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Characterization of subsurface pipes using non-invasive electromagnetic methods

Caracterização de dutos na subsuperfície através de métodos eletromagnéticos não invasivos

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Abstract: This study addresses the characterization of subsurface pipelines using non-invasive electromagnetic methods, specifically with the use of the PROFILER EMP-400 conductivity meter. The measurement of soil electrical conductivity was conducted in Jequié, Bahia, Brazil, where acquisition depths ranged from 0.1 to 15.0 meters. The methodology involved creating several electromagnetic profiles to detect anomalies, correlating each profile with a separate conductivity measurement using frequencies ranging from 1 to 16 kHz. The data were exported to Oasis Montaj software, and kriging interpolation was subsequently applied. This allowed the creation of electrical conductivity maps and longitudinal profiles, enabling the identification of pipelines with high conductivity, along with their respective depths and shapes. The data analysis demonstrated that the electromagnetic profiling technique is both effective and useful, providing a powerful non-destructive approach for subsurface components. Additionally, it generates accurate and timely data, making it essential for applications in environmental geology, hydrogeology, and mineral prospecting.

Keywords: Electromagnetic profiling; Identification of underground pipelines; Applied geophysics.

Resumo: Este estudo aborda a caracterização de dutos na subsuperfície utilizando métodos eletromagnéticos não invasivos, com o uso do condutivímetro modelo PROFILER EMP-400. A medição da condutividade elétrica do solo foi realizada em Jequié, Bahia, Brasil, onde as profundidades de aquisição variaram de 0,1 a 15,0 metros. A metodologia envolveu a criação de vários perfis eletromagnéticos para a detecção de anomalias, correlacionando cada perfil com uma condutividade separadamente, utilizando as frequências de 1 a 16 kHz, os dados foram exportados para o *software* Oasis Montaj e posteriormente aplicando o método da interpolação por krigagem, assim, foi possível criar mapas de condutividade elétrica e perfis longitudinais, possibilitando a identificação das tubulações com anomalias de condutividade, suas respectivas profundidades e formas. Foi realizada uma modelagem tridimensional com a área de estudo, caracterizando o duto através da anomalia da condutividade, sua profundidade e disposição na subsuperfície. A análise dos dados evidenciou que a técnica de perfilagem eletromagnética é eficaz e útil, sendo uma abordagem não destrutiva poderosa para componentes do subsolo, além de gerar dados de forma precisa e em tempo hábil, tornando-se assim, essencial para aplicações na geologia ambiental, hidrogeologia e prospecção mineral.

Palavras-chave: Perfilagem eletromagnética; Identificação de dutos subterrâneos; Geofísica aplicada.

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1. Introduction

The absence of project plans and blueprints for construction or renovation work poses significant challenges in Civil Engineering. A lack of detailed site information prior to project execution, coupled with the risk of improper implementation, can lead to severe consequences, including significant delays in service approvals, increased construction costs, and, in some cases, a complete work stoppage. Such a scenario necessitates the development of new projects to enable the execution of services in the affected locations. (AGYEMAN et al., 2016, p.326).

The application of geophysical and geotechnical methods in civil engineering has intensified, driven by the need for more efficient and reliable techniques to evaluate *in situ* soil properties. Traditional investigation methods, such as percussion and rotary drilling, are more time-consuming and costly. Furthermore, these conventional methods provide only a limited amount of point-based information, which can create data gaps and hinder an adequate assessment of the overall subsurface conditions. (GROVES et al., 2011, p.1364-1377; SOUZA e GANDOLFO, 2012, p.10-27).

Soils in nature are inherently heterogeneous, with properties that exhibit significant spatial variability. This makes it unfeasible for conventional methods to fully characterize the investigated subsurface. Therefore, although traditional sampling techniques provide detailed information at specific, discrete locations, they have limitations in terms of number, volume, and spatial coverage. Furthermore, these methods are time-consuming and expensive, rendering the use of point sampling impractical in certain cases. (PATHIRANA et al., 2023). The alternative to these restrictive scenarios is the application of non-invasive methods, which include: Electromagnetic Induction, Electrical Resistivity, Optical Reflectance, and Radar. (CAMARGO et al., 2001, p.1403-1422; ADAMCHUK et al., 2011, p.12).

Inductive electromagnetic (EM) methods are based on the propagation of low-frequency electromagnetic waves. The induction of electrical currents in the ground can be described as a diffusion process of an electromagnetic field, where displacement currents are disregarded and only conduction currents are considered. When a current passes through a conductor, a primary magnetic field is generated around it. If the magnetic field flux through a loop varies, it will induce a current in the loop. This process is known as electromagnetic induction and is illustrated in Figure 01.

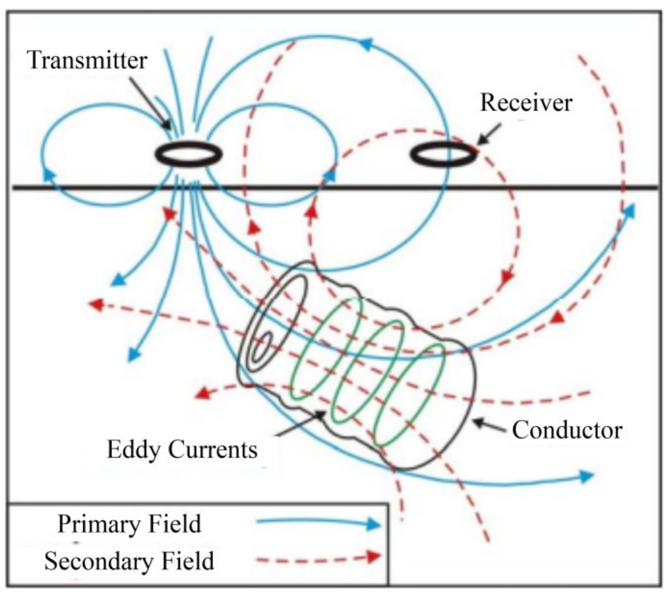

Figure 01 – Current flow paths in the electromagnetic induction (EMI) technique.
Source: Borges (2002).

The equations for a magnetic dipole are well-known. Accordingly, for a pair of horizontally aligned coils (with their central axis perpendicular to the ground) resting on a homogeneous surface, the magnetic field can be understood as a mutual coupling relationship (NABIGHIAN, 1988).

$$\frac{Z}{Z_0} = \frac{2}{k^2r^2}[(9 + 9ikr - 4k^2r^2 - ik^3r^3)e^{-ikr} - 9] \tag{1}$$

where:
r = Distance between coils [m];
k = (μεω² + iσμω)½ complex propagation constant;
i = $\sqrt{-1}$;
σ = electrical conductivity, $\frac{S}{m} = \frac{1}{\rho}$, where ρ = resistivity, [Ω.m];
μ = magnetic permeability, $[\frac{H}{m}]$;
ε = dielectric permittivity, $[\frac{F}{m}]$;
ω = 2πf, angular frequency, [Hz];
f = frequency, [Hz];
μ_0 = magnetic permeability of vacuum = 4π · 10^{-7} $[\frac{H}{m}]$;
ε_0 = Vacuum dielectric permittivity = 8,854 · 10^{-12} $[\frac{F}{m}]$.
μ_r e ε_r Relative magnetic permeability and relative dielectric permittivity, respectively
h = height relative to the ground

From equation (1), it is noted that the resultant field can be separated into two components: the first being in-phase or real, and the second being out-of-phase (quadrature) or imaginary. The ratio between these components is commonly expressed in percentage or parts per million (ppm). In the frequency domain, a key parameter is the induction number, B. Variations in the excitation frequency, in conjunction with the properties of the medium, conductivity (σ), magnetic permeability (μ), and electrical permittivity (ε), alter the secondary field response from the half-space, enabling the resulting waves to be measured by the instrument.

$$B = (\sigma\mu\omega/2)^{\frac{1}{2}}r \tag{2}$$

When the dipole height deviates from zero, a complete analytical solution is required to resolve the electromagnetic field components. This solution necessitates numerical integration for both the homogeneous half-space model and for horizontally layered earth models. However, the increasing influence of height and the attenuation of the imaginary (Im) components can be obtained using quasi-static formulas (FRISCHKNECHT ET AL., 1991) within the Low Induction Number (LIN) range, for the horizontal coplanar (HCP) configuration, as shown in equation (3).

$$\frac{Im_h}{Im_0} = [4(\frac{h}{r})^2 + 1]^{-\frac{1}{2}} \tag{3}$$

Through analytical methods and in agreement with experimental results, it can be observed that frequency and soil electrical conductivity have a limited influence on the investigation depth. Saksa & Sorsa (2017) determined that for a soil with a resistivity of 100 Ω.m, the penetration depth is approximately 12.6 m at a frequency of 1 kHz, and approximately 7.1 m at 10 kHz. For a soil of 10 Ω.m, the penetration depth at 10 kHz is approximately 4.0 m.

After data collection, the datasets are exported to a Geographic Information System (GIS) software environment. The data undergo pre-processing and are subsequently processed using kriging and interpolation techniques to generate three-dimensional conductivity maps of the study area, enabling the identification of subsurface anomalies. The use of 3D mapping allows for the construction of three-dimensional models that facilitate the analysis of geological and geotechnical data. By dividing the space into small volumetric units, known as voxels, the representation of complex terrain features, such as sedimentary layers and variations in electrical resistivity within 3D geological models, achieves a closer approximation to reality (JØRGENSEN ET AL., 2013).

In the kriging stage of the conductivity data, ordinary kriging is performed using the Oasis Montaj software. This process aims to determine values for the entire sampled area by applying the following equation:

$$Z(x, y, z) = z_0 + \sum_{1}^{n} w_i[z(x_i, y_i, z_i) - z_0] \tag{1}$$

Being:
$Z(x,y,z)$ is the estimated value of the variable Z at the point of interest (x, y, z);
$Z(x_i, y_i, z_i)$ is the observed value of the variable Z at sample location i;
Z_0 is the mean value of the variable Z in the study area;
w_i is the weight assigned to sample i;
n is the total number of observed samples in the study area.

The application of this technique makes it possible to generate a conductivity map of the area, enabling the identification of potential subsurface anomalies.

The PROFILER EMP-400 conductivity meter, illustrated in Figure 02, is a portable, multi-frequency instrument with a coil spacing of 1.22 m. The PROFILER EMP-400 features an integrated GPS and weighs 4.5 kg, which allows for high mobility. The apparent electrical conductivity reading is taken directly on the instrument in milliSiemens per meter (mS/m). Thus, the Inductive Electromagnetic method employs low-frequency radio waves and can be used to study the subsurface.

Figure 02 – The PROFILER EMP-400 GSSI conductivity meter.
Source: Authors (2024).

This study aims to analyze apparent electrical conductivity data acquired with the portable EMP-400 electromagnetic profiler, in order to identify anomalies associated with subsurface lithological and structural variations along the highway section between the municipalities of Jequié and Maracás.

2. Methodology

The study area is located in the vicinity of the road interchange between highways BR-116 and BA-130, near Tote Lomanto Avenue (Figure 03), in the municipality of Jequié, in the southwest region of the state of Bahia, Brazil. Founded in 1897, the predominant climate in the region is semi-arid, with high temperatures for most of the year. According to the Köppen-Geiger climate classification, the Jequié region is classified mainly as type Aw, characterized by a tropical climate with a pronounced dry season during the winter (ALVARES et al., 2013).

According to the Brazilian Institute of Geography and Statistics (IBGE; 2020), Jequié has established itself as an important regional hub, notable for its agricultural production. Furthermore, it possesses strong potential for the development of new industrial activities due to its strategic location in the southwest of Bahia.

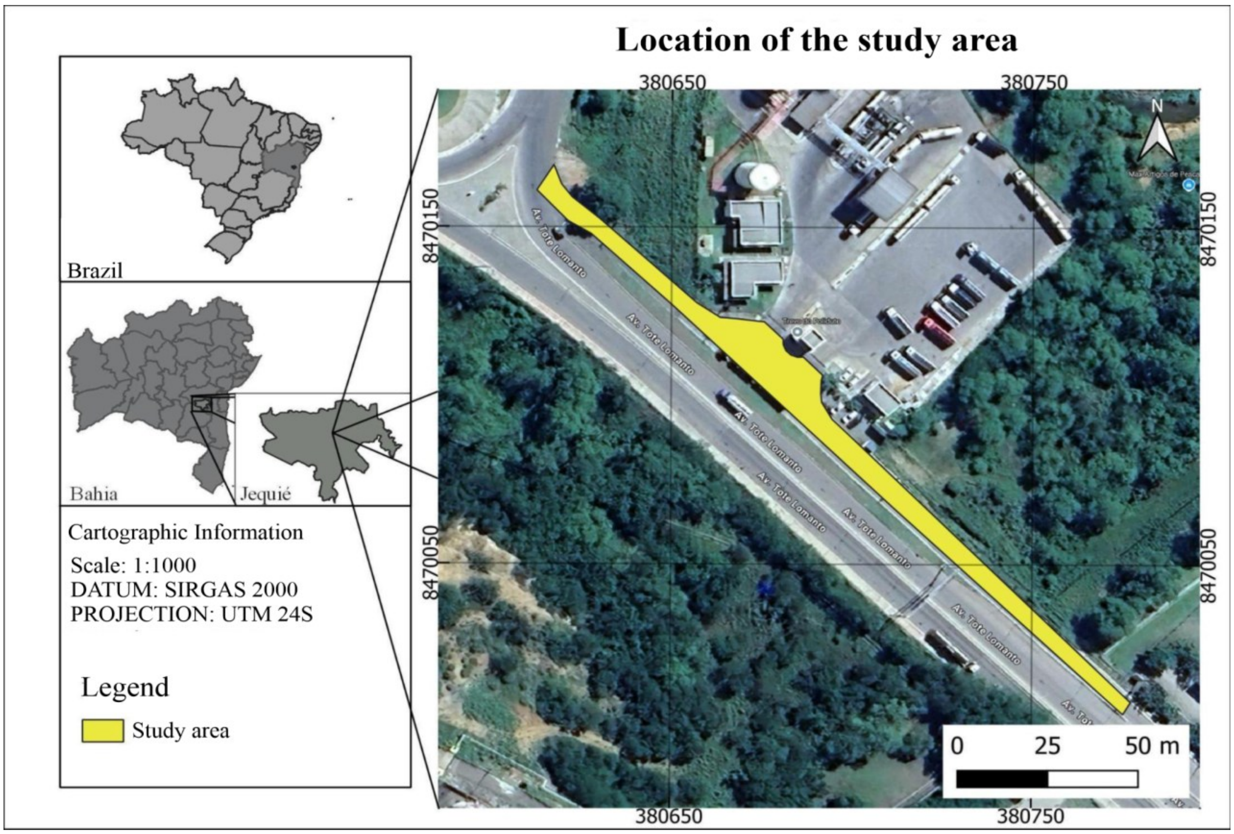

Figure 03 – Location of the study area in the municipality of Jequié, Bahia.
Source: Authors (2024).

Prior to each data collection, both GPS and field calibrations were performed. The field calibration consisted of collecting samples at an arbitrary point within the study area, maintaining a minimum distance of 5 meters from people and objects. This procedure is fundamental to minimize interference with the electrical field and ensure data accuracy.

Six survey lines were acquired using the EMP-400, covering the full operational spectrum of the equipment. The spacing between collection lines was 1.5 meters, following the survey path shown in Figure 04, using a separate-line method where each transect was saved as a distinct file. The time interval between data points was 0.5 seconds, ensuring sufficient data density for a detailed analysis. The survey covered the entire study area, providing a robust basis for subsequent processing.

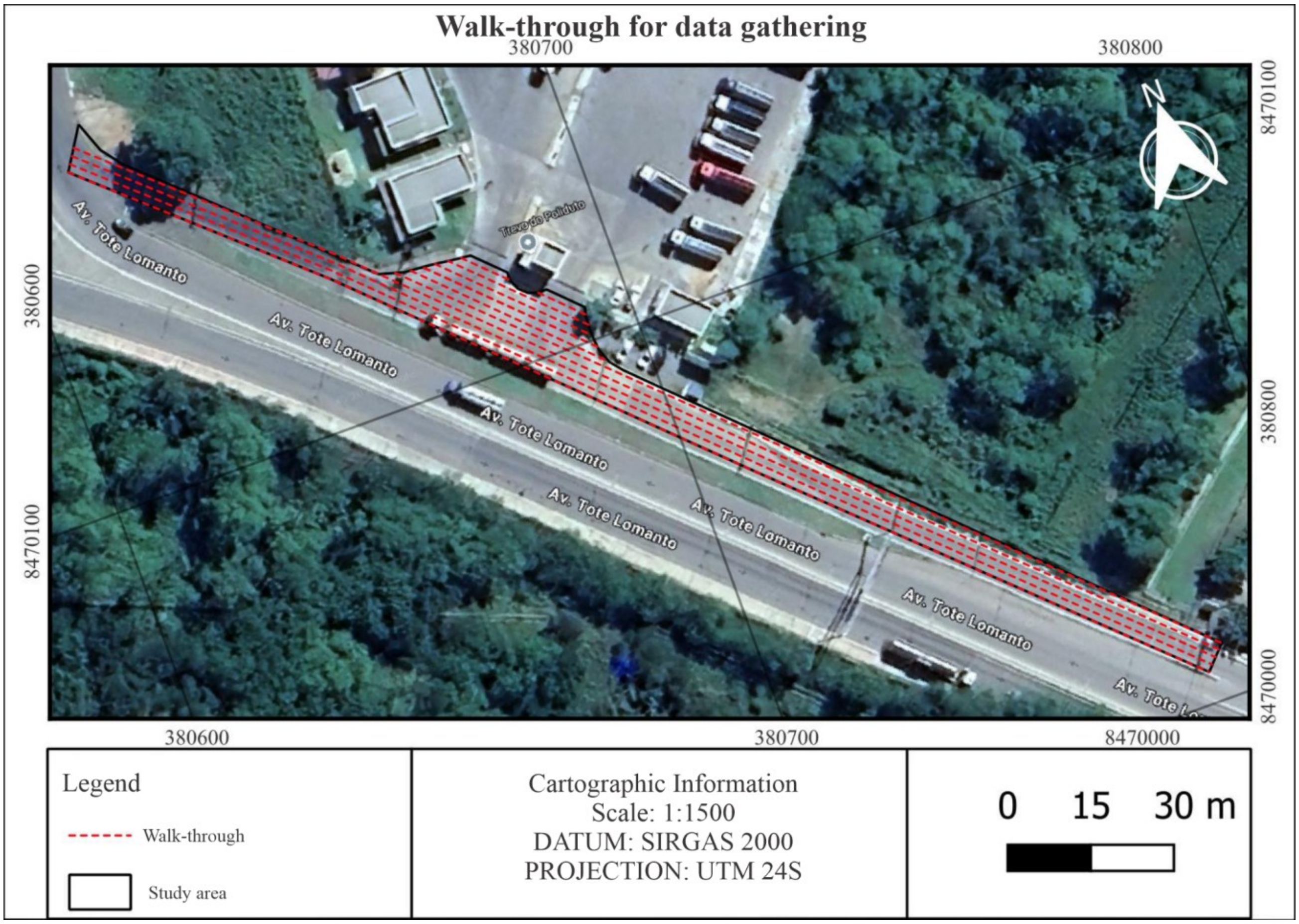

Figure 04 – Survey path for the electromagnetic profiling data acquisition.
Source: Authors (2024).

Following the acquisition of the electrical conductivity data, the processing stage was initiated. The objective of this stage was to remove noise and perform modeling to create three-dimensional representations of the subsurface and identify potential anomalies. The processing was carried out in the following steps:

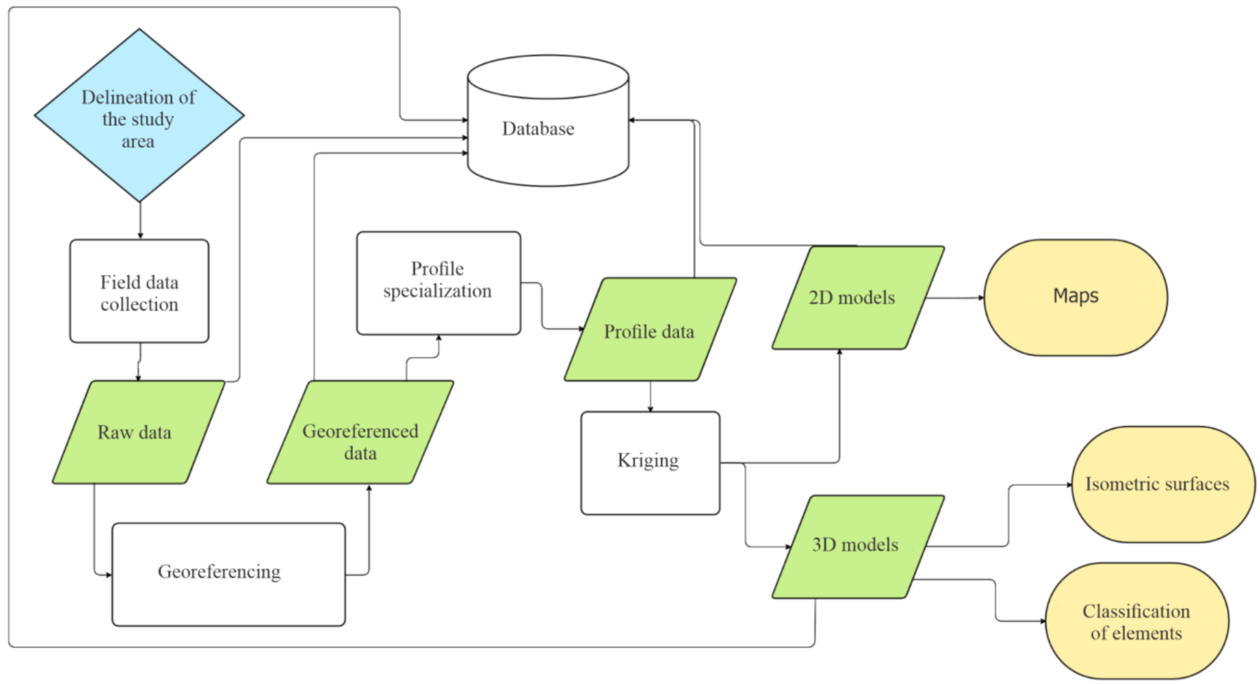

Figure 05 – Processing flowchart.
Source: Authors (2024).

Figure 05 illustrates the methodological flowchart adopted for the acquisition and processing of geophysical data applied to the subsurface study. The process begins with the definition of the area and the field collection of raw data, which are subsequently georeferenced. This data is stored in a database and spatialized into georeferenced profiles, which then undergo kriging interpolation. The results include 2D models for map production and 3D models used for creating isosurfaces and classifying the identified features, allowing for a detailed analysis of the characteristics of the study area.

3. Results and Discussion

Geophysical investigations conducted in urban and anthropogenic environments often face significant obstacles, as was observed in the study carried out in the city of Jequié. During the surveys, high electrical conductivity peaks were detected in concreted areas, attributed to the presence of steel reinforcement. Such an occurrence is a recurring challenge in near-surface geophysical surveys, especially those using Electromagnetic Induction (EMI) methods. Anthropogenic elements with high conductivity, such as rebar-reinforced concrete, can attenuate electromagnetic waves, creating a shielding effect that compromises the investigation of deeper or adjacent subsurface targets (AL-HUSSAINY ET AL., 2022; MINECLOSURE, 2019).

This phenomenon is based on the physical effect known as the Faraday cage, in which conductive materials redistribute electrical charges on their external surface, canceling the incident electromagnetic fields and shielding the structure's interior (HOLSTON; STOKES, 2023). In the context of the survey conducted with the PROFILER EMP-400 instrument, this shielding prevented the primary electromagnetic field from penetrating beyond the conductive structures. This significantly limited the induction of eddy currents and, consequently, the detection of secondary fields generated at depth (BUNTIN, 2023). As a result, a precise analysis of the subsurface layers in these areas was rendered unfeasible, reducing the reliability of the obtained data.

As a mitigation measure, a spatial offset technique was implemented, in which the data obtained directly beneath the conductive reinforcement and within a 2-meter radius around it were excluded from processing. Figure 06 visually illustrates this approach, which aimed to preserve the integrity and reliability of the remaining data.

Figure 06 – Delineation of the offset in the area.
Source: Authors (2024).

The exclusion of data contaminated by surface metallic interference or cultural features is a well-established practice in the interpretation of geophysical surveys (MINECLOSURE, 2019). However, the field now has more advanced methodologies for noise treatment, including filtering techniques in the frequency and time domains, as well as methods like wavelet denoising, aimed at improving the signal-to-noise ratio (AL-HUSSAINY ET AL., 2022).

Following the initial data acquisition and the application of the offset, the collected apparent electrical conductivity data underwent a crucial processing step involving Kriging interpolation. This geostatistical technique, implemented using software such as Oasis Montaj, is fundamental for transforming discrete measurement points into continuous spatial fields, enabling the generation of two-dimensional conductivity maps and longitudinal profiles. Kriging differs from simpler interpolation methods by being based on the spatial correlation (autocorrelation) between sampled points (JOURNEL; HUIJBREGTS, 1978). The method operates in two main stages: first, an empirical variogram is constructed to model the spatial covariance structure of the data, quantifying the decrease in similarity between points as distance increases. Second, weights derived from this model are applied to the observed values to estimate values at unsampled locations using the Best Linear Unbiased Predictor (BLUP), while simultaneously calculating the uncertainty associated with these predictions (ISAAKS; SRIVASTAVA, 1989). The performance of Kriging is highly dependent on assumptions such as stationarity (constancy of the variable's statistical properties in space) and isotropy (directional uniformity), although variants of the technique exist that relax these assumptions (CHILÈS; DELFINER, 1999). Recent 3D geological modeling studies in complex soils have also adopted Kriging for interpolation (FRONT_ES, 2023).

One of the significant outcomes of this processing workflow was the generation of three-dimensional voxel models. Voxel modeling is an effective technique in geophysical and geological visualization, as it subdivides the subsurface space into a three-dimensional grid of volumetric cells (voxels), each representing specific properties, such as electrical conductivity. This approach allows for a more realistic and integrated representation of stratigraphy and subsurface anomalies, especially in contexts with geological discontinuities. In addition to their visual function, voxel models facilitate advanced analyses, such as the extraction of isosurfaces and the classification of detected features, which simplifies interpretation and can reduce the volume of data needed for certain applications (JØRGENSEN ET AL., 2013). These models can also be subjected to filtering, statistical analysis, and visualization in fence diagrams, offering in-depth three-dimensional insights into the investigated medium. The literature highlights the growing importance of integrating these models in studies aimed at identifying complex underground structures, such as conduits and geological formations (CAMBRIDGE CORE, 2015).

Using the filtered data, a planar conductivity map was generated (Figure 07), along with a longitudinal profile of conductivity with depth (Figure 08). The 1.5 m spacing between collection lines, combined with Kriging interpolation, resulted in a 3D model of voxels and isosurfaces capable of highlighting elongated and linear bodies, which are typical characteristics of subsurface conduits (PELLERIN, 2002).

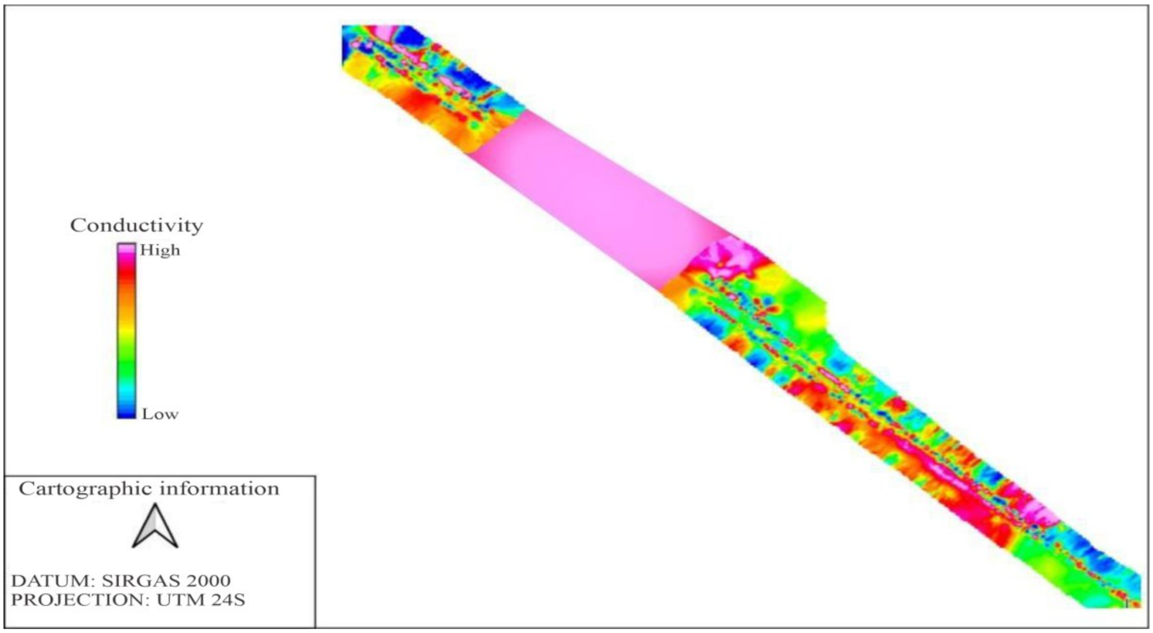

Figure 07 – Electrical conductivity map of the study area.
Source: Authors (2024).

Alongside the conductivity map, a longitudinal profile is generated that shows the electrical conductivity with depth, as seen in Figure 08.

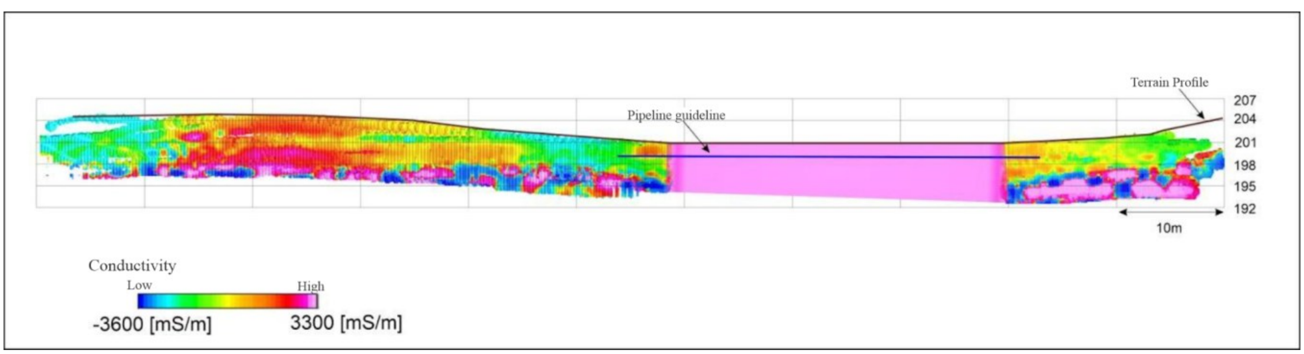

Figure 08 – Longitudinal profile of electrical conductivity for the study area.
Source: Authors (2024).

Furthermore, recent studies have demonstrated the effectiveness of correcting instrumental drifts caused by temperature variations in identifying metallic pipes and buried cables. This correction has been made possible by filtering routines such as Savitzky–Golay and rolling ball, which allow for the revealing of hidden subsurface utilities (DOOLITTLE & BREVIK, 2014). Even more sophisticated strategies have been incorporated through the use of machine learning algorithms and deep neural networks, aimed at eliminating electromagnetic noise and recovering data in complex and contaminated environments (HUANG et al., 2025).

The combined application of Kriging and voxel modeling, as conducted in this study, indicates the existence of adequate spatial autocorrelation in the data to support both techniques. However, for future investigations, especially those aiming to characterize smaller or more heterogeneous targets, it will be essential to perform a rigorous evaluation of the sampling density, the quality of the variogram model, and the adopted voxel resolution (JØRGENSEN ET AL., 2013). The iterative refinement of these parameters can substantially increase confidence in the interpretations and contribute to a more robust and accurate subsurface mapping.

The main contribution of this study lies in the successful differentiation of subsurface materials based on their distinct electrical conductivity (EC) signatures. The analysis identified specific EC ranges: values between -3608 and 0 mS/m were associated with general subsurface anomalies; the range of 0 to 300 mS/m was consistently related to natural soils and rock materials; while the highest range, from 301 to 3353 mS/m (the maximum observed value), was strongly correlated with the presence of high-conductivity materials, especially metals such as copper, aluminum, iron, and steel. This classification allows for the identification of anthropogenic structures embedded within the natural geological medium. Such a distinction is based on well-established geophysical principles, which state that metallic conductors exhibit electrical conductivities many orders of magnitude higher (often above 10^7 S/m) than those observed in non-metallic soils or rocks (PARKHOMENKO, 1967; NABIGHIAN, 1988). Figure 07, which presents the spatial map of electrical conductivity for the study area, is a direct reflection of this interpretation and allows for the visualization of zones with different conductivity levels.

The finding that soils with low clay and moisture content, such as sandy or medium-textured soils, exhibit lower conductivities (0–300 mS/m) is in agreement with hydrogeophysical and pedological literature. The electrical conductivity of soil is an indirect yet highly sensitive measurement that correlates with various physicochemical properties, including texture, salinity, mineralogy, porosity, and water content (SUDDUTH ET AL., 2005; DOOLITTLE; BREVIK, 2014). Finer-grained soils, such as silts and clays, tend to show higher EC values compared to coarser sands and gravels, owing to their greater surface area and cation exchange capacity, which facilitate the retention of water and dissolved ions—factors directly related to electrical conductivity. Figure 08, with its longitudinal EC profile, complements the two-dimensional map by revealing the variation of conductivity with depth, which is essential for inferring the depth of detected anomalies.

The most relevant result was the association of the highest conductivity range (301 to 3353 mS/m) with metallic materials that, when visualized in the 3D model, displayed a linear pattern indicative of subsurface pipelines. This finding reinforces the efficiency of the electromagnetic profiling technique in detecting such structures. Electromagnetic methods are particularly effective in identifying conductive objects, such as buried metallic pipes and cables, due to the strong conductivity contrast with the surrounding geological medium (NABIGHIAN, 1988; GABRYS; ORTYL, 2020). The underlying principle involves the induction of an alternating current magnetic field by the transmitter coil, which generates eddy currents in nearby conductive objects. These induced currents produce a secondary magnetic field, which is detected by the receiver coil, allowing for the location and characterization of the conductive anomaly (GABRYS; ORTYL, 2020; MINECLOSURE, 2019). The amplitude and phase shift of this secondary field relative to the primary field provide important information about the electromagnetic properties of the investigated materials. Studies evaluating the permeability and conductivity of magnetic metal rods with multi-frequency systems also confirm the high electromagnetic response of metals (HUANG et al., 2025).

Despite the successful application of EC contrast to identify metallic structures, the literature highlights that soil electrical conductivity is influenced by various factors beyond the mere presence of anthropogenic objects. This means that a conductivity anomaly outside the metallic range could be due to natural soil characteristics, such as clay lenses, variations in moisture content (like the presence of perched water tables), or higher salinity. For example, a clay lens can generate a higher EC signal than the surrounding sandy soils (SUDDUTH ET AL., 2005). This natural variability can introduce ambiguity to the interpretation, as moderate anomalies may be erroneously attributed or have their true origin masked. Such complexity underscores the importance of integrating geophysical data with geological, hydrogeological, and historical site information for a more accurate interpretation. Relying solely on conductivity values, without considering the local edaphoclimatic and geological context, can lead to false positives or incorrect interpretations of subsurface features.

Future investigations should consider complementary validation methods, such as targeted drilling or test pits, in areas of ambiguous interpretation. Furthermore, the incorporation of complementary geophysical techniques, like GPR (Ground Penetrating Radar), can provide additional structural information and help confirm the presence of non-metallic features (GABRYS; ORTYL, 2020). These approaches are fundamental for reducing interpretive uncertainty and increasing confidence in the characterization of anomalies. The need for local data calibration and a thorough understanding of the geological context before applying EMI-based methods is also emphasized.

Based on the electrical conductivity mapping, the study identified two distinct zones of high conductivity interpreted as subsurface anomalies. "Interference 1" (Anomaly 01), presented in Figure 09 of the original article, was characterized as a "probable pipeline, PVC or metallic," located at an average depth of 7 meters. This result demonstrates the capability of the electromagnetic profiling technique to detect linear buried structures, even if the precise identification of the material remains limited with data obtained exclusively by EMI. A second anomaly, named "Interference 2," was interpreted as a "possible gas pipe" at an average depth of 4 to 5 meters, as illustrated in Figure 10. The difference in the depths attributed to each anomaly reinforces the technique's ability to provide vertical resolution, a critical aspect for safety in excavation interventions and infrastructure projects.

Figure 09 – Top view, location of electromagnetic anomaly 01.
Source: Authors (2024).

Figure 10 – Top view, location of electromagnetic anomalies (interference 1 and 2), possible gas pipe. Source: Authors (2024).

The effectiveness of electromagnetic induction in detecting buried metallic pipes and cables is well-documented and is based on the sharp contrast between the electrical conductivity and magnetic permeability of these targets compared to the soil. Case studies show that, beyond simple detection, EMI can provide information on the material type (magnetic or conductive response), the pipe's diameter, and its depth. For example, a precise detection of a cable at a depth of 0.56 m was recorded, which was previously known to be buried at 0.5 m.

Despite the technique's precision, several factors can affect the reliability of pipe characterization using EMI. The signal range and detection accuracy depend on variables such as the pipe's diameter and the soil's electrical conductivity as highly conductive soils can attenuate the signal and the degree of contact between the pipe and the soil, which can cause current loss through dissipation (GABRYS; ORTYL, 2020). Furthermore, although EMI is particularly effective for metallic materials, its applicability to non-metallic pipes, such as those made of PVC, is quite limited, requiring integration with complementary methods like GPR (Ground Penetrating Radar) or sonic surveys (DELEFORTRIE et al., 2014). GPR, in turn, allows for the detection of non-metallic objects but exhibits reduced performance in clayey or saturated soils due to signal attenuation; additionally, it does not permit the precise identification of the detected object's material.

4. Conclusion

The recommendation that future research should enhance electrical conductivity standards for different materials and refine existing models is in line with trends in applied geophysics. Significant advances are being made in areas such as forward modeling, inversion techniques, and data processing algorithms. These efforts include the development of more efficient 3D inversion methods for complex structures, addressing challenges like non-uniqueness and model instability. Sophisticated filtering techniques have also been developed to handle ambiguity in apparent conductivity maps caused by complex anomaly shapes, the presence of irrelevant conductive bodies, and random noise. The incorporation of machine learning algorithms and deep neural networks is opening new possibilities for noise reduction and automated data interpretation.

The recognized applicability of EMI, coupled with the challenges of interference and interpretive uncertainty, points to a clear trend: the evolution from single-method surveys to integrated, data- and technology-driven solutions. The proposal to improve models and develop advanced algorithms signals a growing need for tools capable of handling the increasing complexity of the urban and rural subsurface. The specialized literature corroborates this trend, highlighting the use of deep learning to eliminate interference, advances in 3D geological and utility modeling, and the emerging concept of "digital twins" to represent underground networks and infrastructure.

The transition from interpretive surveys to dynamic and predictive systems is transforming how subsurface characterization is conceived. The future of applied geophysics is moving towards the continuous integration of multiple methods (EMI, GPR, electrical resistivity, magnetometry), supported by advanced computational tools such as artificial intelligence, data fusion algorithms, and geostatistical modeling (like Kriging). This convergence allows for the construction of highly detailed and functional volumetric models that will serve as digital twins of the subsurface environment. Such models not only enable the precise detection of anomalies but also promote predictive modeling, risk analysis, and the optimized management of networks and infrastructure. The study conducted in Jequié represents a significant step along this path, demonstrating the potential of EMI and pointing towards a paradigm of geophysical investigation that is more integrated, intelligent, and applied to sustainable development and urban resilience.

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