DOI: 10.24996/ijs.2024.65.12.19

ISSN: 0067-2904

Archaeological prospecting using the Electric Resistivity Imaging method at the Borsippa site, Near Babylon, Central Iraq

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Received: 10/10/2023 Accepted: 29/11/2023 Published: 30/12/2024

Abstract

Many important archaeological sites in Iraq still need to be preserved. Some of these sites were subjected to destruction and negligence. So, exploring these sites represents a priority for its protection. A 2D Electrical Resistivity Imaging (ERI) as a non-invasive geophysical survey method was implemented at a part of the Borsippa archaeological site near Babylon to search for the subsurface archaeological artefacts/structures. Electrical resistivity measurements were carried out using a Dipole-Dipole array. Steps were taken to process and filter using Horizontal profiles, forward modelling, and 2D inverse models to analyze the resistivity measurements. The ERI inversion results show that the superficial conductive zone produced variations in ERI inverse models. The low resistivity caused by the relatively high conductivity was observed due to rainwater leaking into the topsoil zone. The ERI sections revealed a coherent depth of approximately 7 meters and the anomalies geometry and semi-layering soil. These changes can be attributed to the high resistivity contrast between the relatively high-resistivity anomalies and the surrounding intact soil. The soil types include dry silty and clayey soils and crushed refractory materials such as broken bricks and ruins mixed with rock pulp. These materials have resulted in the collapse of walls due to weathering and erosion. Based on the identified patterns, shallow-depth high-resistive anomalies are present and extend throughout some parts of the study area. These anomalies are represented in a SW-NE trend of the mound area. At the bottom of this zone is another zone with low resistance values and variable thickness, which varies from place to place within the study area. The results proved the efficiency of the ERI technique in detecting archaeological wall-like artefacts, which represents a data bank for any future archaeological prospection.

Keywords: Electrical Resistivity Imaging; Borsippa Site; Near-surface Archaeological Investigation, Artifacts Detection

التحري الآثاري باستخدام طريقة المقاومة النوعية الكهربائية التصويرية في موقع بورسيبا، قرب مدينة بابل الاثرية، وسط العراق

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الخلاصة:

لا تزال العديد من المواقع الأثرية المهمة في العراق بحاجة إلى التحري للحفاظ عليها. اذ تعرضت بعض

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هذه المواقع للتدمير والإهمال. لذا فإن استكشاف هذه المواقع يمثل أولوية لحمايتها. تم تنفيذ تصوير المقاومة النوعية الكهربائية ثنائية الأبعاد (ERI) كطريقة مسح غير مدمرة في جزء من موقع بورسيبا الأثري بالقرب من بابل الاثرية للبحث عن القطع/ الهياكل الأثرية التحت السطحية. تم إجراء قياسات المقاومة الكهربائية بواسطة أداة SYSCAL pro + باستخدام مصفوفة ثنائي القطب ثنائي القطب. تم اتخاذ خطوات المعالجة والتصفية باستخدام المقاطع الأفقية والنمذجة المتقدمة ونماذج المقاومة العكسية ثنائية الأبعاد لتحليل القياسات الناتجة. تظهر النتائج أن المنطقة القريبة للسطح أنتجت شذوذ في نماذج المقاومة التصويرية المعكوسة أثناء المسح الحقلي. لوحظ انخفاض المقاومة الناتجة عن الموصلية العالية بسبب تسرب مياه الأمطار إلى النطاق العلوي. كشف تحليل النموذج العكسي عن عمق متماسك يبلغ حوالي 7 متر وتصوير امتداد الشذوذات وأنطقه التربة بدقة عالية. يمكن أن تعزى هذه التغييرات إلى التباين العالي في المقاومة بين الحالات الشاذة شديدة المقاومة والتربة السليمة المحيطة بها. وتشمل أنواع التربة الجافة الغرينية والطينية والمواد الحرارية المسحوقة مثل الطوب المكسور والخراب المخلوطة باللب الصخري. وقد نتجت هذه المواد عن انهيار الجدران بسبب العوامل الجوية والتآكل. بناءً على الأنماط التي حددتها طريقة المقاومة النوعية التصويرية، توجد شذوذات في العمق الضحل ذات مقاومة نوعية عالية نسبيا ممتدة في بعض أجزاء منطقة الدراسة. تأخذ هذه التراكيب الشاذة اتجاه SW–NE من منطقة التل. وأسفل هذا النطاق يوجد نطاق أخر ذو قيم مقاومة نوعية منخفضة وسمك متغير يختلف من مكان إلى آخر داخل منطقة الدراسة. توضح نتائج المسح الكهربائي التصويري إلى مدى كفاءة الطريقة الكهربائية في الكشف عن التراكيب الأثرية المحتملة كجدران، والتي تمثل بنك بيانات لأي تنقيبات آثاريه مستقبلية.

1. Introduction

Archaeological sites transpose an overview of the history of ancient people, e.g., living conditions, knowledge, and cultures. Prospecting the archaeological sites is a priority to protect these areas from destruction and negligence. Vast parts of Babylon's ancient city and the Borsippa site (Figure 1) are still mostly unknown, hidden under the earth and groundwater, and many aspects of this great city need further investigation. There is an urgent need to explore the Babylon dynasty further and highlight how important this civilization is for the Iraqi heritage as much as the importance of other civilizations.

However, suppose there are proper/accurate geophysical surveys, such as GPR and electrical resistivity imaging, which can provide two and three-dimensional images/maps that efficiently identify the buried archaeological structures. The goal is not to conduct costly and extensive excavations in that case. Subsurface prospecting applies electrical geophysical techniques to locate subsurface bodies and structures that impact/are important in various related disciplines [1]. The resistivity method was initiated in the 1920s through the work of the Schlumberger brothers. Research in engineering, environment, and archaeology increasingly depends on geophysical methods like electrical resistivity tomography [2] and [3]. Such investigations are usually shallow, limited to around 50 meters, but in exceptional cases, can reach hundreds of meters [4]. Investigation methods of archaeology are divided into invasive (e.g., drilling or excavation) and non-invasive, e.g., geophysical techniques such as Electrical Resistivity Imaging (ERI) [5]. When using the 2D resistivity approach, several electrodes connected to multi-core cables (25 or more) are commonly used [6] and [7]. Due to the substantial amount of data that must be collected, the survey is run automatically. Therefore, all relevant measures should be obtained to get the best outcomes. According to [8], the resistivity technique is an excellent way to assess the electrical characteristics of subsurface materials. Electrical resistivity maps geologic structures, stratigraphy units, fracture zones, sinkholes, and groundwater, correlating with lithological variations, water saturation, conductivity of fluids, porosity, and permeability [1]. A single or pair of steel electrodes is utilized to inject current into the ground during the acquisition of resistivity data, and a similar pair of potential electrodes is then used to measure the potential field that results [1]. Many archaeo-geophysical investigations using electrical resistivity methods have been conducted over the last four decades [9]. The structure of Roman villas in southwest Germany has been identified using the Electrical resistivity technique [7]. The study demonstrated how well the 3D ERT method can represent buried subterranean archaeological structures. The ground material resistance versus depth variations in the physical parameters of underground formations are described and shown using the electrical resistivity method [10]. The author's endeavor is to uncover the hidden structures of the ancient city of Ur within Iraq's Babylonian Houses District. They used electrical resistance tomography (ERT). The main objective was to obtain/extract information about the depths of archaeological features within clayey, salty, and saturated soils [11]. ERT measurements can detect kind bricks in the adjacent clay and mud. Results of the study showed high resistivity near the surface due to dried clay and sandy soil mixed with brick fragments and slags [12]. The ERT and Ground-Penetrating Radar (GPR) has been used by [13] to map the walls of the eastern side of the Northern Ishtar Gate in ancient Babylon. To identify the palace wall and other surrounding walls. The fact that there is only one set of buried walls was underlined. Further analysis of the composition showed that some shallower walls could have been used as residences for soldiers. Further, the ERT survey was conducted in ancient Babylon City at nine selected locations utilizing both Dipole-Dipole and Wenner-Schlumberger arrays. The study aimed to probe the impact of different types of inhomogeneity on the apparent resistivity variation. The ERT results showed that the Dipole-Dipole array had better resolution and accuracy in depicting the underground structures [14]. Furthermore, the Dipole-Dipole array and three parallel profiles were used at the Diyala University site to locate underground utilities (cables and pipes). The interpretation of actual field data demonstrated how practical the ERI approach was at finding buried structures [15].

The current research uses the Electrical Resistivity Imaging (ERI) technique for investigating subsurface archaeological structures in a certain part of Borsippa, which has yet to be applied to investigate this site. The archaeologists will receive the results so they can use them as a guide for future appropriate prospecting of the area.

2. Location and History of the Study Site

The current archaeological site of interest is the Borsippa site. After official approval from the Iraqi State Boards of Antiquities and Heritage, and with the advice and guidance of archaeologists, they prioritize important parts within the vast site for investigation.
Borsippa (Sumerian called Bad-si-a-ib-ba and in Akkadian Persib or Tel Persib) and currently called Birs Nimrud (Archaeology of Press), is an important ancient Sumerian city, built on both sides of a lake, about 15 to16 km to the south of the city center of Hilla, lies about 18 Km southwest of the ancient famous city of Babylon. It is a Sumero-Akkadian city built on either side of the Euphrates River. It lies within the Babel Governorate, in the middle of Iraq. Borsippa (Ishan or Birs Nimrud) site is located at the intersection of longitude (44°20'30"E) and latitude (32°23'30"N) (Figure 1), within the village of Ibrahim al-Khalil, and sub-district of Al-Kifl in plot 12 and the district (10 /Al-Hamsaniyah). Table 1 shows the boundary coordinates of the study area, which is covered around 3040 m^2 [16].

Small parts of the site have been excavated from foreign expeditions, e.g., the Austrian expedition worked there till 2002 [17]. The site mainly consists of two large mounds, the Ibrahim Al-Khalil mound and the Ziggurat-Nimrud archaeological mound. Each mound is surrounded by many relatively small archaeological mounds that have not been investigated yet.

Table 1: Coordinates of the study area boundaries in the DMS system.

Point	Latitude (°)	Longitude (°)	Elevation (m)
a	32°23'36"N	44°20'27"E	28.53
b	32°23'38"N	44°20'28"E	28.44
c	32°23'36"N	44°20'28"E	28.73
d	32°23'37"N	44°20'30"E	29.22

2.1. Geology and Hydrogeology of the Study Area

According to the tectonic division of Iraq, the study area falls within the Mesopotamian zone [18]. Geologically, recent deposits cover the study area, and Quaternary sediments are represented by gravel, sand, silt, and silty clay deposits. The thickness of the sediments ranges between 20-25 meters from the ground surface. Further, the western part of the study area is covered by alluvial deposits resulting from the Shatt al-Hilla River (Figure 2) [19]. The groundwater level near the study area was 5–6 m from the ground surface, as measured from some drilled boreholes in the surrounding agricultural areas.

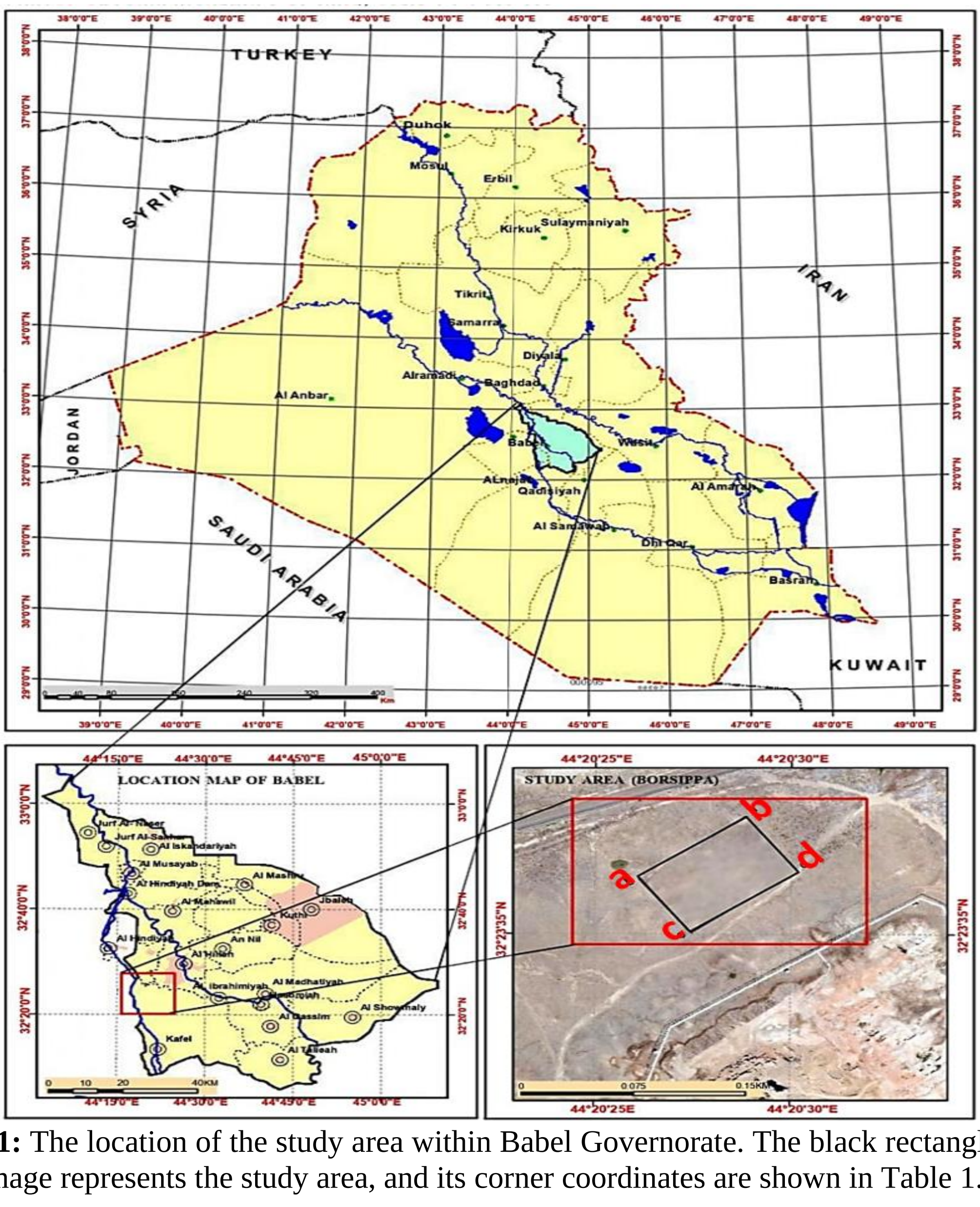

Figure 1: The location of the study area within Babel Governorate. The black rectangle in the aerial image represents the study area, and its corner coordinates are shown in Table 1.

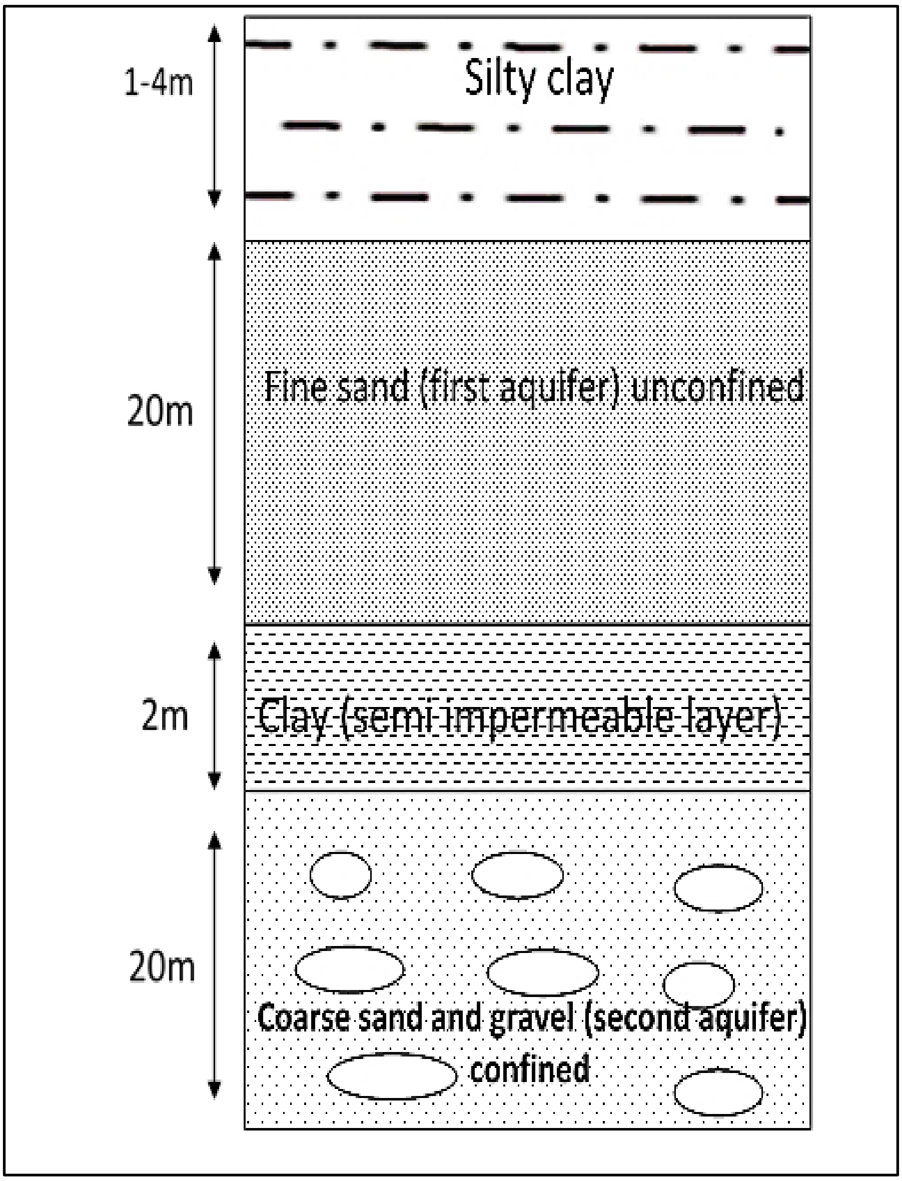

Figure 2: Lithological section of the dominated deposits from the ground surface within the study area [20].

As for topography and geomorphology, the study area is located within the alluvial plain, which is characterized by its flat surface, flatness, and general lack of slope, where the degree of slope is about 22 cm/km, and there are secondary slopes [21], as shown in Figure 3. The land slopes from the northern and western sides and towards the eastern and southeastern parts, and there are some sand dunes in some areas, such as south of the city of Hilla. These dunes have fixed bases, but their peaks are mobile, from which the winds form shapes according to their directions [21]. However, the dunes do not really affect the current study area.

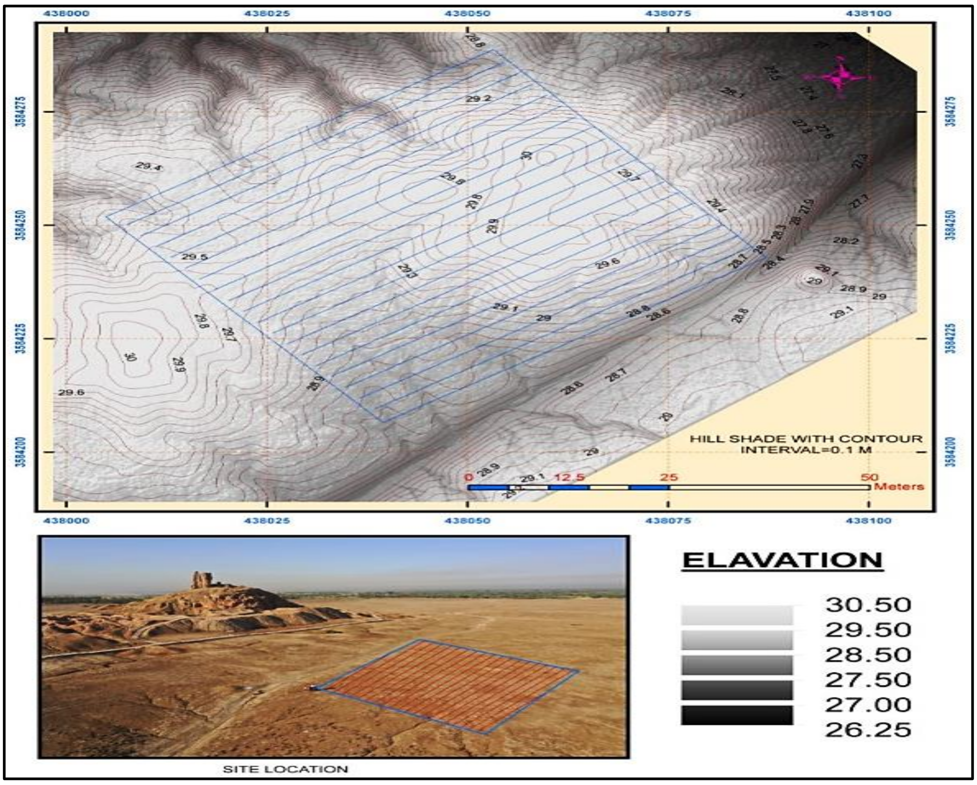

Figure 3: Map of archaeological mound shaded with contour lines (upper image) showing the elevations of the mound, the aerial bottom image showing the grid of ERI survey in front of Ziggurat Nimrud.

3. Materials and Methods

The basic principle of the electrical resistivity imaging technique depends on identifying the variation of electrical resistivity characteristics in the subsurface (Figure 4). In contrast, the ERI technique is non-destructive, sensitive, fast, and relatively cost-effective compared to physical excavation at a site of interest [22] and [23].

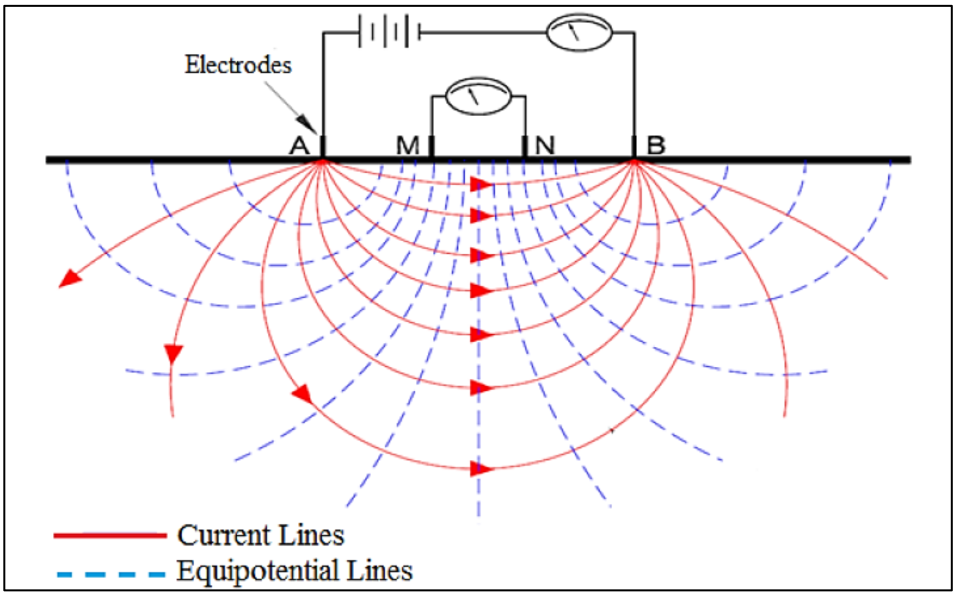

Figure 4: The geometry of current distribution within homogeneous and isotropic subsurface media [24].

3.1 Fieldwork Survey

The fieldwork was conducted in springtime (i.e., end of April 2023), and the surface soil condition was proper (wet) to complete the survey. A set of electrodes that are evenly spaced apart and connected to a central control unit via multi-core cables make up the field setup. After that, resistivity data is collected using intricate example configurations of Dipole-Dipole for the current and potential electrode pairs to create a fictitious cross-section of apparent resistivity below the survey line [25].

The SYSCAL pro+ Instrument is a resistance meter designed for high throughput surveillance and profiling techniques for environmental and engineering geophysical observations. The 2D electrical profiles were performed using a Dipole-dipole array with a spacing of 0.5 m for each array within the study area. The Dipole-Dipole array comprises four liner electrodes with fixed a-spacing between the current (AB) and potential (MN) electrodes (Figure 5). The Dipole-Dipole array is more sensitive to vertical variations in resistivity than horizontal variations, making it better for mapping vertical subsurface structural bodies like dykes, and archaeology bodies [26], [27] and [28]. The Dipole-Dipole array was also a proper technique for determining and mapping subsurface weak zones [29] and [30].

3.2 Data Acquisition and Processing

The resistivity field data have been processed using the ProSysll software (supplementary software from Geotomosoft to process and convert the ERI data to be readable in RES2D inversion program) to view, check, eliminate the bad data points and sort the readings before carrying out the 2D inversion. Very few data points have been eliminated from certain profiles. Afterwards, the 2D model inversion was performed using the "RES2DINVx64" program. RES2DINV is a computer program developed by Geotomosoft and utilized for processing the resistivity data and calculating the inverse model of the field data to a resistivity section, which can finally be used for geological interpretation. The processing parameters applied to the data are listed in Table 2. The same inversion parameters were applied/unified to all data sets, so the software generated an inverse resistivity depth image for each profile. The results of resistivity inverse model surveys of Dipole-Dipole arrays with a-spacing = 0.25 m are shown in Figures 6 and 7.

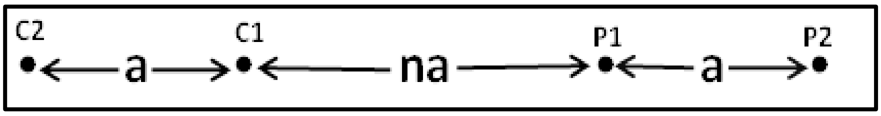

Figure 5: The electrical electrode setup of the dipole-dipole array [26].

Table 2: Parameters used for 2D electrical resistivity inverse for the measured data.

Damping factors	**1.5**
Minimum Damping Factor	**0.02**
Use a higher damping factor for the first layer	**3**
Vertical to Horizontal Flatness Filter Ratio (Weight)	**1.7**
Robust model Constrain cutoff factor	**0.05**
Robust model Constrain cutoff factor	**0.005**
Forward modeling method setting	**finite-element method**
Use model refinement	**Use model cells with widths of half the unit electrode spacing**
Use incomplete Gauss-Newton	**0.005**
Number of Iterations	**5**
Contour Interval	**Logarithmic Contour Interval.**

3.3 Topography Measurements and Effects

The electrical resistivity measurements were standardized to all profiles to facilitate the interpretation and comparison of the inverse results. In some cases, with long surveys and

slight (but important) elevation variability, it might be more convenient to incorporate the topography information to visualize and export inversion results. Geophysical analysis programs typically combine electrical data with topographical data to improve the accuracy of interpretations and interference correction. A Topcon GR-5 GPS measured the precise elevation and horizontal distances between electrodes. These coordinates were then integrated into subsequent ERI data using ProsysII software. After adding topographic values, a slight shift was observed in the shape and location of the anomaly beneath the ground surface, as shown in Figure 6 (A and B). A set of electrodes evenly spaced apart and connected to a central control unit via multi-core cables make up the field setup.

In summary, 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 provide a more comprehensive view of the geological features of the subsurface, e.g., rock layers, geological types, and topographic formations. Without topography, the focus will solely be on resistance variations. The approach chosen should depend on the study's goals and the desired level of detail and context in the results to avoid misinterpretation.

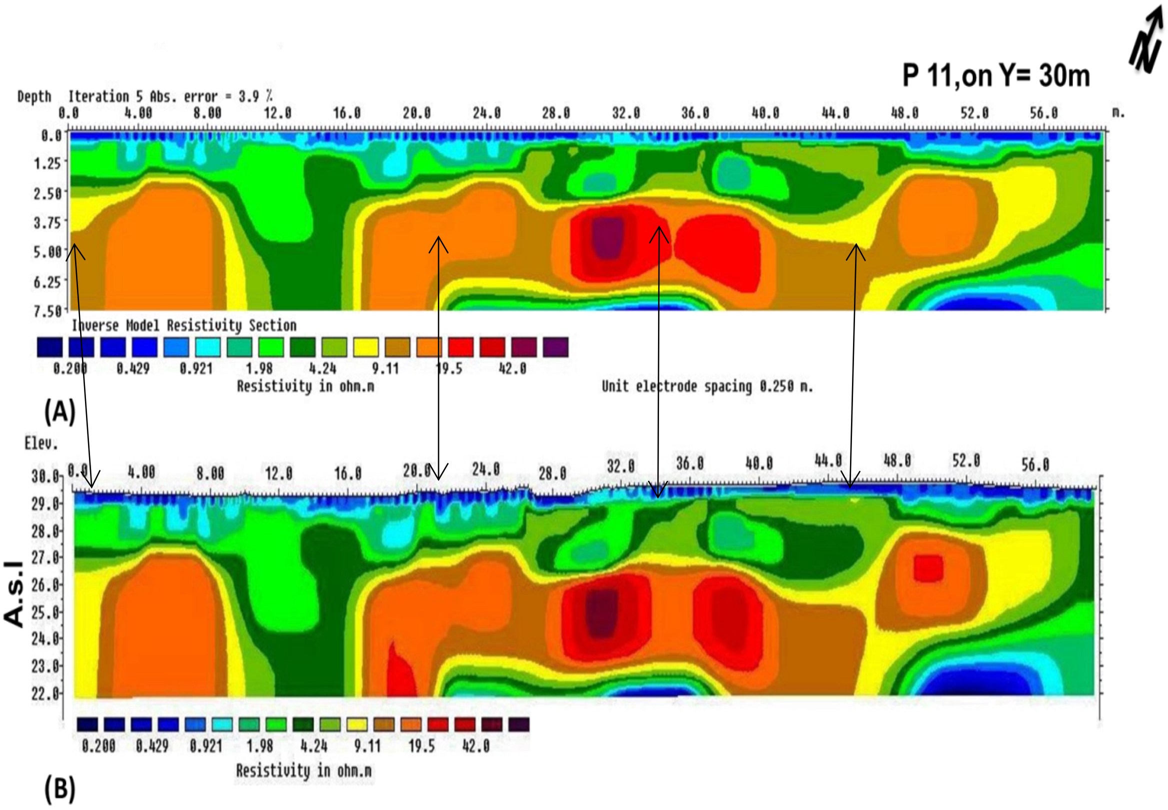

Figure 6: An example of the 2D ERI model showing the results of the inversion: (A) inverse model section without topography, and (B) model section with inserted topography, the black arrows indicate the change that occurred after inserting the topography.

4. ERI Inversion Results and Discussion

The inversion results demonstrate subsurface images with slightly sharper resistivity boundaries (Figure 7). The inverse models reveal zones of high and low anomalies. The subsurface resistivities of the 2D ERI span a broad range from 0.2 to 61 ohm.m. Low-to-moderate resistivity anomalies within and around some relatively resistive anomalies can be seen in the shallow-depth profiles, showing an inhomogeneous, especially from 3.55 to 8.05 m depth (Figure 7). After five iterations, the RMS (i.e., data misfit ratio) ranged between 4.3 % and 5.4 %. The inverse model can be divided into almost three zones: the upper zone, a low to middle-resistivity values between 0.20 to 6.21 ohm.m and a thickness of about 3.55 m were noticed in the sections, which may indicate a zone of rainwater infiltration into the soil and silt clay where the soil is wet. The second middle zone represents the medium to relatively high resistivity values between 6.21 to 9.11 ohm.m. A thickness of 4.5 m probably represents the incubating layer of the archaeological structures, and the third bottom zone is illustrated at a depth of 5.65 m with relatively low-resistivity values of 0.20 to 6.21 ohm.m. The resistivity values of 13.34 to ≈ 20 ohm.m may represent the decomposed materials from the walls, rubble, or a layer filled with sediment or wall fractures of medium resistivity. Relatively high resistivity values of 30 to 61.41 ohm.m at different depths below the surface can be caused by the anomalous buried structures in the clayey soil. The thicknesses and geometry of these resistive structures are varied from one profile to another, as well as along the profile. The Dipole-Dipole arrays detect anomaly boundaries with better accuracy. However, it is susceptible to horizontal resistivity changes, which influence the outcome of several observed anomalies (Figure 7) and the effect of near-surface inhomogeneities, especially between 24-54.3 m on the X-distance. The depth investigated Dipole-Dipole array has a depth of 7 m. The results showed that the Dipole-Dipole array is the suitable electrode array when both vertical and horizontal changes are present in the subsurface. Therefore, using the Dipole-Dipole array for shallow investigations is recommended. The electrical resistivity measurements were standardized to all profiles to facilitate the interpretation and comparison of the inverse results. We will use "P-symbol" to refer to the profile in the upcoming texts.

In Figure 7, the ERT profiles of 16, 17, and 18 indicate that the zone containing the archaeological anomalies is between a 3 m to ≈ 4.6 m depth and exhibits high resistivity values ranging from 30 ohm.m to ≈ 61 ohm.m. Based on the inverse model, these structures have longitudinal extensions ranging from 4.5 m to 11.35 m and occur at depths between 2 m and 6 m. These anomalies can extend continuously in all three profiles, except for the 18th profile, where anomaly (E18) may be an extension of anomaly (A18) or a separate anomaly. As in Figures 7 and 8, This information is detailed in Table 3. At a depth of 2.7 m, there is a unique layer with extremely low resistance. It stretches horizontally for 25.6 m in the seventeenth profile and appears in the eighteenth profile at a depth of 2.9 m with a longitudinal extension of 5.5 m. This layer is likely composed of clay with high permeability.

Table 3: The dimensions of the archaeological structures and their locations below the earth's surface.

Line number	Name structure	Distance(m)	Longitudinal extension	Depth (m)	electrode number	Resistivity value (Ωm)
Line 16	**A16**	**3.25 to 8.25**	**5**	**3**	**6 to 16**	**30 to 42**
	B16	**32.25 to 37.25**	**5**	**6**	**64 to 74**	**30 to 61**
	C16	**52.75 to 57.25**	**4.5**	**2**	**105 to 114**	**30 to 61**
Line 17	**A17**	**1.75 to 12**	**10.25**	**4**	**3 to 24**	**30 to 50**
	B17	**32.5 to 37**	**4.5**	**4.1**	**65 to 74**	**30 to 61**
	C17	**52.25 to 56.75**	**4.5**	**2.8**	**104 to 113**	**30 to 61**
Line 18	**A18**	**4 to 9.25**	**5.25**	**4**	**8 to 18**	**30**
	E18	**13.25 to 24.6**	**11.35**	**6**	**26 to 48**	**30 to 61**
	B18	**31.75 to 38**	**6.25**	**3.3**	**63 to 76**	**30 to 61**
	C18	**52.25 to 57.28**	**5.03**	**4**	**104 to 114**	**30 to 61**

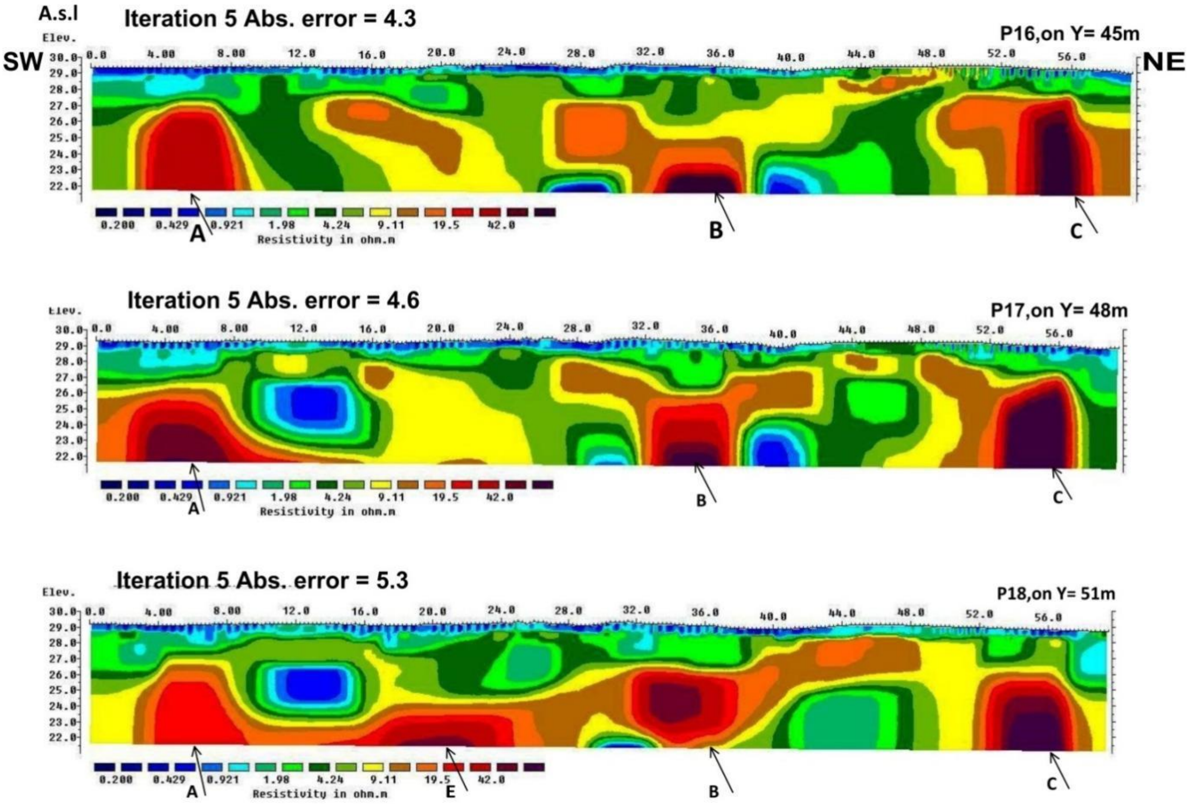

Figure 7: Results of the inverse models for the Dipole-Dipole array with a-spacing = 0.25 m for profiles 16, 17, and 18. The black arrows highlight the main relatively resistive anomalies.

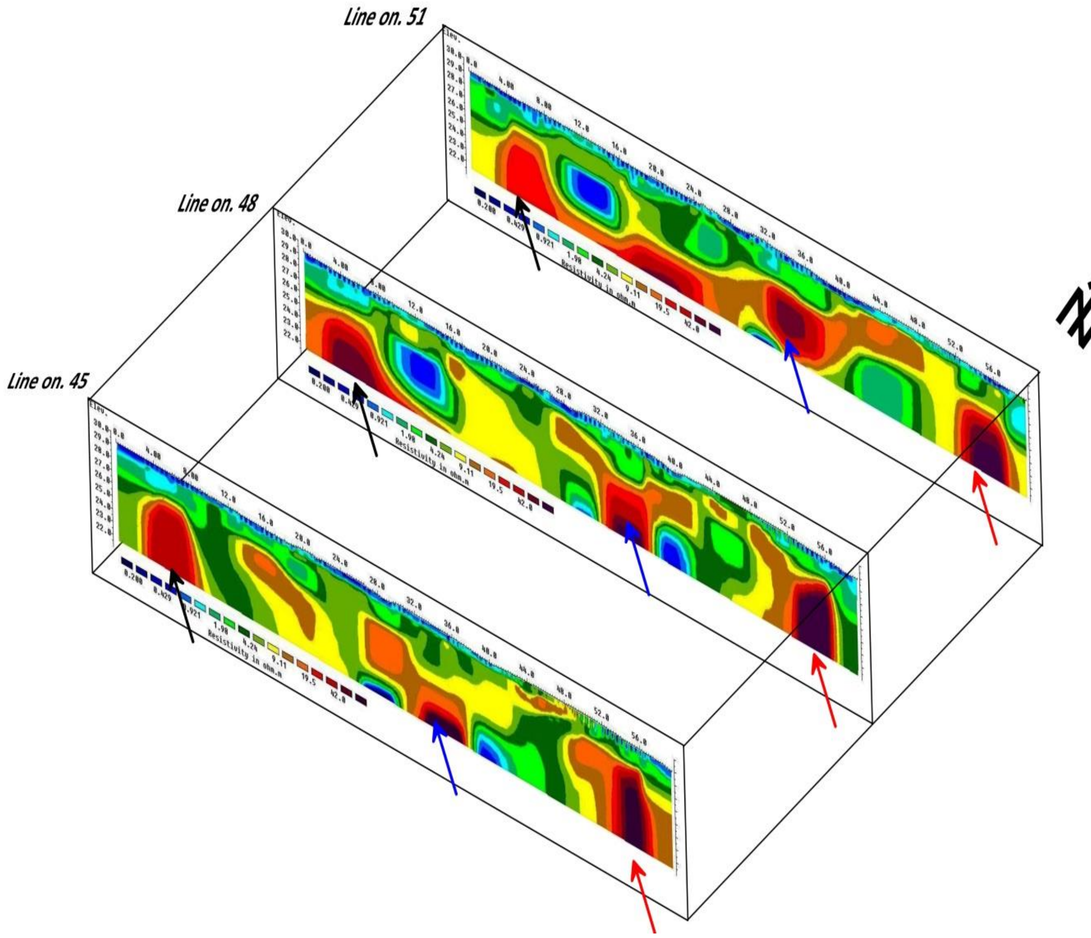

Figure 8: The relatively high-resistivity subsurface features (indicated by arrows) are probably related to the wall-like structures which are carefully identified as consequent features on inversion models of surveyed ERI profiles.

5. Conclusions

From the ERI survey results of the Borsippa site, the following could be concluded:

1. Main soil lithology characteristics have been identified, e.g., clastic materials and sediments of clay, silt, and saturated fine sands with relatively low-resistivity anomalies in the shallow depths. These detected sediments are consistent with the soil column of the previous studies and outcrops near and within the study area.
2. The resistivity values near the surface and down to about 3.5 m depth vary laterally and correspond to the zones ranging from clay to silt and sandy-silt deposits. This variation is due to an increase in moisture content. At these depths, the resistivity varies from 0.2 ohm.m to 0.92 ohm.m. Further, the ERI results show similar anomalies with relatively high resistivity and large thickness structures between 6-2 m. These structures probably represent an internal wall, the walls of soldiers' residences, or large furnaces with highly resistant deposits.
3. Adding topographic data to datasets when interpreting resistivity with Res2DInv can positively impact interpretation accuracy and understanding of subsurface structures.
4. The study illustrated the efficiency of the Electrical Resistivity Imaging technique for shallow-depth investigations. ERI efficiently identified and imaged anomalies' geometry, providing a proper image of the subsurface walls, artefacts, and structures.

Acknowledgements

The authors would like to thank the general director of the General Commission for Groundwater and express their gratitude to Dr Ameer, Dr Firas H. Al-Menshed, and Dr

Mohammad Mohsen, as well as the members of the Geology Department at the General Commission for Groundwater, for generously providing them with ERI and GPR devices, as well as other necessary tools to carry out their field survey. We would also like to thank Mr. Maan Al-Azzawi, Mr. Ahmed Al-Tamimi, and Mr. Hamza Ali for their assistance during the field survey. Lastly, we thank Mrs. Omnia Kazem and Mr. Bakr Samar.

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