

Geotechnical parameters estimation using electrical resistivity tomography data: Case study of Jorf Lasfar, western Morocco

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ABSTRACT

Geotechnical techniques are essential for subsurface geological investigations during the pre-feasibility phase of engineering projects. When the area under investigation is extensive, the density and consistency required for a conventional geotechnical reconnaissance program become both logistically complex and costly. The present study aims to estimate the main geotechnical parameters of the subsoil studied, namely water content (or moisture content), plasticity index, friction angle and cohesion from electrical resistivity data, through empirical equation calculations. The study area is located within the western Moroccan, a region characterized by karstic phenomena expressed in various forms. This work combined electrical resistivity tomography (ERT) surveys with targeted core drilling, complemented by laboratory geotechnical testing of collected samples. The inverted resistivity models were then used to estimate geotechnical parameters through empirical relationships, and the predicted values were statistically compared with laboratory measurements. The obtained results indicate variable predictive performance depending on the parameter considered. A strong correlation between measured and estimated values is observed for the plasticity index ($R^2 = 0.73$), while moisture content shows a moderate correlation ($R^2 = 0.45$). In contrast, cohesion and friction angle exhibit very weak correlations, $R^2 = 0.04$ and $R^2 = 0.05$, respectively, highlighting the influence of structural and mechanical factors, such as fracturing, cementation, and lithological heterogeneity, that are not directly governed by electrical conduction processes. Three-dimensional modelling of ERT-derived properties reveals the spatial distribution of the main geotechnical units and identifies a three-layered subsurface structure composed of a resistive weathered limestone tuff cap, an intermediate conductive silty-marl horizon, and a deeper fractured limestone unit. Although the estimated parameters show broader ranges due to the spatial continuity of geophysical data, laboratory measurements generally fall within the ranges of these estimates. These results demonstrate that ERT based empirical modelling can provide reasonable preliminary estimates for parameters closely linked to electrical resistivity, particularly moisture content and plasticity index. However, mechanical strength parameters such as cohesion and friction angle require cautious interpretation and must be validated through direct laboratory testing. Overall, the integrated approach offers a cost-effective tool for large-scale preliminary geotechnical reconnaissance, improved identification of potentially unstable zones in karst environments, and optimization of borehole investigation strategies.

Keywords: geotechnical parameters, Electrical resistivity tomography, 3D modelling.

INTRODUCTION

Karst environments are special geological structures, mainly developed in carbonate rocks. These geological formations are characterized by very rapid solubility (Al-Zarah, 2007; Metwaly

and AlFouzan, 2013; Boualla et al., 2021), which gives rise to sinkholes, chasms, underground galleries, etc. (Metwaly and AlFouzan, 2013; Youssef et al., 2016, Boualla et al., 2021). The high permeability and rapid infiltration of surface water also make these environments extremely vulnerable

to dissolution (Panno et al., 2019; Boualla et al., 2021; Zahorodniuk et al., 2019). The progressive dissolution of soluble bedrock confers upon karst terrains a significant geotechnical instability hazard. The underground cavities generated by this process may induce gradual ground subsidence or trigger sudden collapse events (Boualla et al., 2021; Fadili et al., 2024). These phenomena can damage infrastructure, agricultural land and threaten the safety of residents. To minimize the associated risks with karst environments, rigorous management and special attention to geotechnical and environmental issues must be taken into consideration before the implementation of any project.

Due to their complex and heterogeneous structure, karst environments present many challenges in identifying and characterizing them in order to assess the potential risks related to soil instability and vulnerability. In this context, electrical resistivity tomography (ERT) plays an essential role as a leading tool for mapping and assessing the risks associated with these environments. This technique enables the detection of the dissolution zones, underground cavities, karst conduits, and fractured zones, which are often associated with ground instability and collapse phenomena (Rizzo et al., 2019; Alqahtani et al., 2021; Boualla et al., 2021; Fadili et al., 2024; Mehdi et al., 2024). It makes also to allows determining and delineating deep altered areas and cavities filled with material in the subsurface. Numerous studies have demonstrated that this geophysical technique can be used to assess and anticipate ground instability hazards, thereby supporting safer and more sustainable land-use planning and development decisions (Cardarelli et al., 2010; Imposa et al., 2018; Ducut et al., 2022; Boualla et al., 2021; Guedes et al., 2023; Mehdi et al., 2024).

Geotechnical investigations are also essential to assess the physical and mechanical properties of karst terrains, which are characterized by great complexity and spatial heterogeneity (Calembert, 1975; Tarcan and Koca, 2001; Sopaci, 2012; Dindaroglu et al., 2023). Reliable subsurface characterization in such environments typically requires a large number of boreholes distributed throughout the study area. Nevertheless, this strategy can be costly, as geological uncertainty may require extensive additional investigations to gather as much information as possible and ensure an accurate site assessment. As such, electrical resistivity tomography combined with geotechnical investigations, boreholes and testing,

represent a promising and objective alternative (Bryson 2005, Ayolabi et al. 2012, Rupesh et al. 2024). This hybrid approach allows the respective advantages of each method to be exploited to obtain a more comprehensive and cost-effective characterization of the subsurface (Bryson 2005, Sudha et al. 2009, Jusoh and Osman 2017, Mohammed et al. 2019, Rupesh et al. 2024, Junaid et al. 2024). Thus, electrical resistivity surveys are commonly combined with borehole investigations to improve the reliability of subsurface characterization by providing complementary indirect and direct information, thereby reducing interpretation uncertainties.

The area understudy of Jorf Lasfar, located on the Atlantic coast of Morocco, is characterized by distinctive geological features, particularly the presence of karst formations and structures (Boualla et al., 2021; Fadili et al., 2024; Bouzerda et al., 2024; Mehdi et al., 2024). According to these authors, karst-related phenomena constitute a significant geotechnical hazard due to the development of subsurface cavities and associated ground instability. These risks are further exacerbated by the rapid urban and industrial expansion occurring in the region. Consequently, the study area is considered highly susceptible to geotechnical hazards associated with karstification. In the framework of the present study, geophysical and geotechnical investigations carried out at the study area focused on the deployment, respectively, of the electrical resistivity tomography (ERT) and the core drillings with geotechnical tests in the laboratory, namely the water content (also moisture content $W\%$), the plasticity index ($IP\%$), the cohesion (C' , in kPa) and the angle of internal friction (Φ' , $^\circ$). These parameters were chosen because of their geotechnical importance, as they provide a physical and mechanical characterization of the underground geological formations. Thus, the present work is based on the interpretation of the results of the ERT and on the estimated geotechnical data. These later was estimated using empirical equations developed from statistical correlations between ERT and geotechnical laboratory tests, proposed by Jusoh and Osman (2017) as well as Rupesh et al. (2024). The empirical relationships were originally developed for near-surface unconsolidated to semi-consolidated materials obtained from boreholes sampling. However electrical resistivity is mainly controlled by porosity, moisture content, and clay fraction rather than intact rock strength. Although

these formulas were not calibrated on competent rock masses, Rupesh et al. (2024) demonstrated their applicability to heterogeneous formations including sandstones, shale, and clay-rich layers.

In the present study, the investigated lithology consists of karstified limestones interbedded with marls that are highly fractured, weathered, and locally filled with clayey and marly residues, exhibiting physical behavior comparable to a soil and rock transition medium. From both geological and geophysical perspectives, electrical conduction in these formations is governed by interconnected pores, fracture networks, saturation degree, and fine-grained components, which are consistent with the physical assumptions underlying the cited empirical models of Jusoh and Osman (2017) and Rupesh et al. 2024. Therefore, the application of these formulas is justified from a methodological standpoint and allows for testing their effectiveness in a heterogeneous geological context. Nevertheless, given their empirical nature and the uncertainties associated with them, the geotechnical parameters obtained are interpreted in a semi-quantitative manner and are used primarily to assess relative spatial variations rather than absolute values. Thus, in this study, the results obtained were then calibrated against data from specific localized samples obtained from laboratory tests for evaluation and calibration purposes.

Finally, a fence diagrams and 3D model will be carried out to allow a perspective visualization of the variability of the geotechnical parameters of the terrain. The originality of this paper lies in the application of this approach which proposes an innovative method of geotechnical characterization based on geoelectrical data, calibrated by localized laboratory tests in the heterogeneous karst limestone on this site. It thus makes it possible to target the areas to be drilled with precision while reducing the costs of geotechnical studies over large areas.

MATERIALS AND METHODS

Study area overview

The Jorf Lasfar area, the area of interest for this study, is located approximately 20 km south of El Jadida city, and is part of the northern Sahel Doukkala region (Figure 1). Geologically, this area is a segment of the western Moroccan Meseta, characterized by tabular formations of secondary and tertiary deposits covering primary terrains (Gigout 1951; Ferre et Ruhard 1975). The southern part of the Doukkala Sahel is characterized by Jurassic deposits consisting of yellowish limestone and marl mixed with gypsiferous clays (Ferre et

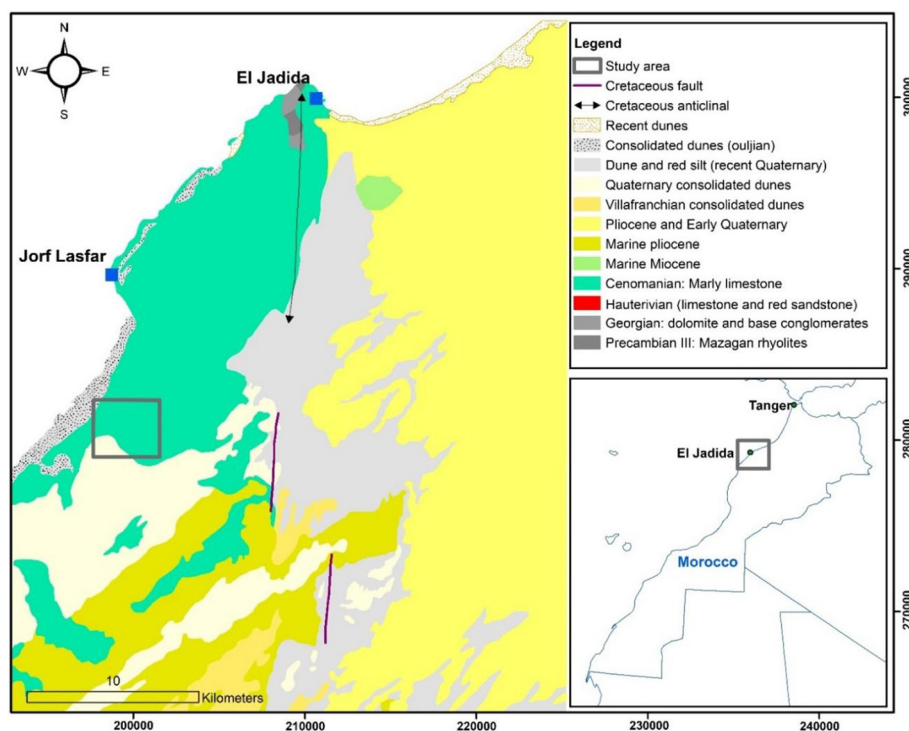


Figure 1. Geological map of the study area

Ruhard, 1975). In addition, the Cretaceous formations, mainly of Cenomanian age, include siliceous or sandstone limestones rich in shell footprints. These formations have an alternation of clayey limestone and marl beds, as well as relatively thick marl joints, while the Upper Hauterivian is distinguished by the limestone known in the region as the Dridrat limestones. This Cretaceous formation dominates the region and serves as an almost continuous substrate for the Plio-Quaternary deposits, consisting of marls and calcareous sandstones. This geological composition makes the study area very prone to significant instability due to karstification (Gigout, 1951; Ferre et Ruhard, 1975, Bouzerda et al., 2020).

The hydrogeological characteristics of the Sahel Doukkala are distinguished by the absence of a well-defined water table on a regional scale, due to the structural complexity of the subsoil and the lack of hydraulic continuity within the same geological formation. However, the primary aquifers of the region are located in the Plio-Quaternary layer, mainly located in the southern part and overlying the limestones and marls of the Cenomanian (Fadili, 2014). Generally, localized water levels have been identified in the Plio-Quaternary cover, but it is likely that the hydrogeology of this area is influenced by the Cenomanian (Upper Cretaceous) layer. The

predominant flow occurs in the Cenomanian marly limestones, directed towards the Atlantic Ocean in a northeast to southwest direction. Several independent karst systems appear to coexist, contributing to relatively variable water levels in adjacent wells (Fadili, 2014).

Geophysical investigations

In order to study the geological and geotechnical properties of the subsurface, an investigation was conducted using eight electrical resistivity tomography (ERT) profiles, as shown in Figure 2. The measuring device consisted of four longitudinal profiles of 1500 meters each, spaced 250 to 500 meters apart, supplemented by four transverse profiles with a length of 1800 meters. This configuration, combining longitudinal and transverse orientations, was chosen to ensure complete coverage of the study area and to allow accurate mapping of the main underground anomalies. The Wenner-Schlumberger array was selected in this study for its ability to reach significant depths and for the optimization of its measurement sequences. Each ERT profile was made using an LS2 Terameter instrument and 64 electrodes spaced 5 meters apart, representing a base length of 315 meters. To extend the

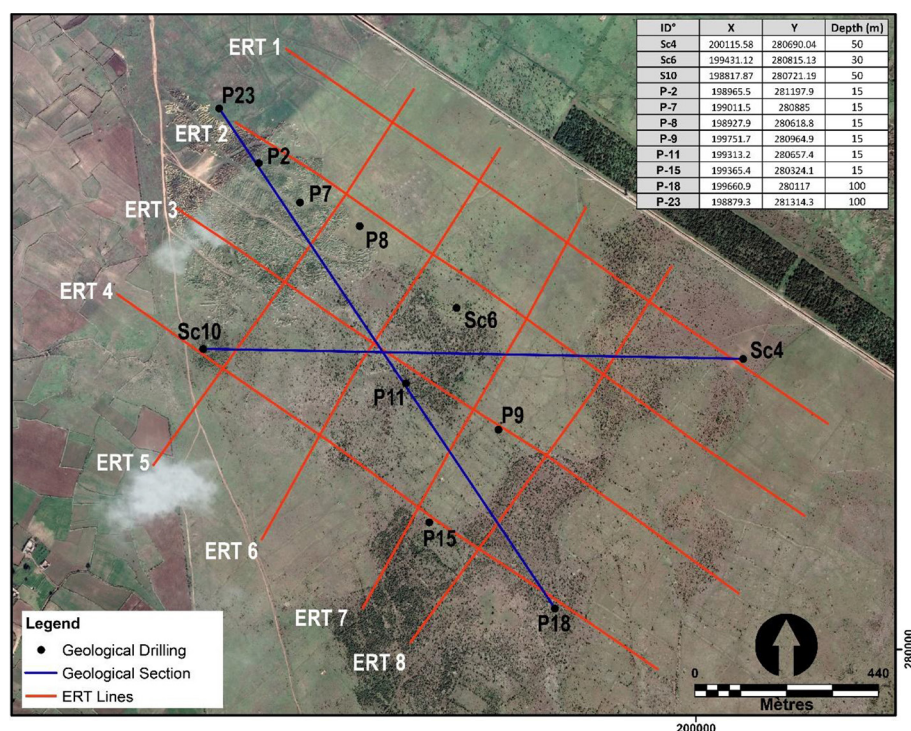


Figure 2. Location map of electrical resistivity tomography profiles and boreholes used for geotechnical testing

coverage and increase the depth of investigation, three roll-along sections were implemented per profile, allowing a maximum exploration depth of 60 meters to be reached. The data acquired in the field was then processed, inverted and interpreted using the Res2DInv software (Loke and Barker; 1996, Loke, 2004), recognized for its performance in 2D modeling of the electrical resistivity tomography of the subsurface. The inversion was calculated using a smoothness-constrained least-squares algorithm, applied to a regular mesh that was refined based on the density of the measurement points. The damping factor was adjusted between 0.1 and 0.5, and horizontal and vertical smoothness constraints were applied to limit inversion artifacts. Convergence was achieved after 5 to 7 iterations, with a final RMS error of less than 10%.

Geotechnical investigations

To complement the results of the geophysical investigations, the study focused on the geological and geotechnical identification of the different subsurface formations. Two approaches have been applied to this objective; a mechanical approach based on laboratory geotechnical tests and measurements, and the other mathematical approach based on equations and calculations for the estimation of geotechnical parameters. Indeed, the first experimental approach involves laboratory characterization of soil samples collected from eleven borehole drilled in the study area. The coordinates of the survey and sampling points are mentioned to the map in Figure 2. This study aims to determine the physical parameters, namely, water content (W %) and plasticity index (IP %), as well as mechanical parameters such as cohesion (C') and angle of friction (ϕ') which are obtained from direct shear tests. More than 200 tests were conducted, and each parameter was measured three times for each test to ensure the statistical reliability of the results. Almost 100 samples were extracted using the diamond crown perforated core holes, where the size of retrieved samples was 30cm. As such, the sampling concerned the different geological facies of the subsoil at several levels up to 50 m deep (Figure 2). The mathematical approach relies on calculations using empirical equations to estimate the same geotechnical parameters of the subsurface based on their electrical resistivity data obtained

through inversion. These parameters were selected based on their geotechnical significance, as they provide a comprehensive characterization of the physical and mechanical behaviors of rocks and the subsurface. In particular, the plasticity index was chosen because of the presence of clay and marl within rock fractures and karst cavities filled with clay or loose sediments (Mehdi et al. 2024).

The geotechnical parameters estimation is made by applying the Equations 1 to 4, established by Jusoh and Osman (2017) and Rupesh et al. (2024) from electrical resistivities. These equations were developed from laboratory tests conducted on undisturbed soil samples, taken after drilling in order to characterize the mechanical and physical properties of the selected soil. The use of the empirical equations proposed by Osman (2017) and Rupesh et al. (2024) is justified by the presence of similar sedimentological characteristics between the formations under study, and the materials used to develop these correlations. Consequently, from a geological and physical standpoint, these conditions are consistent with the underlying assumptions of these empirical models, making their preliminary application relevant in the context under study. However, the objective of this approach was not to replace conventional geotechnical tests, but to verify the relevance and applicability of existing relationships between electrical resistivity and geotechnical parameters within a heterogeneous karst environment. The electrical resistivity values embedded in these equations are derived directly from the electrical resistivity tomography (ERT) inversion data.

Moreover, the efficiency of these equations in estimating geotechnical parameters has been rigorously validated through comparative studies between the results obtained by these empirical models and data from experimental measurements on the one hand, and a wide applicability tested and successfully used on a wide variety of geological formations on the other hand (Jusoh and Osman, 2017; Rupesh et al. 2024). As mentioned above, their use in this study can be explained in part by the similarity of the materials studied and by their recognized scientific applicability to various types of soil and subsoil.

$$C = -3e^{-0.5} rs^2 + 0.0918 rs + 21.544 \quad (1)$$

$$PI = -2.71 \ln(rs) + 29.793 \quad (2)$$

$$W = 123.93 rs^{-0.252} \quad (3)$$

$$F = (4.7036 \times (\ln rs) + 6.6297) \quad (4)$$

where: C – cohesion, PI – plastic index, W – water content, F – angle of friction, rs – inverted resistivity. Here, the cohesion is calculated in kPa (Kilopascal), the angle of friction in degrees ($^{\circ}$), and the plastic index and water content in % (percentage).

The flowchart shown in Figure 3 outlines the successive steps followed in this study to derive the estimated parameters.

RESULTS

Electrical resistivity tomography profile

The fence diagrams of electrical resistivity tomography (ERT) models, illustrated in Figure 4, are used to distinguish underground geological structures and identify subsurface anomalies. Three main layers are identified, with resistivities ranging from 1.7 to more than 26.5 Ohm.m. The profiles show homogeneity in terms of resistivity, structure and depth over the entire study area, which reinforces the reliability of the geophysical data.

The geoelectrical profiles reveals a three-layer succession consisting of a moderately resistive surface horizon (14.1–26.5 $\Omega \cdot m$), an intermediate conductive layer (1.7–7.9 $\Omega \cdot m$), and a deeper resistive unit with resistivity values comparable to those of the surface layer (14.1–26.5 $\Omega \cdot m$) (Figure 4). The shallow horizon, extending to a depth of approximately 2–3 m, corresponds to weathered tufa limestone that forms the geotechnical cover of the site. Beneath this layer, the thick conductive

unit reaching depths of about 40 m is interpreted as impermeable silty marl, which restricts water infiltration and, owing to its low permeability and weak mechanical characteristics, is generally unfavorable to the development of karst features or subsurface cavities (Mehdi et al., 2024). The deepest resistive horizon, extending to approximately 50 m depth, is attributed to fractured sandstone limestone, a lithology that is more susceptible to karstification and cavity formation (Mehdi et al., 2024). The identified fracture network within this unit may act as pathways for the downward migration and accumulation of marly materials from the overlying conductive layer. Such infilling processes can locally alter the hydraulic and geomechanical properties of the subsurface, potentially creating zones of weakness and increasing the risk of ground instability at the surface.

Geotechnical parameters measured by laboratory tests

The geotechnical parameters measured from the laboratory tests and used for this study are the water content (W), the plasticity index (IP), the cohesion (C') and the friction angle (Φ'). The results obtained from the core holes to a depth of 50 m highlighted the following lithological succession (Figure 5):

- Whitish limestone tuff with a thickness varying from 0.7 to 3 m.
- Silty and indurated clayey marls: this horizon varies in thickness from 10 to 21–35 m.
- Limestone with yellowish marl passage: Found at a depth of 50 m, this layer has fractured passages with a brecciated passage.

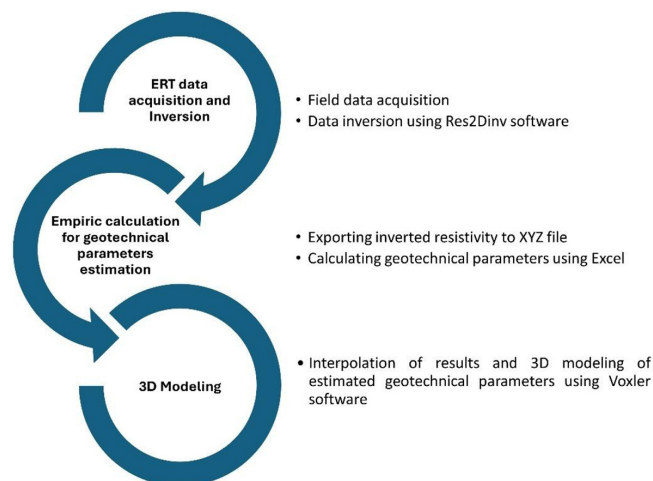


Figure 3. Flowchart presenting the adopted methodology

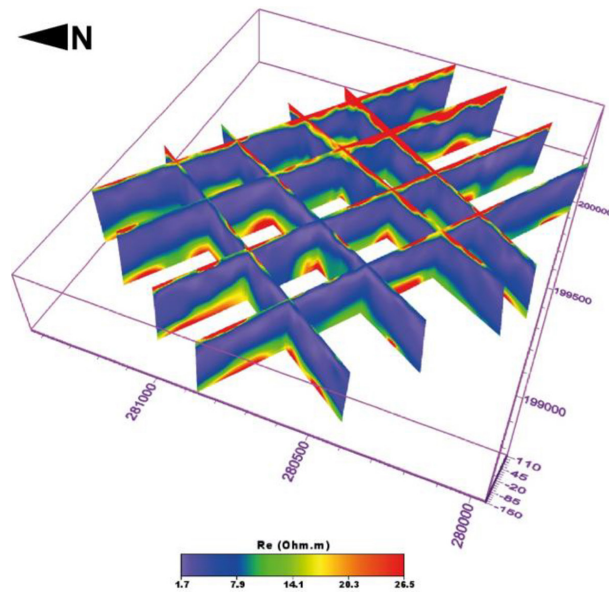


Figure 4. Fence diagram of original ERT data measured in the study area

The Figure 5 is a representative geological cross section constructed from multiple boreholes, showing the main stratigraphic units of the study area. Regarding the geotechnical characterization of soils, the Table 1 presents key data from laboratory tests.

The results obtained indicate that the identified formations present diversified geotechnical behaviors, as well as a variability of parameters within the same formation, reflecting a local heterogeneity of the layers crossed. The Figure 6 summarizes the results of these tests carried out on

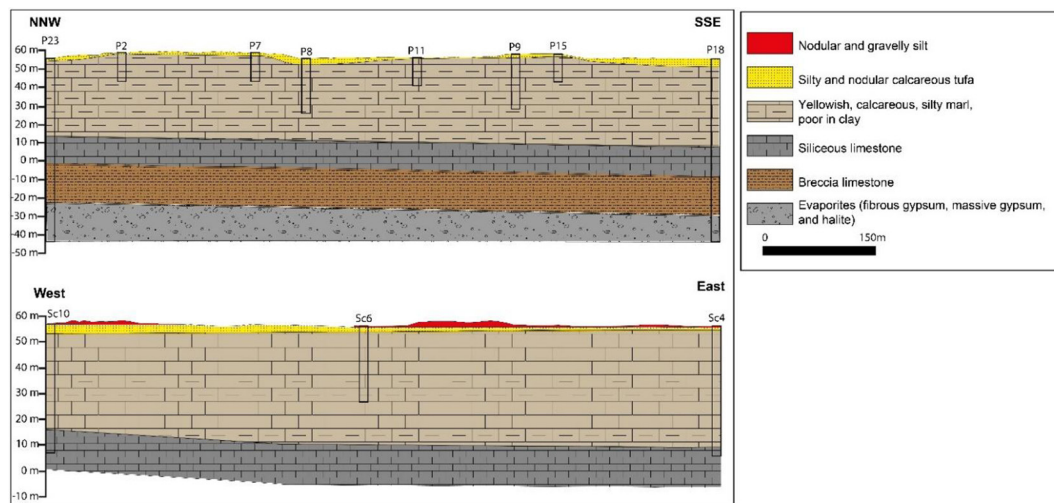


Figure 5. Geological cross-section (E-W) and (NNW-SSE) in the study area

Table 1. Laboratory test results from primary geotechnical test data

Geological layer	Water content (%)			Plastic index (%)			Cohesion (Kpa)			Angle of friction (°)		
	Min	Max	Moy	Min	Max	Moy	Min	Max	Moy	Min	Max	Moy
Calcareous tuff	11	25	19	15	18	16	41	50	47	15	15	15
Silty marl	12	32	22	14	52	19	34	53	44	15	16	15
Silty and clayey marl	15	30	25	23	26	24	32	46	38	15	16	15
Limestone	-									16	16	16

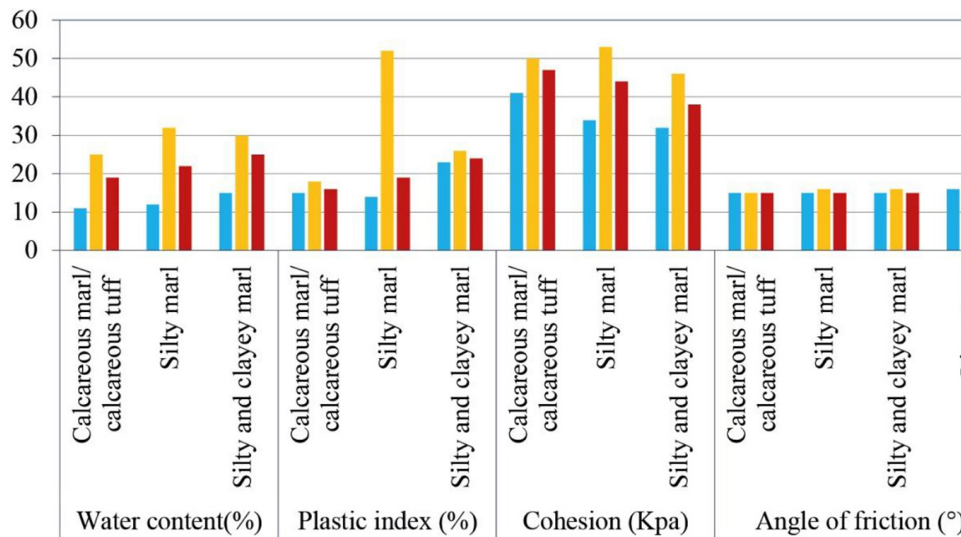


Figure 6. Experimental results of the different geological formations obtained from geotechnical tests

the samples recovered from the drill holes relating to the different facies and lithology encountered.

According to the results obtained from *the in-situ* measurements, the first tuff limestone layer with marl-limestone passage is a formation with a good internal resistance capacity, more cohesive ($c = 47$ kPa), but a low slip resistance ($\phi' = 15^\circ$). The second layer, corresponding to fine silty marl with clayey marl, is moderately plastic and quite cohesive with a relatively stable deformation behavior, but sensitive to variations in humidity. Although their respective average cohesion (C°) varies between 44 kPa and 38 kPa, this result can be attributed to the higher water content of the silty marls, which may indicate a greater susceptibility to saturation and swelling. Limestone as a support layer, and consolidated, has strong and stable performance, with high compressive strength, good slip resistance and significant cohesion. However, this result can be influenced by several factors, such as the presence of alterations, fractures or other geological defects, including karstification, which can affect the performance of the rock under real loading conditions (Mehdi et al., 2024).

Statistical study of estimated geotechnical parameters

Figure 7 presents a statistical summary of the geotechnical parameters calculated from the inverted resistivities. The obtained result highlights the variability of the physical and mechanical characteristics of the formations studied and its heterogeneous character. The resistivity

shows a very widely range of values (from 0.31 to 2275.50 ohm.m) with an average of 13.87 ohm.m and an extremely high coefficient of variation of 276%, which testifies to a very strong heterogeneity of the crossed media. This result is probably related to marked contrasts in terms of water content, porosity or change in lithological nature. The water content ranges between 17.67 to 166%, with a high average of 80% and a moderate dispersion of 24%. This result reflects highly variable humidity conditions in the horizons studied, probably due to the presence of a groundwater table or the abundance of clays potentially influencing the mechanical properties of the soil. Moreover, the estimated values of the plasticity index are between 8.84 and 32.95 % with an average of 24.72%. This parameter also shows a low dispersion (12%), reflecting a relatively constant mineralogical composition, probably dominated by plastic clays. On the other hand, the cohesion coefficient indicates values between 18 and 230 kPa, with an average of 22.7 kPa and a low coefficient of variation (16%), which suggests a relative homogeneity in the ability of the soils to resist fracture without normal stress. The angle of friction varies from 1.2° to 43° with an average of 15° and a coefficient of variation of 32%, revealing a high diversity of materials, probably ranging from very coherent formation to more shear-resistant formations. Overall, the results obtained highlight a geotechnical context marked by a strong heterogeneity in terms of electrical behavior and shear strength.

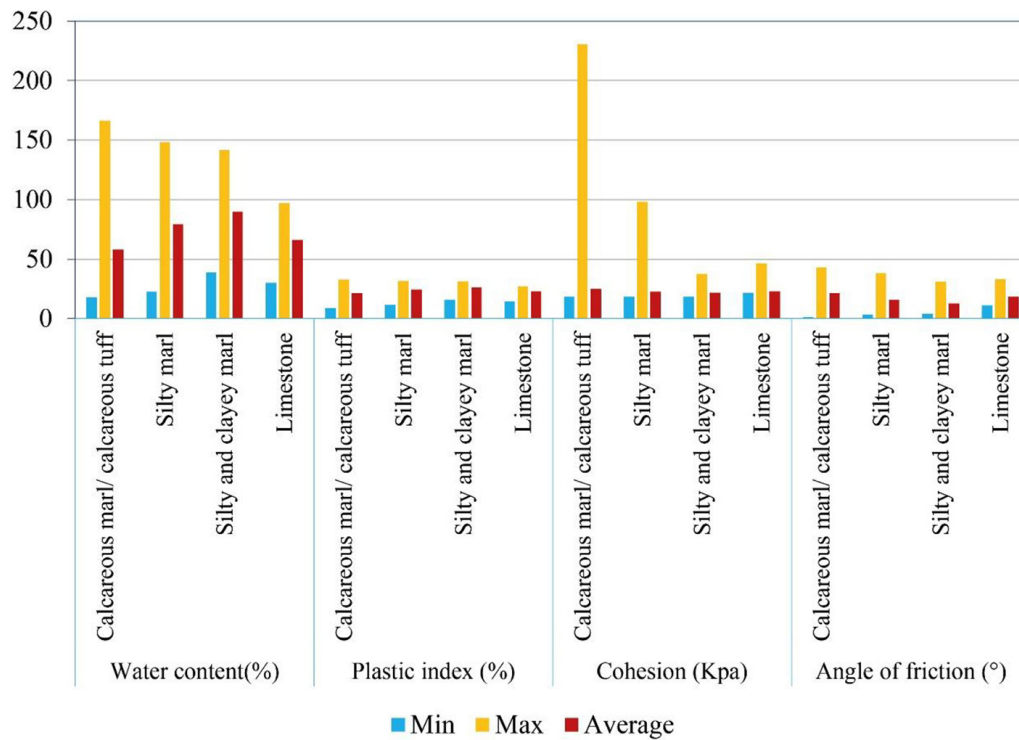


Figure 7. Statistical summary of estimated geotechnical parameters

Correlation between measured and estimated geotechnical values

The comparison between the ranges, on average, of the geotechnical parameters calculated and measured is given in Table 2.

It highlights significant differences between the ranges of the values obtained by the two approaches, highlighting the limitations of indirect estimation methods compared to experimental measurements and thus confirming the heterogeneity of the field. The calculated water content varies extremely wide (from 17% to 166%), while the measured values are in a much narrower range (from 19% to 25%), indicating that the calculation methods tend to overestimate or incorporate atypical values that are not representative of the actual behavior of the soil. Also, the plasticity index, although more consistent, shows a calculated range (from 9% to 33%) that is wider than that measured (16% to 24%), suggesting a better estimate of this parameter. As far as the internal friction angle is concerned, the measured value (15°)

is contained within the calculated range (from 1° to 43°), but the very large difference in the calculations reflects a high uncertainty probably due to particle size, density or humidity variations that are not taken into account and also the density of the field sampling. The cohesion also shows a marked contrast between widely dispersed calculated values (19 to 230 kPa) and more homogeneous measured values (34 to 47 kPa), which can be attributed to the high sensitivity of empirical models to input parameters.

The coefficient of determination (R^2), varying between 0 and 1, measures the precision of the statistical correlation between two variables. A value of R^2 close to 0 indicates a lack of correlation, indicating that the independent variable does not predict the dependent variable. Conversely, a value close to 1 indicates a strong correlation and a good predictive capacity of the model. Figure 8a shows the correlation between the calculated and measured moisture content values, illustrated by a linear regression with the equation $y = 0.36x - 6.54$ with a coefficient

Table 2. Comparison of the calculated and measured values of the geotechnical parameters

Parameter	Water content (%)	Plastic index (%)	Cohesion (Kpa)	Angle of friction (°)
Calculated	17–166	9–33	19–230	1–43
Measured	19–25	16–24	38–47	15–16

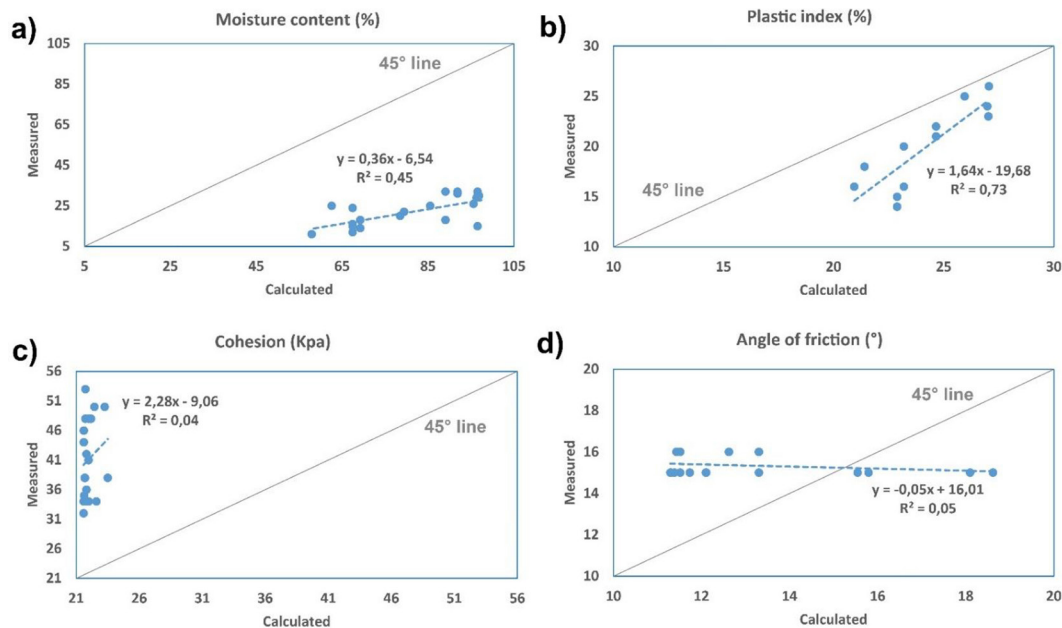


Figure 8. Correlation between calculated and estimated parameters

of determination $R^2 = 0.45$. The latter value reflects a positive but moderate to significant correlation, indicating that 45% of the variability of the measurements can be explained by the estimation, while 55% remains influenced by other non-modelled factors, such as soil heterogeneity, in-situ measurement inaccuracies or limitations of the equations used. The relatively low slope shows a moderate sensitivity of the measurement compared to the estimate, and the visible dispersion of the points, especially at the ends. This result could be the consequence of specific local conditions not considered in the estimation, such as water saturation and heterogeneity of geological formations. However, this calculation suggests that the estimation method loses reliability for very low or very high values. Nevertheless, the general trend observed partially validates the approach, which allows it to be considered as a tool for preliminary estimation of water content, provided that it is accompanied by experimental spot checks to ensure the reliability of the results.

The correlation between the calculated and measured values of the plasticity index (PI%) is shown in Figure 8b. It shows a linear regression line whose equation is $y = 1.64x - 19.68$, with a coefficient of determination $R^2=0.73$. This relatively high value reflects a good correlation between the estimated results and those obtained experimentally, suggesting that the equation used for the calculation provides a reliable estimation of this geotechnical parameter. Indeed, the slope

of the line greater than 1 indicates that the measured values increase faster than the calculated values, which may reflect a slight underestimation of the model in some cases. The dispersion of the dots around the line remains moderate, confirming the overall consistency between the two data sets. Therefore, the Figure 8b demonstrates that the approach used to estimate the plasticity index is globally relevant, with satisfactory accuracy that makes it usable for practical applications, especially in the preliminary reconnaissance phase or in areas where laboratory testing is limited.

The correlation between the measured and estimated cohesion values (in kPa) is shown in Figure 8c. This correlation is described by the equation $y = 2.28x - 9.06$, with a very low coefficient of determination ($R^2 = 0.04$). This result indicates a high degree of data dispersion and the absence of a significant linear correlation. Indeed, this could be explained by a high degree of heterogeneity in the geological formations, such as variations in composition (presence of fractures, stratification, karstification, or weathered zones), irregular grain size distribution, or variable moisture conditions affecting cohesion, compounded by the limited and localized number of tests conducted.

The correlation between the values of the friction angle, shown in Figure 8d, reveals a notable discrepancy between the measured and estimated values. This result confirms the complexity of the characteristics of the geological formations in the study area. The regression line ($y = -0.05x +$

16.01) has a slope close to zero and a very low coefficient of determination ($R^2 = 0.05$), indicating a complete lack of linear relationship and data variability. This finding is likely due to the complex geological conditions of the studied environment, such as the presence of fractures, karstification, and filled or dry joints creating mechanical discontinuities, as well as spatial variations in water content that locally alter friction properties.

Despite the differences observed between the calculated and measured values, it is important to note that the ranges of measured values generally fall within the estimation intervals provided by the empirical equations (Table 2). These differences are primarily due to the lithological and structural heterogeneity of the terrain, which results in significant local variations in geotechnical properties. Furthermore, the measured parameters generally come from isolated, localized boreholes, which limits their spatial representativeness. Conversely, estimates derived from empirical models applied to ERT data are based on a much larger number of calculation points distributed throughout the entire study area, thereby incorporating greater spatial variability and explaining the wide range of the estimated intervals. However, the correlations established between the measured and estimated values at equivalent depths for water content and plasticity index show satisfactory agreement, confirming the consistency of the observed trends. Thus, although the estimated values show some dispersion, they remain generally consistent with the measured data and can be used with caution for geotechnical interpretation at the site scale. These results show that the correlations proposed by Jusoh and Osman (2017) and Rupesh et al. (2024) constitute a relevant tool for the preliminary estimation of geotechnical parameters, mainly water content and plasticity index, as well as for the analysis of their spatial distribution. Nevertheless, this approach should be considered as an aid to geotechnical characterization and not as a substitute for conventional geotechnical investigations conducted in situ and in the laboratory.

Interpretation of estimated geotechnical parameters

The integration of geotechnical values into a perspective model (fence diagrams) makes it possible to obtain a detailed stratigraphic visualization, thus facilitating the interpretation of lithological and geotechnical variations within

the studied layers. As presented in the flowchart of Figure 3, to obtain the fence diagrams and 3D models, the inverted ERT sections were first exported and converted into XYZ data files (X, Y spatial coordinates and Z the resistivity values). These datasets were then used to estimate the corresponding geotechnical parameters through the empirical equations of Jusoh and Osman, 2017; Rupesh et al. 2024. This calculation was carried out in Microsoft Excel, and subsequently, the fence diagrams and 3D models of resistivity and derived geotechnical parameters were constructed using Voxler software. The 3D interpolation was performed using the Inverse Distance Weighting (IDW) method, allowing the spatial distribution of the parameters to be visualized and analyzed in three dimensions.

Water content (%)

The Figure 9 illustrates the fence diagram of water content, also named moisture content, that shows three-layer ranges. The first layer shows values comprise between 45–61.25 %. These values are indicative of a wet to very humid material, with low resistance. In fact, limestone tuff, if friable or weathered, can behave like a very plastic or cohesive soil, but the residual coherence depends on its degree of degradation. The second layer with values of 61.25 to 110% relates to a very wet to saturated water status, suggesting a cohesive but soft soil. This zone corresponds to very thick silty marls. The third deep layer also shows values between 45–61.25 %. Overall, this model shows a significant variation in soil water content, ranging from relatively dry conditions to saturated areas.

Plastic index (%)

The obtained values of plasticity index (PI), an indicator of the clay content and mechanical behavior of soils, varies between 18% and 29% as presented in Figure 10. Also, three classes of PI stand out in these results. A surface layer, with values between 18 and 20.75%, indicating low clay content, low to moderate plasticity. An intermediate layer, with values between 26 and 29%, with a high clay content, high plasticity, high water sensitivity, and strong plastic and compressible behavior (risks of shrinkage-swelling). At the base, a deep layer of values ranging from 23.5 to 26.25 %, with moderate plasticity, a good balance of stiffness and plasticity, acting as a base.

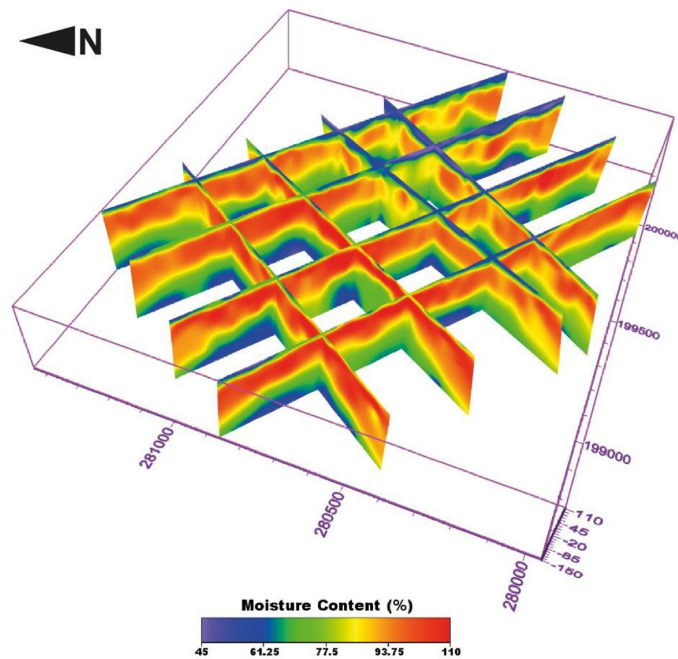


Figure 9. Fence diagram model of the estimated values of the water content (%)

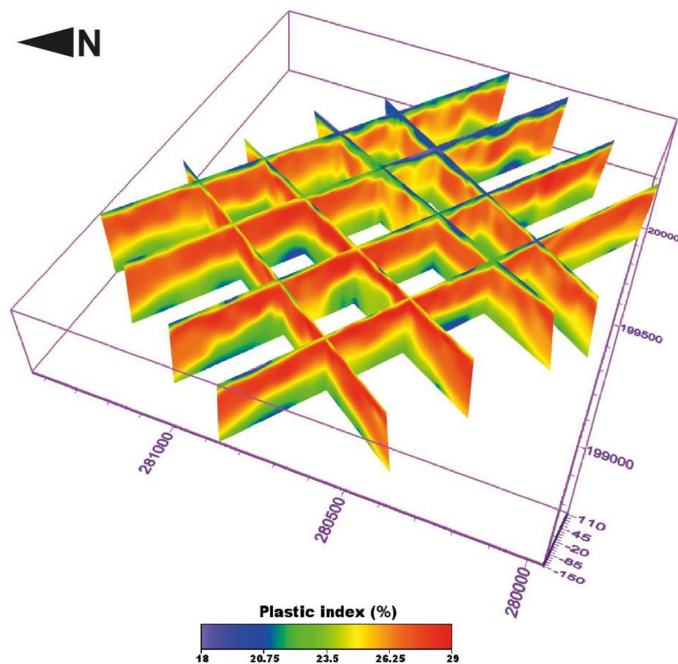


Figure 10. Fence diagram model of the estimated values of the Plastic index (%)

Cohesion (Kpa)

Interpolation of cohesion shows values that are between 20 and 26 kPa as presented in Figure 11. Such result reflecting significant variations in the mechanical properties of the formations as a function of depth. Indeed, the high values (23–26 kPa) located on the surface correspond to silty limestone tuff and at depth to siliceous limestone.

These values are correlated with the presence of some cementation (calcium carbonate, silica), which would increase cohesion. Therefore, it remains plausible for a fragmented and coherent tuff or limestone. However, the low values (20–23 kPa) observed at medium depths, are attributed to silty, clayey materials in a compacted or consolidated state.

Angle of friction (°)

The angle of friction is an indicator of shear strength, varies according to the nature of geological formations. Figure 12 illustrates the obtained result of the model of friction angles at different depths. According to the obtained results, it appears that the surface layer, indicating values of 15 to 22°, has a weak to moderate cohesion can be attributed to tuffaceous limestone. The intermediate layer, with values of 8–11.5°, is correlated with silty marls poorly consolidated and sensitive to water and overload. It is an area of potential weakness. The deep layer of 15 to 22° regains moderate internal friction with good shear strength thanks to better consolidation. These variations reflect the influence of lithologic properties and the nature of geological formations in the study area on their geotechnical properties and their behavior in response to mechanical stresses.

DISCUSSION

Geotechnical parameter estimation from ERT data

The results obtained show that the experimental values of geotechnical parameters fall globally within the ranges estimated through empirical equations derived from electrical

resistivity measurements. Figure 13 illustrates the 3D model of these estimated value intervals alongside the corresponding experimental ranges. The plasticity index and friction angle (Figures 13b and 13d) exhibit a relatively extensive spatial distribution, reflecting the greater sensitivity of these parameters to geological variability and the broader spatial coverage afforded by empirical estimation. Conversely, cohesion and water content (Figures 13a and 13c) remain confined to localized measurement points, a limitation inherent to the punctual nature of laboratory testing. This observation underscores the importance of coupling laboratory data with indirect geophysical methods, such as electrical resistivity tomography (ERT), to achieve a more continuous and spatially comprehensive characterization of subsurface geotechnical properties.

The apparent dispersion in the estimated results should not be interpreted as a methodological deficiency, but rather as a consequence of an approach that inherently accounts for subsurface heterogeneity. Mohammed et al. (2019) showed that correlations between electrical resistivity and geotechnical parameters are satisfactory, particularly for dry and weakly cohesive clay soils or rocks, with moisture and clay content identified as primary controlling factors. In the present study, the very low coefficients of determination obtained for cohesion (C') and friction

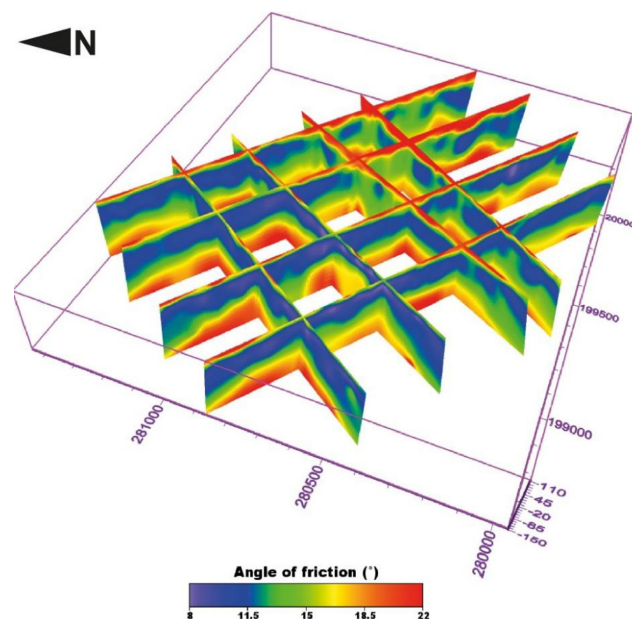


Figure 12. Fence diagram model of the estimated values of the Angle of friction (°)

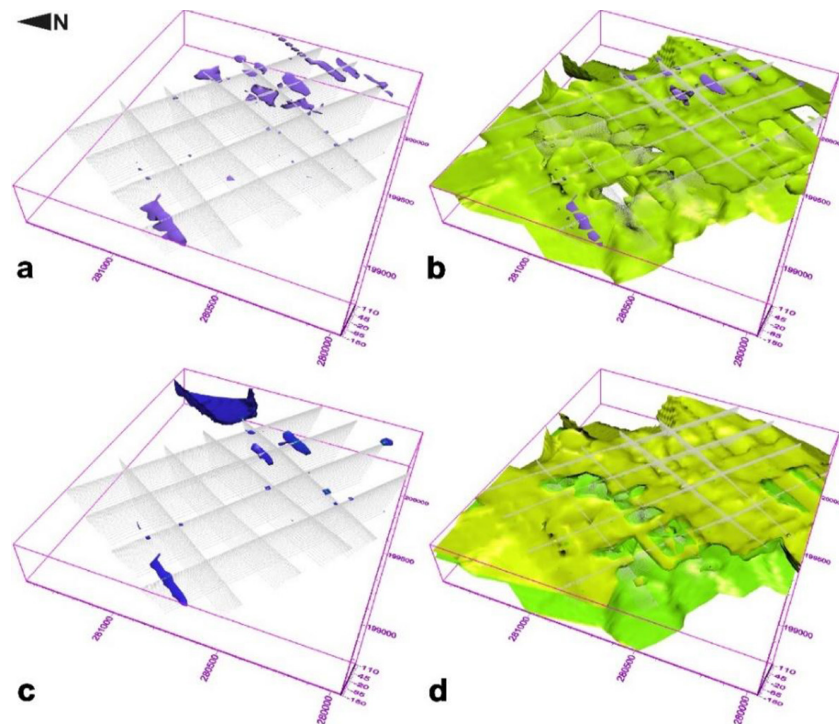


Figure 13. Range of experimental values inferred from estimated results: a) value of 26 of Water content(%), b) value of 18–24 Plastic index (%), c) values between 34–47 of Cohesion (Kpa), and d) value between 15–16 of Angle of friction (°)

angle (Φ') ($R^2 = 0.04$ and 0.05 , respectively) are physically consistent with the governing processes involved. Indeed, C' and Φ' are inherently multivariate parameters governed by mineralogical composition, grain-size distribution, microstructure, cementation degree, and saturation conditions. In contrast, electrical resistivity is primarily sensitive to pore water content, degree of saturation, fracture connectivity, and the presence of conductive clay or marly fractions. In the investigated formations, resistivity variations reflect lithological heterogeneities rather than interparticle bonding or frictional resistance characteristics, which explains the weak correlations observed for these mechanical parameters.

The inverse relationship observed between resistivity and water content confirms that wetter zones are more electrically conductive, owing to the presence of dissolved ions in pore water (Griffiths and Barker, 1993; Rupesh et al., 2024). The plasticity index decreases with increasing moisture content, while cohesion and friction angle vary with the degree of saturation. The friction angle is additionally influenced by grain-size distribution and particle angularity; coarse, angular soils generally exhibit higher friction angles than fine-grained soils (Pulat et al., 2018; Rupesh

et al., 2024). Furthermore, Jusoh and Osman (2017) demonstrated that the friction angle tends to increase with electrical resistivity.

The deviations observed between estimated and measured values are also attributable to the limited number of geotechnical sampling points, which constrains the spatial representativeness of conventional testing. On the other hand, Estimation based on ERT provides extensive spatial coverage at high resolution, resulting in empirical models that incorporate greater geological variability and thus wider value intervals. The overlap between experimental and estimated ranges confirms the methodological validity of the approach and its potential as a reliable tool for the preliminary assessment of geotechnical parameters, particularly in areas where access conditions restrict conventional in-depth investigations. Several studies corroborate this integrated approach: Jusoh and Osman (2017) demonstrated effective correlations between resistivity and both moisture content and cohesion; Rupesh et al. (2024) validated the method in a mining context; Bryson (2005) confirmed resistivity as a reliable proxy for soil behavior; and Sudha et al. (2009) showed that resistivity-based estimates of soil strength offer a faster, more cost-effective alternative to traditional in situ methods.

Geological and geotechnical implications

The estimation of geotechnical parameters based on ERT enabled the identification of three main geological layers in the study area: a resistive surface layer (calcareous tuff), a conductive intermediate layer (silty and clayey marls), and a deep resistive layer (sandstone limestone). The correspondence between the electrical signatures and the geo mechanical properties of these formations confirms the reliability of ERT for stratigraphic interpretation (Loke et al., 2004). The intermediate conductive layer exhibits the weakest mechanical behavior, characterized by low friction angles and high plasticity indices, conditions consistent with the karstic nature of the environment (Mehdi et al., 2024). The ERT ability to detect karst cavities and water-saturated zones further enhances its value for structural stability assessment (Reynolds, 2011; Mehdi et al., 2024).

The spatial modeling of estimated geotechnical parameters facilitates the identification of potentially unstable zones, providing a valuable tool for anticipating geotechnical hazards in industrial and urban environments. Insufficient soil strength may result in ground subsidence, a phenomenon frequently observed in karst settings (Mehdi et al., 2024; Boualla et al., 2021; Fadili et al., 2024). Given that structural stability is primarily governed by cohesion and internal friction angle (Fuentes et al., 2013; Rupesh et al., 2024), zones exhibiting high water content combined with low friction angles constitute priority targets for focused in situ geotechnical investigations

Limitations of empirical estimation approach

In the context of fractured and karstified rock masses, C' and Φ' are predominantly controlled by structural discontinuities, particularly joints, fractures, and karst features which introduce strong mechanical anisotropy that the bulk volumetric resistivity derived from ERT inversion cannot resolve. The ERT signal is sensitive to pore water distribution, clay and marl fraction, and fracture-related moisture pathways, but cannot capture the mechanical attributes of discontinuities that critically govern shear strength parameters. This fundamental incompatibility between the physical bases of electrical and mechanical measurements constitutes an inherent limitation of the method for C' and Φ' estimation in such geological

settings, and physically explains the very low R^2 values obtained. In contrast, water content and plasticity index, being more directly linked to the mechanisms governing electrical conduction, yield comparatively better correspondences.

Consequently, the proposed approach is explicitly intended as a complementary tool to conventional geotechnical characterization, not as a substitute for laboratory or in situ testing. It is most reliable for parameters directly linked to electrical conduction mechanisms (water content and plasticity index), while C' and Φ' estimates should be treated as indicative only but non-predictive. Empirical models also require rigorous local calibration, as electrical and mechanical soil properties vary considerably with geological context (Sudha et al., 2009). Future improvements should integrate in situ measurements and temporal monitoring to refine the predictive models.

Within these limitations, the 3D estimation models serve as effective rapid interpolation tools during preliminary site investigations. Their primary operational contributions include the delineation of homogeneous geotechnical units, probabilistic risk assessment, and the spatial targeting of subsequent direct investigations. For instance, zones of high-water content can inform consolidation assessments, while areas of low friction angle can guide slope stability analyses. This approach thus optimizes the allocation of resources in geotechnical reconnaissance, combining the spatial continuity of ERT with the quantitative accuracy of targeted laboratory and in situ testing.

CONCLUSIONS

The present study, conducted in the Jorf Lasfar region, clearly highlights the relevance of an integrated approach combining electrical resistivity tomography (ERT) and geotechnical analyses for the characterization of the subsurface. The main objective was the estimation of geotechnical parameters from the TRE using empirical equations. The results demonstrate that the empirical correlations established between the resistivity data and geotechnical parameters, such as water content, plasticity index, cohesion and friction angle, provide a basis for the indirect estimation of the mechanical properties of the subsurface. Despite some quantitative discrepancies between the estimated and measured values, in particular due to the natural heterogeneity of the formations,

the presence of clays, water saturation and the limitations of empirical models. The measured data are broadly within the estimated ranges of variation, which make this method applicable or exploratory purposes. However, the adopted approach is demonstrated to be more applicable for estimating water content (%) and plasticity index (%), which are parameters closely linked to the electrical resistivity measurements. In contrast, it is less reliable for estimating cohesion (kPa) and friction angle ($^{\circ}$), which are governed by multiple mechanical and structural factors that are only weakly captured by resistivity. These strength parameters, therefore, must be interpreted with precaution and used as complementary or preliminary data of the laboratory tests.

The modelling of the obtained results made it possible to finely visualize the spatial distribution of the geological units and geotechnical parameters, thus facilitating the detection of risk areas, in particular those related to karstification, low shear strength or high water or clay content. This modelling also makes it possible to identify the target areas concerned by experimental tests to reduce the cost and time of drilling. This ability to combine point data and continuous spatial information is a major advantage during preliminary studies for the planning of infrastructure projects, especially in complex or inaccessible contexts. However, the full exploitation of this method requires rigorous local validation and the integration of complementary data in order to strengthen the accuracy of the predictive models and their representativeness. With this in mind, electrical resistivity tomography, used in synergy with conventional and direct techniques, is a valuable tool for optimizing reconnaissance campaigns, reducing geotechnical uncertainties and improving the management of associated risks.

The proposed approach should be considered as preliminary qualitative tool for regional-scale geotechnical characterization, particularly useful for identifying spatial trends in parameters closely linked to electrical conduction mechanisms, principally water content and plasticity index. However, the adopted method cannot be used for quantitative geotechnical design or risk assessment without site-specific calibration and direct geotechnical testing. Integrating ERT surveys with targeted borehole investigations does not reduce the necessary number of boreholes needed. Instead, it serves to optimize their spatial placement by identifying geotechnically distinct zones,

potential anomalies, and areas of lateral continuity before drilling. This qualitative approach therefore helps prioritize the most suitable drilling locations, potentially lowering both the cost and duration of the geotechnical study. Direct sampling and laboratory testing remain mandatory and must meet the minimum survey requirements prescribed by the applicable geotechnical standards. This study contributes to reinforcing the growing interest in geophysical methods in the field of geotechnical engineering, demonstrating that they can, when properly calibrated and interpreted, serve as a tool for the assessment of subsurface conditions. It thus paves the way for wider applications in the fields of planning and the prevention of ground instability.

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