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Geotechnical assessment of fractured limestone bedrock using DC resistivity method: a case study at New Minia City, Egypt

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ABSTRACT
The new urban development is an important priority in Egypt to face a rapid increase in the population during the last few decades. As a case study, the geotechnical assessment of the New Minia City is studied applying direct current (DC) resistivity technique. In the presented study, the DC resistivity data are interpreted to (i) characterize the subsurface layer distributions, (ii) deduce the subsurface structures considering the surface geological and structural setting and borehole information and (iii) predict geotechnical parameters of the bedrock based on empirical relationships. The inversion results of DC resistivity data indicate that a lens of clay is locally capping the fractured limestone in different parts of the area. The constructed geoelectrical cross-sections show that the limestone bedrock is highly fractured regarding many normal faults trending in the NW and NE directions. In an attempt to derive empirical relationships for predicting the geotechnical parameters, the inverted resistivity values of the fractured limestone were correlated with different geotechnical parameters, Rock Quality Designation (RQD) and Unconfined Compressive Strength (UCS). It is noticed that there are good correlations between the limestone resistivity values and geotechnical parameters obtained from borehole data applying linear relations. Accordingly, the results indicate that the DC resistivity method constitutes a valuable technique to introduce a preliminary geotechnical assessment for new urban areas.

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1. Introduction

Nowadays, urbanization and development are becoming so rapid. Further, the construction activities with economic development have been increased. Obviously, land reclamation projects have been increased especially in desert regions. In such desert lands, many new communities construction (e.g., El Obour and Badr cities) has been established. The study site (New Minia City) lies on the eastern side of the Nile Valley. It is situated 248 km south of Cairo, between latitudes 28° 4′ 45” and 28° 7′ 20” N, and longitudes 30° 50′ 48” and 30°53′ 50” E with an area about 11 km^2 approximately (Figure 1).

From a geotechnical point of view, insufficient information about subsurface geological structures complicates the subsurface composition which in turn introduces significant engineering hazards. To improve the subsurface geology characterisation, geophysical investigations pose a costly alternative. Geophysical methods are effectively applied for engineering assessment of new urban areas. Recently, state-of-the-art field measurement methods (e.g. direct current (DC) resistivity technique) are capable to deduce the subsurface geology and structures information correlated with borehole data with high resolution on various spatial scales (e.g. Attwa et al. 2016).

General speaking, the electrical resistivity value of subsurface geological layers depends mainly on the lithological properties (e.g. density and porosity), and saturation degree and its quality. Moreover, the total resistivity is controlled by the water content than by the resistivity values of the solid rock. Currently, several published studies indicate the applicability of the geoelectrical method for prediction hydrogeological and geotechnical parameters using empirical to semi-empirical relationships (e.g. Henaish and Attwa 2018). Additionally, the application of DC resistivity method for delineating near-surface soils, detecting faults and predicting hydrogeological/geotechnical parameters has been increased (e.g. Steeples 2001; Attwa and Henaish 2018).

In this study, the DC resistivity technique was applied to characterize the geological conditions of New Minia City. Rock samples collected from boreholes were analyzed in the laboratory to identify Rock Quality Designation (RQD) and Unconfined Compressive Strength values (UCS). Because geotechnical parameters determination is a substantial important task for civil engineering before making any construction process.The geotechnical parameters were deduced based on empirical relationships between the resistivity values and the measured geotechnical parameters of collected rock samples.

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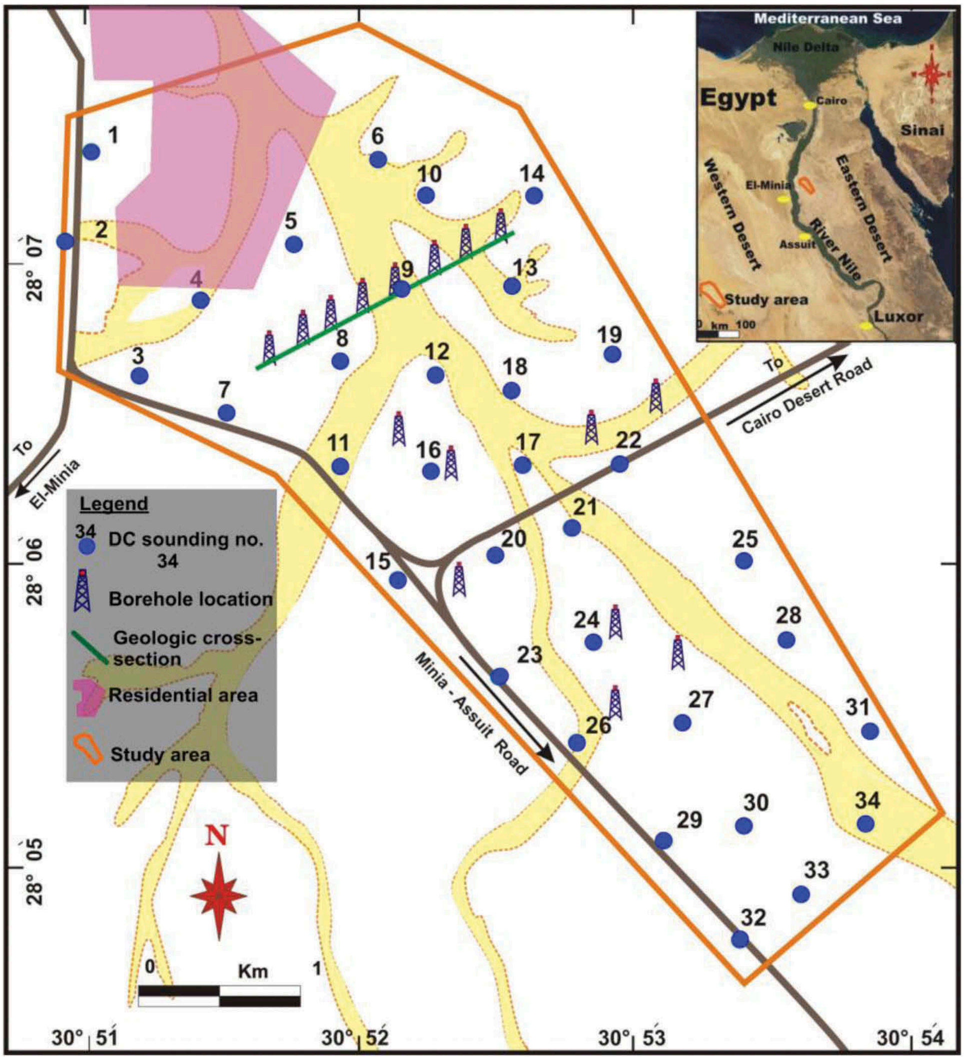

Figure 1. A base map illustrates the locations of the study area, the boreholes, and the DC resistivity measurements.

2. Geological and geotechnical background

Middle Eocene carbonate rocks have covered the study area, these rocks are mainly formed of limestone intercalated with, thin beds of clayey, sandy, and cherty limestone (Bishay 1961). These rocks are covered, in some locations, by Quaternary conglomerates, wadi fills and talus. The carbonate rocks in the area divided into two formations; Minia Formation and Samalut Formation (Said 1962).

Minia Formation consists of succession intercalated chalk and limestone which are cross-bedded and containing flint and chert at its bottom (Abdel-Meguid et al. 1998). The top consists of hard massive and karstic limestone with numerous vugs, holes and caves which are sometimes connected with each other. The area underlies by Samalout Formation. It conformably underlined by Minia Formation and consists of a white to yellowish limestone and chalk with some clay, marl intercalations and coquina beds. In many places in the area, Samalout Formation is considered as the foundation bedrock (Figure 2).

From shallow boreholes which drilled in the area by Arab contractors (ACLD, 2012), the shallow subsurface section consists of three main units from top to bottom (Figure 3): the first is the surface layer of recent deposits consists of sand, and gravel with a thickness ranging from 0.5 m to 3.5 m. The second unit corresponds to the Middle Eocene of Samalout Formation and recent sand with limestone fragments.

Structural studies indicate that the study area subjected to major and minor normal faults and fractures trending in the NW and NE directions and the NW one is dominant with caves and sinkholes (Abdel-Meguid et al. 1998; Shebl et al. 2019). Most of the caves are distributed along major faults with different sizes and their lengths range from some meters to more than one kilometer. Additionally, fractures increase along the major faults and the combination of fractures and caves may affect the area foundations. Fractures and joints may act as conduits for surface and ground water, which can dissolve the limestone and change the stability of the ground due to the relative decrease of shearing resistance. In the lower part of Samalout Formation, many vugs, voids and caves are distributed almost in NW–SE direction following the main faults. This may be reflecting the effect of surface and/or groundwater

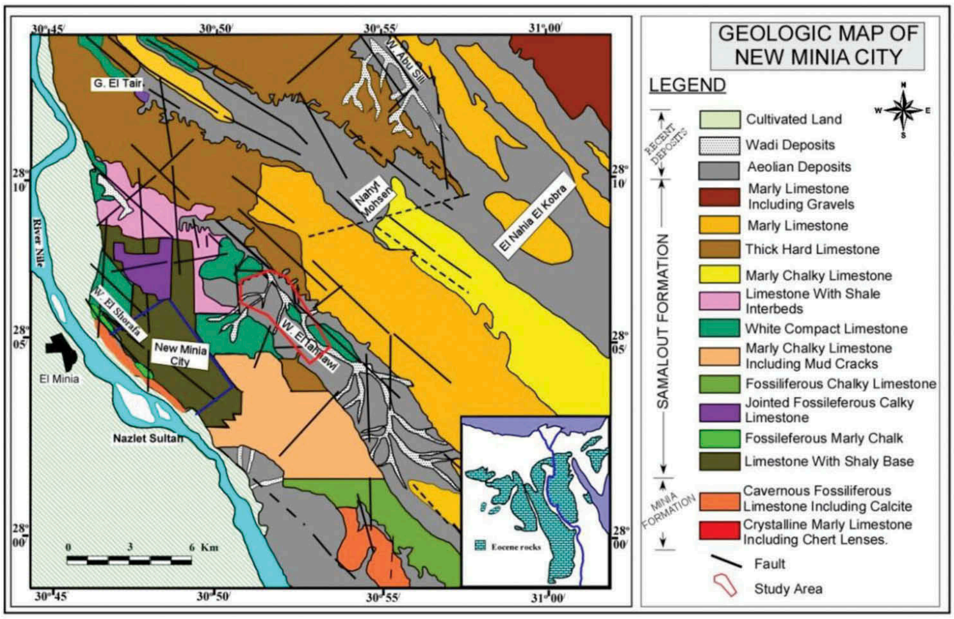

Figure 2. Surface geological map of the study area and its surroundings (modified after Abdel-Meguid et al. 1998).

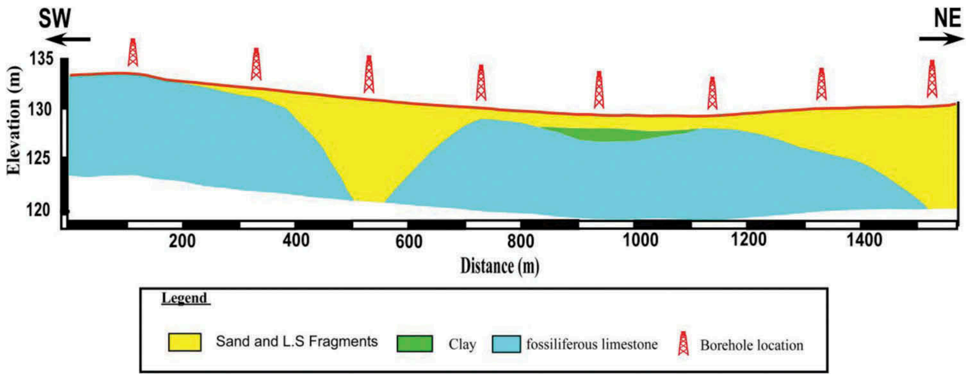

Figure 3. Lithological cross-section based on boreholes drilled by Arab contractors (.ACLD, 2012) for boreholes location, see Figure 1.

percolation through fracture zones where permeability increases (Philip et al. 1991).

Regionally, major NW and NE trending faults control the main wadis and escarpment boundaries (Figure 2). The geomorphology of the area of study is structurally controlled, mainly by NW fault trend and partially by the N–S and NE trends.

3. Materials and methods

3.1. Geotechnical data collection

The data of geotechnical parameters (RQD and UCS) were collected from boreholes drilled by Arab contractors (ACLD, 2012). The collected data were used for making a correlation between DC resistivity and the geotechnical parameters of the rock. The geotechnical data include RQD and UCS.

3.1.1. Rock Quality Designation (RQD)

Rock-quality designation RQD is defined in Equation as the quotient Deere (1989):

$$RQD = \left[\frac{L_{sum}\ \text{of}\ 100}{L_{tot}.\ \text{core run}}\right] \times 100$$

$L_{sum.\ Of\ 100}$ = Sum of the length of core sticks longer than 100 mm measured along the center of the core, and $L_{tot.\ Core\ run}$ = Total length of core run.

According to laboratory measurements which made by Arab Contractors (ACLD, 2012) the rock-quality designation of the limestone bedrock ranged from 10 to 30 which, according to Egyptian code Table 1 reflect very poor to poor bedrock.

3.1.2. Unconfined compressive strength (UCS)

Unconfined compressive strength is a measure of a material's strength.

Table 1. Rock classification according to RQD ECP – 202/1 (2001).

RQD %	Rock quality
< 25	Very poor
25–50	Poor
50–75	Fair
75–90	Good
90–100	Excellent

The test is performed on a rock core sample with a length to diameter ratio of 2.0 to 2.5. The sample is placed in a loading device and an axial load is applied to the sample. The load is continuously increased until the specimen fails. The compressive strength is calculated by dividing the failure load by the sample cross-sectional area.

Unconfined compressive strength of the collected samples ranges from 51 Kg/cm^2 to 409 Kg/cm^2which, according to Egyptian code Table 2 reflect Weak to Medium hard bedrock.

3.2. *DC resistivity data acquisition and inversion*

The subsurface geological and geotechnical information was acquired by both drillings and DC resistivity measurements. To avoid random subsurface data measurements, the locations of acquired data were distributed considering the detailed field geology and the ground accessibility. Here, 34 vertical electrical soundings were carried out in the area (Figure 1) using resistivity-meter TERRAMETER SAS 300 C, manufactured by ABEM Co. (Figure 4). Schlumberger array was employed with (AB/2) ranged from100 m to 300 m, which was sufficient to achieve the study purpose. Regarding the dry soil conditions, salt-rich water was added around poor contact electrodes to improve electrical contact with the ground. Towards the DCR ambiguity reduction, the DC resistivity measurements were measured as possible over a straight line calibrated with the available geological/borehole data.

In this work, the quantitative interpretation of field data was constructed using IPI2WIN software (Bobachev 2008), to delineate the resistivity and thicknesses of subsurface layers. This program is based on linear filtering as 1D forward modelling and Newton algorithm of the least number of layers to solve the inverse problem. The results obtained from 1D modelling are illustrated in columns with the same scale, as geoelectric horizons are correlated with the data obtained from boreholes (Figure 5).

4. Results and discussion

Preliminary consideration of the inversion results of DC resistivity soundings with lithology of available

Table 2. Rock classification according to unconfined compressive strength (UCS) ECP – 202/1 (2001).

UCS (Kg/cm^2)	Rock type
≤12.5	Very weak
12.5–50	Weak
50–125	Medium weak
125–500	Medium hard
500–1000	Hard
1000–2000	Very hard
>2000	Extremely hard

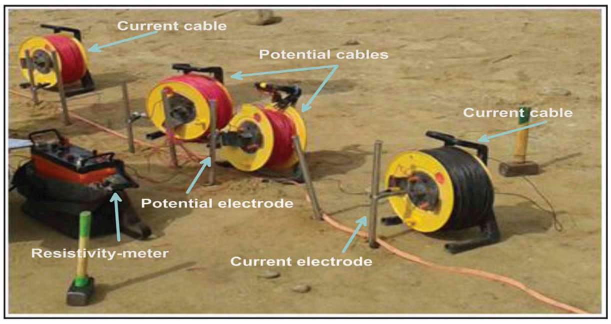

Figure 4. The DC earth resistivity-meter (ABEM-TERRAMETER, SAS 300 C) with accessories during the field measurements.

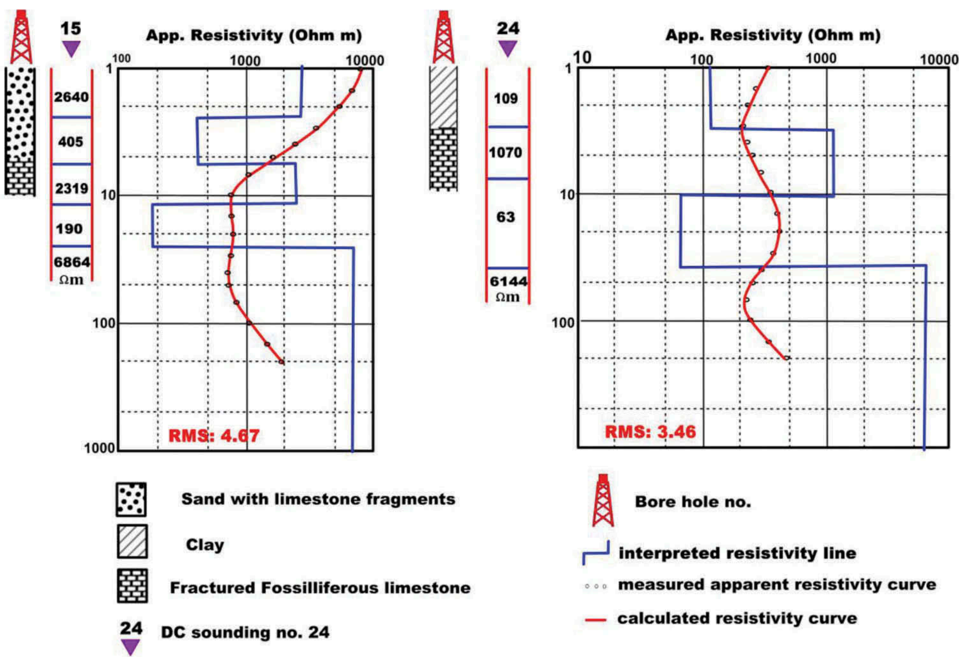

Figure 5. Calibration between the borehole information and interpretation results of sounding 15 and 24 (for location, see Figure 1) using IPI2WIN program (Bobachev 2008).

boreholes established a resistivity range for the subsurface layer distributions. The DC resistivity inversion was carried out to determine the different geoelectrical layers, their depth, thickness and their resistivities. This can help to obtain the lateral and vertical variation of the different geological units. Consequently, the near-surface structures can be deduced by constructing stitched resistivity sections of the interpreted DC resistivity soundings data. Further, in this study, the DC resistivity inversion results were used to predict the UCS and RQD values applying empirical relationships.

The results of DC resistivity data inversion are used to construct four geoelectric sections. These cross-sections are correlated with available boreholes (9 borehole data sets). The geoelectric cross-section of A-A', B-B', C-C' and D-D' together with boreholes location are shown in (Figure 6). Based on such calibration, the subsurface layers can be classified into six geoelectrical layers. The first layer has specific values of resistivity values ranging from 123 to 45,520 Ohm-m and thickness ranges from 0.3 to 5.4 m, which can be attributed to the near-surface layer consisting of dry gravel, sand with some clay and rock fragments. The second geoelectrical

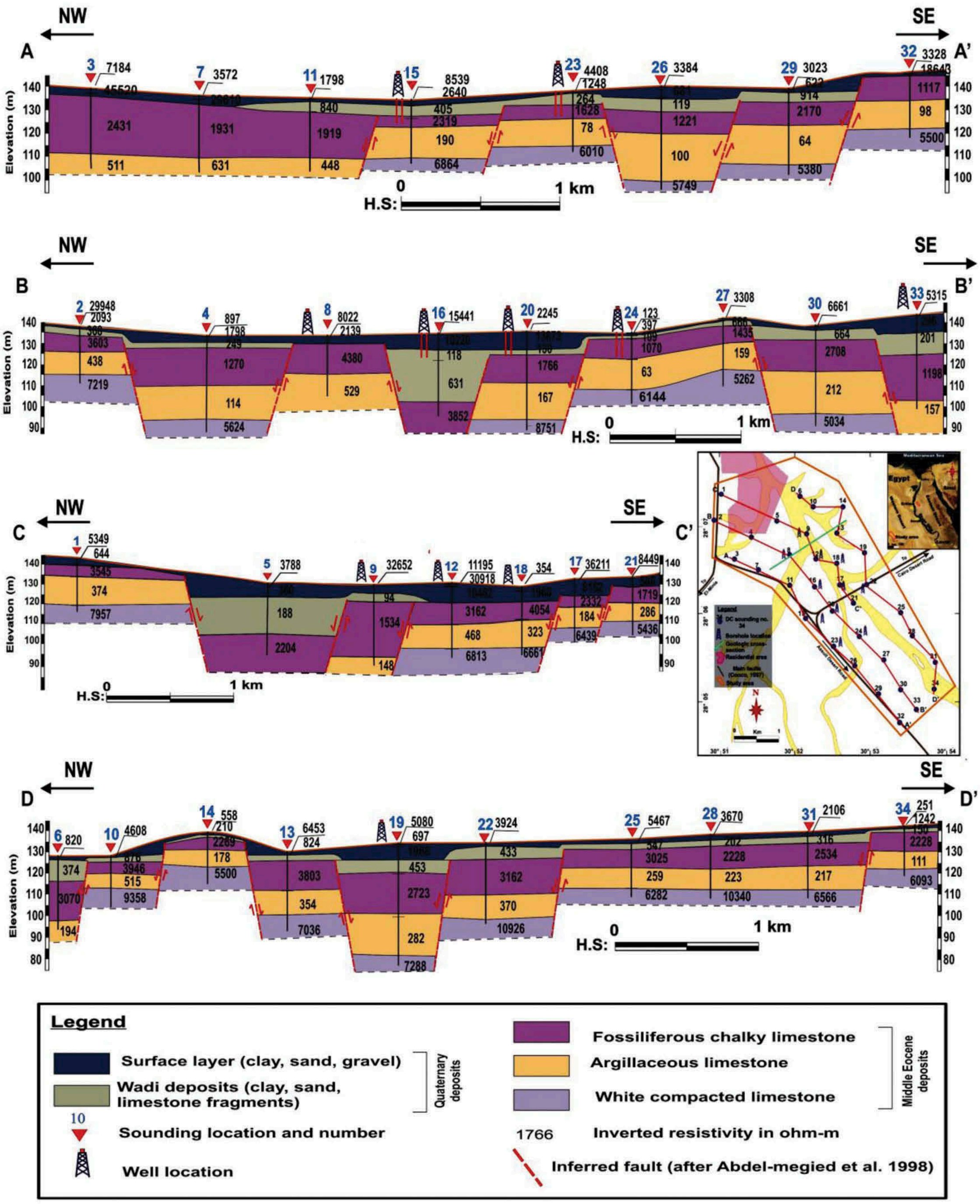

Figure 6. Geoelectric cross-sections A-A', B-B', C-C' and D.

layer resistivities and thickness range from 300 to 900 Ohm-m and 1.3 to 36 m, respectively. This layer can be related to fine to medium clayey sand. The variation in resistivity values can be related to the degree of clay content and rock fragments. The third geoelectrical layer has low to medium resistivity values (77 to 220 Ohm-m) and the layer thickness ranges from 1.4 to 36 m. This layer can be recognized as a sandy clay layer. The fourth geoelectrical layer has resistivity values ranging from 717 to 4380 Ohm-m and the layer thickness ranges from 7.5 to 41.8 m corresponds to the fractured fossiliferous limestone. The fifth geoelectrical layer resistivities range from 41 to 674 Ohm-m and the layer thickness ranges from 14.3 to 36 m referrring to argillaceous limestone. The sixth geoelectrical layer resistivities range from 5436 to 10,926 Ohm-m corresponding to the compact limestone. Structuraly, the geoelectrical layer displacement along the constructed geoelectrical cross-section can be attributed to subsurface faults. It is worth mentioning that the projection of the deduced faults is controlled by the observed surface structures and geological map of the study area (Abdel-Meguid et al. 1998). Figure 7 shows the bedrock depth map over the study site here the depth of rock ranges from 1.2 m at DC sounding no. 32 to 36 m at DC sounding no.16.

The results of interpretation resistivity data and rock characterization tests were analyzed to understand the interrelation between electrical resistivity data and different rock properties such as RQD and UCS. Least-squares regression method was used to evaluate the relation between the different properties of rock samples and electrical resistivity data. Linear curve fitting approximations were applied and the best approximation equation with the highest correlation coefficient was selected.

Relationship between resistivity data and RQD demonstrates a linear correlation with good regression coefficient R^2 = 0.9661 (96.61%) (Figure 8). We observed that the empirical correlation for geotechnical study is RQD = 0.004ρ + 6.7465. Obviously, the inverted resistivity values of subsurface layers increase with increasing RQDof collected rock samples. Furthermore, the intrinsic resistivity values were correlated with the measured UCS of rock samples (Figure 9). Regarding such correlation, it is clear that the UCS can be calculated using a linear relationship

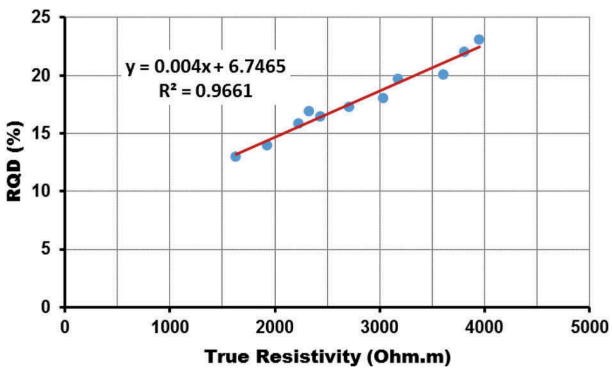

Figure 8. True Resistivity (ohm.m) versus Rock-quality designation (RQD).

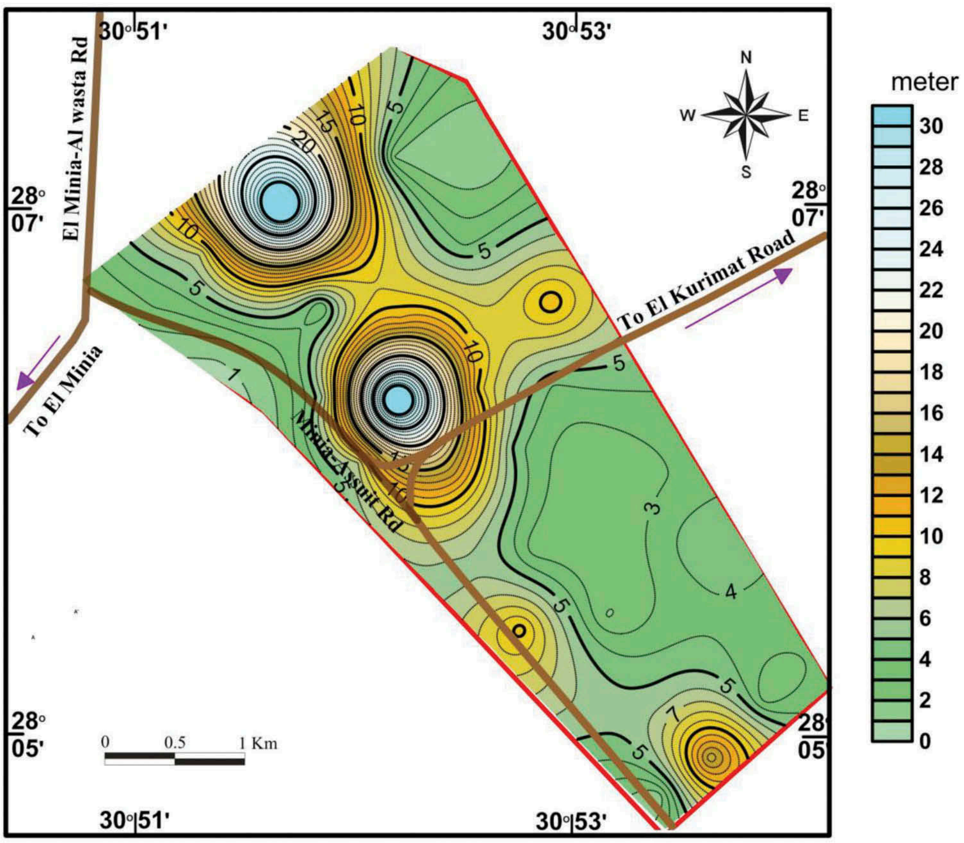

Figure 7. Depth to bedrock contour map of the study area.

(UCS = 0.1493ρ – 155.48) with a correlation coefficient of 0.9803 (98.03%). Regarding the predicted geotechnical parameters, the fractured limestone bedrock in the area can be characterized as very poor to poor and very weak (23 Kg/cm$^{2)}$ to medium hard (375.5 Kg/cm^2). Moreover, the predicted UCS and RQD values are then mapped to characterize the spatial geotechnical properties over the study site (Figures 10 and 11). In general, it can be noticed that both UCS and RQD increase at the northern, southern and eastern parts of the area under investigation.

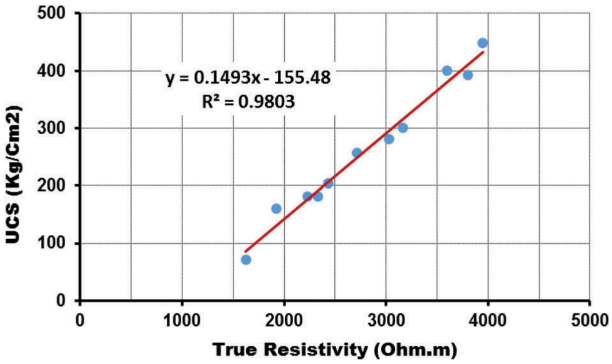

Figure 9. True Resistivity (Ohm.m) versus unconfined compressive strength (UCS).

5. Conclusion

It is worthwhile to point out that the integration of DC resistivity and soil data have been adapted to represent the subsurface layer distributions and the concealed structures in a highly deformed site, i.e. New Minia City. The present study can be applied as preliminary engineering site investigation technique to mitigate the potential hazards through site-specific and urbanization. It was clear that the information coming from DC resistivity inversion results allows depicting the subsurface layers distribution with geoengineering data in low-cost strategy. The DC resistivity soundings show a great potential for large-scale geological surveys, which are required for a preliminary geotechnical assessment. It is of advantage to engineering geologists that they are atten-

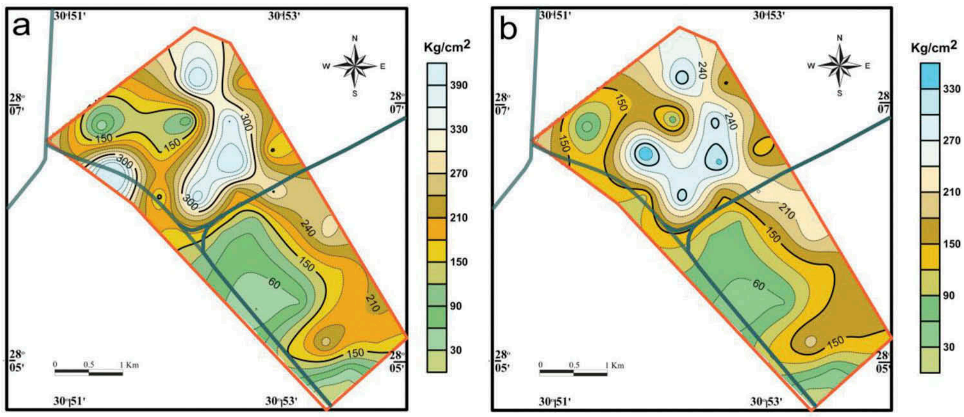

Figure 10. Contour map illustrates (a) The distribution of measured UCS, and (b) The distribution of calculated UCS at the study area.

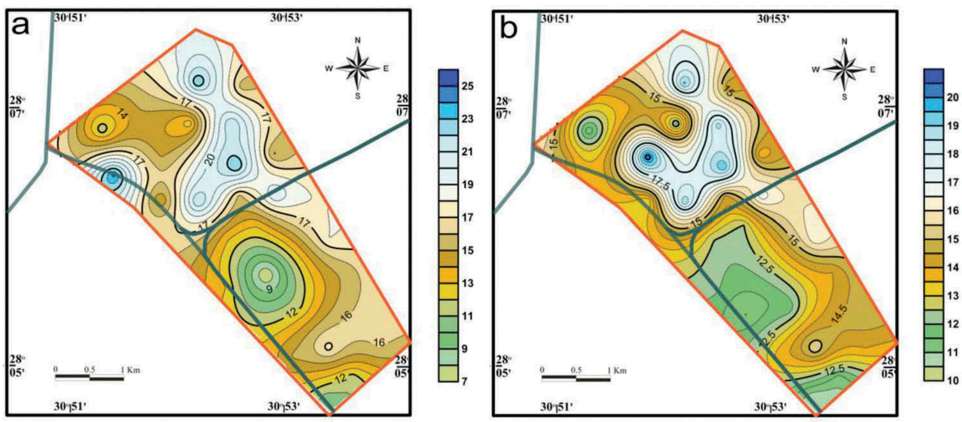

Figure 11. Contour map illustrates (a) The distribution of measured RQD, and (b) The distribution of calculated RQD at the study area.

tive of the geophysical soundings benefit and structural analysis to evaluate a preliminary geotechnical situation particularly when extensive drillings are not available.

It was concluded that the area under investigation is highly fractured (e.g. Normal faults) especially in the presence of limestone rocks. Further, the wadis existence of this site is structurally controlled where the Quaternary deposit thickness is increased. The results contributed to predict geotechnical parameters (RQD and UCS) using the intrinsic resistivity values of bedrocks. The estimation can help to predict the engineering characterizations and DC resistivity of the subsurface material (soils and rocks). Finally, the present study represents a promising approach to evaluate and keep away from future geotechnical difficulties for safe residential site extension in an area prone to natural risks. Accordingly, the present study opens the way for a detailed in-situ geoengineering assessment.

Disclosure statement

There is no potential conflict of interest between authors.

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