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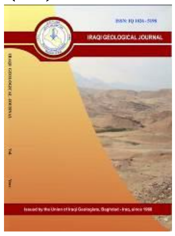

Preconstruction Site Evaluation Using Electrical Resistivity and Geotechnical Investigations in Al-Qasim District, Babylon Governorate, Iraq

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Abstract

This work was conducted by performing resistivity and geotechnical investigations for a transformer electrical station proposed in Al-Qasim District, Babylon Governorate, to assess subsurface conditions and suitability for the station foundation. A total of five Vertical Electrical Soundings employing the Schlumberger array (AB/2=1.5–50 m) and two boreholes (10 m depth) with Standard Penetration Test were executed. The highly dissolved-sulfide groundwater table emerged at ∼a depth of 0.7 m. An indicative compaction and reduced saturation from the surface to a depth of 4 m were noted, with a positive correlation between electrical resistivity (15–90 Ωm) and Standard Penetration Test-N values (10–25). Resistivity decreased significantly below this depth due to the high salinity of the groundwater and the increase in clay content, while Standard Penetration Test-N increased (up to 30), indicating reduced reliability of the resistivity–Standard Penetration Test relationship under saline conditions. The cohesive soil exhibited low activity (PI= 30–41%) and over-consolidated behavior. The allowable bearing capacity ranged from 7.8–11.4 T/m² (dynamic method) to 6.73–9.42 T/m² (static method), and the soil consistency ranged from soft to medium stiff. To minimize compressibility and potential settlement issues, a compacted granular sub-base layer of 1.0–1.5 m thickness is recommended beneath shallow foundations, along with protective measures against sulfate attack.

Keywords: Electrical resistivity; SPT; Bearing capacity; Foundation design; Groundwater salinity; Babylon

1. Introduction

With the increasing demand and urgency of urban development, there is also an increase in failures that can cause structural damage and result in tangible losses. The inaccuracies associated with the design and layout of structures play a major role in such failures. Unknown soil characteristics are among the most important uncertainties that cause design-related failures (Bremmer, 1999). The nonlinear behavior of soils under stress, the difficulty of estimating soil properties in situ, and the high spatial variability of soils and within the soil sector all make it difficult to predict the exact mechanical behavior of soils in space and time. These difficulties require ensuring an adequate safety factor against unforeseen changes that may occur later (Terzaghi et al., 1996).

Various field investigation techniques are employed to assess soil geotechnical properties, including geophysical methods like electrical resistivity sounding and seismic refraction, as well as direct methods such as Standard Penetration Test (SPT) and boreholes (Nassereddine, et al., 2013; Olawale and Michael, 2018; Jaafar et al., 2026). The effectiveness of geophysical surveys depend on their ability to detect significant variations in properties such as elasticity, resistivity, density, and environmental conditions. Electrical resistivity surveys are particularly valuable because of their strong correlation with numerous geotechnical properties, including soil hardness, density, water content, void ratio, salt content, plasticity, and strength, making them increasingly integral to geotechnical investigations (Kibria and Hossain, 2012).

Due to the increasing demand for generating and developing electrical energy fields in Iraq, especially in areas with a shortage of power generation stations, such as the central regions of Iraq, including the current study area, located in Al-Qasim city in Babylon Governorate, central Iraq. Therefore, it is essential to identify the most important geotechnical criteria relevant to the engineering structure, such as foundation depth, the allowable bearing capacity of the soil, and the consolidation parameter (Al-Khalidy et al., 2025). Vertical Electrical Sounding (VES) is a widely used electrical resistivity method for investigating subsurface layering by measuring the variation of apparent resistivity with current electrode spacing. The apparent resistivity of soils is influenced by several geological factors, including water saturation, pore fluid chemistry, porosity, temperature, and mineral composition (Loke et al., 2013). Electrical current propagates through the ground mainly by electrolytic conduction through ion-rich groundwater and, to a lesser extent, by electronic conduction through metallic minerals.

The aims of this research are to determine the relationship between the electrical resistivity data and geotechnical factors for the soils, then to depict the geological effects on the correlation between resistivity data and the SPT method for geotechnical parameter assessments, as well as propose geotechnical parameter estimations using ERD as an alternate tool for subsurface layers.

1.1. Geology and Location of the Study Area

The study area is located in Al-Qasim District, approximately 130 km south of Baghdad, within Babylon Governorate, central Iraq (Fig. 1). The site lies on the Mesopotamian floodplain, consisting of Quaternary alluvial deposits derived primarily from the Tigris and Euphrates rivers (Jassim and Goff, 2006). The topography is relatively flat and dominated by soft fine-grained sediments, including silty clay, clayey silt, and fine sand, often influenced by seasonal flooding and shallow groundwater. The total survey area is about 50 m × 50 m and is situated near the main road leading to the Imam Al-Qasim Shrine (Fig. 1).

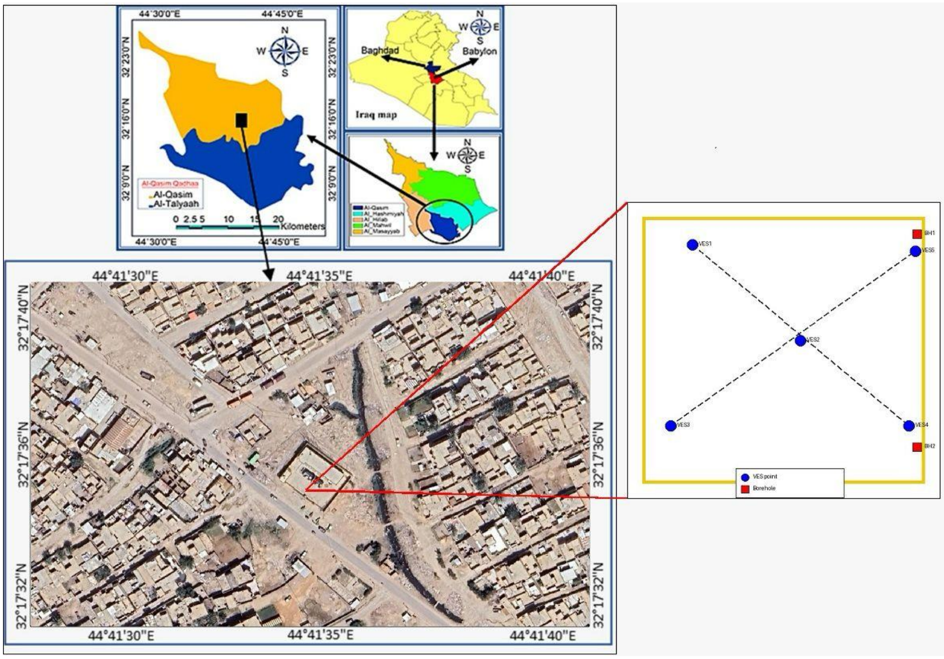

Fig. 1. The satellite image of the investigated site with VES points in the site

2. Materials and Methods

2.1. Vertical Electric Sounding (VES)

In this study, five VES stations (VES1–VES5) were established along a straight profile with 35 m spacing between stations (Fig. 2). Measurements were acquired using the Schlumberger array configuration, with current electrode spacing (AB/2) ranging from 1.5 to 50 m. A resistivity meter (ABEM Tetrameters SAS or equivalent; specify model) was used to inject current through the outer electrodes and measure the resulting potential difference using the inner electrodes.

The measured apparent resistivity data were plotted against electrode spacing on logarithmic scales. Preliminary layer parameters were estimated by curve fitting, followed by inversion modeling using the IPI2WIN software (version 3.5b) to obtain the thickness and resistivity of subsurface layers. The quality of inversion was evaluated using the Root Mean Square (RMS) error to ensure reliable and geologically consistent results.

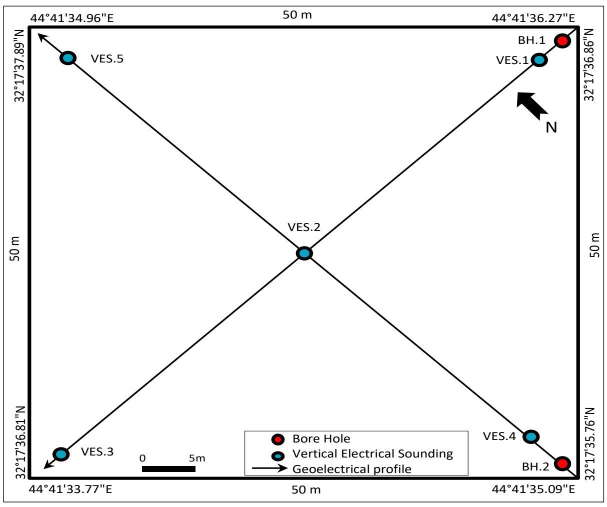

Fig. 2. Map of data acquisition showing the VES points and the Geotechnical borehole sites

2.2. Geotechnical Investigation

The Standard Penetration Test (SPT) is an indispensable in-situ test used to evaluate the ability of soil to resist penetration and to deduce other geotechnical properties such as relative density, consistency, compaction, cohesion, and friction angle. In the Standard Penetration Test (SPT), the measured penetration resistance "N" (also called the SPT blow count) is obtained according to procedure (ASTM, 2022) by counting the number of hammer blows required to drive a standard split-spoon sampler a specified distance into the soil at the bottom of a borehole. After advancing the borehole to the test depth and cleaning the bottom,

A split-spoon sampler is seated at the test depth. The sampler is driven by a standard hammer (commonly 63.5 kg) that falls 760 mm (free fall) onto an anvil. The number of blows is recorded for three consecutive penetration increments, each of 150 mm (total = 450 mm). The measured penetration number is defined as the sum of the blows for the second and third 150-mm increments (i.e., the last 300 mm of penetration), while the first 150 mm is considered "seating."

$$N = N_2 + N_3 \quad (1)$$

Where:

N = measured SPT blow count (blows/300 mm)

N_2 = number of blows for penetration from 150 to 300 mm

N_3 = number of blows for penetration from 300 to 450 mm

(Optionally reported during logging)

N_1 = blows for the first 150 mm (seating drive), usually not included in N.

Thus, the recorded blow sequence is commonly written as:

$N_1 / N_2 / N_3 \Rightarrow N = N_2 + N_3$

The value presented here represents the measured field N-value. Other values, such as N_{60} or $(N_1)_{60}$, are corrected forms (energy, overburden pressure, etc.) and are not equivalent to the basic measured N.

In this work, two boreholes (BH-1 and BH-2) were drilled to a depth of 10 m using a flight auger rig for subsurface investigation at the site, within the anticipated foundation-influence depth as per (ASTM,2020).

Three types of samples were collected:

(i) Disturbed Samples (DS) obtained at 0.5–1.5 m intervals for soil classification,

(ii) Split-spoon samples (SS) from SPT blow counts, and

(iii) Undisturbed Samples (US) obtained at 1.0–2.0 m intervals or whenever a change in lithology occurred(ASTM,2022).

(iv) The test consists of driving a standard split spoon (35mm) in side diameter and (50.8mm) outside diameter through three successive lengths by a (63.3kg) hammer falling freely through a height of (76cm) on the head of the drilled rod connected to the upper of the spoon.

Recovered samples were sealed and transported to the laboratory to preserve natural moisture conditions.

The number of blows required to drive through each of the three 15cm lengths was recorded. Generally, the summation of the number of blows required for the second and third 15cm lengths is taken as the standard penetration.

Groundwater level was recorded 24 hours post-drilling, in accordance with (ASTM, 2021), and was encountered at approximately 0.7 m below ground surface in both boreholes. Chemical analysis of groundwater (Table 1) indicates moderately to highly saline conditions with elevated sulfate concentrations, suggesting potential risks of sulfate attack on reinforced concrete structures.

Table 1. Groundwater table depth

No of BH.	SO_4 ppm	Cl ppm	PH	TSS ppm	Depth (m)
1	1025	59	8.0	1216	0.70
2	1022	58	8.1	1210	0.70

High sulfate concentrations and moderate chloride content in shallow groundwater increase ionic conductivity, which significantly reduces the electrical resistivity of the saturated layers. Therefore, below 4 m deep, where salinity effects predominate, resistivity-based correlations with SPT become questionable. High levels of sulfate ($SO_4 \approx 0.10$–0.12%) and Total Soluble Salts (TSS >1200 ppm) in groundwater, as determined by chemical analysis, greatly enhance electrolytic conduction in soil pores. Thus, the decrease in resistivity values below a depth of 4 m is attributed to groundwater salinity rather than soil density, and increasing clay content in wet soil may also reduce resistivity values. This explains the divergence between resistivity and SPT trends in deeper layers, confirming that geoelectrical parameters must be interpreted cautiously in saline environments.

3. Results

3.1. Resistivity Curves and Geoelectrical Sections

Based on the shape of the resistivity curves, which relate to the variation of resistivity values with depth, these curves were classified into two types. Type HK ($\rho 1 > \rho 2 < \rho 3 > \rho 4$), which was classified based on the presence of four layers, is the dominant type and included all VES points except point VES1, which obtained a Type K curve ($\rho 1 < \rho 2 > \rho 3$) (Fig. 3), The RMS% value during the forward and reverse regression process when interpreting the five VES points ranged from 3.23% at VES4 to 5.27% at VES5. The behavior of the resistivity values in the HK-type curves is represented by the higher resistivity values for the surface layer than for the second layer. These values then increase at the third layer and decrease again at the fourth layer. In order to obtain the geoelectrical sections (an interpretation of the subsurface layers in terms of resistivity values and lithological features), integration was achieved between the resistivity and lithological values derived from the bore holes (Figs. 4 and 5, Table 2). The HK-type responses at VES2–VES5 reflect a heterogeneous subsurface (as revealed by the displacement occurring along parts of the curve when the distance MN/2 is changed to the same distance as AB/2), with alternating sandy-silty and clayey layers affected by groundwater salinity. The decrease in resistivity below 4 m, despite increasing SPT values, confirms that salinity and degree of saturation become dominant in controlling electrical response, rather than soil stiffness alone.

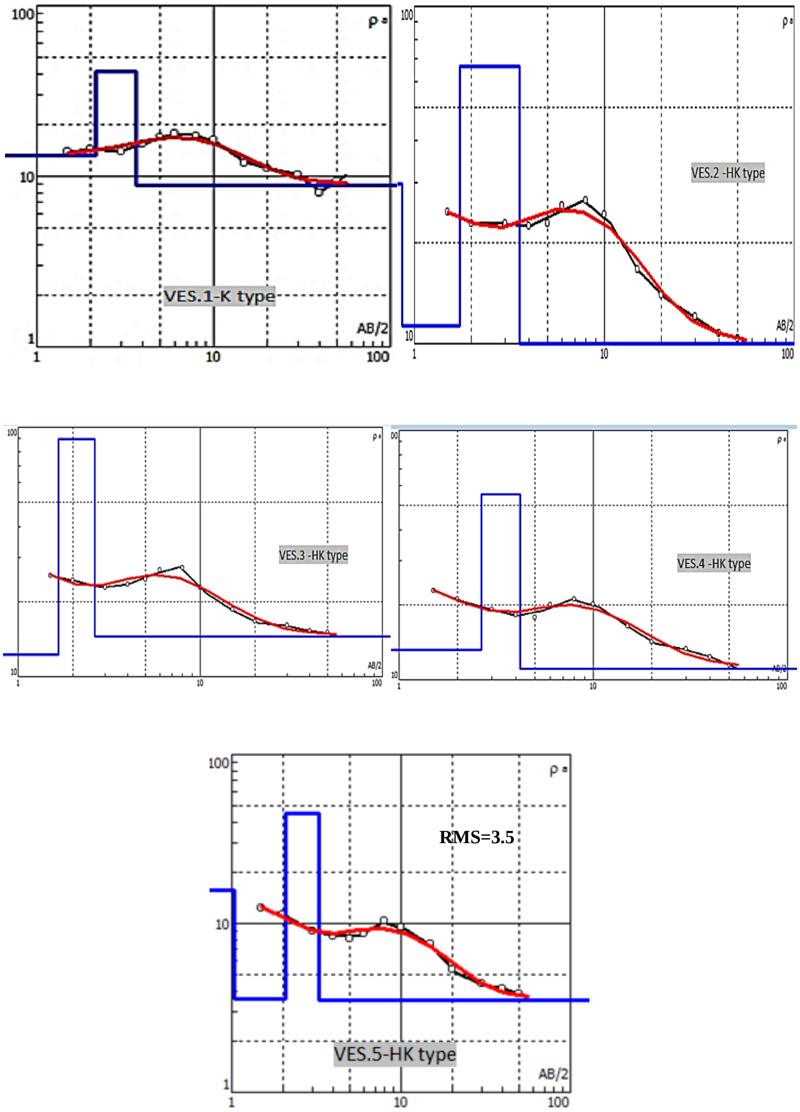

Fig. 3. The VES curve types of the study site

Table 2. The lithological description and the results of electrical resistance and SPT for BH1

Layer	Depth (m)	Lithology	Resistivity (Ωm)	SPT-N
Layer 1	0–2	Surface fill material, mixed loose soil	29.8–32.4	5–10, very weak
Layer 2	2–4	Grayish silty sandy clay	11.2-13.2	10–15, soft to medium stiff
Layer 3	4–7	Brownish sandy silty clay	41–89.8	18–25, medium stiffness to stiff
Layer4	7–10	Silty clay with full saturation	8.9–14.5	20–28, strength increases slightly

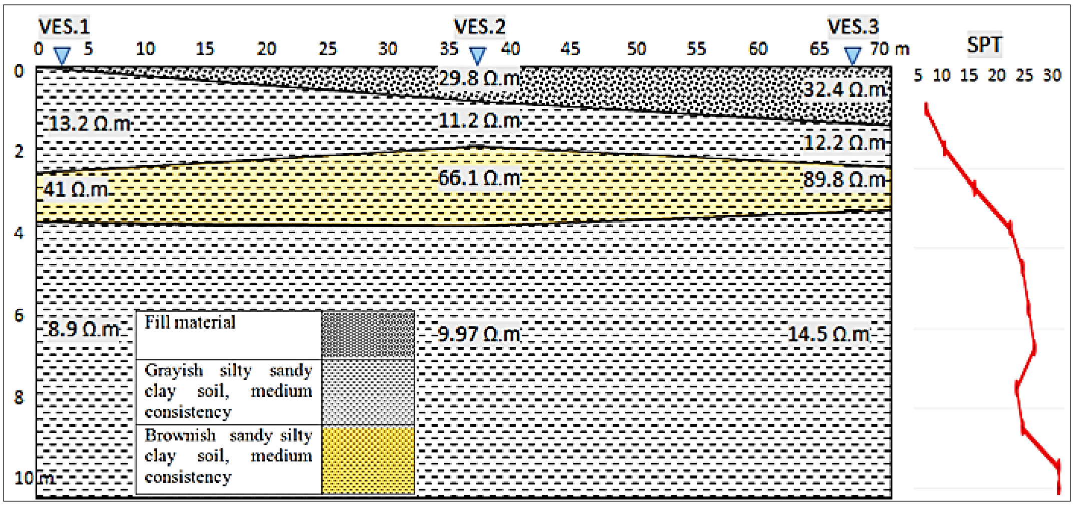

Fig. 4. Geoelectrical section vs SPT for BH.1

Fig. 5 and Table 3 present the integrated geoelectrical section along the VES2–VES5 profile, correlated with SPT values obtained from borehole BH-2. The results reveal four distinct subsurface geoelectrical units with different geotechnical characteristics influenced mainly by groundwater saturation and salinity conditions. The interpretation of each layer is summarized as follows:

Table 3. The lithological description and the results of electrical resistance and SPTfor BH2.

Layer	Depth (m)	Lithology	Resistivity (Ωm)	SPT-N
Layer 1	0–2	Fill material, mixed loose soil	15.7–33.2	5–10, very weak
Layer 2	2–4	Silty sandy clay, moderate saturation	11.2–16.3	10–14, soft to medium stiff
Layer 3	4–6	Brownish sandy silty clay	44.7–66.1	18–23, medium stiff to stiff
Layer 4	>6	Silty clay with full saturation	3.54–9.97	20–28, strength increases slightly

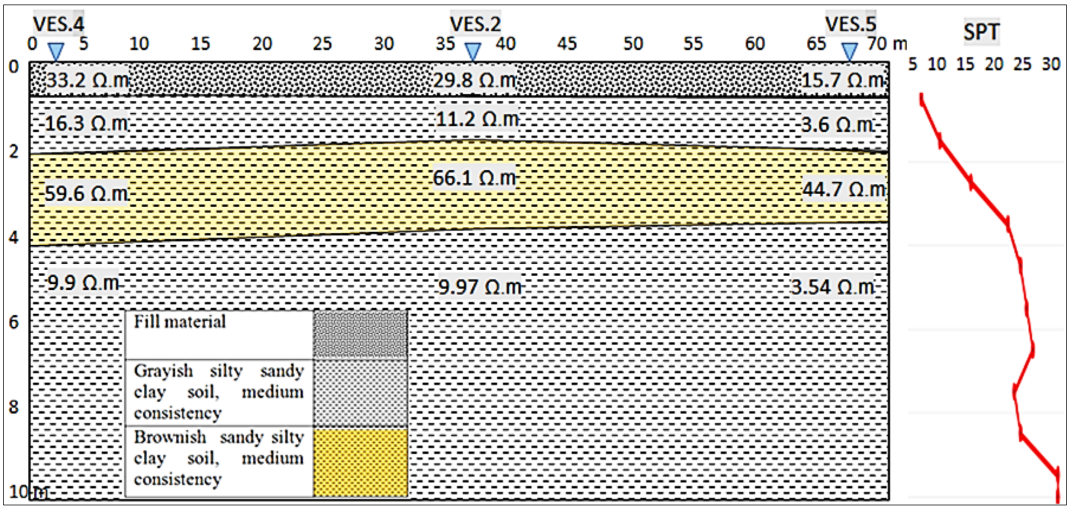

Fig. 5. Geoelectrical section vs SPT for BH.2

3.2. Geotechnical Properties

3.2.1. Soil plasticity

Based on the USCS classification system, the cohesive soils onsite are mostly classified as CL (clays of medium plasticity) and CH (clays of high plasticity); some portions are classified as OL/ML (organic or silt soils of medium to high compressibility), as shown in Table 4. Such cohesive soils have a substantial range of plasticity. The average Plasticity Index-to-clay content ratio (PI/Clay) ranges from 0.50 to 0.60, indicating low clay activity according to ASTM standards. Therefore, these soils are expected to exhibit low swelling potential. Moreover, the measured natural moisture contents are generally closer to the Plastic Limit (PL) than to the Liquid Limit (LL), suggesting that the cohesive layers are over-consolidated, likely due to previous desiccation or stress history. Plasticity Index ranging from 30% to 41% and Linear shrinkage values ranging from 11.0% to 15.0% indicate that the soil may still experience noticeable shrink–swell behavior in the upper layers, although not at a critical level.

Table 4. Grain size and Plasticity properties.

B.H. No	Depth (m)	System of classification				Properties index		
		Clay %	Silt %	Sand %	Grave.%	PL %	LL %	PI %
1	2.5-3	53	22	25	0	17.0	51.0	34.0
	8.5-9	65	20	15	0	21.0	61.0	40.0
2	5-5.5	57	17	26	0	20.0	51.0	30.0
	9.5-10	64	21	15	0	18.0	59.0	41.0

3.2.2. Bearing capacity by dynamic method

The allowable bearing capacity of the soil determined using the in-site N-SPT method for depths between 2-9.5 m ranges from (7.8-11.4) T/m² at all boreholes. This capacity was calculated using the Meyerhof (1963) formula, which is suitable for cohesionless soil for (25mm) of settlement (Fig. 6).

$$qult = \frac{N}{0.08}\left[\frac{(B+0.3)}{B}\right]^2\left(\frac{1+0.33Df}{B}\right) \quad (2)$$

Where:

qult: The ultimate bearing capacity

N: SPT resistance in blows/300 mm

B: footing width in meters

Df = depth of foundation

3.2.3. Bearing capacity by static method

The laboratory results were conducted in accordance with ASTM standards, using the Terzaghi equation with the modification suggested by Meyerhof 1963.

$$q_{ult} = C\,N_c + q\,N_q + 0.5B\gamma N\gamma \qquad \text{continuous footing} \quad (3)$$

$$qult = 1.3CNc + q\,Nq + 0.4\gamma BN\gamma \qquad \text{square footing} \quad (4)$$

$$qult = 1.3CNc + q\,Nq + 0.3\gamma BN\gamma \qquad \text{round footing} \quad (5)$$

$q_{ult}= C\ Nc\ Sc\ dc + q\ Nq\ Sq\ dq + 0.5\gamma\ B\ N\gamma\ S\gamma\ d\gamma$ (Meyerhof, 1963) , (6)

q_{ult} : Ultimate Bearing Capacity, B: Width of footing, C: Cohesion, γ: Unit weight of soil, Nc: Bearing capacity factor for cohesion, q: Effective overburden pressure

Nc ,Nq, N γ Bearing capacity factor

Sc, Sq ,S γ Shape factors

dc , dq , d γ Depth factors

Table 5 indicates that the consistency of the cohesive soil layer is soft to medium-stiff. These results indicate the foundation's bearing capacity, as shown in Table 6.

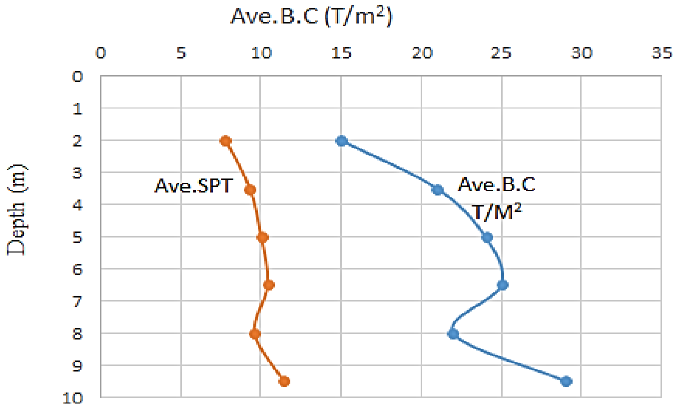

Fig. 6. Average Bearing capacity from N-SPT for 300mm for two boreholes

Table 5. Strength parameters, unconfined and triaxial test, and direct shear test results with depth.

BH.NO	Depth m	Triaxial test		Direct shear test		γ wet gm/cm³	γ dry gm/cm³	Qu T/m²
		Un draine Cu T/m²	Un drained ϕu	Drained C T/m²	Drained Ø			
BH.1	2.5-3	2.47	9	-	-	1.83	1.44	4.90
=	5.5-6	3.53	9	-	-	1.84	1.47	7.12
=	8.5-9	3.30	6	-	-	1.83	1.47	6.70
BH.2	2-2.5	3.16	8	-	-	1.84	1.45	6.34
=	5-5.5	3.60	9	-	-	1.84	1.48	7.28
=	8-8.5	3.88	6	-	-	1.85	1.51	7.73

Table 6. The allowable bearing capacity for the foundation

Df = the depth of foundation (m)	allowable bearing capacity T/m²
(1.0) m	(6.73) T/m²
(2.0) m	(8.10) T/m²
(3.0) m	(9.42) T/m²

3.2.4.Settlement

Based on the allowable bearing capacity values derived for the proposed shallow foundation, the applied structural loads must not induce settlements exceeding the permissible limit of 5.0 cm for serviceability (Das, 2016). The consolidation test results shown in Table (7) provide the variation of overburden pressure (Po) and reconsolidation pressure (Pc) with depth. The calculated ratio (Pc > Po) confirms that the cohesive soil layer is over-consolidated, which reduces the likelihood of excessive post-construction settlement. Primary consolidation settlement was evaluated using standard one-dimensional consolidation theory (Terzaghi's method), considering soil compressibility parameters (Cc, Cr, and e0). The estimated settlement for foundations placed at depths of 2–3 m is expected to remain below the allowable limit (≤ 5.0 cm), provided that proper compaction and a well-graded granular sub-base layer are required beneath the foundation. Therefore, the settlement behavior is anticipated to be acceptable for the required structural performance of the electrical station.

Table 7. Consolidation parameters with depth

No of BH	Depth m	Consolidation test				
		e0	**Cc**	**Cr**	**Po T/m^2**	**Pc T/m^2**
BH.1	2.5-3	0.752	0.154	0.033	4.49	11.5
BH.2	5-5.5	0.714	0.183	0.024	10.12	14.0

The consolidation data show that the cohesive soils are over-consolidated, with both borehole OCR values for these areas ranging from 1.38 to 2.56. A mild compressibility is implied by the comparatively low compression index (Cc < 0.18) and recompression index (Cr ≤ 0.033), suggesting that post-construction consolidation settlement will likely remain within allowable limits. The over-consolidated state improves soil stiffness and bearing capacity for the planned electrical station foundations by indicating a prior stress history likely related to erosion or desiccation. As long as the applied stresses remain below the reconsolidation pressure and appropriate sub-base improvement is implemented, the clay layers are suitable for shallow foundation construction.

4. Chemical Tests

The chemical composition of the soil samples taken from boreholes BH-1 and BH-2 at varying depths is shown in Table 8. The results reveal significant variations in Total Soluble Salts (TSS), Gypsum content % (Gyp.), and sulfate content % (SO_4), which influence the concrete foundation's durability and electrical resistivity with the surrounding soil.

4.1. Sulfates (SO_4%)

Higher levels are seen at deeper depths, suggesting more aggressive chemical conditions in saturated zones. The sulfate content varies from 0.39% to 1.16%. Sulfates cause concrete to expand, crack, and lose strength through sulfate attack. According to ACI and BS limitations, it is categorized as extremely aggressive. Type V sulfate-resistant Portland cement and a protective coating for subterranean concrete surfaces are prerequisites.

4.2. Gypsum Content (Gyp. %)

At deeper levels, gypsum rises from 1.51% close to the surface to 5.18%. shows that the soil matrix contains active sulfate minerals. Under extended soaking, there may be volume changes and a reduction in soil strength. contributes to the low electrical resistivity of the deeper layers (as seen in VES inversion).

4.3. Total Soluble Salts (TSS%)

With depth, TSS levels progressively rise from 3.90% to 8.35%. Deeper layers have lower resistivity values due to increased electrolytic conduction. increases the likelihood that steel reinforcement may corrode. The significant discrepancy between resistivity and SPT readings below 4 m can be explained by this.

4.4. Chlorides (Cl%)

The chloride content range of 0.031% to 0.059% is sufficient to accelerate reinforcing steel corrosion, particularly in saturated areas, and to reduce resistance levels as conductivity increases.

4.5. pH

pH values range 7.9–8.1 → slightly alkaline. This does not neutralize the risks posed by sulfate and chloride.

Table 8. Chemical soil tests

No. of BH	Depth (m)	SO4 (%)	Gyp. (%)	TSS (%)	CaCO3 (%)	PH %	Cl%
BH.1	1.5-2	0.39	1.51	3.90	12.0	8.0	0.059
=	3.5-4	0.58	2.73	4.31	14.0	8.0	0.054
=	5.5-6	0.71	4.60	6.42	17.0	8.0	0.046
=	7.5-8	0.98	3.72	5.60	18.0	7.9	0.037
BH.2	8-8.5	1.03	3.26	6.24	21.0	8.1	0.031
=	9-9.5	1.16	5.18	8.35	23.0	-	-

The aggressive geochemical environment, mainly composed of sulfates and dissolved salts, confirms that resistivity values are lowered, and long-term protective measures for the concrete and foundations are necessary for durability.

5. Discussion

Soil layer materials have different electrical resistivities due to variations in texture, saturation, porosity, salinity, and dissolved ions (Zonge, 1972; Utset and Castellanos, 1999). These attributes also influence the engineering characteristics, compressibility, and stiffness of the soil (Carroll and Oliver, 2005). From the study, the major reason the resistivity decreases significantly below 4 m depth, and continues to do so with increasing SPT-N values, suggests that the overriding factors are groundwater salinity and full saturation. This demonstrates that under high-sulfate and high-TSS conditions, electrical resistivity does not necessarily correlate with soil strength. Therefore, resistivity-based geotechnical predictions in saline clayey environments must be interpreted with caution and supported by direct testing, such as SPT and consolidation tests, for reliable foundation design. Consider that, generally, the clay content increases with depth, which will lower the resistivity value as well.

5.1. Correlation between the Geotechnical Test and the Soil Resistivity Test Results

To evaluate the relationship between electrical resistivity and geotechnical parameters, resistivity profiles were compared with SPT results and lithology data from boreholes. From the surface to a depth of around 4 m, resistivity values correlate positively with SPT-N values, suggesting that soil strength increases as saturation decreases and sand content increases. Soil stiffness increases naturally with depth until about 4 m, after which the relationship begins to weaken. Resistivity begins to drop significantly at a depth of 10 m. Meanwhile, the SPT-N values are increasing to 30. This suggests that, unlike soil stiffness, groundwater salinity and saturation are the dominant factors in changes in electrical resistivity. The factor responsible for the discrepancy in this relationship is water saturation, specifically, the quality of groundwater, not its quantity, many studies have indicated that groundwater quality plays a significant role in influencing resistivity values, even when subsurface materials remain unchanged (Griffiths and King,1981; Loke, 2000; Frohlich and Urish, 2002; Al-Musawi and Khorshid, 2013; Thabit and Khalid, 2016 and Mohammed, et al., 2025).

Although there is no consistent linear relationship between resistivity values and geotechnical parameters in the present study, studying the behavior of resistivity with these parameters is of significant benefit in geotechnical investigations, as many studies have shown a relationship between resistivity values and the angle of friction (Siddiqui and Osman, 2013; Boobalan and Ramanujam, 2015; Osman et al., 2016), a negative relationship has been mentioned in clayey sand (Bery and Saad, 2012), while a positive relationship has been mentioned by Razali and Osman, 2011and Qazi et al., (2016).

Chemical analyses of groundwater showed that it contained high amounts of sulfates. This is a logical result because the selected site is located within an area densely populated with residential houses that rely on many river streams to drain their water for human use. Regardless of soil density, the chemical tests verified high levels of gypsum, total soluble salts, and sulfates, which greatly improve electrical conduction in pore water and lower resistivity. Therefore, electrical resistivity alone cannot be utilized as a measure of soil bearing capacity in saline clayey situations.

The main problem that could be encountered during and after constructing the project is the fluctuation of water table that causes variations in porewater chemistry of soil layers, such as gypsum and total soluble salts. It is important to note, even though the electrical resistivity and SPT-N values may both reveal consistent variations and coherent trend (Rafique et al. 2025), there have been still caution of employing this correlation seeking the bearing capacity of soil layer. As demonstrated, the electrical resistivity is signifcanlty impacted by porewater chemistry, while SPT-N values are affected by mechanical stiffening/densification with depth. Therefore, to approach reliable subsurface characterization, SPT-N and geoelectrical measurments should be integrated with large dataset.

5.2. Proposed Foundation

The type and functioning of a structure’s foundation system are integral to its proposed form. The proposed shallow foundations will also be the best option for the planned electricity station, based on subsurface soil conditions, geotechnical parameters, load requirements, and the findings of the current study. With a factor of safety of 3, spread, strip, and raft foundations positioned 1.0 m below the current ground level can be safely supported by a net permitted soil bearing pressure of roughly 6.73 T/m², according to allowable bearing capacity values calculated using the static technique. It is anticipated that this applied pressure will keep the resulting stresses within the soil's elastic range.

Underneath the foundation, a granular sub-base layer about 1.5 m thick should be used to improve bearing conditions, facilitate load transfer, and reduce settlement. Based on assessments of the settlement of typical footings, the overall elastic settlement will remain within the permitted upper bound of 5.0 cm with proper design and construction methods. In accordance with the estimated serviceability requirements for the envisaged structures, the forecasted differential settlement is anticipated to be less than 50% of the total settlement. Table (9) summarizes the geotechnical input parameters used for foundation analysis and settlement computations, including the coefficient of subgrade reaction obtained from the empirical relationship:

$$Ks = 40 \cdot \mathrm{SF} \cdot \mathrm{qa} \quad 7)$$

Where Ks is the coefficient of subgrade reaction, SF is a soil flexibility factor, and qa is the allowable bearing capacity. Therefore, shallow foundations with adequate rigidity and proper sub-base treatment are deemed suitable and safe for supporting the anticipated structural loads at the site.

Table 9. Required parameter Modulus Ks

Depth (m)	qa(kN/m^2)	Modulus of subgrade reaction, Ks
1.0	67.3	8076
2.0	81.0	9720
3.0	94.2	11304

6. Conclusions

- This study integrated electrical resistivity surveying with geotechnical investigations to evaluate the subsurface conditions at the proposed electrical station site in Al-Qasim District, Babylon Governorate. The soil profile generally consists of fine sand, silt, and clay to a depth of at least 10 m, representing the alluvial deposits of the Mesopotamian floodplain.
- The resulting salinity and groundwater influence variability probably explains the vertical variability in resistivity. From the surface to about 4 m depth, there was a consistent increase in SPT-N value and resistivity, consistent with the increase in SPT-N. Below 4 m, the diminishing resistivity was likely due to saline groundwater, full saturation, alignment of salt groundwater with dominantly unsaturated pores, and increasing clay content with depth.
- The chemistry of the pore water and the saline groundwater subordinated the stiff clay to the overburden pressure. Results from consolidating the soft and stiff clays with a PI range of 0.50–0.60 towards 0, with consolidation and consolidation stress ratios exceeding 1, provide indirect evidence that it will limit long-term settlement. The evaluated settlement confirms that there is more than enough compacted granular sub-base to support shallow foundations, with settlement to 5.0 cm. The groundwater and soil chemistry indicated elevated levels of sulfates, total soluble salts, and gypsum, creating a potentially aggressive chemical environment for reinforced concrete. This may lower the electrical resistivity due to poor management of structural element deterioration based on static method estimates.
- The net allowable bearing capacities at 1.0, 2.0, and 3.0 m depths were 6.73 T/m^2, 8.10 T/m^2, and 9.42 T/m^2, respectively. These results enable the design of spread, strip, and raft foundations with adequate stiffness for the proposed structures. In general, the combined approach of geophysics and geotechnical studies is the most reliable for assessing subsurface structure in areas where the hydro-chemical regime predominantly influences geoelectrical properties. Therefore, this integrated approach can be applied to analogous areas with shallow groundwater and soils with salinity and structural inconsistencies.

Author contributions: CRediT

Corresponding authors are required to acknowledge co-author contributions using CRediT (Contributor Roles Taxonomy) roles:

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- Data curation : Iman M. Jaafar
- Formal analysis: Iman M. Jaafar
- Investigation : Amer A. Alkhaldy, Mohammed Ali Haiwe
- Methodology : Yasmin Ibrahim Khalf, Mohammed Ali Haiwe

- Project administration: Amer A. Alkhaldy
- Resources : Yasmin Ibrahim Khalf
- Software : Al-Mosawi Walaa M.
- Supervision : Amer A. Alkhaldy
- Validation : Iman M. Jaafar, Al-Mosawi Walaa M., Amer A. Alkhaldy,
- Writing – original draft : Al-Mosawi Walaa M.
- Writing – review and editing: Iman M. Jaafar

Declaration of Competing Interest

The authors declare both: (Iman M. Jaafar, Al-Mosawi Walaa M., Yasmin Ibrahim Khalf , Amer A. Alkhaldy and Mohammed Ali Haiwe) that we do not have no competing financial interests or personal relationships that could influence the work reported in this study.

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Data Availability

The data used in this study were obtained from a third party and are not publicly available.

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