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Electrical Resistivity Synthetic Modeling and Field Survey for Subsurface Features Investigation of the Borsippa Archaeological Site, Babylon Governorate, Middle Iraq

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Abstract

The selection of proper field survey parameters of electrical resistivity can significantly provide efficient results within a reasonable time and cost. Four electrode arrays of 2D Electric Resistivity Imaging (ERI) surveys were applied to characterize and detect subsurface archaeological bodies and to determine the appropriate array type that should be applied in the field survey. This research is to identify the subsurface features of the Borsippa archaeological site, Babylon Governorate, Middle Iraq. Synthetic modeling studies were conducted to determine the proper array and parameters for imaging the shallow subsurface features or targets. The efficiency of many array types has been tested for the detection the buried archaeological artifacts by enhancing the data coverage and sensitivity with minimizing ambiguity, from the observations. The applied arrays are Wenner, Wenner-Schlumberger, Pole-Dipole, and Dipole-Dipole. The simulated synthetic model consists of five shallow artifacts or walls embedded in the proposed silt clayey soil deposits. The models were constructed using the RES2DMOD program, and the Inversion approach was conducted using the RES2DINV program. Data of subsurface resistivity variation were inverted using the robust (i.e., L1-norm) inversion algorithm. The results reflect that the Dipole-Dipole array is recommended for shallow depths investigations, while for greater depths, the Wenner-Schlumberger array is proper to apply. The concluded results were applied in real case studies, to effectively image archaeological bodies, and successfully detecting low resistivity zones at superficial and greater depths. The relatively high resistivity features have been imaged which is probably related to the archaeological features. The results of the investigation provide archaeologists with proper insights for assessing and excavating properly the surveyed part of the Borsippa and any archaeological sites in future work.

Keywords: Synthetic modeling; Electrical resistivity imaging; Array types; Real case study; Borsippa Archaeological site

1. Introduction

Geophysical techniques are valuable in identifying archaeological sites and provide archaeologists with a subsurface features map without any destruction with good-resolution data in a relatively short time. The geophysical investigations were necessary as a quicker way to determine the presence of archaeological features with less time and cost. The resistivity technique is the first to gain prominence

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among all shallow investigation geophysical techniques (Al-Zubedi, 2016). Besides its application in mining engineering, and hydrogeological and environmental investigations. It is used to assess the electrical resistivity characteristics of subsurface materials and is frequently used for shallow investigations, such as archeological-buried features (Linford, 2006). The 2D resistivity technique has become significant in investigating underground features, including archaeological remains, due to its ease, speed, and low-cost in comparison to other field techniques (Loke, 2022). This method has been applied and utilized by several researchers in various shallow-depth case studies (e.g., Kemna et al., 2002; Zhou et al., 2004; Loke et al., 2013; Al-Zubedi and Thabit, 2014; Al-Awsi and Abdulrazzaq, 2022). In the 2D resistivity imaging survey, selecting the optimal array depends on multiple factors such as depth, sensitivity, vertical and horizontal data coverage, the array's resolution, and the background noise level (Loke, 2022). According to Zhou et al, (2002) and Seaton and Burbey (2002), the most effective method for imaging shallow targets is electrical resistivity. Eissa, (2021) investigated the archaeological site at Uruk, in Southern Iraq by applying three common arrays of Wenner, Wenner-Schlumberger, and Dipole-Dipole. Thabit et al. (2016), concluded that the Dipole-Dipole array provided the best resolution and horizontal data coverage in comparison to the Wenner and Wenner-Schlumberger survey results. However, the depth of investigation of the Dipole-Dipole array was lesser than the depths of the other two tested arrays.

This research aims to compare the responses of specific 2D resistivity array types for synthetic targets (i.e., buried bodies), the best/proper result will be applied in the real field survey to identify shallow targets in the Borsippa archaeological site, Babylon Governorate.

1.2. Location and Geological Setting

The selected archaeological site is the Borsippa or Birs Nimrud, (an important ancient Sumerian city), about 15 km to the south of Hilla City, Babylon Governorate, Middle of Iraq (Fig.1). The Borsippa site is located about 18 Km Southwest of the ancient famous city of Babylon, and lies within the village of Ibrahim al-Khalil, and sub-district of Al-Kifl (Al-Asadi and Al-Aboodi, 2018).

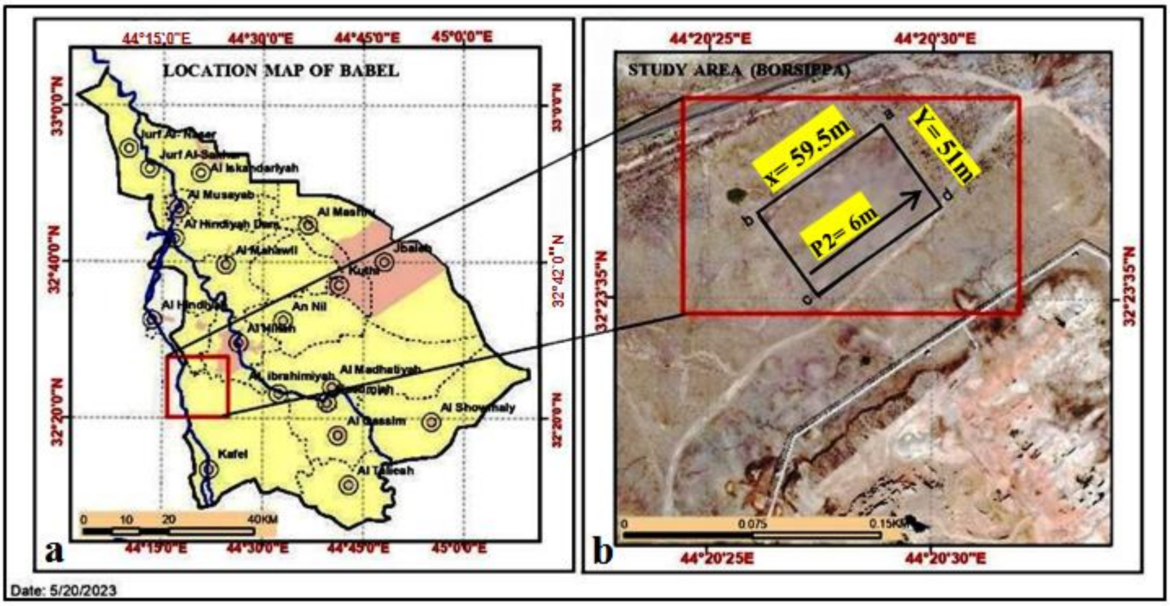

Fig. 1. a) The location of the study area (red rectangle) within Babylon Governorate, b) An aerial image highlighting the survey area by the black rectangle in front of Ziggurat Nimrud (the Borsippa archaeological site).

The study area is located within the alluvial plain, which is characterized by a flat surface, flatness, and a general lack of slope, where the degree of slope is about 22 cm per kilometer (Al-Jubouri, 2002). It is covered by Quaternary sediments represented by gravel, sand, silt, and silty clay deposits. The thickness of the sediments ranges between 20-25 meters (Banat, and Al-Rawi, 1986). Tectonically, the study area is located within the Mesopotamian zone (Jassim and Goff, 2006).

2. Materials and Methods

The test of 2D electrical resistivity profiles (ERI) Fieldwork survey at the Borsippa Site was performed in April 2023. To conduct the ERT survey, it is important to consider the profile's location, orientation, and dimension on the ground surface (Fig.1). 2D ERT profiles can reveal variations in the ground underneath the survey profile. However, features on the profile side may not be visible depending on the array's sensitivity. Each array has different sensitivities for vertical and horizontal changes in the ground. Profile 2 is the most effective choice for arrays test detecting the target when conducting a survey. Because Profile 1 is located near a street, it could cause difficulties in interpreting resistivity values and create more noise, resulting in a lower chance of detecting any features. Over time, high soil compression will also lead to incorrect resistivity measurement interpretation.
Table 1 shows the boundary coordinates of the selected part of the study area.

Table 1. Coordinates of the study area boundaries as indicated in Fig. 1.

Point	Longitude (°)	Latitude (°)	Elevation (m)
a	44° 20` 28" E	32° 23` 38" N	28.53
b	44° 20` 27" E	32° 23` 36" N	28.44
c	44° 20` 28" E	32° 23` 37" N	29.22
d	44° 20` 30" E	32° 23` 37" N	28.732

2.1 Synthetic Modeling Study and Field Example

The electrical resistivity method uses different electrode arrays such as Wenner, Wenner-Schlumberger, Dipole-Dipole, Pole-Dipole, Pole-Pole, and Multiple gradient arrays, which are frequently applied in near-surface investigations (Loke, 2022; Abbas et al. 2022; Abed et al. 2020 and 2021).

Before beginning a certain fieldwork survey, an electric resistivity synthetic modeling study will be an excellent choice to understand the ERT or ERI parameters and methodologies. It is one of the fundamental or forward exploratory models used in this study. This will assist, to a large extent, in understanding and probing the targets or features properly and effectively, which in turn assists in reducing survey costs and efforts. RES2DMOD software (version 3.01) constructed by Loke (2002) was utilized to create a computer-generated electrical resistivity data set to produce a 2-D Synthetic model. A user-defined 2D subsurface model is input into the 2D forward modeling application, which calculates the apparent resistivity pseudo-section (i.e., forward models). The resistivity relies on finite-difference or finite-element formula for calculating apparent resistivity values (Silvester, 1990; Loke, 1999 and 2002). The measured data are inverted using the Inversion approach RES2DINV (ver. 4.8.10) software to produce a cross-sectional model of subsurface resistivity data. Then, it was compared to the observed data and modified. A two-dimensional (2D) simulated subsurface model (Synthetic model) is created.

The Synthetic models produce 2D electrical resistivity models for simulating archaeological buried walls or artifacts and recording the responses of apparent resistivity data to those bodies. The tomographic inversions of synthetic data were used to reconstruct the subsurface resistivity features. The constructed model was approximately 60 m long, using 120 electrodes with a 0.5 m inter-electrode spacing. Both noise-free (0% noise) and random noise of 3% for the apparent resistivity values of the used arrays were tested. The model includes five homogeneous layers with apparent resistance values ranging from 0.2-9 Ohm.m. The simulated background layers consist of non-cohesive soil (silty clay and clayey deposits). At the same time, the buried archaeological walls have apparent resistivity values ranging from 25-180 Ohm.m. Resistivities were deduced and selected according to their common ranges in different rock types (Palacky, 1987; Miensopust, 2010) (Fig 2). The constructed model displays the synthetic resistivity of six homogeneous subsurface layers. The resistivity values and corresponding colors are as follows: Soil is 0.2 Ohm.m (dark blue), layer 2 is 0.9 Ohm.m (dodger blue), layer 3 is 1.9 Ohm.m (turquoise), layer 4 is 4.2 Ohm.m (aquamarine), layer 5 is 9 Ohm.m (dodger blue), and layer 6 is 1.9 Ohm.m (dark blue color). Five buried suggested walls from brown to red colors are included, as shown in Fig.3, which represents the resistivity pseudo-section models of the Schlumberger array.

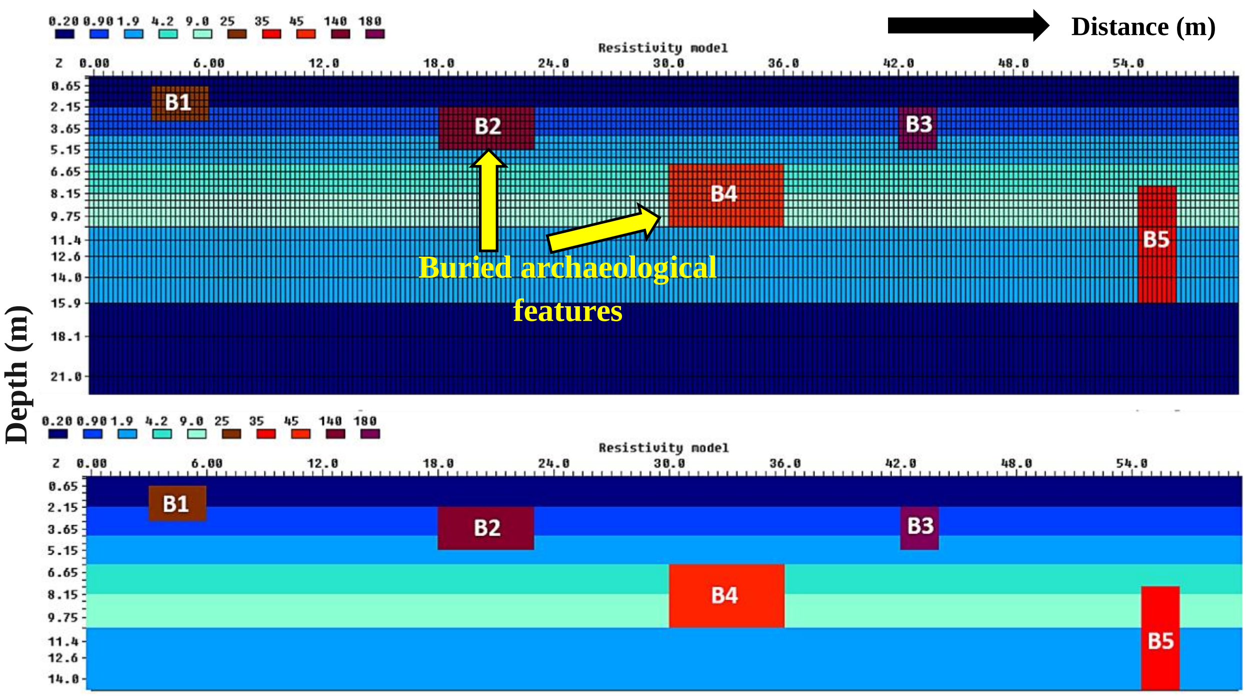

Fig. 2. The model displays the synthetic resistivity of Six homogeneous subsurface layers with five suggested buried walls or artifacts with different resistivities, the bottom figure is the calculated synthetic model

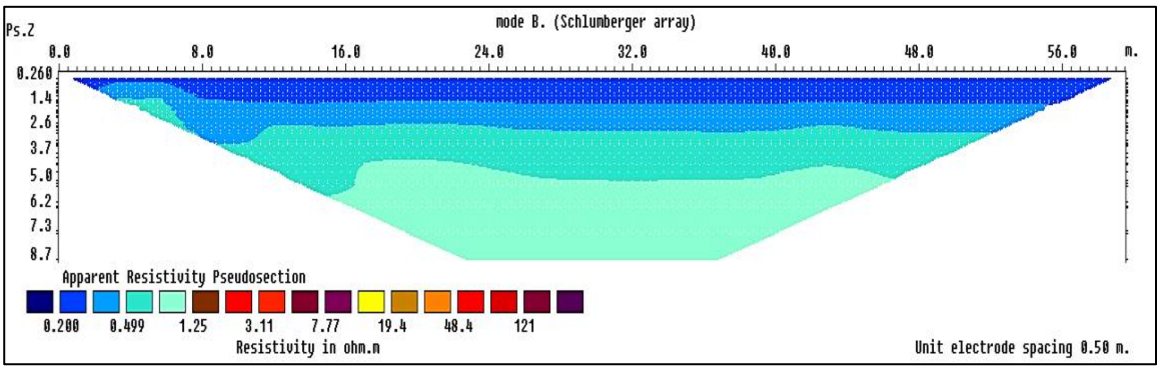

Fig. 3. The resistivity pseudo-section model of the Schlumberger array in response to the calculated synthetic model of the bottom section in Fig. 2.

2.2. 2D Data Processing, Filtering, and Inversion

The RES2DINV (Ver. 4.8.10) software (Geotomosoft.com) has been used to process and invert the 2D electrical resistivity synthetic data. It automatically generates 2D resistivity models for subsurface data obtained from 2D electrical investigations or the synthetically generated resistivity model.

Fig. 4 illustrates how the apparent resistivity values are transformed, operated, and displayed via a segment of the resistivity model using RES2DINV software that may be used for further geological and geophysical data interpretation (Salman et al., 2020). Fig. 5 illustrates the processing steps including forward modeling options to finally produce the proper inversion model of the resistivity data.

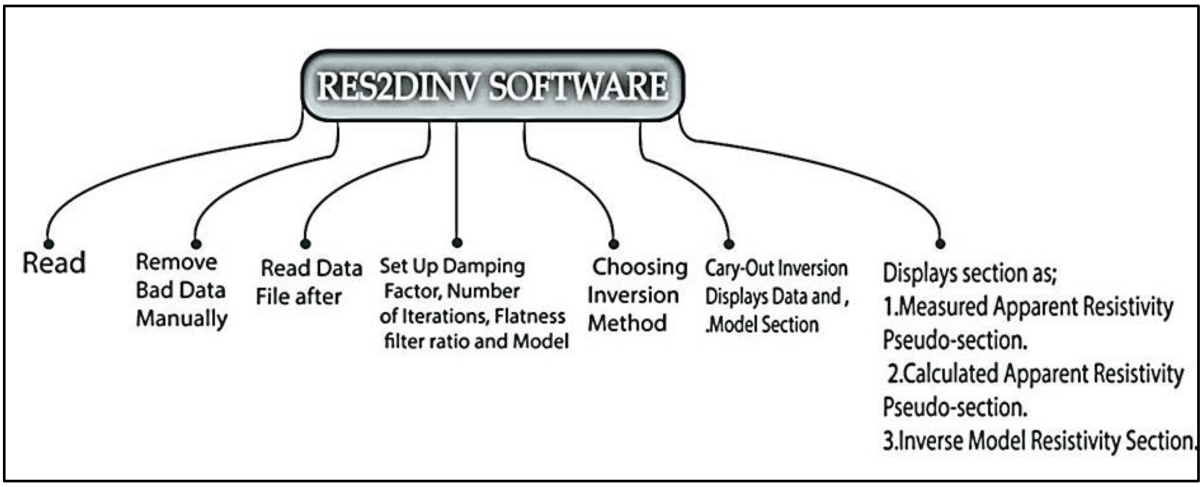

Fig. 4. The operation procedure of RES2DINV software to interpret a segment of the resistivity model inverted from synthetic apparent resistivity values (Salman et al., 2020)

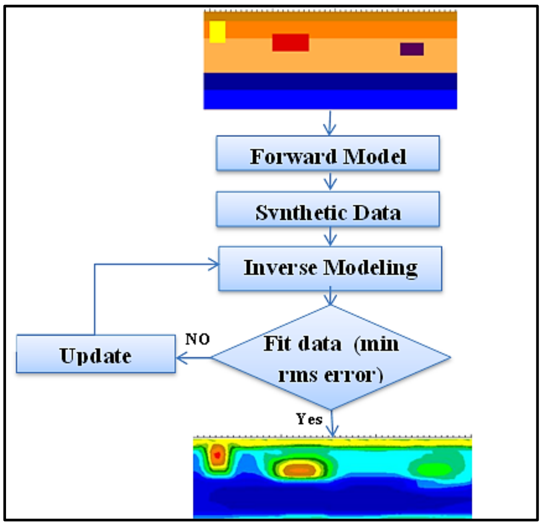

Fig. 5. The forward modeling parameters and the inverse modeling processing steps of the ERI data

Moreover, the inversion results of noise-free (0%) resistivity data and the 3% added noise level data will be displayed for all selected common arrays to probe the response for each array to the inserted simulated bodies, i.e., their depths, and extensions, in addition to the background noise level.

3. Results and Discussion

3.1. Inversion Results of Synthetic Models

All electrode array designs have advantages and disadvantages in real-field applications but can be useful for 2D and 3D tomography and geo-electrical field studies. An effective geophysical application that acts as a contact between the variable soil layers with low resistivity and the objects with relatively high resistivity. In the previewed synthetic models, the Wenner-Schlumberger, Dipole-Dipole, and Pole-Dipole arrays reach approximately a depth of investigation of about 8.45m, while the Wenner array reaches a depth of investigation of about 12 m (Figs. 6 and 7). Some of the electrode's arrays that have been tested were able to identify the suggested electrical features (i.e., buried walls) in all sections of the inverted resistivity, which is due to the good contrast between the values of the resistivity of the compacted wall itself and the sediments surrounding them. The 2D resistivity inversion models and interpretation of resistivity variation of tested arrays are shown in Figs. 6-a, b, c, and d. The results showed that the Dipole-Dipole inversion model was effective in identifying the features of the four buried walls and their thickness. The finding indicates that when there is both vertical and horizontal resistivity contrast in the subsurface, the selection of a Dipole-Dipole array according to the synthetic results seems to be the preferable choice to employ. However, with a low-contrast resistivity value, less thickness, and deeper depth, the fifth wall did not correctly detect from all arrays. Further, the RMS ratio does not surpass 5% in any of the profiles, which is an acceptable percentage and proves that electrical features variation exists. 2D electrical resistivity tomography (ERT) is the ideal survey for shallow investigations. The results of the synthetic study show the crucial role that 2D resistivity imaging plays in archaeology for swiftly detecting and identifying embedded archaeological features.

By comparing resistivity values, geometric dimensions, and RMS values between the synthetic models and the inverted sections, as shown in Figs. 6a, b, c, and d and 7, and Tables 2, 3, and 4. It can be noticed the following results:

(1) The first body (B1), the closest value to the assumed resistivity value was obtained using the following arrays in order: Dipole-Dipole, Wenner-Schlumberger, Pole-Dipole, and Wenner array, respectively.

(2) The second body (B2), the Dipole-Dipole array provided the value closest to the assumed value followed by Wenner-Schlumberger and Pole-Dipole, respectively.

(3) The third body (B3), only the Dipole-Dipole and Wenner-Schlumberger arrays illustrated values closest to the assumed resistivity value, while the others did not characterize that. The Dipole-Dipole array was effective in determining the geometry of the third wall, as it is not affected by the surrounding buried walls.

(4) The fourth body (B4), Feature of this body is only imaged by Dipole-Dipole and Wenner-Schlumberger array, respectively. However, the Wenner-Schlumberger inversion model probably merged the two walls B3 and B4 (Fig.6c). This leads to a distorted image that does not accurately represent their location, width, extension, and depth, making it inadequate for imaging B3 and B4 the buried walls separately. This means that the sensitivity function of the array may face difficulties in simultaneously imaging both horizontal and vertical structures, or difficulty in characterizing the resistivity variation between these two adjacent bodies (Loke, 2022).

(5) For the fifth body (B5), the data obtained from arrays and their inverse models do not show evidence of the buried wall. This is due to its depth and lateral location on the edge of the synthetic model and the resolution and depth sensitivity function for the arrays are not sufficient to detect the resistivity variation close to the edge of the profile.

(6) The accuracy and clarity of the imaging using the Wenner Alpha array ranks lower than other arrays. However, the Wenner array provides a greater depth of investigation than other arrays to reach about 12m depth.
(7) Due to the low contrast ratio between the body and its surroundings, detecting deeper bodies with diffusion becomes less effective.
(8) The Dipole-Dipole array is typically the proper choice for locating and identifying dimensions of most presumed buried bodies/wall features.
(9) The best model is not always determined by the lowest RMS error rate. It is essential to compare the model output with the survey data.
(10) The proper or efficient arrangements for determining the location and dimensions of buried walls are Dipole-Dipole, Wenner-Schlumberger, Pole-Dipole, and Wenner-Alpha, respectively.

Studies utilizing synthetic data show that the Dipole-Dipole arrangement yields a more precise representation of the subsurface and decreases uncertainty compared to the Wenner, Wenner-Schlumberger, and Pole-Dipole electrode-arrays. The Dipole-Dipole array was the preferred one in imaging the four suggested bodies, followed by the Wenner-Schlumberger array. Moreover, the results provide valuable information for designing field surveys that probably will meet field survey objectives. So, it is recommended to first conduct synthetic studies using synthetic models before conducting any field surveys, whereas it is necessary to demonstrate and deduce the proper survey results of a selected resistivity array.

Depending on the synthetic results, two of the efficient array results will be chosen (i.e., Dipole-Dipole and Wenner-Schlumberger electrode arrays) to probe and investigate archaeological features and subsurface heterogeneity of the selected study area for the fieldwork survey in the Borsippa site.

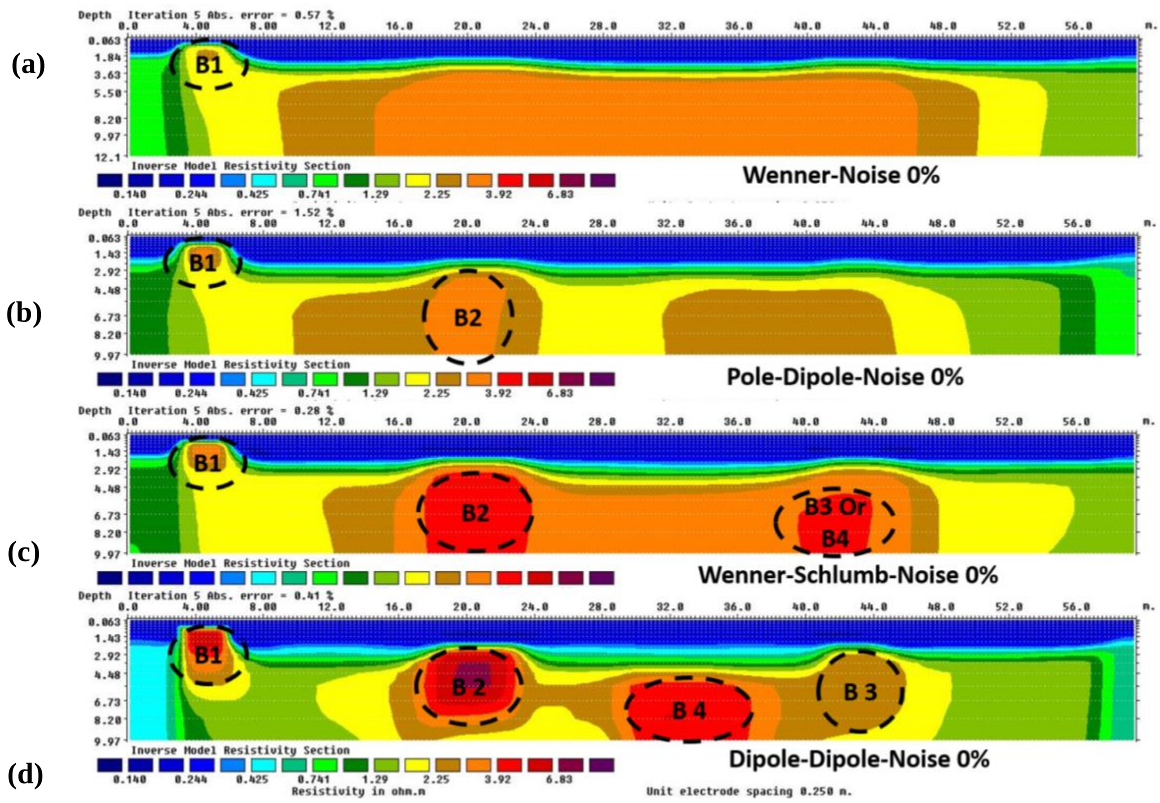

Fig. 6. The inverted resistivity sections of the synthetic model using (a) Wenner, (b) Pole-Dipole, (c) Wenner-Schlumberger, and (d) Dipole-Dipole arrays with noise-free level, i.e., 0%

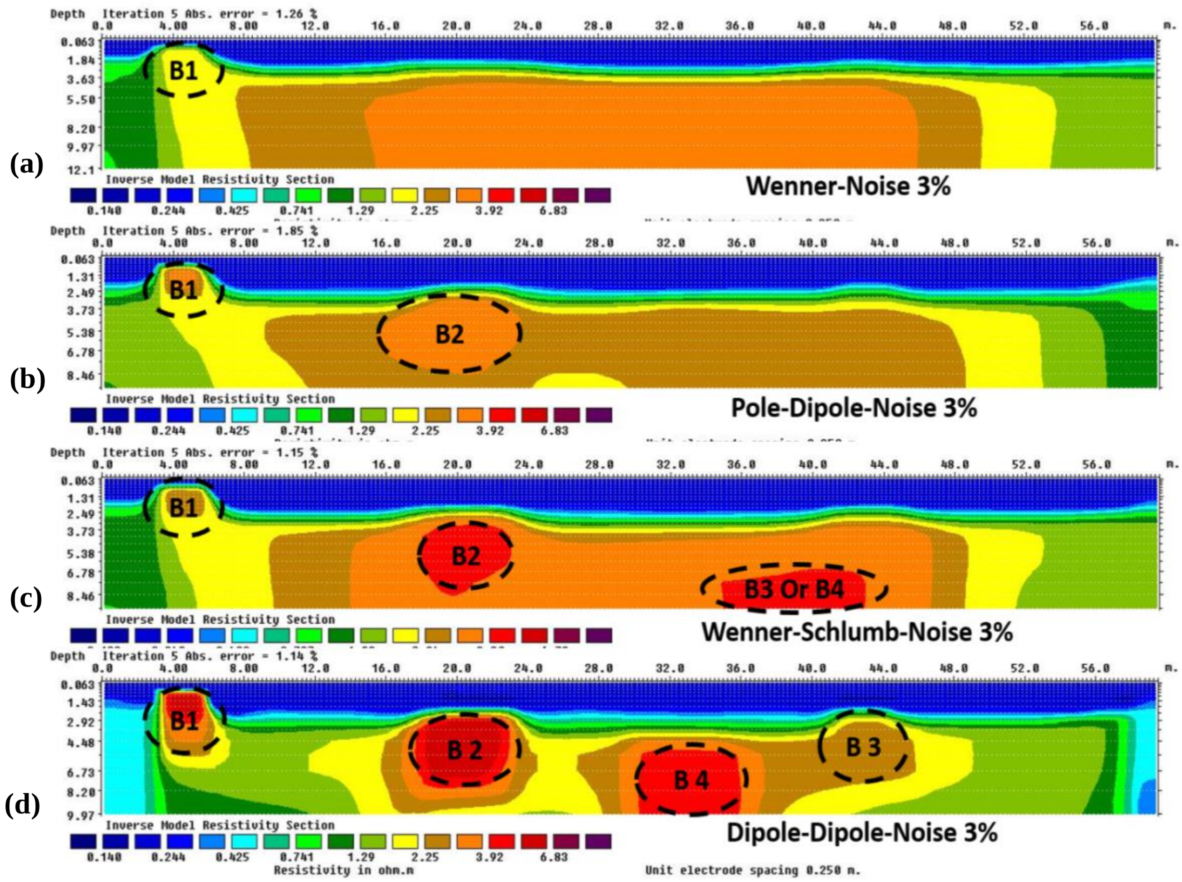

Fig. 7. The inverted resistivity sections of the constructed synthetic models using a: Wenner, b: Pole-Dipole, c: Wenner-Schlumberger, and d: Dipole-Dipole arrays with the 3% added noise levels

Table 2. Approximate dimensions (depth, length, width) of proposed walls in the synthetic models, with their counterparts in the inverse sections of the types of Arrays used

Wall Model	**Geometry d: depth (m) l: length (m) w: width (m)**	**Arrays**			
		Wenner-alpha	**Pole-Dipole**	**Wenner-Schlumberger**	**Dipole-Dipole**
	D = 0.65	1.5	1.6	1.5	1.4
B1	L = 3	1	2	2.27	4.49
	W = 3	1.25	2.26	2.5	2
	D = 2.15	/	2.14	3	2.2
B2	L = 3	/	7.83	6.97	6.2
	W = 5	/	4.75	6.5	6
	D = 2.15	/	/	5	2.92
B3	L = 3	/	/	4.97	5.48
	W =2	/	/	4.5	5
	D = 6.65	/	/	5	5
B4	L = 4	/	/	4.97	4.97
	W = 6	/	/	4.5	7.25
	D = 7.65	/	/	/	/
B5	L = 4.5	/	/	/	/
	W = 2	/	/	/	/

Table 3. The resistivity values between generated synthetic bodies and their inverted models

Wall Model	True Resistivity (Ohm.m)	Range of Inverse resistivity values (Ohm.m)			
		Wenner-alpha	**Pole-Dipole**	**Wenner-Schlumb.**	**Dipole-Dipole**
B1	**25**	**2.25-3.92**	**2.25-3.92**	**2.25-3.92**	**2.25-5.5**
B2	**140**	/	**3-3.92**	**3.92-6.83**	**3.92-5.5**
B3	**45**	/	/	**3.92-5.5**	**2.25**
B4	**180**	/	/	**≈4.5**	**3.92-5.5**
B5	**35**	/	/	/	/

Table 4. The RMS percentages for the inversion models of the four types of tested electrode arrangements

	Abs. (RMS %)			
Noise levels (0%)	**Wenner-Alpha**	**Pole-Dipole**	**Wenner-Schlumb.**	**Dipole-Dipole**
	0.57%	1.52%	0.28%	0.41%

3.2. ERI Field work Survey at the Borsippa Site

3.2.1. Data acquisition and processing

The Dipole-Dipole and Wenner–Schlumberger arrays were applied during the ERI Fieldwork Survey at the Borsippa Site, with a 0.5m distance between electrodes for each used array, a length profile of 59.5m and the number of electrodes was 120 used in this survey, which was conducted on the same profile position within the study area (Fig. 1).The Dipole-Dipole array comprises four co-linear electrodes with equal a-spacing between the Current (C1, C2) and the Potential (P1, P2) electrodes (Fig. 8A). The Wenner-Schlumberger array combines the Wenner and conventional Schlumberger arrays, with the electrode position being the same as the Wenner Alpha array. The spread between the potential and current electrodes is "n" times the distance of the two involved potential electrodes (Fig. 8B).

The two 2D ERI surveys were conducted in the same weather conditions, which was good enough to carry out the resistivity surveys, i.e., the surface soil was conducive and saturated due to the rainy weather for a few days before the fieldwork time.

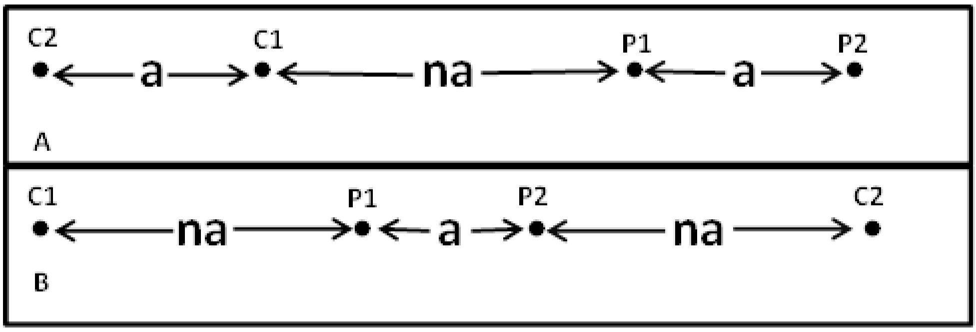

Fig. 8. The D.C. resistivity electrode Setup of: (A) Dipole-Dipole configuration; (B) Wenner-Schlumberger configuration (Salman et al., 2020)

The acquired 2D resistivity field data is preliminary displayed and processed using the PROSYS II software (Geotomosoft.com) to check, eliminate bad data points, and sort or convert the measurements before implementing the 2D inversion procedure (Geotomosoft.com). The "RES2DINVx64" software is utilized for processing the apparent resistivity data to calculate a resistivity model (Geotomosoft.com). It in turn will be used to produce an inverse resistivity section of the calculated model, the latter model will be dependent on the geological interpretation. The same inversion procedure was applied to all data sets as illustrated in (Fig 4). The inversion software generates an inverse resistivity 2D image for each profile, with a-spacing discretization of 0.25 m, as shown in Fig. 9. It illustrates the results of inverse model resistivity surveys using Wenner-Schlumberger and Dipole-Dipole arrays.

The scale of 2D electrical resistivity measurements was standardized to all profiles to facilitate the interpretation and comparison of the inversion models. A Topcon GR-5 GPS measured the precise horizontal and elevational distances between the 120 used electrodes.

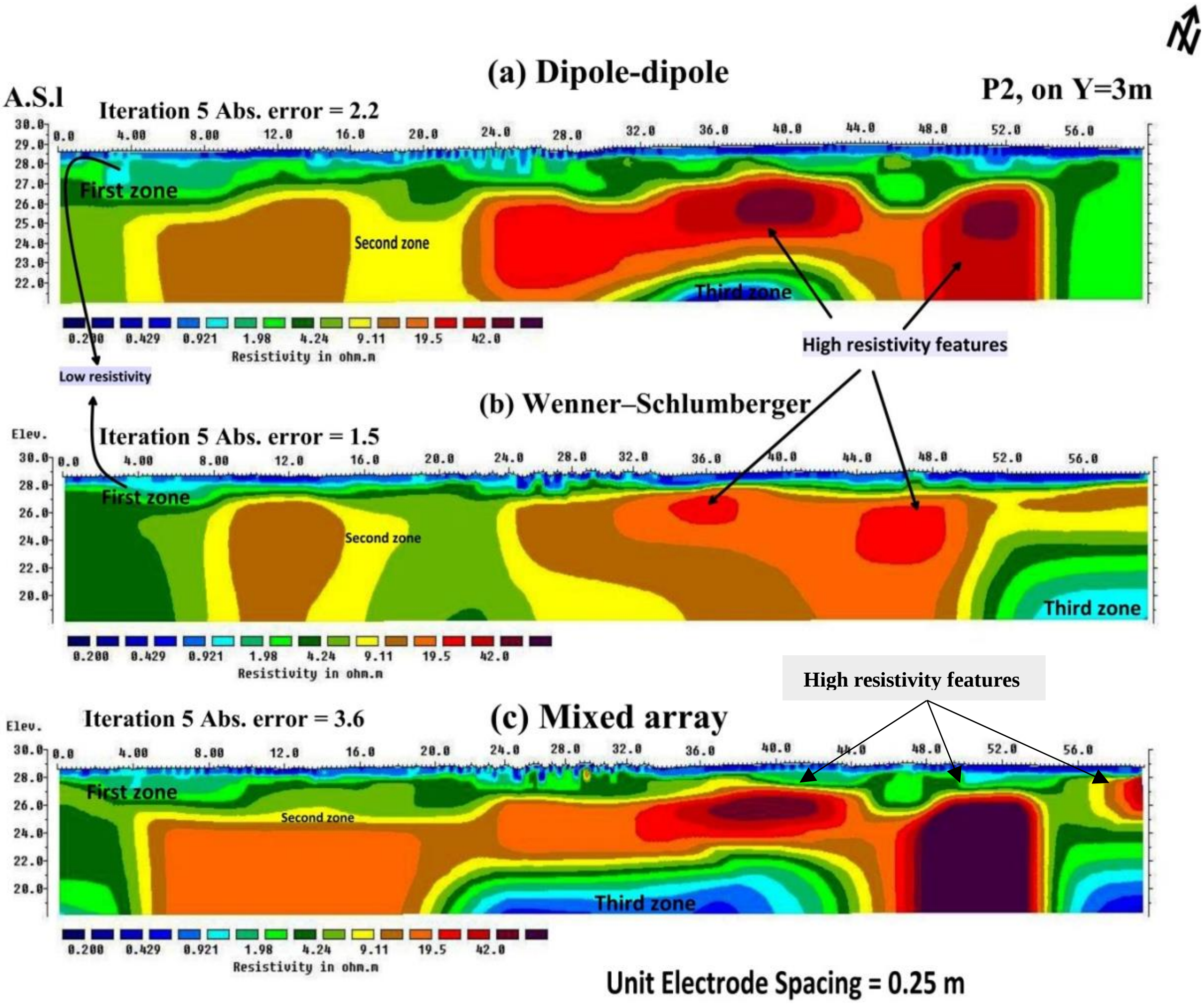

Fig. 9. Results of the inverted resistivity models of (a) Dipole-Dipole array, (b) Wenner–Schlumberger array, and (c) Mixed array with a-spacing = 0.25 m for the second surveyed ERI profile

3.3. Inversion Results and Discussion

The inversion results demonstrate subsurface images with slightly sharper resistivity boundaries (Fig. 9). The inverse models reveal areas of high and low resistance. The subsurface resistivities of the 2D ERT span a broad range, from 0.2 to 61 Ohm.m. Low-to-moderate resistivity features within and around some resistive features can be seen in the shallow-depth profiles, showing an inhomogeneous, especially when 3.55 to 7.5 m depth (Fig. 9). By comparing the field results of the two array methods for Profile 2 (Fig 9), it can be noticed that the Dipole-Dipole array method has shown the inversion results clearly and is high resolution in distinguishing the subsurface heterogeneity and the geometry of the walls. Fig. 9 shows that the RMS values of the Dipole-Dipole arrays after five iterations range between (1.93% and 2.2%). The subsurface resistivity values for the Dipole-Dipole are 0.20 and 61 Ohm.m, the inverse model was divided into three zones: the upper zone, a low to middle-resistivity feature between (0.20 to 6.21 Ohm .m) and a thickness of 3.55 m were Interpreted in the profile, which may indicate a zone of rainwater infiltration into the soil and silt clay where the soil is wet. The second middle zone of high resistivity values may be between (6.21 to 9.11 Ohm.m). A thickness of 4.5 m represents the incubating layer of the archaeological features, and the third bottom zone appears at a depth of 5.65 m and relatively low resistivity values (0.20 to 6.21 Ohm.m). The resistivity values (13.34 to 19.5 Ohm m) may represent the decomposed materials from the walls, rubble, or a zone filled with sediment or wall fractures of medium resistivity. Relatively high range Resistivity values (i.e., 30 to 61.41 Ohm m) below the surface can be caused probably by the buried wall or features in the soil (Fig 9). The thicknesses of these resistive features are varied from one profile to another, as well as along the profile. The Dipole-Dipole arrays detect feature geometry with better resolution and characterization in comparison to the Wenner-Schlumberger array. However, this is due to the good sensitivity of the array to horizontal resistivity changes, which influence the outcome of several observed features (Fig 9) and the effect of near-surface inhomogeneities, especially between 24-54.3 m on x-distance. The Wenner-Schlumberger array senses and detects the high resistivity variation below the current electrodes. The depth of the two matrices varies; Wenner-Schlumberger arrays have a depth of 10.5 m, while the Dipole-Dipole array has a depth of 7.5 m.

Furthermore, the Wenner-Schlumberger and Dipole-Dipole array measurements were combined to create a mixed array of data using PROSYS II software. The data from all arrays were then analyzed and processed via RES2DINVx64 software as well.

The non-traditional mixed array increased data coverage, and sensitivity, and reduced uncertainty. There is little difference in subsurface soil resistivity variation in the inversion models in the study area. The mixed array model has a slightly different sensitivity pattern than the Dipole-Dipole and Wenner-Schlumberger arrays, providing higher resolution for feature identification. The mixed array shows increased depth, coverage, resolution, and number of measurements, making it the proper option for detecting subsurface features but with higher costs, time, and effort The Dipole-Dipole and mixed arrays in Profile 2 (Fig. 9 a and c) show that the vertical extension ratio of the two features is almost similar, and the resistance value corresponds to the subsurface (Fig 9) The Wenner-Schlumberger array shows an unclear image of what is under the subsurface. As mentioned above, due to the large number of data, the difficulty of applying mixed array, shortening time and effort, and accelerating the speed of fieldwork, it will be continued the investigation of the rest part of the archaeological site using the Dipole-Dipole array, which the synthetic and real field data proved the high ability of the array in imaging the shallow-depth features.

3.3.1 Inversion model of ERI profile

The inverse model of the ERT profile 2 shows distinctive high resistivity features. That is at a depth between a 1.5 m SW- 1.7 m NE direction. The inverse model has two features. The first feature has a higher resistivity than the second does. It occurs at a depth of about 2.6-1.5m with extension of about 20m and resistivity ranges of 30 to more than 42 Ohm.m. Its limits appear at a distance of 24 to 44m and are located below electrode numbers 45 to 90 (Fig 10). Moreover, the thickness of the eroded area of the feature extends between 28 to 33m. The feature raises the incubating zone to a depth of 1.4m, and the incubating zone extends from 3.5 to 53.5m. The second feature is just next to the first feature. It occurs at a depth of about 2.5 m with an extension of about 6 m and a resistivity range between 30 to more than 42 Ohm.m. The limits of this feature are located between electrodes number 95 to 107, with a distance of 47.5 to 53.5 m (Fig.10). On the southwest side, we observe a resistivity gradation with depth increasing. This inverse model provides an excellent example of high-quality fieldwork data and a pure geophysical model (Fig.10), where it shows a misfit error of 2.2%. The two high resistivity features are denoted by blue and black rectangles with an additional exciting feature marked with a black arrow Fig.10. This additional feature has a lower resistivity value (about 19.5 Ohm.m) compared to the neighboring high resistivity features. Two possible interpretations can be made from these features. The first interpretation is that the high resistivity features may represent the location of buried archaeological walls (Fig.10: the blue and black rectangle). The second interpretation considers the in-between feature, which may represent the location of the corridor (Fig.10, black arrow). This interpretation could be accepted if we know that local minors may have stolen the bricks from the wall. The location was then filled with other sediments, revealing a lower resistivity value than its surrounding features. Alternatively, the program adds cells with similar resistivity values to provide an acceptable explanation and better results based on interpretations.

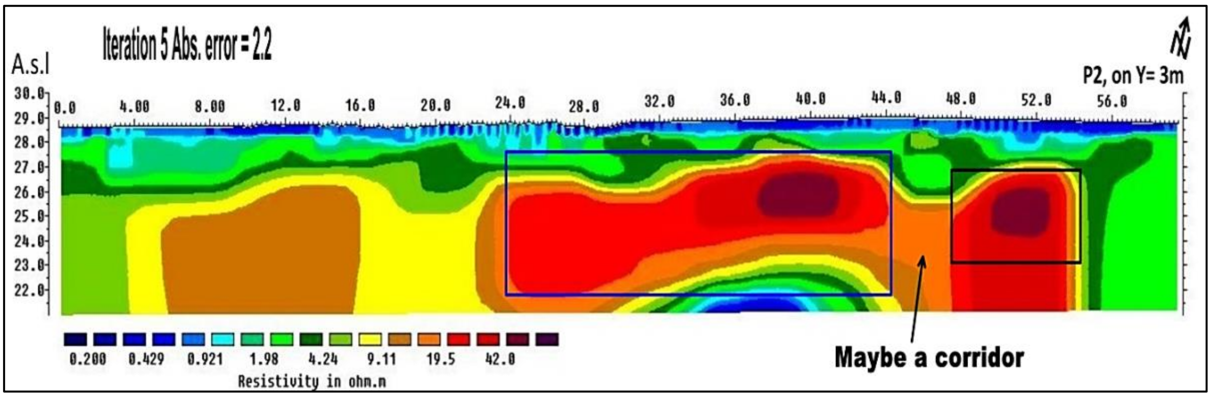

Fig. 10. Results of the inverse models for the Dipole-Dipole array with a-spacing = 0.25 m for the second surveyed profile. The rectangles refer to the wall-like features that reflect the possible location of the wall. The black arrow refers to the in-between wall features that may reflect the maybe location of a corridor

4. Conclusions

The study of resistivity synthetic models demonstrates the applicability of the ERI method in detecting archaeological or near-surface features. The current research highlights a set of effective parameters that influence the ERI method's efficiency.

This study tested the common four electrode arrays of 2D imaging resistivity data were tested in this research, through a synthetic model to determine the efficient or proper array in imaging the subsurface shallow targets, which can be tested before undertaking the field investigation.

The results of tested arrays illustrated that the Dipole-Dipole is the efficient and more suitable array when both lateral and vertical resistivity variations exist in the subsurface and are more effective at locating the model of the buried feature in comparison to other tested array types.

Arrays of Wenner and Pole-Dipole, the major drawback of these arrays is their inability to distinguish between spatial dimensions vertically. This is because they are less sensitive when detecting variations in this direction. This problem becomes even more critical when there is an increase in depth, a decrease in thickness, an increase in electrode spacing, or during dry or warm seasons.

The investigation of the Borsippa archaeological site is conducted using the Dipole-Dipole array. The electrical resistivity measurements were standardized to all profiles to facilitate the interpretation and comparison of the inverse results.

Using the Dipole-Dipole array in the current study was preferred for shallow investigations and can characterize the features with a good-resolution image; however, the Wenner-Schlumberger array is recommended if greater depths of investigation are required.

The comparison of inversion results for Wenner-Schlumberger, Dipole-Dipole, and Mixed arrays (i.e., merging of the two used arrays) illustrated the efficiency of Dipole-Dipole and Mixed arrays in characterizing the subsurface features, which was better than the Wenner-Schlumberger array.

The mixed array is highly sensitive to vertical and horizontal changes in subsurface resistivities. It can provide the best data coverage for the subsurface, but this will be at the expense of each field investigation's efforts, time, and cost, so using the Dipole-Dipole array will be efficient, to a large extent for the near-surface investigations.

Incorporating topographic data into datasets can improve accuracy when interpreting subsurface geological structures. This will allow for broader visualizations and exports that include both resistivity information and surface topography, which assist in providing a more comprehensive view of the geological features of the subsurface.

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