

3D ERT comparative assessment of Wenner, Wenner-Schlumberger, and Dipole-Dipole arrays for geotechnical characterisation in carbonate environments at Shakrook, Erbil Governorate, Iraqi Kurdistan Region

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Abstract: This study presents a comparative geoelectrical survey utilising Wenner, Wenner-Schlumberger, and Dipole-Dipole arrays to evaluate the subsurface of the Shakrook anticline in the Erbil Governorate. 3D electrical resistivity tomography (ERT) images are obtained using IRIS Syscal Junior with 72 electrodes and three arrays operating concurrently. To assess the engineering behaviour at the site, a 2D parallel array of seven profiles measuring 2D (213 m in length, 3 m between electrodes, 5 m between profiles, with a maximum study depth of 35.6 m) is established. The data inversion is performed using ZondRes3D software to generate a 3D resistivity model. The Wenner array emphasis on vertical resistivity differences facilitated the identification of three separate electro-lithological units in the region: a shallow conductive soil layer (5–30 $\Omega\cdot\text{m}$) with variable thickness (2.5–12.5 m), marly limestone (30–136 $\Omega\cdot\text{m}$) with (10–23 m) thickness, and deeper, competent dolomitic limestone (136–398 $\Omega\cdot\text{m}$) from the depth 10 m to the depth of the block. The Wenner-Schlumberger array facilitated a balance between vertical and lateral sensitivity, hence enhancing the resolution of fracture zones. The enhanced lateral resolution of the Dipole-Dipole array delineated the precise limits of narrower conductive anomalies, notably a prominent vertical low-resistivity corridor between $x = 95\text{--}125\text{ m}$, consistently characterised as a fault-controlled karst or seepage conduit. Geotechnical interpretation indicates that high-resistivity benches at depths of 13–36 m serve as optimal foundation layers for supporting substantial loads, but conductive seams are associated with weak, damp, or clay-rich zones that pose risks of settlement, seepage, and instability. The integration of all three arrays demonstrates that no one array can fully resolve complex carbonate environments; rather, their collective use establishes a versatile frame-

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work for site characterisation, foundation planning, and hazard assessment in the absence of boreholes. The results illustrate the importance of multi-array ERT for geotechnical design in the structurally complex carbonate terrains of northern Iraq.

Key words: 3D ERT Wenner, Wenner-Schlumberger, Dipole-Dipole, geotechnical characterisation

1. Introduction

1.1. Importance of subsurface characterisation in carbonate terrains

Geotechnical site characterisation is a critical phase in the construction of buildings, roadways, and large-scale national projects (*El-Badrawy et al., 2024*). Subterranean voids are significant in geoscience, especially in civil engineering, hydrogeology and natural hazard mitigation (*Wanaim et al., 2025*). In civil engineering, the major objective of site assessment is the discovery and characterisation of cavities, which is essential for evaluating ground stability, minimising risks, and preventing natural hazards that could compromise civil structures, hence extending the duration of their life (*Jongmans and Garambois, 2007; El-Badrawy et al., 2024*). Constructing a precise geological visualisation for engineering building design using standard geotechnical methods is challenging, as these approaches only obtain point data around subsurface features (*El-Badrawy et al., 2024*). Moreover, they are expensive, time-intensive, necessitate supplementary equipment, and are linked to model uncertainty (*McCann and Forster, 1990*); for instance, conventional drilling techniques may inadequately define geological formations in limestone settings. In contrast, non-invasive, economical shallow geophysical techniques are essential for delineating near-surface characteristics that require ongoing spatial information and evaluating their geotechnical circumstances (*Verdet et al., 2020; Amin et al., 2024*).

The examination of karst systems is highly significant in hydrogeology, hydrocarbon prospecting, and geological engineering. Karstification produces secondary porosity and permeability mostly in carbonate formations. A karst system forms through chemical dissolution when acidified fluids interact with carbonate rocks, primarily limestone and dolostone. Karst systems possess complicated three-dimensional structures that hinder their geometric characterisation (*Eissa, 2022*). Shallow karsts pose a significant threat to existing structures and civil engineering efforts due to the potential

for resurgence, subsurface sinkhole creation, and subsidence (*Samyn et al., 2014; Sigdel et al., 2025*).

1.2. Role of 3D electrical resistivity tomography in geotechnical investigations

The implementation of 3D ERT represents a substantial advancement over 2D surveys, facilitating volumetric visualisation of resistivity structures and enhancing the resolution of complex buried elements. 3D surveys can reduce interpretation uncertainty relative to two-dimensional surveys by effectively capturing horizontal and vertical resistance contrasts, thereby providing more dependable data regarding heterogeneous outcrop characteristics (*Loke et al., 2013*). The limestone in the survey area may be extensively fractured and karstified. These features can be difficult to find by traditional geological exploration. A number of near-surface geophysical techniques are favourable for geotechnical site assessments (*Ercoli et al., 2012*). The selection of the geophysical method depends on the variation in physical properties between the karst structures and the host rock, as well as the link between resolution and investigation depth (*Eissa, 2022; El-Badrawy et al., 2024*). Considering these other approaches, ERT seems to be the preferred method due to its versatility as well as its ability to determine subsurface risks. The DC resistivity method, especially in its electrical resistivity tomography (ERT) type, is extensively employed for the detection and mapping of subsurface cavities (*Reynolds, 2011*). These cavities comprise natural karst systems and artificial voids, making ERT an important instrument in civil engineering, environmental assessments, and geological research (*Romano et al., 2023; Martínez-López et al., 2013; Jabrane et al., 2023*). The electrical resistivity tomography (ERT) technique is an efficient instrument for delineating karst patterns, as it can detect underlying resistive structures and detect slight variations in electrical resistivity in both vertical and horizontal directions (*Noel and Xu, 1992; Abbas et al., 2008; Araffa, 2010; Putiška et al., 2012; McCrackin et al., 2022*). In recent decades, advances in data collection and inversion methodologies have considerably improved their capabilities. Advanced resistivity surveys now acquire large data sets in both (2D) and (3D) formats, facilitating the detailed reconstruction of complex underground geological formations that were previously inaccessible with traditional (1D) techniques (*Dahlin and*

Zhou, 2004; Sharma and Verma, 2015). Electrical resistivity tomography (ERT) may identify subsurface resistivity variations indicative of abnormalities such as fractures or karstified areas (Liu et al., 2023), making it especially effective for revealing hidden cavities related to fracture pathways in limestone formations (Wanaim et al., 2025). A number of studies emphasise the efficacy of ERT to identify resistivity anomalies associated with voids (Chan et al., 1996; Batayneh and Al-Zoubi, 2000; Tejero et al., 2002; Hutchinson, 2005; Cardarelli and Fischanger, 2006; Cardarelli et al., 2010; Zhu et al., 2011; Charbaoui et al., 2024; Gardi et al., 2026; Monsard et al., 2023). Abed et al. (2021) successfully employed the 2D and 3D resistivity methods to visualise natural cavities in the arid region of Hit, Iraq.

1.3. Known characteristics of different arrays

The efficiency of ERT surveys is significantly affected by the selection of electrode array arrangement, including commonly utilised arrays that include Dipole-Dipole, Wenner, Wenner-Schlumberger, Pole-Dipole, and Pole-Pole arrays (Telford et al., 1990; Szalai and Szarka, 2008; Wilkinson et al., 2010). Each array provides specific advantages in depth penetration, resolution, and sensitivity to noise (Loke, 2022). The selection of a suitable electrode array is an essential factor in the success of (ERT) surveys, especially for cavity detection (Storz et al., 2000). Equally-spaced-electrode Wenner arrays exhibit a high signal-to-noise ratio and are especially responsive to vertical resistivity contrasts, thereby making them highly suitable for identifying extensive stratigraphic units; however, they display limited horizontal resolution and require a change of electrodes in the field (Reynolds, 2011; Loke, 2022). The Wenner-Schlumberger configuration is a hybrid of the Wenner and Schlumberger electrode arrangements, combining earth penetration with lateral resolution. This adaptability enables its application in various terrains where both vertical stratification and lateral variations are significant, even with increased implementation complexity (Dahlin and Zhou, 2004). The Dipole-Dipole array consists of current and potential dipoles separated progressively to gather data highly sensitive to lateral variations in resistivity, enabling the identification of faults, voids, and fractures. However, it exhibits reduced signal efficiency and limited depth penetration, particularly in noisy environments (Loke and Barker, 1996b; Dahlin and Zhou, 2004). These differences illustrate that no single array is optimal

for all conditions and highlight the necessity for comparative evaluation when designing effective survey acquisition strategies in complex geological environments, such as carbonates. The main hypothesis states that the comparative utilisation of Wenner, Wenner-Schlumberger, and Dipole-Dipole arrays in 3D ERT will reveal significant variations in imaging resolution, depth penetrated, and sensitivity to underground heterogeneities. In contrast, the integrated approach will exhibit enhanced reliability in the geotechnical assessment of carbonate environments in comparison with the individual use of these arrays. The efficacy of these arrays is further evaluated by their employment in data collection and inversion operations, which are crucial to the successful completion of ERT surveys. Numerous studies have evaluated the performance of various electrode arrays, focusing on their resolution, efficiency, noise sensitivity, and inversion results. *Dahlin and Zhou (2004)* systematically compared 10 different electrode arrays and evaluated their resolution, efficiency, noise sensitivity, and inversion performance. They specifically examined the results using both robust and smoothness-constrained inversion. *Martorana et al. (2017)* investigated conventional arrays using both synthetic and field data obtained from multichannel 2D imaging systems. They compared different array configurations for multichannel 2D ERT, including Dipole-Dipole, Pole-Dipole, Wenner-Schlumberger, and multiple-gradient configurations. The resulting inverted models were quantitatively compared using data misfit, relative model resolution, and model misfit, based on both synthetic and field data, whilst *Cubbage et al. (2017)* proposed improvements to the Wenner array to improve its efficiency in field data collecting. Similarly, *Al-Hameedawi and Thabit (2017)* compared four traditional arrays to assess their resolution and efficacy in delineating complex sedimentary layers, while *Abdullah et al. (2018)* conducted a numerical evaluation of the performance of optimised compared to traditional arrays in shallow underground investigations. In more recent work, *Jabrane et al. (2025)* evaluate the effectiveness of open-source inversion tools like BERT and PyGIMLi in reconstructing subsurface anomalies for cavity detection and landslide assessment.

The absence of comparative analysis for Wenner, Wenner-Schlumberger, and Dipole-Dipole arrays in 3D ERT within carbonate settings substantiates this work. Carbonate rocks exhibit significant heterogeneity, featuring cracks, voids, and variable porosity levels, which makes their geotechnical

characterisation complex. Despite the application of individual array modes in prior studies, a systematic comparison of their relative performance for depth penetration, lateral resolution, and subsurface heterogeneities in 3D penetrating-pulse imaging applications remains unexamined. This study aims to address this gap by optimising array selection for geotechnical investigations to enhance the reliability and precision of subsurface models. These findings will enhance best practices in geophysical site characterisation, especially in carbonate terrains when borehole or laboratory data are limited. The conceptual framework for this work is shown in Fig. 1. The objectives of this study are:

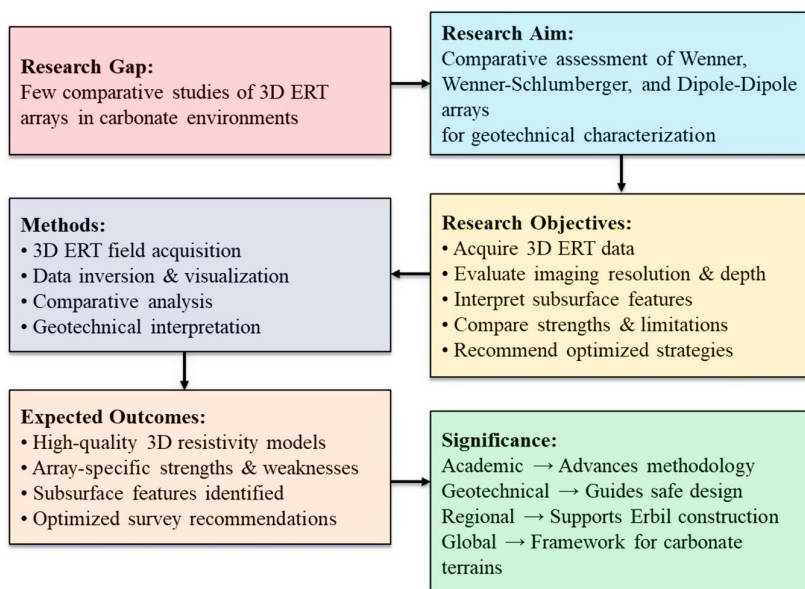


Fig. 1. Conceptual framework diagram for the research.

1. To acquire and process 3D ERT data utilising Wenner, Wenner-Schlumberger, and Dipole-Dipole configurations at a carbonate study location.
2. To evaluate the imaging capabilities of each array with respect to resolution, penetration depth, and sensitivity to horizontal and vertical subsurface heterogeneities.
3. To delineate and analyse subsurface characteristics, including fractures, cavities, and heterogeneities, that influence the geotechnical situation in carbonate formations.

4. To evaluate the strengths and limitations of the three arrays for geotechnical subsurface characterisation.
5. Recommendations for preferential array configurations and survey techniques for 3D ERT applications in carbonate terrains characterised by limited borehole and laboratory data.

2. Study area and geological setting

2.1. Study area

The study area lies in the Shakrook anticline, immediately beside Shakrook village in Shaqlawa district, Erbil Governorate, Kurdistan Region, Iraq, about 45.5 km northeast of Erbil City. Location of the site investigation taken by Global Positioning System (GPS) with the coordinate: UTM time zone, which lies in latitudes between 4035301 N and 4035089 N and in longitudes between 445379 E and 445453 E (Fig. 2). The higher elevation is 789 m a.m.s.l. and the lower elevation is 769 m a.m.s.l. The examined site is exemplified by the Shakrook Anticline as a representative location for prospective initiatives in the area for proposed engineering projects. The carbonate lithology, topographic position, and practical accessibility of the site are typical of those found in planned developments; therefore, this study can serve as a preliminary design assessment and siting reference for similar sites in the Shaqlawa district and, more broadly, in the High Folded Zone.

2.2. Geological setting

The Shakrook Anticline is a double plunging anticline orientated NW–SE, located in the Shaqlawa region, characterised by a complicated geological and topographical environment. It is situated within the High Folded Zone of the Outer Platform of the Arabian plate in the Zagros fold-and-thrust belt, formed by the collision of the Arabian and Iranian plates during the Late Cretaceous period. This tectonic collision continues today with a convergent plate boundary (*Sissakian et al., 2021*). North of the Shakrook anticline lie the Hareer, Balisan, and Kamosk anticlines, while to the south is the extensive Safeen anticline, which separates from the Shakrook anticline by a broad, hanging Shaqlawa syncline (*Sissakian and Fouad, 2015*).

The stratigraphic composition of the exposed rocks in the Shakrook Anticline generally ranges from the Upper Jurassic to the Paleogene period.

The core of the Shakrook anticline predominantly consists of the Bekhme Formation (Late Cretaceous) (*Sissakian et al., 2021*). The formation constitutes the majority of the Shakrook anticline, with well-bedded and extensively bedded dolostone and limestone. The lower section is well-stratified, consisting of conglomerate and bituminous substances. The central unit consists of densely stratified coral reef limestone. The upper section is the thickest unit, formed of hard dolomite and including substantial rudist debris (*Sissakian et al., 2021*). The average thickness of the Shakrook is 180 m, and it was deposited in reef, shoal, and fore reef facies. In the Shakrook Anticline, the formation is underlain unconformably by the Qamchuqa Formation (*Sissakian and Al-Jiburi, 2014*). The Aqrah Formation (Late Cretaceous) is situated at the centre of the Shakrook Anticline, below the Bekmah Formation and above the Qamchuqa Formation. It is distinguished by a well-bedded shallow-marine association with limestone facies. The formation consists mostly of limestone and dolomite strata, characterised by grey and greyish-brown colours, hardness ranging from hard to extremely hard, and a well-bedded to massive structure. The Aqra Formation has a thickness of 739.5 metres (*Sissakian and Al-Jiburi, 2014*).

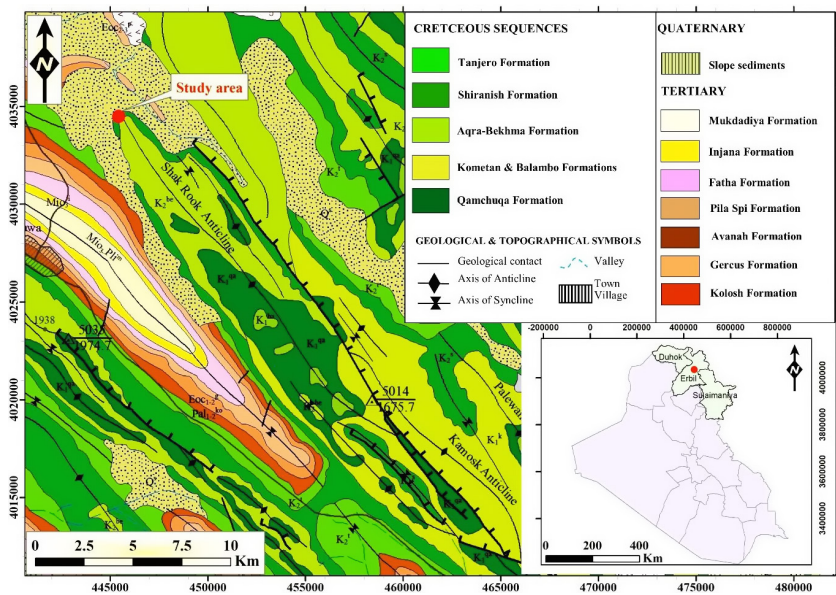


Fig. 2. The location and geological map of the study area (*Sissakian and Fouad, 2014*).

The Shiranish Formation (Late Cretaceous) is extensively distributed throughout Iraq, occupying the troughs of the principal synclines situated between the anticlines in the High Folded Zone (*Sissakian and Al-Jiburi, 2014*). This formation is revealed in both limbs of the Shakrook anticline and in the adjacent region, as well as in the study area (Fig. 2), which is situated on the northwestern plunge. The formation comprises two sections: the upper section is defined by soft rock, such as shale, whilst the lower section consists of limestone, sometimes characterised by marly or clayey rocks that are well-bedded (*Ahmed and Salman, 2020*). The formation in the Safeen, Hareer, and Shakrook anticlines comprises two components: the lower section, which consists of well-bedded white and grey limestone, occasionally with iron and chert concretions. The upper section comprises blue and bluish-grey marls and shales, with a nearly papery texture (*Sissakian and Youkhanna, 1979*). The formation's thickness is around 75 metres (*Sissakian et al., 2021*). The interface between the Shiranish and the underlying Bekhme Formation is conformable (*Sissakian and Al-Jiburi, 2014*). Based on *Al-Qayim et al. (1986)*, deposition of the Shiranish Formation occurred within the anoxic zone, namely at water depths exceeding 150 m in the lower section and significantly exceeding 150 m in the upper section. The assumption is predicated on the absence of bioturbation and existing benthic organisms. Quaternary Sediments (Pleistocene-Holocene) are insufficiently developed and comprise alluvial fan sediments (both ancient and present), slope sediments, and valley-filling sediments (*Sissakian et al., 2021*).

3. Methods adopted

3.1. 2D and 3D electrical resistivity tomography

The 2D survey images depict a deployed profile in the X-direction and depth in the Z-direction, assuming no variations in the Y-direction, which may represent a significant limitation of 2D surveys, while 3D surveys surpass 2D surveys in this aspect, as resistivity data is further captured in the Y-direction. For a thorough examination of complex subsurface conditions, 3D surveys are the most appropriate (*Loke and Barker, 1996a*). For 3D surveys, both current and potential electrodes are required and must be organised in a precise electrode (*Eissa, 2022*). In recent years, 3D ERT has emerged

as an effective instrument for near-surface geophysical exploration. The utilisation of 3D ERT for geotechnical studies in civil construction within the Kurdistan Region remains infrequent. 3D ERT is more precise than the 2D approach for identifying 3D objects in the subsurface. The inversion of the 3D data produces a distribution of electrical resistivity within the study volume, hence enhancing the localisation of the objects (*Le et al., 2022*). Nonetheless, the feasibility of a 3D resistivity survey is hindered by the substantial expenses associated with the survey. Data obtained in two dimensions can be inverted and analysed in three dimensions (*Ayolabi et al., 2012*).

3.2. Survey geometry (3D block)

The 3D ERT survey is executed by the 2D ERT methodology for geotechnical assessment in a carbonate environment. The IRIS SYSCAL Junior Switch-72 electrode system is employed for geoelectric resistivity measurement, featuring a 72-take-out multi-core cable, steel electrodes, a contact-resistance meter, an external battery, tape, a mallet, GPS, and saltwater. This study used Wenner, hybrid Wenner-Schlumberger, and Dipole-Dipole arrays to acquire ERT profiles due to their ability to reach significant depths and provide sufficient resolution for geotechnical investigations. A 3D ERT block survey done on September 17–18, 2024, comprises seven parallel 2D ERT profiles (P1 to P7) orientated in a NW–SE direction, aligning with the predominant structural trend in the research area. The total length of the profiles is 213 metres, facilitating a maximum investigative depth of approximately 35 metres. The electrode spacing is 3 metres, and the distance between profiles is 5 metres, encompassing an area of approximately 6,390 m² (Fig. 3). Use the same survey geometry for all three arrays.

Three-dimensional models were constructed from seven parallel 2D ERT profiles, which were processed and interpreted using ZondRes3D, a software for the inversion and visualisation of resistivity and induced polarisation (IP) data (*Zond Software, 2017*). The software possesses robust capabilities for handling extensive datasets, executing topographic adjustments, and performing reliable inversions, enabling it to rebuild subsurface resistivity structures. Iterative inversions were conducted to derive the optimal model, employing a maximum of four iterations to minimise the RMS error (2.2%) between observed apparent resistivities and computed values, using

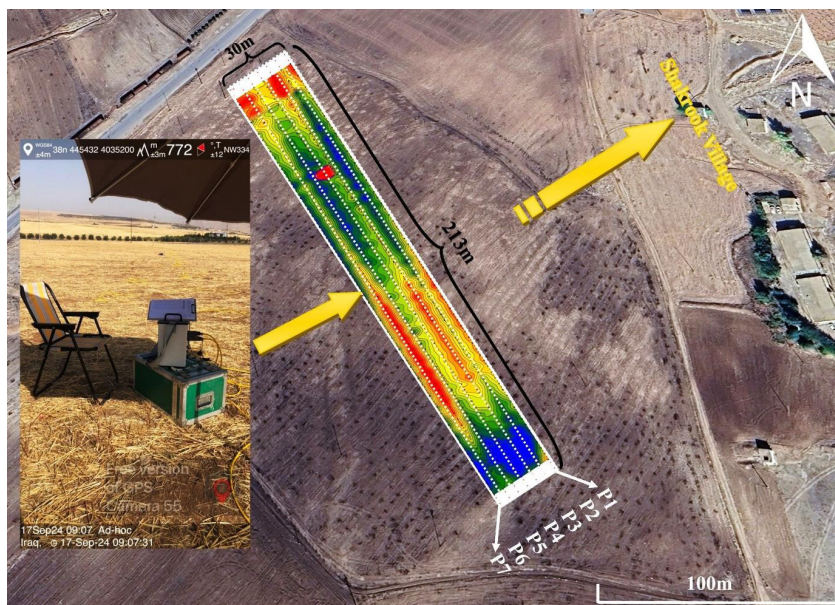


Fig. 3. Google Earth image of the Shakrook study area showing the locations and orientations of the ERT profiles, overlaid with the surface-calculated apparent resistivity distribution. The coloured contours represent apparent resistivity values ranging from 11 to 16.6 $\Omega\cdot\text{m}$. The ERT survey investigates the subsurface to a maximum depth of approximately 35.6 m. Source: Google Earth imagery (Google Earth_2025 Airbus, ERT data acquired and processed by the authors).

a designated threshold.

The analysed data provide effective geotechnical insights on carbonates, facilitated by the integration of topography, the use of stringent inversion techniques, and validation using sensitivity tests. This method has facilitated the engineering of significant zone delineation, identification of structural discontinuities, and assessment of foundation suitability without the need for borehole and laboratory data.

4. Results

4.1. Wenner array 3D block model

This model demonstrates a clear vertical stratification of resistivity, marked by conductive zones at the surface that transition into deeper, more resistive features, with an RMS error of 3.0%. The Wenner array 3D block confirms

a stratified subsurface configuration within the Lower Shiranish Formation and delineates three geoelectric units (Fig. 4), constrained to the following ranges: (a) conductive near-surface clay layer or soil cover ($14\text{--}30\ \Omega\cdot\text{m}$), with thickness ($5\text{--}12.5\ \text{m}$), (b) a transitional fractured carbonate/marly limestone layer of the Lower Shiranish Formation. The resistivity value ranges from ($30\text{--}136\ \Omega\cdot\text{m}$), with a thickness of $10\ \text{m}$ that increases to about $20\ \text{m}$ towards the northwest. (c) At greater depths, a highly resistive competent layer with values between ($136\text{--}300\ \Omega\cdot\text{m}$) is observed, particularly at depths from the southeast to $16\text{--}25\ \text{m}$ and from the northwest to $35.6\ \text{m}$, especially along the $x = 110\text{--}160\ \text{m}$, which may be interpreted as a possible fault. It is characterised as a competent dolomitic limestone of the Bekhma Formation.

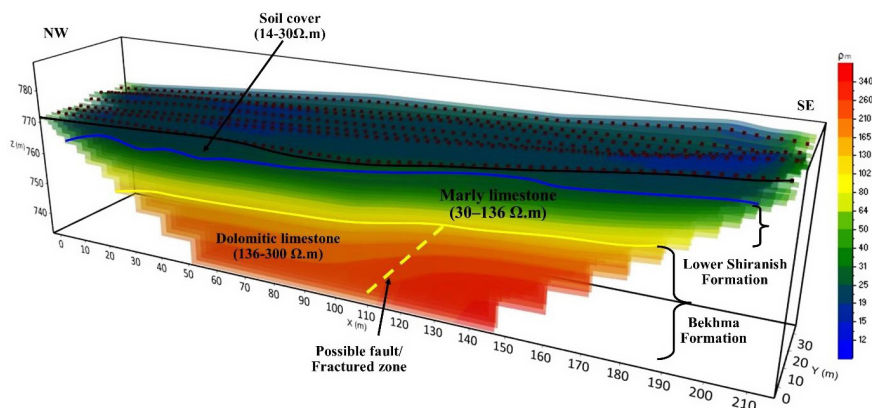


Fig. 4. 3D Resistivity model by Wenner array.

4.2. Wenner-Schlumberger array 3D block model

The second is this instructive arrangement, in which both lateral and vertical sensitivity contribute to a comprehensive understanding of the stratigraphic and structural features (RMS error 2.9%). The Wenner-Schlumberger 3D block illustrates a subsurface stratification featuring a highly conductive and wide zone across the block (Fig. 5). It represents a moist clay or soil cover ($14\text{--}30\ \Omega\cdot\text{m}$, $8\text{--}12\ \text{m}$ thickness) overlaying a moderately resistive layer, which features a prominent middle stratum throughout a substantial portion of the block. The material exhibits nominal resistivity values ranging from 30 to $133\ \Omega\cdot\text{m}$ and has an initial thickness of $10\ \text{m}$, which increases to $23\ \text{m}$

towards the northwest in the study region. This layer, interpreted as marly limestone, contains interbedded or partially water-saturated carbonate from the Lower Shiranish Formation. This area is more clearly delineated on the Wenner-Schlumberger block compared to the pure Wenner block and exhibits minor lateral changes and profound, proficient limestone ledges. It provides superior lateral resolution compared to the Wenner array, facilitating the identification of minor fracture-related anomalies while maintaining stratigraphic continuity. The subsurface deeper layer, ranging from (13–35.6 m) in depth and exhibiting resistivity values between (133–283 $\Omega\cdot\text{m}$), encompasses the dolomitic limestone Formation of Bekhma. Below around 20 m, the most pronounced resistive benches prevail in the deepest parts of the block, especially beneath $x = 80\text{--}160\text{ m}$.

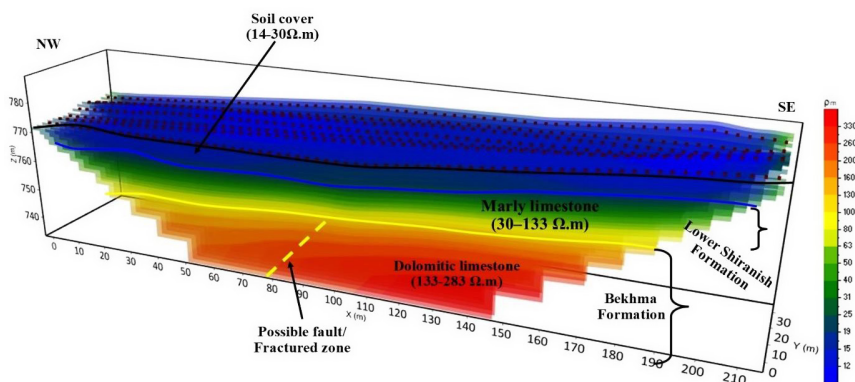


Fig. 5. 3D Resistivity model by Wenner-Schlumberger array.

4.3. Dipole-Dipole array 3D block model

The 3D Dipole-Dipole resistivity block provides high-resolution visualisation of lateral subsurface variations in the Lower Shiranish Formation, with a root-mean-square error of 5.5%. The superficial layer (5–29 $\Omega\cdot\text{m}$, 2.5–6 m thick) is distinguished by a severely fractured and discontinuous conductive stratum (Fig. 6). It indicates moist soil distribution, significant variability, and several small regions with comparatively higher moisture. The intermediate layer has varying resistivities (29–107 $\Omega\cdot\text{m}$) and thicknesses ranging from 13 to 23 m. It illustrates the karstic marly limestone of the Shiranish Formation within the block's internal structure (Fig. 7).

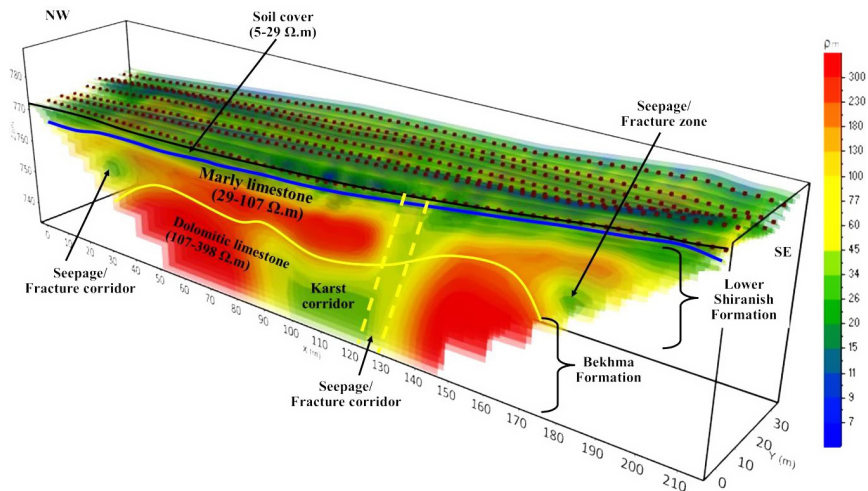


Fig. 6. 3D Resistivity model by Dipole-Dipole array.

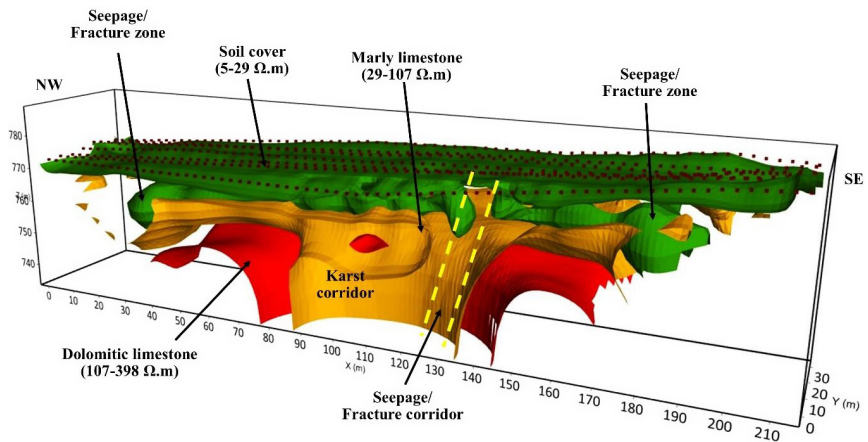


Fig. 7. 3D Resistivity iso-surfaces by Dipole-Dipole array.

At intermediate (5–25 m) and face of the block (first profile) the model shows several vertical to sub-vertical conductive features (notably between $x = 95 - 125$ m) as well as minor ones at $x = 20 - 40$ m and $x = 170 - 195$ m, and thickness of the most conductive clay features attains (25 m), interpreted as the presence of seepage zones or clay-filled dissolution features that cut the section. Flanking resistive shoulders ($> 150 \Omega \cdot \text{m}$) of truncated carbonate benches by this conductive channel. These anomalies attenuate

the continuity of the resistive carbonate bodies and characterise weak positions of lands and show areas of structural weakness which leave the surface prone to subsidence of the central block (Fig. 7). At the flanks, on the other hand, in the deeper levels (10–35.6 m; 8–35.6 m) the resistivity ranges (107–398 $\Omega\cdot\text{m}$) occurred defined by extensive resistive benches, par-

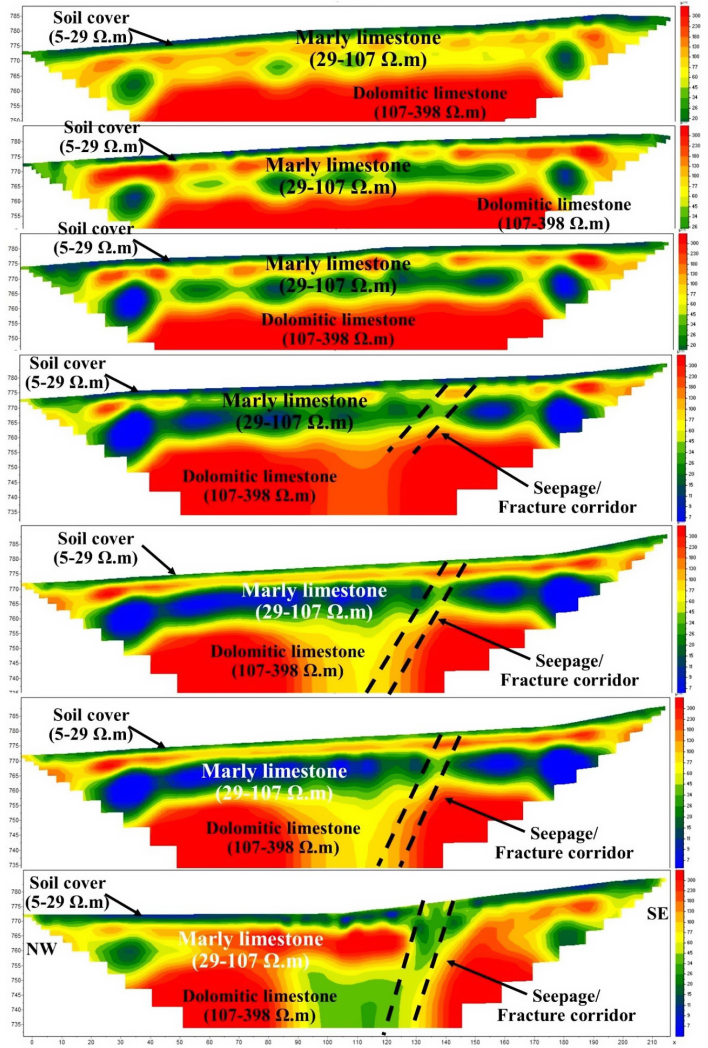


Fig. 8. 2D vertical resistivity slices extracted from the 3D ERT model obtained using the Dipole-Dipole array along the seven parallel ERT profiles.

ticularly on the flanks ($x = 40\text{--}85\text{ m}$ and $x = 140\text{--}170\text{ m}$). These are the competent dolomitic limestone horizons of the Bekhma Formation. The persistence of a central low-resistivity corridor ($x = 95\text{--}125\text{ m}$) despite cutting across the resistive layers suggests the existence of a fault-controlled karst or seepage conduit. These geometries are demonstrated in the first three 2D ERT profiles (Fig. 8), whereas the others are presented as a continuous competent dolostone or dolomitic limestone.

5. Comparisons of Wenner, Wenner-Schlumberger and Dipole-Dipole arrays

The comparison of various operational modes of the investigated Wenner, Wenner-Schlumberger, and Dipole-Dipole configurations is presented in Table 1, corresponding to the resistivity profiles acquired over the Lower Shiranish Formation with dimensions of 213 m (profile length) $\times$ 30 m (width) $\times$ 35.6 m (depth).

Table 1. The comparison between Wenner, Wenner-Schlumberger and Dipole-Dipole arrays in a 3D resistivity model.

Aspects	Wenner	Wenner-Schlumberger	Dipole-Dipole
Resolution	Strong vertical resolution, smooth layering, but lateral features blurred	Balanced vertical and lateral resolution compared to Wenner, sharper transitions	Excellent lateral resolution, narrow anomalies sharply imaged, weak layering
Depth penetration	Good penetration, stable inversion	Good penetration with balanced sensitivity	Reduced penetration, noisy at depth
Strengths	Clear vertical stratification	Reveals fracture zones while keeping stratigraphy visible	Map faults, fractures, seepage corridors and karst conduits clearly
Limitations	Lateral discontinuities and faults appear smeared	Moderate resolution of very small features, some pockets smoothed out	Stratigraphy looks disrupted, less effective for smooth layering
Best use	General layering and stratigraphic interpretation	Compromise array: good for both stratigraphy and structures	Detecting faults, karst systems and lateral heterogeneity

6. Geotechnical implications and array suitability

The inversion of 3D ERT data utilising Wenner, Wenner-Schlumberger, and Dipole-Dipole arrays in the Lower Shiranish Formation facilitated significant geotechnical insights for engineering applications. By correlating resistivity measurements with lithological and structural features, multiple geotechnical zones can be deduced (Table 2). Each array possesses distinct strengths: Wenner highlights vertical stratigraphy, Wenner-Schlumberger achieves a balance between vertical and horizontal sensitivity, and Dipole-Dipole focuses on imaging faults, fractures, and karst corridors.

Table 2. Geotechnical implications inferred from 3D ERT.

Resistivity range	Lithology/Material	Inferred geotechnical implications	Array suitability
< 5 – 30 Ω·m	Moist clay-soil cover	Indicates soft, compressible soils with high moisture content, potential seepage, less suitable for heavy load-bearing without improvement	Wenner (layering), Dipole-Dipole (detecting narrow conductive/seepage zones)
30 – 136 Ω·m	Fractured limestone with clay/silt infill or transitional marly limestone of Shiranish Formation	Subject to localised weakness and possible seepage through fractures, controlled groundwater pathways. Foundations placed may face differential settlement risks	Wenner-Schlumberger (balanced imaging), Dipole-Dipole (fractures/seepage zones)
136 to > 398 Ω·m	Competent/massive dolomitic limestone of the Bekhma Formation	Preferred foundation horizon with high load-bearing capacity, though karst features must be considered	Wenner (depth to bedrock), Wenner-Schlumberger (continuity of benches), Dipole-Dipole (karst detection)

7. Discussion

The comparison of Wenner, Wenner-Schlumberger, and Dipole-Dipole arrays facilitates a comprehensive analysis of the subsurface condition of the

Lower Shiranish Formation, distinguished by intercalations of carbonate and marl. Each array exhibits distinct subsurface characteristics, and their combination significantly enhances geotechnical interpretation.

The Wenner and Wenner-Schlumberger arrays emphasise vertical resistivity contrasts, producing a smooth layered and stratified image of the subsurface structure. In the present study, these arrays delineate three primary electro-lithological units: a conductive soil cover, an intermediate fractured carbonate horizon of the Lower Shiranish Formation, and deep competent dolomitic limestone benches. Stratigraphic clarity is crucial for establishing the regional geotechnical framework, including the thickness of the weak overburden and the depth to competent bedrock. Lateral discontinuities such as fault zones and narrow seepage corridors appeared smoothed or diffused while employing the Wenner array, hence constraining the Wenner system's capacity to delineate structural heterogeneities critical to engineering design.

The Wenner-Schlumberger array for geotechnical assessment gives an optimal model, yielding balanced data for both stratigraphic and structural aspects. The Wenner array is optimal for assessing overburden thickness and vertical stratigraphy, whereas the Dipole-Dipole array is suited for delineating faults, fractures, seepage channels, and karst systems that may affect foundation stability. The integration of the three arrays ensures a comprehensive and reliable geotechnical evaluation.

The Wenner-Schlumberger array exhibited balanced imaging capabilities, integrating excellent vertical resolution with enhanced lateral sensitivity. The ability to identify stratigraphic and structural anomalies makes the Wenner-Schlumberger array particularly suitable for geotechnical site investigations that require the differentiation of foundation horizons and potential danger zones. In addition, the Dipole-Dipole array is required to detect small, weak zones, narrow channels, and seepage corridors. For engineering applications, it offers an optimal compromise between the continuous mapping of strata (Wenner-Schlumberger array) and the detection of structural anomalies (Dipole-Dipole) that may affect slope stability, bearing capacity, or groundwater flow.

The features preferentially highlighted by the Dipole-Dipole array are those with narrow lateral contrast. High sensitivity to changes in horizontal resistivity made it possible to detect a vertical conductive corridor at

($x = 95–125$ m), which is interpreted in the context of a fault-influenced fracture system/karst conduit. They are sources of large geotechnical hazards, such as seepage, settlement, and local collapse. While it underperforms in determining continuous layering and depth penetration, the potential to identify structurally weak corridors is invaluable for foundation design and risk management. For instance, the area of competent limestone ($107–398 \Omega\cdot\text{m}$) is clearly distinguished from faulted and water-bearing corridors ($29–107 \Omega\cdot\text{m}$) to help with the selection of an appropriate foundation block.

The stratigraphic sequence revealed by the 3D resistivity images, including a conductive, clay-rich soil cover, intermediate fractured carbonate horizons (or may be marly limestone), and deeper competent dolomitic limestone benches, aligns closely with the documented regional subsurface structure of the Lower Shiranish Formation. This interpretation is more readily accepted when juxtaposed with the lithological information from the Basrma Badil No. 8 water well, located approximately 1475 m to the southeast (nearly south) of the research region (Fig. 9). The well log reveals the presence of a superficial shallow clayey soil cover, a lower sequence of alternating marly limestone with varying fracture densities, and a deeper, more competent dolomitic limestone layer characterised by reduced porosity. The strong agreement between geoelectrical stratigraphy and borehole succession indicates that the resistivity-derived layering is not an artefact of inversion but reflects the true geological setting.

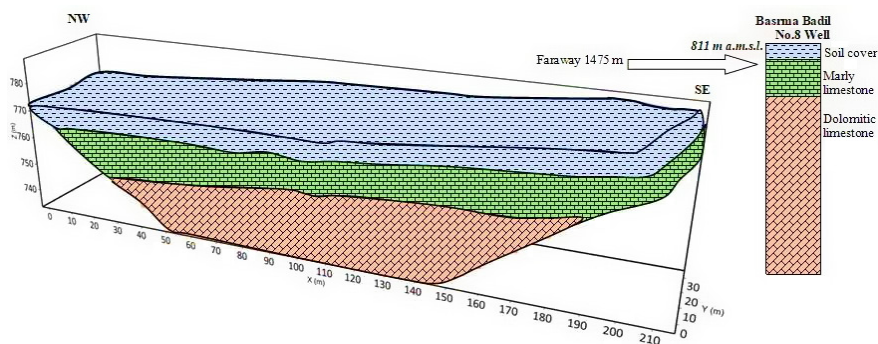


Fig. 9. 3D Resistivity model by Wenner-Schlumberger array and a groundwater well (Basrma Badil No. 8).

This agreement confirms the credibility of the geophysical results for the geotechnical characterisation in a zone without direct borehole control.

The calibration illustrates that ERT, especially when carried out using the Dipole-Dipole array's ability to image laterally heterogeneous structures, makes it possible to reproduce the stratigraphic sequence as inferred from more classical geological surveys. This provides confidence in the use and interpretation of resistivity models to extend the depth and continuity of competent foundation horizons, delineate weak marl and seepage-prone intervals, and detect anomalies that may be controlled by fractures not explicitly logged in the water well. At the end, the agreement between ERT-based successions and the lithological evidence at the well site establishes confidence in the practicality of using multi-array electrical resistivity tomography for engineering designs in carbonate environments.

In geotechnical terms, the integration of the three arrays is essential. Although the Dipole-Dipole array demonstrates considerable sensitivity to lateral variability, such as broken corridors, seepage channels, and karstified zones, it is insufficient alone for a comprehensive interpretation of the geotechnical context. Stratigraphy, overburden, and the depth to competent limestone benches are more precisely delineated using Wenner and Wenner-Schlumberger configurations, which offer enhanced vertical resolution and balanced sensitivity to both horizontal and vertical features. Certain authors have emphasised that reliance solely on a Dipole-Dipole array may lead to an overestimation of the discontinuities and inadequate stratigraphic control, particularly observed in carbonates, where resistivity contrasts are minimal (*Loke et al., 2013; Dahlin and Zhou, 2004*).

On the other hand, the combination of Wenner, Wenner-Schlumberger and Dipole-Dipole arrays produces a stronger geotechnical model. In this regard, Wenner can generally resolve vertical zonation and depth to bedrock; Wenner-Schlumberger can handle the required overall stratigraphy and structural variations; and Dipole-Dipole can delineate the presence of faults and lateral changes. Studies such as those demonstrated by *Chambers et al. (2012)* and *Loke et al. (2013)* have shown that multi-array integration is an important step in reducing inversion ambiguities and improving the reliability of geotechnical interpretation, particularly in cases where borehole control is limited.

Table 3 summarises the strengths, limitations, and geotechnical applications of the three most common applied ERT arrays: Wenner, Wenner-Schlumberger, and Dipole-Dipole. While the Dipole-Dipole array offers ex-

cellent lateral resolution, it should be supplemented with Wenner-Wenner-Schlumberger arrays for a comprehensive geotechnical assessment, particularly in carbonate-marl successions such as the Lower Shiranish Formation.

Table 3. The strengths, limitations, and geotechnical applications of the three most commonly applied ERT arrays.

Arrays	Strengths	Limitations	Geotechnical applications
Wenner	• High vertical resolution • Good for stratigraphy and overburden thickness • Robust against noise	• Poor lateral resolution • Faults and narrow anomalies appear smeared	• Mapping depth to bedrock • Identifying stratigraphic layering • Estimating overburden thickness
Wenner-Schlumberger	• Balanced vertical and lateral sensitivity • Good depth penetration • Resolves both layers and structures	Moderate sensitivity to very small anomalies. Some smoothing of sharp contacts	• Detecting fracture zones • Identifying foundation benches • General geotechnical characterisation
Dipole-Dipole	• Excellent lateral resolution • Detects faults, fractures and karst • Sensitive to narrow conductive zones	• Lower vertical resolution • Reduce depth penetration • Can exaggerate discontinuities	• Locating faults and seepage corridors • Detecting karst conduits • Hazard assessment

8. Conclusions

The combined application of Wenner, Wenner-Schlumberger, and Dipole-Dipole arrays in the Lower Shiranish Formation has provided a comprehensive geotechnical assessment of the subsurface. The Wenner and Wenner-Schlumberger arrays effectively imaged the entire stratigraphy, comprising three primary electro-lithological units: a superficial conductive soil layer (5–30 Ω·m, 2.5–12.5 m), a central marly limestone (Shiranish Formation)

(30–136 $\Omega\cdot\text{m}$, 10–23 m), and a lower, competent dolomitic limestone bench (Bekhma Formation) (136–398 $\Omega\cdot\text{m}$), from the depth 16 until the depth of the block. The Wenner-Schlumberger array, with its balanced vertical and horizontal sensitivities, enhanced the differentiation of fractural zones. Comparison of the two data sets of arrays indicates that the Dipole-Dipole array, exhibiting superior horizontal resolution, delineated a distinctly defined fault-generated corridor ($x = 95\text{--}125\text{ m}$) and other narrow conductive features, which are critical for geotechnical assessment. The three arrays collectively indicate that while competent dolomitic limestone benches at depths of 16–36 metres constitute suitable foundation horizons, conductive corridors and fault-related anomalies present considerable geotechnical risks. The results indicate that a thorough characterisation of complex carbonate sediments cannot be achieved by a single array alone; however, the integration of complementary arrays significantly improves the reliability of geotechnical interpretations for engineering design.

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Statement on the use of AI. AI was used primarily as a language translation and writing-assistance tool to improve the grammar, clarity, readability, and overall academic style of the manuscript. The research itself, including the fieldwork, data acquisition, processing, analysis, interpretation and scientific conclusions, is based on its own research and on its own original data and was conducted with no use or assistance of AI.

References

- Abbas A. M., Sultan S. A., Monteiro Santos F. A., 2008: 2-D and 3-D resistivity in the area of the Menkaure Pyramid Giza, Egypt. *Bull. Eng. Geol. Environ.*, **67**, 3, 411–414, <https://doi.org/10.1007/s10064-008-0142-5>.
- Abdullah F. M., Loke M. H., Nawawi M., Abdullah K., 2018: Assessing the reliability and performance of optimised and conventional resistivity arrays for shallow subsurface investigations. *J. Appl. Geophys.*, **155**, 237–245, <https://doi.org/10.1016/j.japgeo.2018.06.018>.
- Abed A. M., Thabit J. M., Al-Menshed F. H., 2021: An attempt to image Um El-Adam cavity structure in the karst terrain at Hit Area, Western Iraq. *Iraqi Geol. J.*, **54**, 1A, 44–54, <https://doi.org/10.46717/igj.54.1A.5Ms-2021-01-26>.

- Ahmed S. H., Salman M. A. A., 2020: Geology and structural description of Shakrok Anticline; Northern Iraq. *Iraqi J Sci.*, **61**, 8, 2017–2032, <https://doi.org/10.24996/ij.s.2020.61.8.18>.
- Al-Hameedawi M. M., Thabit J. M., 2017: Comparison between four electrode arrays in delineating sedimentary layers of alluvial fan deposits in eastern Iraq using a 2D imaging technique. *Environ. Earth Sci.*, **76**, 15, 525, <https://doi.org/10.1007/s12665-017-6853-9>.
- Al-Qayim B., Habib H., Al-Dyni N., 1986: Petrology and geochemistry of Shiranish Formation (type section) towards sedimentary facies interpretation. *J. Geol. Soc. Iraq*, **19**, 3, 123–136.
- Amin A. K., Mohammed S. S., Baban E. N., 2024: Delineation of subsurface features by electrical resistivity tomography and induced polarisation in upstream basin of Chaq-Chaq dam – northeastern Iraq. *Contrib. Geophys. Geod.*, **54**, 3, 225–250, <https://doi.org/10.31577/congeo.2024.54.3.1>.
- Araffa S. A. S., 2010: Geophysical investigation for shallow subsurface geotechnical problems of Mokattam area, Cairo, Egypt. *Environ. Earth Sci.*, **59**, 6, 1195–1207, <https://doi.org/10.1007/s12665-009-0109-2>.
- Ayolabi E. A., Enoch I. J. E., Folorunso A. F., 2012: Engineering site characterisation using 2-D and 3-D electrical resistivity tomography. *Earth Sci. Res.*, **2**, 1, <https://doi.org/10.5539/esr.v2n1p133>.
- Batayneh A. T., Al-Zoubi A. S., 2000: Detection of a solution cavity adjacent to a highway in southwest Jordan using electrical resistivity methods. *J. Environ. Eng. Geophys.*, **5**, 4, 25–30, <https://doi.org/10.4133/JEEG5.4.25>.
- Cardarelli E., Cercato M., Cerreto A., Di Filippo G., 2010: Electrical resistivity and seismic refraction tomography to detect buried cavities. *Geophys. Prospect.*, **58**, 4, 685–695, <https://doi.org/10.1111/j.1365-2478.2009.00854.x>.
- Cardarelli E., Fischanger F., 2006: 2D data modelling by electrical resistivity tomography for complex subsurface geology. *Geophys. Prospect.*, **54**, 2, 121–133, <https://doi.org/10.1111/j.1365-2478.2006.00522.x>.
- Chambers J. E., Wilkinson P. B., Weller A., Meldrum P. I., Kuras O., Ogilvy R. D., Aumonier J., Bailey E., Griffiths N., Matthews B., Penn S., Wardrop D., 2012: Characterising sand and gravel deposits using electrical resistivity tomography (ERT): case histories from England and Wales. In: Walton G., Hunger E. (Eds.): *Proceedings of the 16th Extractive Industry Geology Conference*, University of Portsmouth, 8–11 September, 2010, pp. 166–172.
- Chan S., Barker R., Owens B., 1996: Tracing cavern systems in Galway, Ireland, using electrical imaging and radar surveys. In: Lagabriele R. (Ed.): *Proceedings of the 2nd Meeting Environmental and Engineering Geophysics*, Nantes, France, September 2–5, 1996, pp. 146–148.
- Charbaoui A., Guernouche M., Kchikach A., Jaffal M., Hadri A., Cimpoiasu M. O., Zapalá S., Amar M., Yazami O. K., 2024: Understanding the impact of deep structures on the hydrological setting of the Eastern Bahira Basin in Morocco using combined geophysical analysis of gravity, seismic, and electrical resistivity data. *J. King Saud Univ. Sci.*, **36**, 11, 103491, <https://doi.org/10.1016/j.jksus.2024.103491>.

- Cubbage B., Noonan G. E., Rucker D. F., 2017: A modified Wenner array for efficient use of eight-channel resistivity meters. *Pure Appl. Geophys.*, **174**, 7, 2705–2718, <https://doi.org/10.1007/s00024-017-1535-9>.
- Dahlin T., Zhou B., 2004: A numerical comparison of 2D resistivity imaging with 10 electrode arrays. *Geophys. Prospect.*, **52**, 5, 379–398, <https://doi.org/10.1111/j.1365-2478.2004.00423.x>.
- Eissa R., 2022: Identification of different shallow foundations using 3D electrical resistivity modeling. *Iraqi Geol. J.*, **55**, 2B, 111–120, <https://doi.org/10.46717/igj.55.2B.10Ms-2022-08-26>.
- El-Badrawy H. T., Abbas M. A., Massoud U., Nagy M., Alrefaee H. A., 2024: Multi-method geophysical characterisation at karst sites: a contribution to geotechnical hazard assessment in west Sohag Province, Upper Egypt. *Euro-Mediterr. J. Environ. Integr.*, **9**, 2, 891–907, <https://doi.org/10.1007/s41207-024-00522-2>.
- Ercoli M., Pauselli C., Forte E., Di Matteo L., Mazzocca M., Frigeri A., Federico C., 2012: A multidisciplinary geological and geophysical approach to define structural and hydrogeological implications of the Molinaccio spring (Spello, Italy). *J. Appl. Geophys.*, **77**, 72–82, <https://doi.org/10.1016/j.jappgeo.2011.11.011>.
- Gardi S. Q., Baban E., Aziz B., 2026: Innovative 3D ERT/IP applications for characterising clastic sediments in the proposed Delopa tourism project, Erbil, Kurdistan Region-Iraq. *Passer J. Basic Appl. Sci.*, **8**, 1, 111–128, <https://doi.org/10.24271/psr.2025.541831.2318>.
- Hutchinson P. J., 2005: Electrical imaging of deep clay-mine voids. In: *Proceedings of the 18th Symposium on the Application of Geophysics in Engineering and Environmental Problems (SAGEEP)*, April 2005, Atlanta, Georgia, Environmental and Engineering Geophysical Society, cp-183-00028, pp. 274–279, <https://doi.org/10.3997/2214-4609-pdb.183.274-279>.
- Jabrane O., El Azzab D., Martínez-Pagán P., Charroud M., El Mansouri B., Martínez-Segura M. A., Himi M., Elgettafi M., 2023: Comparison of the pyGIMLi and BERT packages for landslide and cavity detection: A case study from Tghat-Oued Fez, Morocco. *J. Earth Syst. Sci.*, **132**, 3, 107, <https://doi.org/10.1007/s12040-023-02119-9>.
- Jabrane O., Martínez-Pagán P., Martínez-Segura M. A., Capa-Camacho X., Delimi K., Chourak M., 2025: A comparison of array configurations in Python-based software for ERT data in shallow hazard detection. *Geosciences*, **15**, 4, 127, <https://doi.org/10.3390/geosciences15040127>.
- Jongmans D., Garambois S., 2007: Geophysical investigation of landslides: a review. *Bull. Soc. Géol. Fr.*, **178**, 2, 101–112, <https://doi.org/10.2113/gssgfbull.178.2.101>.
- Le T. H., Ngo S. H., Tran T. N., Nguyen H. T., 2022: Study on factors affecting the synthesis of selenium nanoparticles by solution plasma method. *J. Min. Earth Sci.*, **63**, 6, 53–60, [https://doi.org/10.46326/jmes.2022.63\(6\).06](https://doi.org/10.46326/jmes.2022.63(6).06).
- Liu Y., Lu G., Meng Z., Guo D., Hu D., Zhu L., He H., 2023: GIS approach for expressing structural landforms: Forms, elements, and relationships. *Appl. Sci.*, **13**, 23, 12872, <https://doi.org/10.3390/app132312872>.

- Loke M. H., 2022: Tutorial: 2-D and 3-D electrical imaging surveys. Geotomo Software, accessible at <https://www.geotomosoft.com/coursenotes.zip>.
- Loke M. H., Barker R. D., 1996a: Practical techniques for 3D resistivity surveys and data inversion. *Geophys. Prospect.*, **44**, 3, 499–523, <https://doi.org/10.1111/j.1365-2478.1996.tb00162.x>.
- Loke M. H., Barker R. D., 1996b: Rapid least-squares inversion of apparent resistivity pseudosections by a quasi-Newton method. *Geophys. Prospect.*, **44**, 1, 131–152, <https://doi.org/10.1111/j.1365-2478.1996.tb00142.x>.
- Loke M. H., Chambers J. E., Rucker D. F., Kuras O., Wilkinson P. B., 2013: Recent developments in the direct-current geoelectrical imaging method. *J. Appl. Geophys.*, **95**, 135–156, <https://doi.org/10.1016/j.jappgeo.2013.02.017>.
- Martínez-López J., Rey J., Dueñas J., Hidalgo C., Benavente J., 2013: Electrical tomography applied to the detection of subsurface cavities. *J. Cave Karst Stud.*, **75**, 1, 28–37, <https://doi.org/10.4311/2011ES0242>.
- Martorana R., Capizzi P., D'Alessandro A., Luzio D., 2017: Comparison of different sets of array configurations for multichannel 2D ERT acquisition. *J. Appl. Geophys.*, **137**, 34–48, <https://doi.org/10.1016/j.jappgeo.2016.12.012>.
- McCann D. M., Forster A., 1990: Reconnaissance geophysical methods in landslide investigations. *Eng. Geol.*, **29**, 1, 59–78, [https://doi.org/10.1016/0013-7952\(90\)90082-C](https://doi.org/10.1016/0013-7952(90)90082-C).
- McCrackin C. W., Kiflu H. G., Kruse S. E., Van Beynen P. E., Polk J. S., Miller B., 2022: 3D resistivity survey over mapped caves in eogenetic karst terrane, west-central Florida, USA. *J. Cave Karst Stud.*, **84**, 1, 1–13, <https://doi.org/10.4311/2017ES0125>.
- Monsard N. I., Bencheikroun S., Aarab A., Lakhroufi A., 2023: Contribution of electrical resistivity tomography (ERT) and vertical electrical sounding (VES) to delineate the structural organisation of the Palaeozoic Zone in the Rabat-Tiflet Region (Morocco). *Contrib. Geophys. Geod.*, **53**, 3, 207–224, <https://doi.org/10.31577/congeo.2023.53.3.3>.
- Noel M., Xu B., 1992: Cave detection using electrical resistivity tomography. *Cave Sci.*, **19**, 3, 91–94.
- Putiška R., Nikolaj M., Dostál I., Kušnirák D., 2012: Determination of cavities using electrical resistivity tomography. *Contrib. Geophys. Geod.*, **42**, 2, 201–211, <https://doi.org/10.2478/v10126-012-0018-3>.
- Reynolds J. M., 2011: *An Introduction to Applied and Environmental Geophysics* (2nd ed.). John Wiley & Sons, 712 p.
- Romano G., Capozzoli L., Abate N., De Girolamo M., Liso I. S., Patella D., Parise M., 2023: An integrated geophysical and unmanned aerial systems surveys for multi-sensory, multi-scale and multi-resolution cave detection: the Gravaglione site (Canale di Pirro Polje, Apulia). *Remote Sens.*, **15**, 15, 3820, <https://doi.org/10.3390/rs15153820>.
- Samyn K., Mathieu F., Bitri A., Nachbaur A., Closset L., 2014: Integrated geophysical approach in assessing karst presence and sinkhole susceptibility along flood-protec-

- tion dykes of the Loire River, Orléans, France. *Eng. Geol.*, **183**, 170–184, <https://doi.org/10.1016/j.enggeo.2014.10.013>.
- Sharma S., Verma G. K., 2015: Inversion of electrical resistivity data: A review. *Int. J. Comput. Syst. Eng./WASET*, **9**, 4, 400–406.
- Sigdel A., Dhakal P., Silwal C. B., Acharya S., 2025: Slope stability assessment of Ramche and Dhaibung landslides in Central Nepal using geological, geophysical, and geotechnical approaches. *Contrib. Geophys. Geod.*, **55**, 3, 265–296, <https://doi.org/10.31577/congeo.2025.55.3.1>.
- Sissakian V. K., Al-Jiburi B. S. M., 2014: Stratigraphy of the high folded zone. *Iraqi Bull. Geol. Min.*, **10**, 6 (special issue), 73–161.
- Sissakian V. K., Fouad S. F., 2014: The Geology of Erbil and Mahabad Quadrangles, scale 1:250000 (sheets NJ-38-14 and NJ-38-15), 2nd ed. *Iraq Geol. Surv. Publ.*, Baghdad, Iraq.
- Sissakian V. K., Fouad S. F., 2015: Geological map of Iraq, scale 1:1000000, 4th edition, 2012. *Iraqi Bull. Geol. Min.*, **11**, 1, 9–16.
- Sissakian V. K., Ghafur A. A., Abdulhaq H. A., Omer H. O., 2021: Shakrook anticline, a very complicated structural form, North Iraq, Kurdistan Region. *Iraqi Geol. J.*, **54**, 2F, 162–177, <https://doi.org/10.46717/igj.54.2F.14ms-2021-12-31>.
- Sissakian V. K., Youkhanna R. Y., 1979: Report on Regional Geological Mapping of Erbil–Shaqalawa–Koi Sanjaq–Raidar Area. *Iraq Geological Survey Library (GEO-SURV)*, internal report No. 975.
- Storz H., Storz W., Jacobs F., 2000: Electrical resistivity tomography to investigate geological structures of the earth's upper crust. *Geophys. Prospect.*, **48**, 3, 455–471, <https://doi.org/10.1046/j.1365-2478.2000.00196.x>.
- Szalai S., Szarka L., 2008: On the classification of surface geoelectric arrays. *Geophys. Prospect.*, **56**, 2, 159–175, <https://doi.org/10.1111/j.1365-2478.2007.00673.x>.
- Tejero A., Chávez R. E., Urbieta J., Flores-Márquez E. L., 2002: Cavity detection in the southwestern hilly portion of Mexico City by resistivity imaging. *J. Environ. Eng. Geophys.*, **7**, 130–139, <https://doi.org/10.4133/JEEG7.3.130>.
- Telford W. M., Geldart L. P., Sheriff R. E., 1990: *Applied geophysics* (2nd ed.). Cambridge University Press, 770 p.
- Verdet C., Sirieix C., Marache A., Riss J., Portais J.-C., 2020: Detection of undercover karst features by geophysics (ERT) Lascaux cave hill. *Geomorphology*, **360**, 107177, <https://doi.org/10.1016/j.geomorph.2020.107177>.
- Wanaim A., Ikirri M., Boutaleb S., Fadili A., Belfoul M. A., Boualla O., Ait Haddou M., Echogdali F. Z., Abioui M., 2025: Non-invasive imaging of subsurface karst architecture using electrical resistivity tomography: a case study from carbonate terranes in semi-arid regions (Fouzart cave, Western Anti-Atlas, Morocco). *Carbonates Evaporites*, **40**, 3, 111, <https://doi.org/10.1007/s13146-025-01147-4>.
- Wilkinson P. B., Meldrum P. I., Kuras O., Chambers J. E., Holyoake S. J., Ogilvy R. D., 2010: High-resolution Electrical Resistivity Tomography monitoring of a tracer test in a confined aquifer. *J. Appl. Geophys.*, **70**, 4, 268–276, <https://doi.org/10.1016/j.jappgeo.2009.08.001>.

- Zhu J., Currens J. C., Dinger J. S., 2011: Challenges of using electrical resistivity method to locate karst conduits—A field case in the Inner Bluegrass Region, Kentucky. *J. Appl. Geophys.*, **75**, 3, 523–530, <https://doi.org/10.1016/j.jappgeo.2011.08.009>.
- ZOND Software, 2017: ZondRes3D three-dimensional data interpretation program user manual. Accessible at <http://zond-geo.com/english/zond-software/ert-and-ves/zondres3d/>.