolution and feature distinction is the distance between targets. This study's key finding include:

- Electrode array resolution relates not to sensitivity function but to the separation distance between subsurface structures rather than electrode spacing.
- Estimating geological conditions before surveying - including subsurface resistivity variations, target depth, geometry, and spacing - helps select arrangements that improve resolution through accurate feature identification.
- Increasing measurement density through overlapping data levels with varied "a" and "n" values cannot provide higher resolution when structures are closely spaced.
- Other geophysical methods should complement electrical resistivity surveys when investigating closely spaced subsurface structures to achieve high-resolution imaging.

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