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THE IMPORTANCE OF 2D ELECTRICAL RESISTIVITY IMAGING (ERI) AT A PRE-ENGINEERING CONSTRUCTION SITE IN DUHOK CITY, IRAQ

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Abstract

Cavities and voids near the surface in karstic areas present major geotechnical hazards, such as land subsidence and building cracks, resulting from the dissolution of carbonate rocks by water. Geophysical techniques, particularly Electrical Resistivity Imaging (ERI), are crucial for identifying these subsurface anomalies. During the early stages of excavation at a construction site in Duhok city, unexpected cavities were encountered, leading to project delays. This study aimed to assess the cavities' size, depth, and spatial distribution. To achieve this, twelve 2D ERI profiles using the Wenner-Schlumberger array with a 2-meter electrode spacing were deployed across the site. Additionally, two profiles were surveyed with a 1-meter electrode spacing due to space limitations. The surveyed profiles were divided into several sections, each consisting of three parallel profiles oriented in a specific direction to enhance data accuracy. These sections corresponded to the four residential towers, providing detailed and precise information for each area. The inversion results revealed that the subsurface beneath residential towers 2, 3, 4, and 5 primarily comprises dolomitic reefal limestone and weathered limestone. The cavities encountered varied in size and depth, ranging from 3 to 10 meters. The largest voids were located near residential towers 3 and 4, with depths of 8 and 5 meters, respectively. These cavities were confirmed through drilling. The largest cavity, located beneath tower 4, requires 35 cubic meters of cement for backfilling. Smaller cavities were found at towers 2 and 5, with depths ranging from 3 to 10 meters. This study demonstrates how effective ERI is in providing essential data for geotechnical planning, particularly in areas with karst features or unstable subsoil, helping to reduce risks and improve the stability of construction projects.

Keywords: Electrical Resistivity method; Wenner-Schlumberger array; Cavity detection.

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1. Introduction

Identifying cavities in shallow subsoil layers is crucial, especially in urban areas, as they pose serious risks. Therefore, it is important to accurately determine their size and location to assess subsidence and develop safety strategies. (Cardarelli et al., 2006). In the initial phases of constructing complex buildings, thorough subsurface investigations are crucial for ensuring structural stability and safety. The prompt recognition of such features in areas with documented occurrences can significantly reduce risks to infrastructure, ensure personnel safety, maintain project schedules, and optimize financial resources (Sutter & Barounis, 2021). Electrical resistivity plays a crucial role in both geophysical and civil engineering applications, particularly in identifying subsurface cavities and detecting structural weaknesses. Several studies emphasize the significance of Electrical Resistivity Tomography (ERT) in identifying subsurface weak zones in geotechnically challenging areas, particularly in karstic regions. Each study uses 2D ERT with varying electrode arrays to detect cavities or voids near the surface that pose significant risks, such as land subsidence, infrastructure damage, and structural cracks. The results indicate variations in resistivity values, with high resistivity typically corresponding to solid materials, Non-conductive minerals, or Air-filled cavities, while low resistivity suggests fractured zones, conductive materials, or moisture-filled zones. (Salman & Al-Rahim, 2023; Abbas, Al-Mahemmdi, & Al-Saady, 2024). *A geophysical survey* was conducted by using ERT and ground-penetrating radar (GPR) in Sulaimani Governorate, NE Iraq, to investigate karst formations, revealing a large cave at a depth of 25 meters. The cave has an elongated shape extending from southeast to northwest (Iurkiewicz & Stevanovic, 2010). ERT is widely recognized as a prevalent non-destructive geophysical technique employed for investigating shallow subsurface conditions (Al-Saadi et al., 2021; Gardi et al., 2018). The electrical resistivity methods involve passing an electrical current through the ground and measuring potential differences between electrodes. By analyzing these measurements, geophysicists can determine the electrical properties of subsurface materials, including apparent resistivity, a key parameter for interpretation (Loke, 2018). However, accurate mapping of subsurface geological structures such as cavities depends on a proper array *selection* (Bharti et al., 2022). There are many different types of electrode arrays used in resistivity surveys. Each electrode array exhibits specific advantages in imaging particular geological structures, influenced by depth penetration, resolution capabilities, extent of data coverage, and sensitivity to noise levels (Loke, 2012). Multiple researchers have utilized the application of electrical resistivity methods for engineering site construction. According to Hassan et al. (2018), the Wenner-Schlumberger array was implemented along three profiles at the construction site of Diyala University, northeast of Baghdad city, and the inversion sections showed a buried structure with minimal noise. The importance of pre-engineering investigation by 2D Resistivity methods with a Dipole-Dipole array indicated shallow cavities at a depth between 1 – 23 m (Al-Jumaily et al., 2022). Another study shows that 2D resistivity imaging is effective for detecting cavities by providing a detailed cross-sectional view of subsurface resistivity changes. The inversion of synthetic data into 2D models enables the identification of cavity location, shape, and depth. While individual arrays have depth limits, combining two arrays improves resolution and accuracy, making 2D imaging, especially with mixed-array datasets like Dipole-Dipole and Wenner-Schlumberger, a reliable method for cavity detection (Dosoky,2023). A study shows the use of a 3D electrical resistivity tomography survey to gain deeper insights into the intricate underground structure of the Scaloria Cave system in Apulia, Italy. The findings unveiled high-resistivity anomalies indicative of cavities within the surveyed area (Maerker et al., 2023). ERT survey with the Wenner-Schlumberger array was carried out around the block of flats at the Ugbowo Campus, University of Benin, Benin City, Nigeria. The results suggest that the site is suitable for future construction (Ejiofor & Airen, 2023). A study conducted at Al-Anbar University, Western Iraq, demonstrates the effectiveness of the 2D resistivity imaging technique in mapping subsurface weak zones. This method provides clear imaging of the shape and thickness of weak zones, with depths ranging from 9.5 to 11.5 meters (Abed and Thabit 2016). Another case study demonstrates the adaptability and efficacy of 2D ERT in various engineering applications. From distinguishing between bedrock types for building construction to imaging bridge foundations and assessing seepage in wastewater treatment ponds (Arjwech and Everett, 2015). The 2D resistivity method was applied to assess the subsurface conditions of the Mirakan area, providing essential data for determining the suitability of the site for dam construction. The resistivity measurements revealed the composition and thickness of different layers, along with the absence of risks such as faults or cavities (Othman, Bapeer, & Bakir, 2019). According to Aziz and Rughzai (2023), 2D ERI is an essential geophysical method for delineating the boundaries and true thickness of granular aquifers. This technique is particularly valuable in clastic sediments, where resistivity changes gradually between layers, aiding in more precise groundwater investigations. ERT is a useful method for detecting cavities in karst areas by measuring the electrical resistivity of the subsurface. However, its effectiveness depends on factors like the size, depth, and geological complexity of the cavities, as well as the resistivity contrast between voids and surrounding materials. In areas with high porosity or deeper cavities, ERT may have limited resolution and depth penetration. Environmental factors, such as moisture content and temperature variations, can also affect the accuracy of resistivity measurements, making it necessary to combine ERT with other methods for more reliable results (Funk, Flores-Orozco, & Steiner, 2024).

This study aims to determine the size, depth, and spatial distribution of cavities beneath four residential towers in Duhok City, with the goal of evaluating their impact on foundation stability and identifying potential geotechnical solutions.

2. Materials and methods

2.1. Study area and geology of the site

The study area is situated near Shakhke Cemetery, between latitudes 36°52'41"N and 36°52'48" N and longitudes 42°57'51" E and 42°58'02" E, approximately 2.65 km northeast of Duhok's city center (Figure 1). Tectonically, the site section belongs to the unstable shelf, high folded zone, western Zagros fold-thrust fold, according to the tectonic division of Iraq (Faoud, 2015). Structurally, the study area is distinguished by the Bekhair asymmetrical anticline and Duhok syncline formed due to compressional forces of the Arabian plate with Turkish and Iranian plates (Jassim and Goff, 2006). The study area is situated above the Early Miocene sediment of the Jeribi Formation, which consists mainly of dolomitic reefal limestone (Bamerni et al., 2025). The area is characterized by karstic features due to extensive dissolution processes, leading to the formation of cavities and fractures in the region (Figure 2). In karst areas, the resistivity of rocks changes depending on the cavities, fractures, and air/water-filled pores. This difference in resistivity is important for methods like Electrical Resistivity Tomography (ERT), which can find underground voids by spotting resistivity changes in the data.

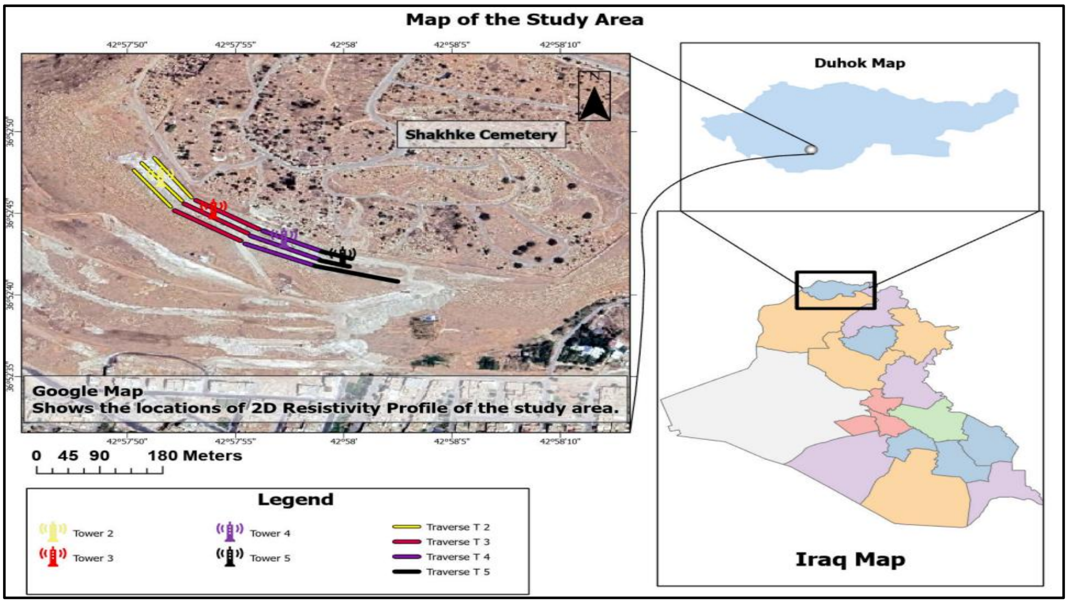

Figure 1. Location map of the studied area (Four Residential Towers) generated using GIS.

Figure 2. Karstification is observed in the Jeribi Formation within the study area.

2.2. Instrumentation and Data Collection

The office work involved using the Electre II software by IRIS Instruments to generate 2D profiling sequences of measurements. This step included selecting the cable set, acquisition parameters, and geometric parameters, such as the electrode array, electrode spacing, and expected levels. The Syscal Junior Switch 72, manufactured by IRIS Instruments (France), was used as the resistivity meter for the field survey. The fieldwork was conducted during the summer over seven working days. Geo-electrical resistivity data were collected along 12 profiles across four residential towers. Each section was surveyed using three profiles to obtain more accurate data on the depth and size of cavities (Figure 3). This approach helps identify which tower is at higher risk and estimate the amount of cement needed for repairs. The profiles were arranged along a northwest-southeast direction, with a 7-meter distance between each parallel profile. During the survey, the dipole-dipole array used with the Syscal device generated significant noise in the field readings. Therefore, the Wenner-Schlumberger array with 60 electrodes was employed instead. For the setup of the twelve resistivity profiles, a 2-meter electrode spacing was used, covering a total length of 118 meters for each individual surveyed profile. However, for two profiles in Tower 5, the electrode spacing was reduced to 1 meter, limiting the length to 59 meters. The depth of penetration was approximately 20 meters.

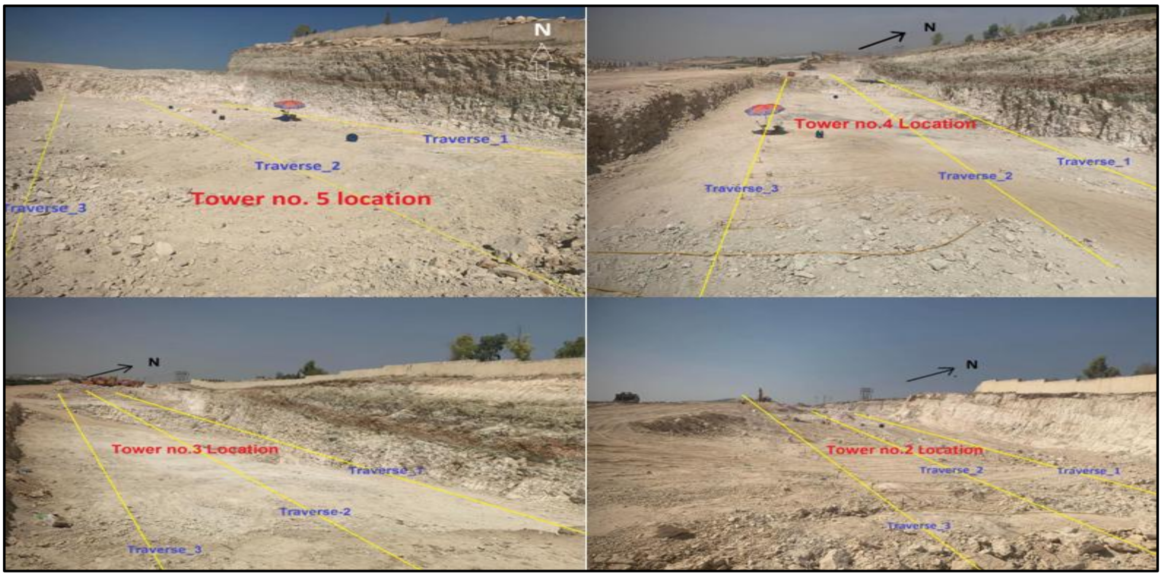

Figure 3. Twelve survey profiles (traverses) were conducted across four residential towers.

2.3. Data processing and Inversion

The resistivity data collected from the survey were first processed using specialized software from the instrument manufacturer (Prosys II, by Iris Instruments). The main steps involved checking the distribution of resistivity values in pseudo-sections and removing any incorrect data points. To enhance the stability and accuracy of the inversion results, RES2DINV employs robust inversion methods based on quasi-Newton optimization algorithms. These algorithms iteratively adjust the subsurface resistivity model to minimize the difference between observed and calculated resistivity values, thereby improving the reliability of the inversion outcomes. This process was repeated for all twelve survey lines, with the data typically achieving a good match after 2-4 iterations. The accuracy of the results was assessed using root mean squared (RMS) error, which quantifies the difference between the predicted and actual resistivity values.

3. Results and Discussion

The ERI survey of the residential area is divided into four towers. The resistivity tomography inversion results will be discussed and interpreted for each tower as follows:

3.1. 2D Inverse Model of Wenner-Schlumberger Array of Residential Tower 2

3.1.1. Profile1

The inverse model is composed of two zones based on the resistivity distribution belonging to the Jeribe Limestone Formation (Figure 4). The first zone (top one) has a resistivity value ranging from 1246 to more than 2570 Ωm, which represents compact carbonate rocks (Limestone and Dolomite) with a thickness ranging from 7 to 14 m. The second zone has a resistivity value ranging from 724 – 1040 ohm.m at an approximate depth of 7 – 20 m and is composed of weathered limestone.

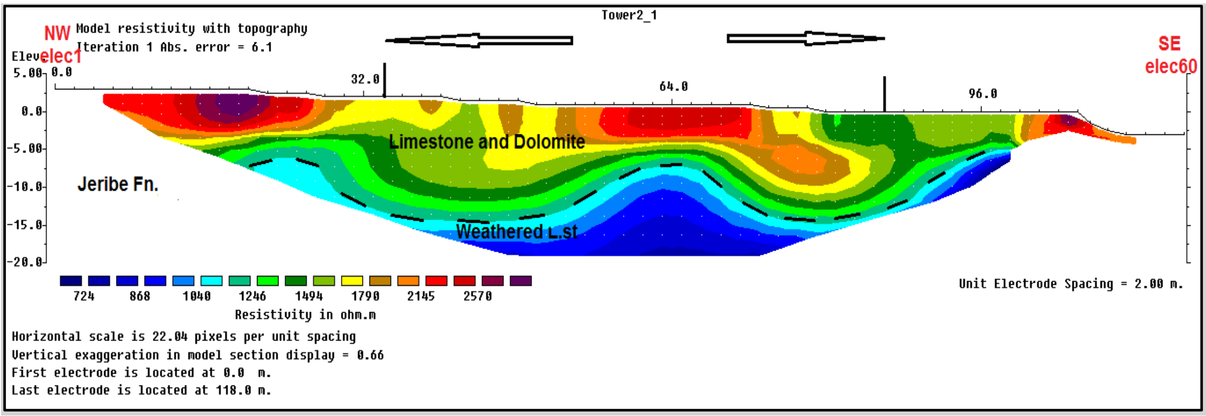

Figure 4. The 2D Resistivity inverse model for profile 1.

3.1.2 Profile 2

The second profile is positioned 7 meters parallel to the first profile, trending NW – SE direction with electrode spacing of 2.00 meters, covering a horizontal distance of 118 meters. The inverse model is composed of two zones based on the resistivity distribution (Figure 5). The first zone at the upper and lower as mentioned below (blue color), has a resistivity value ranging from 724 – 1060 ohm.m between electrodes (#26 – #62) at the top section and (#62 – #88) at the bottom, it typically consists of weathered carbonates, and fine-grained sediments with altered physical and chemical properties. The second zone has a resistivity value ranging from 1283 to more than 2780 Ωm, which typically exhibits high resistivity, especially when subjected to dolomitization, with a thickness of about 15 m. The expected small void showed at the middle of the section, shaped like a semi-circle across the lateral extent from the electrodes (#54 – #60) at an approximate depth of 10 m.

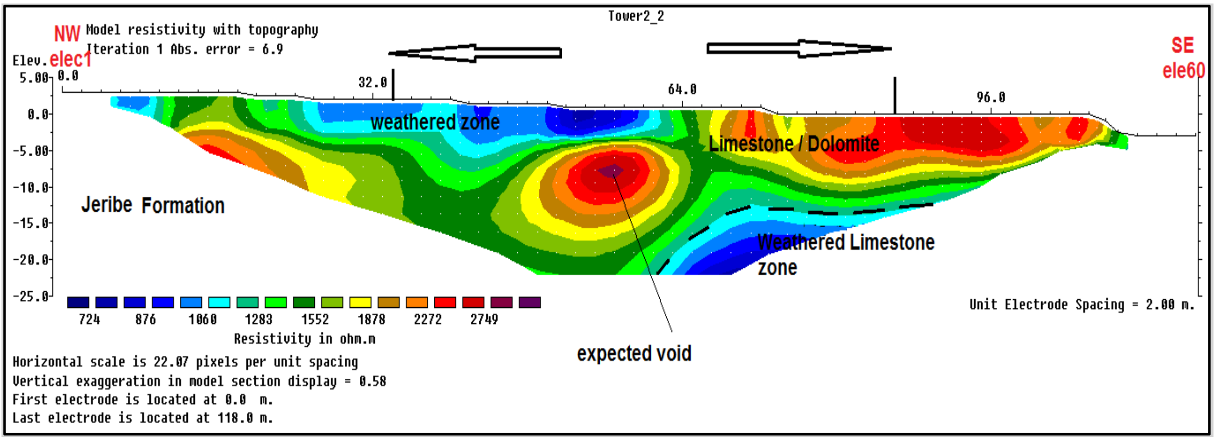

Figure 5. The 2D Resistivity inverse model for profile 2.

3.1.3. Profile 3

The third profile was positioned 7 meters parallel to the second profile, trending in the NW–SE direction with electrode spacing of 2.00 meters, covering a horizontal distance of 118 meters. The inverse model is composed of two zones based on the resistivity distribution (Figure 6). The first zone at the uppermost section has a resistivity value ranging from 623 – 1174 ohm.m, referred to weathered zone, with a depth of around 8 m in the center of the tower, while in the SE part of the section it goes deeper. The second zone has a resistivity value ranging from 1612 to 5722 ohm.m represented with Limestone and Dolomite, with a thickness of about 15m. The expected void showed at the middle of the section has an irregular shape across the lateral extent from electrodes (#62 – #66) at an approximate depth of 6 – 8 m.

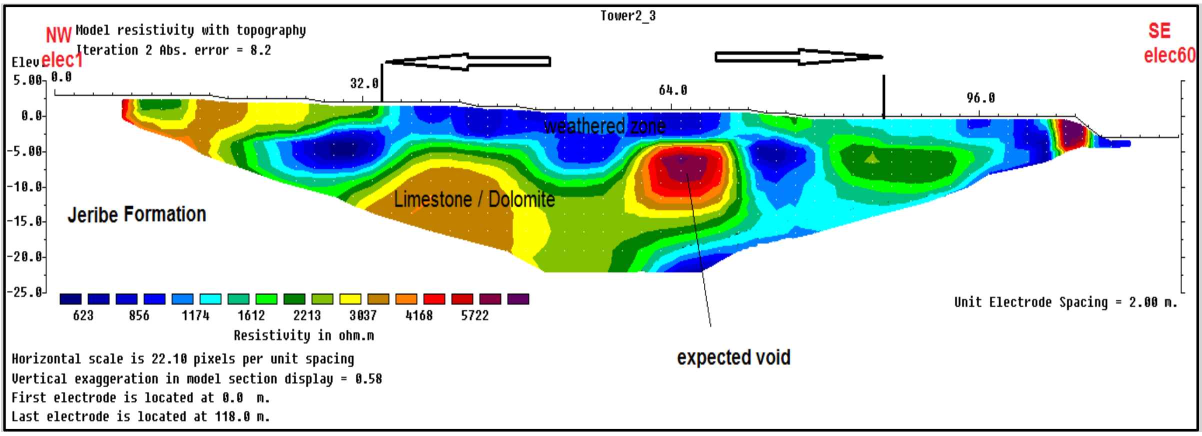

Figure 6. The 2D Resistivity inverse model for profile 3.

3.2. 2D Inverse model of Wenner-Schlumberger Array of Residential Tower 3

3.2.1. Profile

The survey was conducted with an electrode spacing of 2 meters, covering a horizontal distance of 118 meters in the NW–SE direction. The section illustrated a range of resistivity values ranging from 400 to around 3000 ohm.m at a depth limited to 20 m. Based on the resistivity values (Figure 7), it can be divided into two zones belonging to the Jeribe Formation. The first and upper zone has high resistivity values ranging from 900 – 3000 Ωm, and thickness ranging between 5 – 15 m, represented by layers of limestone and dolomite. The second zone, which has lower resistivity values ranging from 400 – 900 ohm.m, lies beneath the first zone and is represented by layers of the weathered zone of limestone. The high and anomalous resistivity values near the surface in the section indicate the presence of voids or small fractures that were observed in the field during preliminary drilling, leveling, and exploration operations. An expected cave or a void is detected between electrodes (72 – 78) at a depth of 8 m, its shape likely rounded or irregular, consistent with a karst feature formed by dissolution in limestone/dolomite.

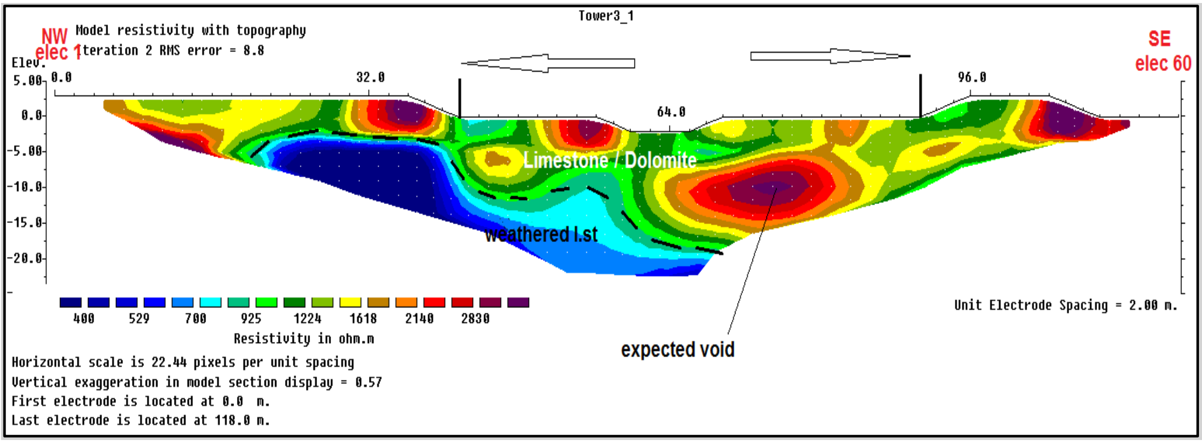

Figure 7. The 2D Resistivity inverse model for profile.

3.2.2. Profile 2

The second profile was conducted parallel to the first one, with the same extension and distance, and does not differ significantly from it. The resistivity values are the same, ranging between 400 and more than 3000 Ωm, while maintaining the same rock distribution across two main zones, but with a greater thickness for the first zone, represented by limestone and dolomite. Additionally, there is an area of low resistivity due to weathering effects and areas of high resistivity due to crystalline structure. The second zone, with lower resistivity values, represented weathered limestone and appeared at a depth of approximately 15 meters. No significant voids or cavities were detected in this section (Figure 8).

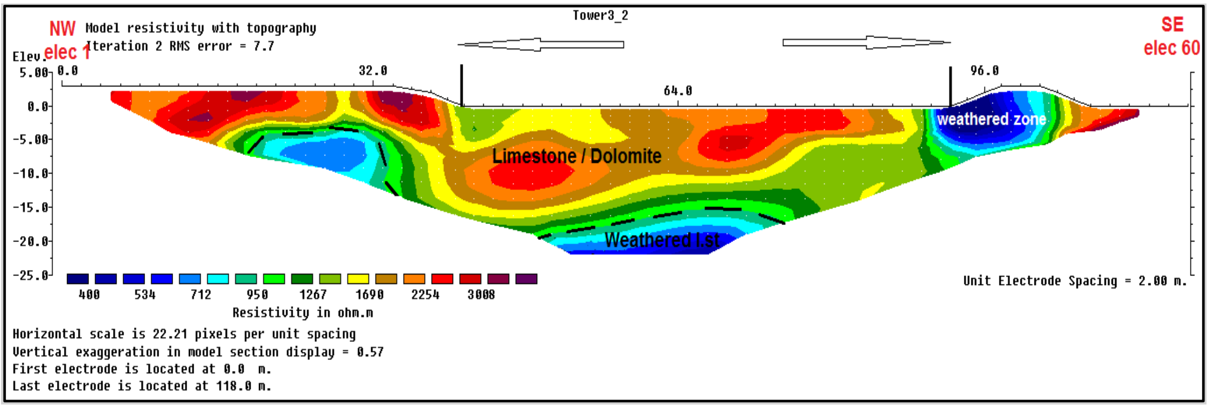

Figure 8. The 2D Resistivity inverse model for profile 2.

3.2.3. Profile 3

This profile is located parallel to and south of the second profile, covering the same distance. The resistivity values range from 400 Ωm to more than 3200 Ωm. The first zone, represented by layers of limestone and dolomite, varies in thickness and has lateral variation observed with the second zone, characterized by lower resistivity values, represented by weathered limestone. An expected void or cavity was detected between electrodes (64 – 68) at a depth of approximately 7 meters, with a circular or oval shape, which can form due to the dissolution of carbonate rocks over time (Figure 9).

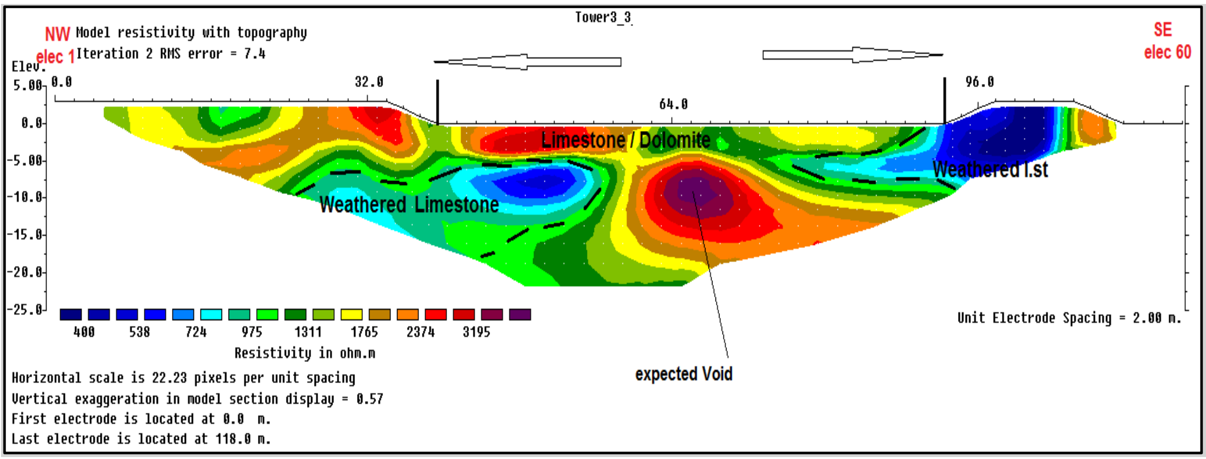

Figure 9. The 2D Resistivity inverse model for profile 3.

3.3. 2D Inverse Model of Wenner-Schlumberger Array of Residential Tower 4

3.3.1. Profile 1

The geophysical profile is situated in the northern section of the engineering site (Tower No. 4). The profile extends in a northwest-southeast direction (Figure 10), with an electrode spacing of 2 meters and a total coverage distance of 118 meters. The resistivity values across the profile range from 200 Ωm to more than 3200 Ωm, distributed consistently along the section. Two distinct zones have been identified, consistent with previous profiles. The upper zone exhibits resistivity values ranging from 900 Ωm to more than 3200 Ωm, with an approximate thickness of 5 to 15 meters. This zone is interpreted to represent layers of limestone and dolomite. The lower zone, characterized by lower resistivity values ranging from 200 – 900 Ωm, is observed at depths greater than 15 meters and is associated with layers of weathered limestone belonging to the Jeribe Limestone Formation. No evidence of voids or caves is detected within this profile, indicating a relatively homogeneous and stable subsurface geological structure in this area.

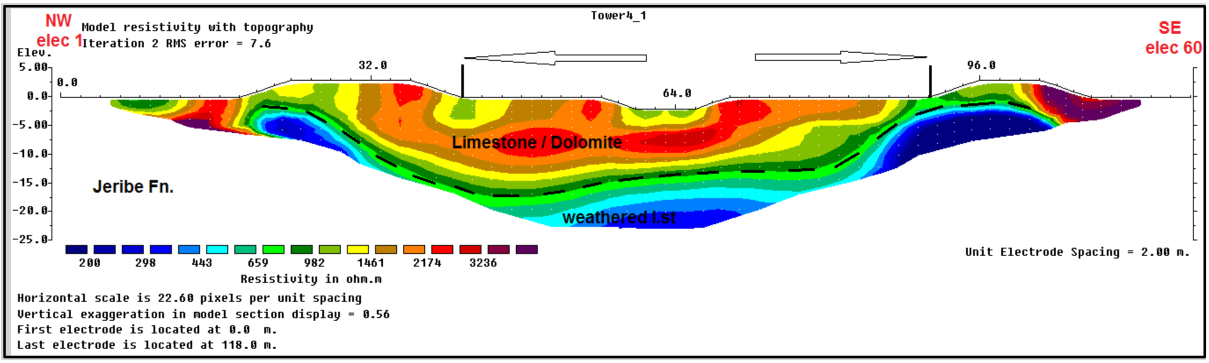

Figure 10. The 2D Resistivity inverse model for profile 1.

3.3.2. Profile 2

The profile is located centrally between the first and third profiles, sharing the same orientation, electrode spacing, and parallel alignment. In this section, it is observed that the resistivity values are similar to those in the previous profile, with the two resistivity zones appearing at the same depth and thickness. Additionally, a zone of fractures or weathering is identified near the surface on the left side of the section between electrodes (#22 – #30; Figure 11). Two expected voids or caves were detected within the limestone and dolomite layers at a depth of 5 meters below the surface. These voids exhibit a spherical or oval shape and are located between electrodes (32 – 36) and electrodes (48 – 54). They are characterized by high resistivity values, consistent with the presence of air-filled or dry cavities within the rock matrix.

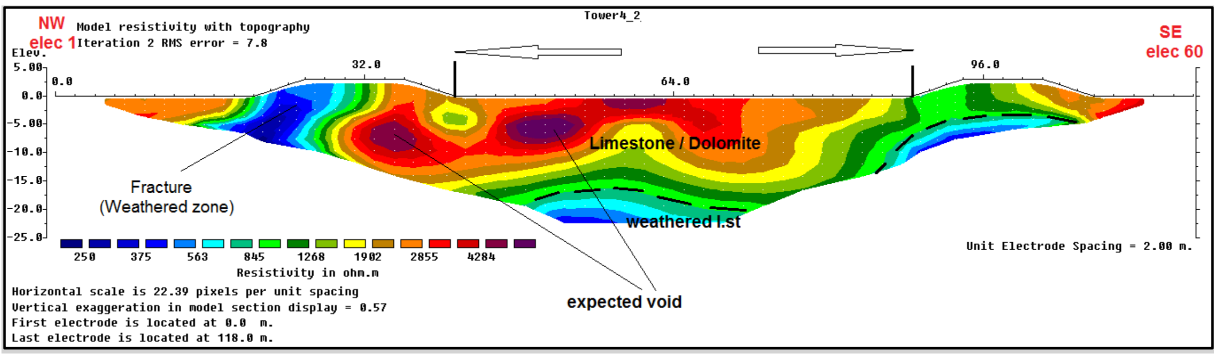

Figure 11. The 2D Resistivity inverse model for profile 2.

3.3.3. Profile 3

The profile extends across the southern part of the site for Tower No. 4, covering the same distance of 118 m. The electrical resistivity values observed are slightly higher but remain within a consistent range (826- more than 4000) ohm.m (Figure 12), with a thickness of 20 meters, corresponding to layers of limestone and dolomite. Additionally, a zone of weathering or fracturing was identified between electrodes (22 – 32), aligning with the second profile's extent (profile_2). Two voids or caves were detected within the section. The first void is large, located at a depth of 5 meters, and exhibits a spherical or oval shape between electrodes (36 – 44). Its presence was confirmed through drilling, after that, it was grouted with cement, requiring a volume of 35cubic meters. The second void is smaller and irregularly shaped, situated between electrodes (58 – 60) at the same depth. These features highlight localized variations in the subsurface geology, likely influenced by weathering processes or structural discontinuities.

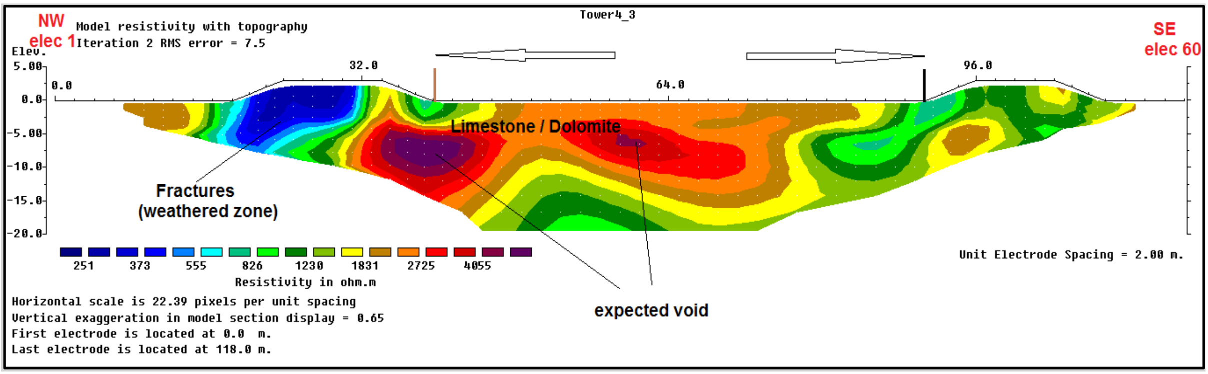

Figure 12. The 2D Resistivity inverse model for profile 3.

3.4. 2D Inverse Model of Wenner-Schlumberger Array of Residential Tower 5

3.4.1. Profile 1

The first geophysical profile conducted at this site extends in a west-east direction. Due to the limited space caused by drilling and leveling operations at the site, we were compelled to reduce the distance between the electrodes to 1 meter. The total distance covered was 59 meters, and the investigation depth reached 12 meters. Based on the high resistivity values observed in the section, two zones are identified: the upper one, 1000 – 7000 ohm.m, has a thickness of about 10 m, represented by layers of limestone and dolomite. The lower zone has resistivity 600 – 900 Ωm, mostly represented by weathered limestone (blue color). An expected cave or void was identified between electrodes number (35 – 41) at a depth of 3 meters, extending to a depth of 5 meters, with an oval shape (Figure 13).

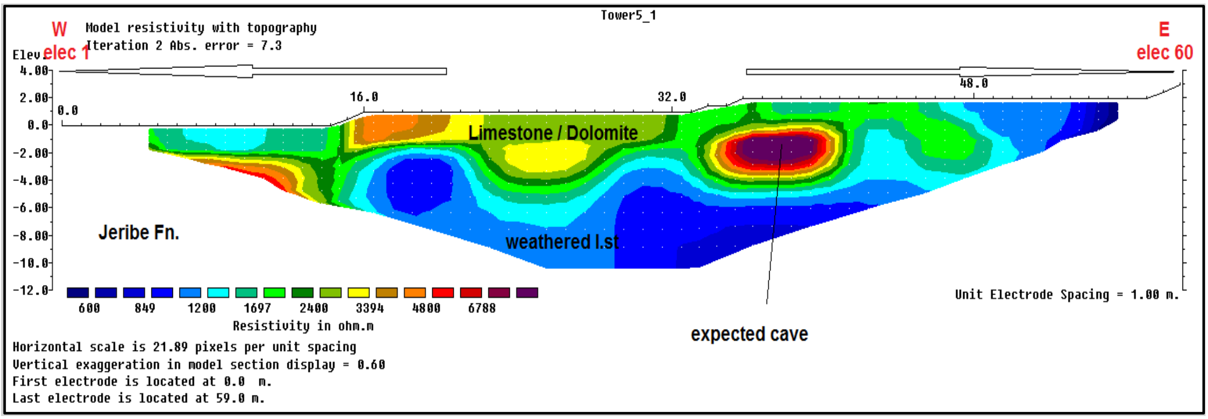

Figure 13. The 2D Resistivity inverse model for profile 1.

3.4.2. Profile 2

This 2D resistivity profile is located in the center of the site, between the first and third profiles, and runs parallel to them, sharing the same west-east extension. The distance between the electrodes is also 1 meter, with a total covered distance of 59 meters, and the investigation depth reached 12 meters (Figure 14). This profile closely matches the first profile in terms of resistivity values and the thickness of the rock layers, which are represented by limestone and dolomite at the top, as well as weathered limestone appearing at the bottom of the section at a depth of 10 meters. A decrease in resistivity values is observed near the surface due to weathering or increased clay content. Two expected voids or caves were identified in this section: the first, notably, is aligned with the cave identified in the first profile, sharing the same depth, extension, and shape, suggesting a karst origin. The second void appears between electrodes (21 – 23), is smaller, oval-shaped, and located at a depth of 3 meters.

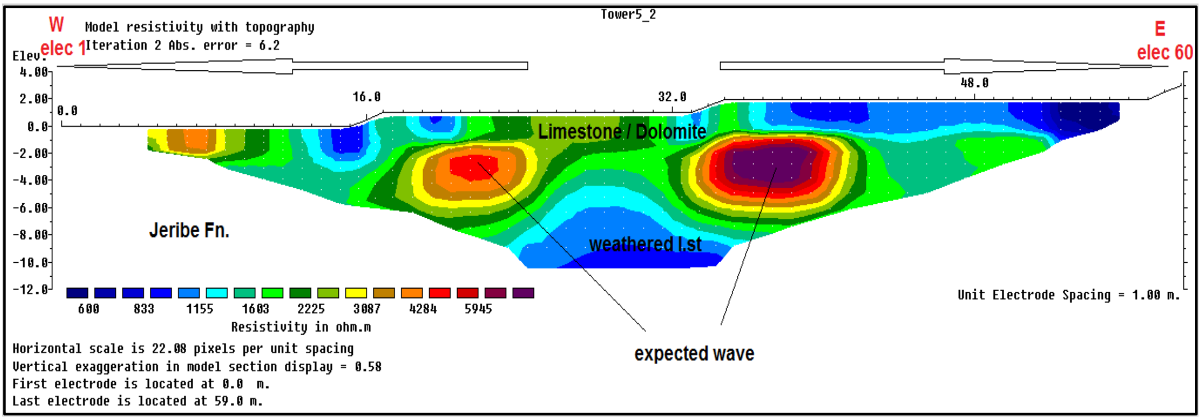

Figure 14. The 2D Resistivity inverse model for profile 2.

3.4.3. Profile 3

The profile runs parallel to the second profile but with a longer extension and in the same west-east direction. The covered distance is 118 meters, with an electrode spacing of 2 meters, and the investigation depth reached 20 meters. The electrical resistivity values ranged between 550 and more than 2000 Ωm, represented by layers of dark-colored limestone and dolomite in the eastern part of the profile, with lateral variations in resistivity values in the western part, most likely due to weathering processes or fractures. No significant caves or voids were observed in the section (Figure 15).

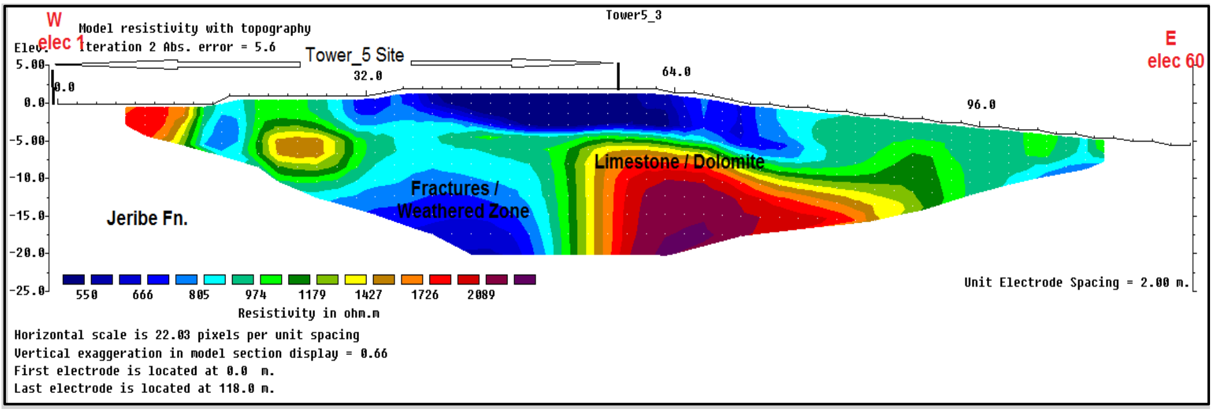

Figure 15. The 2D Resistivity inverse model for profile 3.

5. Conclusions

The surveyed area was mainly characterized by subsurface cavities and voids, which could pose risks to both the construction projects and the stability of the region. At residential tower 4, the largest cavity was detected on profile 3, between electrodes (36 – 44) at a depth of 5 m. This large void was confirmed by drilling and grouted with 35 cubic meters of cement, indicating a significant cavity size. At residential tower 3, a large void was detected on profile 1, between electrodes (72 – 78) at a depth of 8 meters, with a rounded or irregular shape. At Residential Tower 2, Profile 2, a small void is expected in the middle of the section, exhibiting a semi-circular shape extending laterally between electrodes No. 54–60 at an approximate depth of 10 meters. Similarly, in Profile 3, an expected void is observed in the middle of the section; however, it appears with an irregular shape, extending laterally between electrodes No. 62 – 66 at a depth range of approximately 6 – 8 meters. At residential tower 5, the cavity detected on profile 1, between electrodes (35 – 41), at a depth of around 3–5m, and has an oval shape. On profile 2, two cavities were found: one aligns in size and shape with the void on profile 1, while the second is a smaller oval-shaped cavity located at a depth of around 3 meters. The results show that the resistivity survey is an effective method for identifying subsurface cavities, helping to ensure foundation stability and the safety of the construction. Electrical Resistivity Tomography (ERT) is not a replacement for traditional geotechnical methods like coring, but it generates high-resolution 2D subsurface images, offering detailed spatial characterization along the survey profile. Incorporating ERT into pre-construction planning is highly beneficial, as it helps assess subsurface conditions, particularly the load-bearing capacity of the soil and rock formations. This integration allows for better foundation design while also reducing the overall cost of geotechnical investigations. By offering a broader understanding of subsurface variations, ERT enhances the efficiency and reliability of geotechnical assessments, leading to more informed engineering decisions. Despite its effectiveness, ERT has certain limitations, including potential data noise from external sources and ambiguities in resistivity inversion, which should be validated with supplementary borehole investigations or other geophysical methods.

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