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Electrical Resistivity as a Supplementary Site Characterisation Tool Within an Integrated Geotechnical Investigation Framework for Calcareous Desert Deposits

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Abstract

Calcareous desert deposits present significant challenges for geotechnical site characterisation because of their heterogeneous composition, variable carbonate cementation, and complex mechanical behaviour. This study investigates the practical engineering value of electrical resistivity as a supplementary site characterisation tool within an integrated geotechnical investigation framework at the Shagaya area , Kuwait. An integrated geotechnical–geophysical investigation was conducted to evaluate the engineering significance of electrical resistivity in characterising heterogeneous calcareous desert deposits. The results indicate that the site is predominantly underlain by medium-dense to very dense calcareous sandy deposits exhibiting substantial variability in density, fines content, carbonate cementation, penetration resistance, and foundation stiffness. Standard penetration test (SPT) N-values ranged from 10 to 84, CPT cone resistance values ranged from 15 to 27.5 MPa, and PLT-derived modulus of subgrade reaction (Ks) values ranged from 24.3 to 210.3 MN/m^3, demonstrating considerable spatial variability in engineering behaviour. Electrical resistivity values ranged from 57.2 to 271.9 Ω·m and consistently reflected variations in density, carbonate cementation, and foundation stiffness identified from conventional geotechnical testing. Higher resistivity values generally corresponded to denser, more strongly cemented deposits, whereas lower values were associated with finer-grained or less cemented materials. Unlike previous studies that focused on developing empirical resistivity-based correlations, this research evaluates electrical resistivity as a complementary investigation tool integrated with conventional geotechnical methods. Rather than developing site-specific predictive relationships, resistivity measurements were interpreted alongside borehole, laboratory, SPT, CPT, and PLT data to improve the understanding of subsurface variability. Instead, resistivity measurements are interpreted alongside borehole, laboratory, SPT, CPT, and PLT data to improve the understanding of subsurface variability and support engineering judgement. The proposed integrated geotechnical–geophysical framework enhances site characterisation, reduces uncertainty, and provides practical guidance for foundation investigations in heterogeneous calcareous deposits and large-scale renewable energy infrastructure projects in arid environments.

Keywords: electrical resistivity; integrated geotechnical–geophysical investigation; calcareous desert deposits; foundation stiffness; modulus of subgrade reaction (Ks); plate load test (PLT); cone penetration test (CPT); carbonate cementation; spatial variability; renewable energy infrastructure; arid-region geotechnics; Kuwait

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1. Introduction

The rapid expansion of large-scale mega projects in arid regions has increased demand for reliable geotechnical site characterisation methods that support the design of access roads, equipment foundations, electrical substations, and associated infrastructure. In desert environments, foundation performance is strongly influenced by the spatial variability of subsurface conditions, particularly in calcareous soil deposits that commonly exhibit heterogeneous composition, variable cementation, and complex mechanical behaviour.

Accurate characterisation of these deposits is therefore essential for evaluating bearing capacity, settlement behaviour, and foundation stiffness during the design and construction of renewable energy developments. Calcareous desert deposits are widespread throughout the Arabian Gulf region and consist primarily of carbonate-rich sands, sandy silts, and weakly to strongly cemented soil horizons [1]. These deposits exhibit crushing, cementation effects, and high variability in density and structure [2,3].

Consequently, directly applying empirical geotechnical correlations developed for siliceous soils may introduce significant uncertainty when assessing the engineering properties of calcareous deposits [4,5]. Unlike conventional quartz-dominated sands, calcareous soils exhibit unique engineering characteristics resulting from their carbonate mineralogy and susceptibility to particle. This challenge has prompted increasing interest in developing site-specific characterisation methodologies that integrate multiple investigation techniques and datasets [6,7].

Traditional geotechnical investigations typically rely on borehole drilling, laboratory testing, standard penetration tests (SPTs), cone penetration tests (CPTs), and plate load tests (PLTs) to evaluate subsurface conditions and derive design parameters [8,9]. Among available field-testing methods, plate load tests provide one of the most direct assessments of foundation response and modulus of subgrade reaction and are therefore particularly valuable for evaluating the stiffness characteristics of calcareous deposits supporting shallow foundations. These methods provide valuable information regarding soil stratigraphy, density, shear strength, compressibility, and stiffness [10]. However, because boreholes and in situ tests represent discrete sampling locations, they may not fully capture lateral variations in subsurface conditions across large project sites [11,12]. For large-scale developments spanning several square kilometres, integrating supplementary characterisation techniques may improve confidence in geological and geotechnical interpretations [11,13]. Among available geophysical techniques, electrical resistivity surveys have gained increasing attention because of their rapid deployment, non-destructive nature, and ability to provide continuous spatial information [14,15].

Several factors influence electrical resistivity, including soil type, moisture content, density, degree of saturation, pore-water chemistry, and cementation. Variations in resistivity can therefore reflect changes in subsurface materials and may provide useful insights into geological heterogeneity [16,17]. Researchers have widely applied electrical resistivity methods in groundwater investigations, environmental studies, engineering geology, and subsurface characterisation [11,17]. Recent studies have demonstrated the growing value of electrical resistivity and electrical resistivity tomography (ERT) as non-destructive tools for geotechnical site assessment, soil classification, groundwater identification, slope investigation, and infrastructure characterisation [18–21]. Integrated geotechnical–geophysical approaches have shown considerable potential to improve subsurface interpretation by combining resistivity measurements with conventional site investigation data, enhancing spatial understanding of subsurface variability and reducing uncertainty associated with discrete sampling locations. However, their application to calcareous desert deposits remains relatively limited, particularly in arid environments where natural cementation and geological heterogeneity significantly influence engineering behaviour.

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Previous studies have often attempted to establish direct correlations between electrical resistivity and geotechnical parameters such as SPT-N values, cone resistance, density, or shear strength [22]. However, many published correlations are highly site-specific and strongly dependent on local geology, moisture conditions, soil composition, and testing methodology [14,17]. Consequently, the transferability of such empirical relationships between different sites is often limited [11]. Furthermore, reliable statistical correlations generally require large datasets containing numerous paired geophysical and geotechnical observations [23]. In practice, many engineering investigations include only a limited number of resistivity measurements, which may restrict the development of robust predictive models [11,17]. Although electrical resistivity methods have become increasingly popular for geotechnical site characterisation, significant research gaps remain in their practical application to calcareous desert deposits. Most published studies have primarily focused on developing direct empirical correlations between resistivity and isolated geotechnical parameters such as SPT-N values, cone resistance, density, or soil strength [22]. Recent review studies have highlighted that, although resistivity-based correlations can provide useful preliminary estimates of geotechnical properties, their performance remains strongly dependent on soil type, moisture conditions, geological setting, density, and environmental factors, thereby limiting their transferability between different sites and soil deposits [23,24]. Consequently, relatively few studies have examined the practical role of electrical resistivity as a supplementary site characterisation tool within an integrated investigation framework combining boreholes, laboratory testing, SPT, CPT, and plate load tests. This limitation is particularly evident for calcareous desert deposits, where subsurface heterogeneity, variable cementation, and site-specific geological conditions often reduce the reliability and transferability of empirical predictive relationships. Furthermore, published studies integrating electrical resistivity measurements with field-derived foundation stiffness indicators, such as the modulus of subgrade reaction obtained from plate load tests, remain scarce. For this reason, electrical resistivity should not always be viewed as a substitute for conventional geotechnical investigations. More recently, artificial intelligence and machine-learning approaches have been applied to explore resistivity–geotechnical relationships; however, these studies continue to rely on site-specific datasets and predictive modelling frameworks, highlighting the need for practical interpretation approaches that can support engineering decision-making during site investigations [25]. Instead, resistivity surveys can complement and enhance interpretations from boreholes, CPTs, laboratory testing, and plate load testing. Within an integrated investigation framework, geophysical data can help identify zones of differing density, cementation, or material composition and improve understanding of subsurface variability over large areas. Table 1 compares previous studies with the present research.

This study examines the role of electrical resistivity as a supplementary site characterisation tool within a comprehensive geotechnical investigation for the Shagaya Renewable Energy Project, Kuwait. The project site was investigated using an extensive database comprising approximately fifty boreholes, laboratory testing, plate load tests, multiple cone penetration tests, and six electrical resistivity survey locations. The available geotechnical data indicate predominantly calcareous desert deposits with varying density, carbonate content, and engineering behaviour.

Unlike previous studies that primarily focused on developing empirical correlations between electrical resistivity and individual geotechnical parameters, this study evaluates the practical use of electrical resistivity as a supplementary site characterisation tool within an integrated geotechnical investigation framework. The investigation combines data from 50 boreholes, 10 CPT soundings, 19 plate load tests, laboratory testing, and six electrical resistivity survey locations. Rather than developing site-specific predictive equations, the study demonstrates how resistivity measurements can be interpreted alongside

conventional geotechnical data to improve understanding of subsurface variability and foundation-related engineering behaviour in heterogeneous calcareous desert deposits.

Figure 1 presents the integrated geotechnical–geophysical framework adopted in this study to characterise calcareous desert deposits and support foundation assessment. Accordingly, the objectives of this study are to: (i) characterise the engineering behaviour and spatial variability of calcareous desert deposits using integrated geotechnical investigations; (ii) evaluate the usefulness of electrical resistivity measurements as a supplementary site characterisation tool; (iii) investigate the relationship between geophysical observations and geotechnical indicators of soil stiffness and density; and (iv) develop an integrated geotechnical–geophysical framework applicable to large-scale renewable energy infrastructure projects in arid environments. The findings are expected to provide useful guidance for future renewable energy projects in arid regions, where efficient site characterisation is essential to minimise geotechnical uncertainty while optimising site investigation programmes. Furthermore, the study contributes to the growing body of knowledge on the engineering behaviour of calcareous desert soils and highlights the benefits of combining geotechnical and geophysical techniques within a unified site characterisation framework. The principal contribution of this study is the demonstration of an integrated geotechnical–geophysical interpretation framework for foundation investigations in calcareous desert deposits, rather than the development of new resistivity-based predictive correlations.

Table 1. Comparison of previous studies and the present research on the application of electrical resistivity in geotechnical site characterisation.

Reference	Soil Type	Geotechnical Data	Resistivity Application	Main Objective	Novel Contribution
[12]	Tropical clayey sand	Laboratory tests	Resistivity correlation	Empirical correlations	Correlations between soil properties and resistivity
[18]	Residual soils	SPT + GPR + Resistivity	Site characterisation	Water content estimation	Integrated geophysical approach
[19]	Various soils	Geotechnical database	Machine learning	Property prediction	AI-based resistivity prediction
[24]	Review study	Literature data	Correlation review	Evaluation of published correlations	State-of-the-art review
Present study	Calcareous desert deposits (Kuwait)	50 BH, 10 CPT, 19 PLT, laboratory tests	Electrical resistivity as a supplementary investigation tool	Integrated site characterisation	Integration of borehole, SPT, CPT, PLT, and electrical resistivity data within a unified framework for assessing foundation stiffness

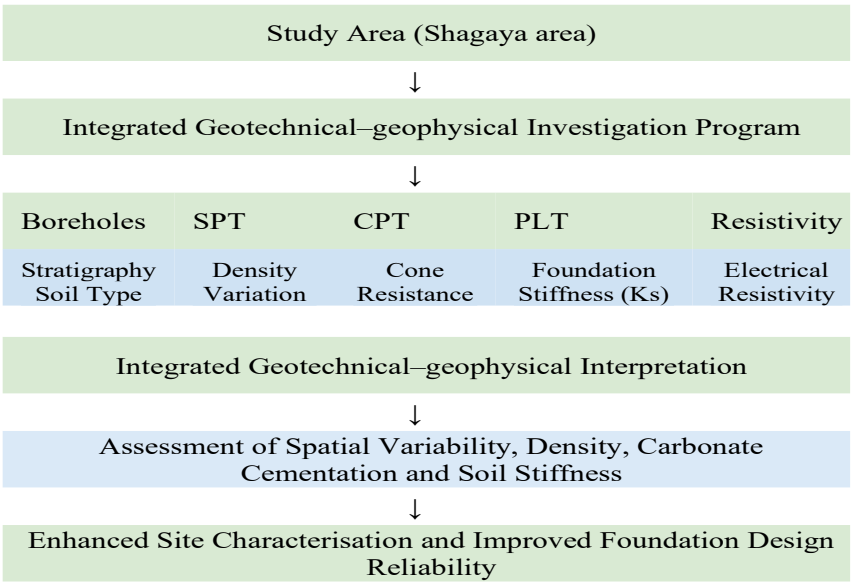


Figure 1. Integrated geotechnical–geophysical framework for site characterisation and foundation assessment.

2. Methodology

2.1. Site Description and Geological Setting

The study site is in the Shagaya area in southwestern Kuwait, about 60 km from Kuwait City, as shown in Figure 2. The Shagaya region is part of Kuwait's western desert and has been selected for several large-scale renewable energy developments because of its favourable climate and geography. The area is characterised by predominantly desert terrain consisting of sandy deposits with varying degrees of carbonate content and natural cementation [26–31]. Subsurface investigations revealed that the site is predominantly underlain by calcareous desert deposits comprising poorly graded sands, silty sands, sandy silts, and locally cemented carbonate-rich horizons. The investigated soils are generally classified as SW-SM, SM, and SC according to the Unified Soil Classification System (USCS). These deposits represent the widespread calcareous soils found throughout Kuwait and the Arabian Gulf region [26–29]. Carbonate mineralogy, particle-crushing susceptibility, and natural cementation strongly influence their engineering behaviour [1–5]. Consequently, the geotechnical response of calcareous soils may differ substantially from that of conventional quartz-dominated sands, particularly in terms of stiffness, strength, compressibility, and settlement behaviour [2–5].

The Shagaya region has an arid desert climate with extremely hot summers, mild winters, and very limited annual precipitation. Average summer temperatures frequently exceed 45 °C, whereas winter temperatures are generally moderate. Rainfall is infrequent and occurs mainly in winter. These climatic conditions contribute to the generally low natural moisture contents observed in the near-surface calcareous deposits and influence the geotechnical behaviour of desert soils [32].

The Shagaya region is also characterised by exceptionally high solar-energy potential, with predominantly clear-sky conditions and a high number of sunny days throughout the year. These favourable climatic conditions have made the area one of Kuwait's principal locations for large-scale renewable energy infrastructure development, including solar-energy projects.



Figure 2. Map of Kuwait showing the Shagaya area.

2.2. Laboratory Testing Programme

Laboratory testing was conducted on representative disturbed and undisturbed samples collected from the boreholes to determine the physical and engineering characteristics of the calcareous deposits investigated. The testing programme included grain-size distribution analysis, natural moisture content determination, Atterberg limits, soil classification, carbonate content determination, Modified Proctor compaction testing, California Bearing Ratio (CBR) testing, and direct shear testing. These laboratory investigations evaluated soil composition, moisture condition, compaction behaviour, bearing characteristics, carbonate content, and shear-strength parameters.

The laboratory results were used to characterise the engineering behaviour of the calcareous deposits and to support the interpretation of borehole logs, standard penetration test (SPT) data, cone penetration test (CPT) results, plate load test (PLT) measurements, and electrical resistivity observations. Variations in particle-size distribution, fines content, carbonate accumulation, moisture condition, and shear-strength characteristics were evaluated to assess their influence on soil stiffness, natural cementation, bearing performance, and overall engineering behaviour. Previous investigations of calcareous desert deposits and renewable energy infrastructure projects in Kuwait adopted similar approaches, integrating laboratory-derived engineering properties with field investigations to improve site characterisation and foundation assessments [27–29,33,34].

2.3. Integrated Site Investigation Programme

The site investigation programme comprised 50 boreholes, 10 CPT soundings, 19 plate load tests (PLTs), laboratory testing, and six electrical resistivity survey locations distributed throughout the project area. The programme was designed to characterise subsurface stratigraphy, evaluate engineering properties, and assess spatial variability within the calcareous desert deposits. Figure 3 shows the spatial distribution of the 50 boreholes across the study area. CPT soundings, plate load tests, and resistivity measurements were conducted within the same project area; however, the original investigation records did not include their individual coordinates. Nevertheless, the borehole

distribution provides representative coverage of the study area and supports the assessment of spatial variability. Similar integrated investigation approaches have been adopted for renewable energy developments and desert soil characterisation in Kuwait [30,31].

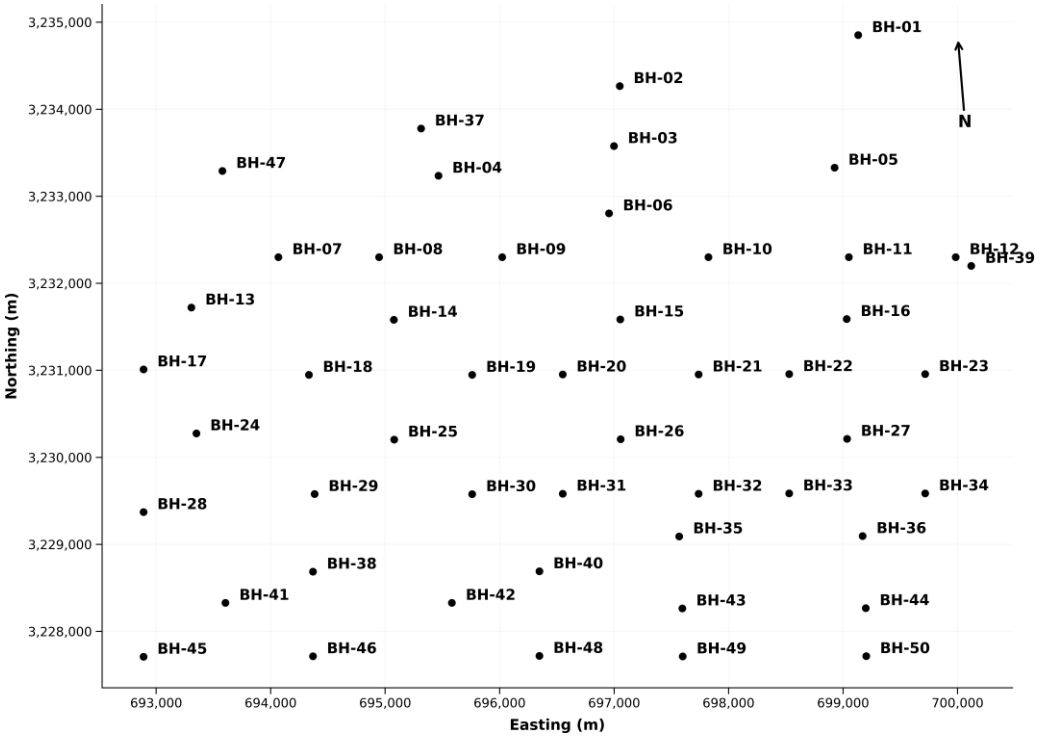


Figure 3. Spatial distribution of boreholes (BH 01 to BH 50) within the study area.

The boreholes were advanced using conventional rotary drilling techniques, and standard penetration tests (SPTs) were performed at regular depth intervals to evaluate in situ density and penetration resistance. Representative disturbed and undisturbed samples obtained from the boreholes were transported to the laboratory for index and engineering property determination. The borehole locations were distributed across the study area to capture lateral variability in subsurface conditions.

Cone penetration tests (CPTs) were conducted to provide continuous profiles of cone resistance and stratigraphic variability. Compared with the borehole investigations, CPTs provided high-resolution measurements of subsurface conditions and helped identify local variations that discrete sampling may miss. The CPT results were interpreted together with borehole logs and laboratory data to establish a consistent geotechnical model of the site.

Plate load tests were performed at selected locations to evaluate the deformation behaviour of the near-surface deposits and to derive the modulus of subgrade reaction for foundation design. Incremental static loads were applied to a rigid steel plate positioned at the test surface, and corresponding settlements were recorded at each loading stage until the maximum test load was reached. Load–settlement curves were developed for each test location and subsequently used to evaluate foundation stiffness characteristics. The PLT results were considered the primary field-based indicator of foundation response and formed the basis for comparison with SPT, CPT, laboratory, and geophysical observations.

Electrical resistivity measurements were conducted at six locations (ER-01 to ER-06) distributed across the Shagaya Renewable Energy Project site to provide supplementary information on near-surface subsurface variability. The surveys used the four-electrode Wenner array, widely used in geotechnical and engineering geophysical investigations because of its simplicity, good signal-to-noise ratio, and sensitivity to changes in soil composition and stratigraphy.

For each survey location, resistivity measurements were obtained along two orthogonal directions (north–south and east–west) to account for potential lateral variability and anisotropy within the calcareous desert deposits. Apparent resistivity values were measured using electrode spacings of 1, 3, 5, and 10 m. Increasing electrode spacing increases the effective depth of investigation, allowing the assessment of resistivity variations within progressively larger volumes of soil. Consequently, the adopted electrode spacings provided information on both shallow and relatively deeper subsurface conditions.

Prior to testing, the ground surface was prepared to ensure adequate electrode contact and stable measurements. Where possible, metallic objects and potential sources of electrical interference were avoided. At each measurement location, current was introduced into the ground through the outer electrodes, while the resulting electrical potential difference was measured between the inner electrodes. Apparent resistivity values were subsequently calculated using the geometric factor associated with the Wenner configuration.

The resistivity survey was designed primarily as a site characterisation tool rather than a geophysical imaging programme. Therefore, the measurements were interpreted qualitatively alongside borehole logs, laboratory testing, standard penetration test (SPT) results, cone penetration test (CPT) soundings, and plate load test (PLT) data. Particular attention was given to identifying variations in apparent resistivity that could indicate changes in soil density, fines content, moisture condition, and carbonate cementation. Because direct spatial matching between geophysical and geotechnical investigation points was unavailable, the resistivity results supported interpretation of subsurface heterogeneity rather than establishing quantitative predictive correlations. The field and laboratory data utilised in this study were obtained from the comprehensive geotechnical investigation programme conducted for the Shagaya Renewable Energy Project. Field investigations, including SPT, CPT, plate load testing, and electrical resistivity testing, were performed in accordance with the relevant ASTM standards documented in the original investigation report. Electrical resistivity measurements were obtained using the Wenner four-pin method in accordance with ASTM G57 [34], while CPT and plate load testing were conducted in accordance with ASTM D5778 [35] and ASTM D1194 [36], respectively. Laboratory testing was performed following applicable ASTM and BS procedures. As the present study is based on a previously completed site investigation database, detailed instrument calibration records, measurement uncertainties, and repeatability assessments were not available in the source documentation and therefore could not be independently evaluated. Nevertheless, the use of multiple independent investigation methods (boreholes, laboratory tests, SPT, CPT, PLT, and resistivity surveys) provided cross-validation of site conditions and increased confidence in the interpretation of subsurface variability.

2.4. Data Integration and Interpretation

The integrated interpretation framework combined borehole, laboratory, SPT, CPT, PLT, and electrical resistivity datasets to achieve a comprehensive geotechnical and geophysical characterisation of the study area. Initially, borehole logs, laboratory testing, standard penetration test (SPT) data, cone penetration test (CPT) soundings, and plate load test (PLT) results were evaluated independently to establish the subsurface stratigraphy and assess the engineering properties of the calcareous deposits. Subsequently, electrical resistivity measurements were interpreted to identify spatial variations in near-surface electrical properties and to provide supplementary information on subsurface heterogeneity.

The integration process involved comparing resistivity measurements with geotechnical indicators of density, stiffness, and soil composition derived from the borehole, laboratory, SPT, CPT, and PLT datasets. Particular attention focused on the relationship between resistivity variations and observed changes in fines content, carbonate content, penetration resistance, and foundation stiffness. Because direct spatial matching between

individual resistivity stations and specific boreholes, CPTs, or PLTs was unavailable, the interpretation focused on identifying consistent qualitative trends rather than developing site-specific predictive correlations.

This study did not aim to develop statistical predictive relationships between electrical resistivity and geotechnical parameters. Rather, the study aimed to evaluate the practical engineering value of electrical resistivity as a supplementary site characterisation tool within an integrated investigation framework incorporating borehole, laboratory, SPT, CPT, and plate load test data. Consequently, the interpretation focused on identifying consistent geotechnical–geophysical trends and improving understanding of subsurface variability rather than establishing site-specific predictive models.

The integrated interpretation enabled assessment of the spatial variability of the calcareous desert deposits and improved confidence in geological and geotechnical characterisation across the project area. Furthermore, combining geotechnical and geophysical observations provided a more comprehensive understanding of subsurface conditions than individual investigation methods alone, supporting more reliable engineering assessments and foundation design decisions for large-scale renewable energy developments.

3. Results and Discussion

3.1. General Characteristics of the Calcareous Desert Deposits

Table 2 summarises the laboratory testing programme and the principal engineering characteristics of the investigated calcareous deposits, while Table 3 presents the statistical summary of the key physical and engineering properties. The results indicate that the Shagaya site is predominantly underlain by calcareous sandy deposits exhibiting considerable variability in composition and engineering behaviour. The soils were primarily classified as SP-SM, SM, SC-SM, SW-SM, and SC, with sand contents ranging from 56.1% to 87.6% (mean 73.7%) and fines contents ranging from 8.3% to 43.9% (mean 24.04%). Carbonate ($CaCO_3$) contents ranged from 2.0% to 13.0% (mean 6.4%), confirming the deposits' calcareous nature and indicating varying degrees of natural cementation.

Moisture contents ranged from 1.7% to 10.0%, reflecting the study area's arid environmental conditions. Maximum dry density and optimum moisture content ranged from 1785 to 1995 kg/m^3 and 8.5% to 13.8%, respectively, indicating favourable compaction characteristics. The direct shear test results in Figure 4 show friction angles from 36.9° to 49.5° and cohesion from 7.81 to 19.14 kPa, reflecting generally favourable shear-strength characteristics for shallow foundation support.

Overall, the investigated deposits comprise medium-dense to very dense calcareous sands with variable fines content and degrees of carbonate cementation. This variability highlights the heterogeneous nature of subsurface conditions and is expected to influence density, stiffness, and foundation performance across the site. These laboratory findings provide the basis for interpreting the SPT, CPT, PLT, and electrical resistivity results presented in the subsequent sections.

Table 2. Summary of laboratory testing programme and engineering parameters evaluated.

Parameter	Detailed Value
Soil Classifications	SP-SM, SM, SC-SM, SW-SM, SC
Relative Density	Medium Dense to Very Dense
Sand Content	56.1–87.6%
Fines Content	8.3–43.9%
Gravel Content	0–20%
Liquid Limit (LL)	29–39%
Plasticity Index (PI)	7–31%

Hydraulic Conductivity	1.7×10^{-5}–15.2×10^{-5} cm/s
Sulfate Content	77–2750 ppm
Chloride Content	65–650 ppm
pH Level	7.5–7.8
Friction Angle	36.9–49.5°
Cohesion	7.81 to 19.14 kPa

Table 3. Statistical summary of key physical and engineering properties of the calcareous desert deposits.

Parameter	Minimum	Maximum	Mean
Water Content (%)	1.7	10	6
Sand Content (%)	56.1	87.6	73.7
Fines Content (%)	8.3	43.9	24.04
Cohesion, c (kPa)	7.81	19.14	14.95
Friction Angle, φ (°)	36.9	49.5	40.73
$CaCO_3$ Content (%)	2	13	6.4
Maximum Dry Density (kg/m^3)	1785	1995	1887.8
Optimum Water Content (%)	8.5	13.8	11.3

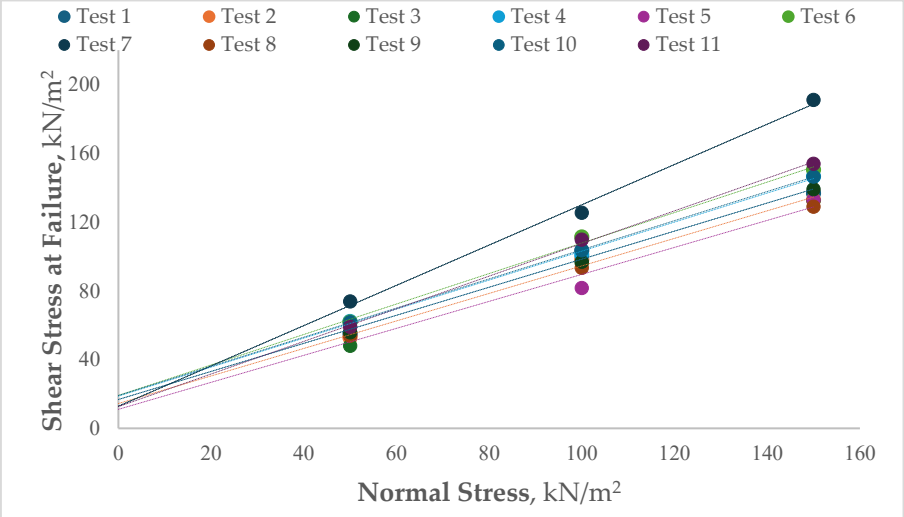


Figure 4. Direct shear test results obtained from representative samples of the Shagaya deposits.

3.2. Standard Penetration Test (SPT) Results

Table 4 summarises the standard penetration test (SPT) results from 50 boreholes across the study area. The recorded SPT-N values ranged from 10 to 84, with a representative value of approximately 45, indicating predominantly dense to very dense calcareous deposits. Many boreholes showed increasing penetration resistance with depth and reached refusal or near-refusal conditions ($N \geq 50$) below approximately 2 to 3 m, suggesting dense to very dense sandy deposits and locally cemented horizons.

The wide range of SPT-N values reflects significant spatial variability in subsurface conditions, consistent with the variations in fines content, carbonate accumulation, and cementation identified in the laboratory testing programme. Elevated penetration resistance values reflect the combined effects of soil densification and natural carbonate cementation, both of which increase the stiffness and strength of the calcareous deposits. Overall, the SPT results confirm that the site is predominantly underlain by competent calcareous sandy deposits with favourable engineering characteristics for shallow foundation support. The observed variability highlights the deposits' heterogeneity and provides evidence of local changes in density and cementation across the project area. These

findings align with the CPT, PLT, and laboratory results presented in the following sections and support an integrated interpretation of site conditions.

Table 4. Summary of SPT results.

Parameter	Value
Number of Boreholes	50
Minimum SPT-N	10
Maximum SPT-N	84
Representative SPT-N	~45
Predominant Soil Condition	Dense to Very Dense

3.3. Cone Penetration Test (CPT) Results

Table 5 summarises the CPT programme, and Table 6 presents the measured cone resistance values obtained from the ten CPT soundings. The CPT results indicate that the study area is predominantly underlain by dense to very dense calcareous sandy deposits. Measured cone resistance (qc) values ranged from 15 to 27.5 MPa, with an average value of approximately 22 MPa, confirming the generally competent nature of the subsurface materials.

Variations in cone resistance reflect differences in soil density, fines content, and carbonate cementation across the site. Higher qc values are associated with denser and locally cemented horizons, whereas lower values indicate comparatively less cemented deposits. These observations are consistent with the variability identified from the laboratory testing programme and SPT investigations.

Overall, the CPT results confirm favourable subsurface conditions and provide continuous profiling of the calcareous deposits, complementing the borehole and SPT data. The CPT soundings also highlight local variations in soil behaviour and contribute to the integrated geotechnical characterisation of the study area.

Table 5. Summary of CPT results.

Parameter	Value
Number of CPTs	10
Approximate qc Range (MPa)	15–27.5
Average qc (MPa)	22
Soil Behaviour	Dense to Very Dense Sand

Table 6. Cone penetration resistance values obtained from the CPT programme at the Shagaya site.

Test No.	q_c (MPa)
CPT1	27.5
CPT2	26
CPT3	23
CPT4	20
CPT5	25
CPT6	17
CPT7	15
CPT8	25
CPT9	16
CPT10	24
CPT_average	22

3.4. Plate Load Test Results

It should be noted that several plate load test curves exhibit non-zero initial settlement values. These offsets arise from the field measurement procedure adopted during testing, whereby settlement readings were referenced to the initial dial-gauge readings established during test setup rather than to an absolute zero-displacement datum. Consequently, the plotted settlements represent corrected incremental displacements relative to the initial reference readings. This referencing approach does not affect the interpretation of load–settlement behaviour or the estimation of bearing capacity, as the analysis is based on the incremental settlement developed during loading. The plate load tests were conducted in accordance with ASTM D1194 [36].

Table 7 summarises the results of the 19 plate load tests (PLTs) conducted across the study area, and Figures 5–9 present the corresponding load–settlement curves. The calculated modulus of subgrade reaction (Ks) values ranged from 24.3 to 210.3 MN/m^3, with mean and median values of 107.4 and 114.1 MN/m^3, respectively, indicating considerable variability in foundation stiffness across the site.

The variability in Ks values reflects differences in soil density, fines content, and carbonate cementation within the calcareous deposits. Higher stiffness values are associated with dense and locally cemented horizons, whereas lower values indicate comparatively less competent materials. The load–settlement responses shown in Figures 5–9 further demonstrate how deformation behaviour varies under applied loading.

Overall, the PLT results confirm favourable conditions for shallow foundations while highlighting significant spatial variations in stiffness. As the only field test that directly measures foundation response, the PLT programme provides a key dataset for evaluating settlement behaviour and supporting the integrated characterisation of the calcareous deposits.

Table 7. Statistical summary of PLT results.

Parameter	Value
Number of PLTs	19
Minimum Ks (MN/m^3)	24.3
Maximum Ks (MN/m^3)	210.3
Mean Ks (MN/m^3)	107.4
Median Ks (MN/m^3)	114.1

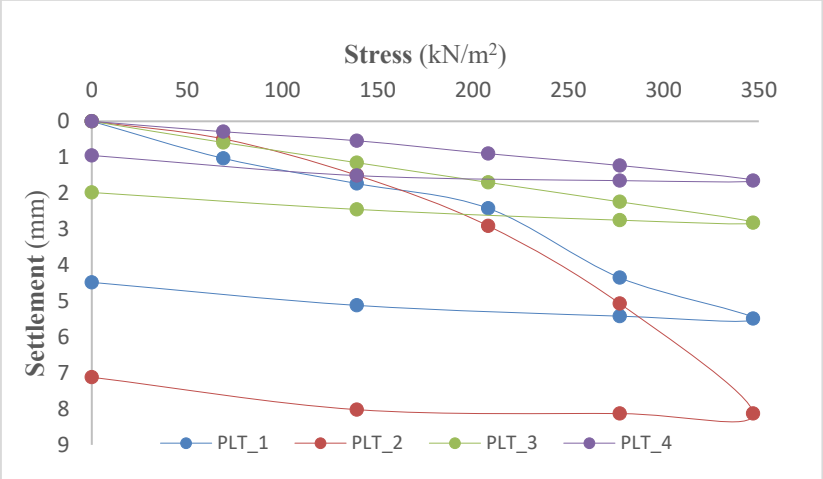


Figure 5. The plate load tests conducted at the Shagaya site (1–4).

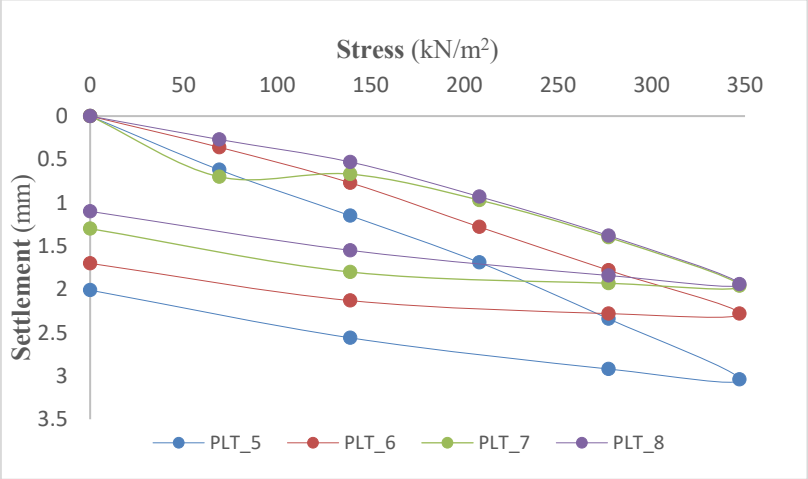


Figure 6. The plate load tests conducted at the Shagaya site (5–8).

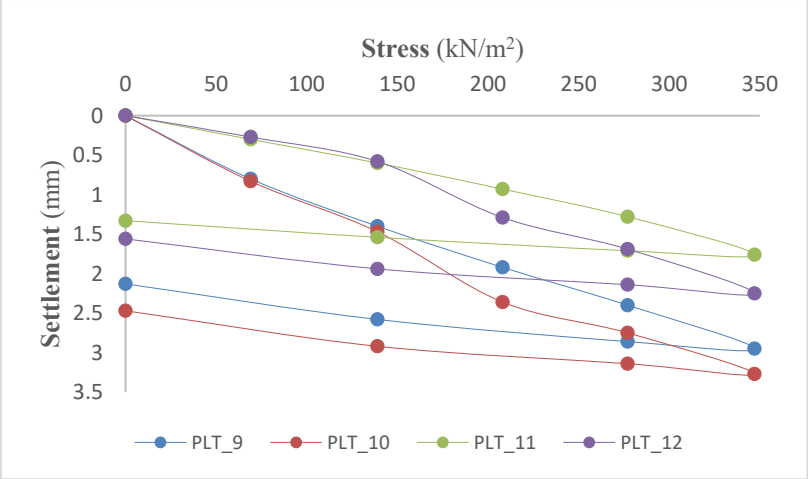


Figure 7. The plate load tests conducted at the Shagaya site (9–12).

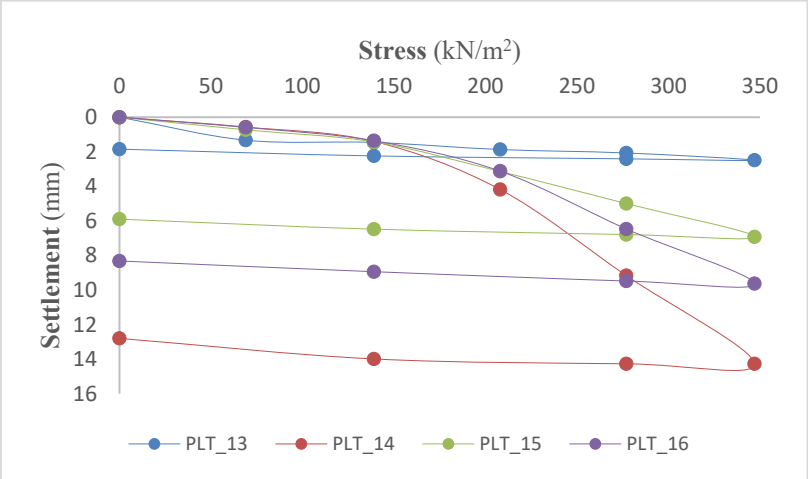


Figure 8. The plate load tests conducted at the Shagaya site (13–16).

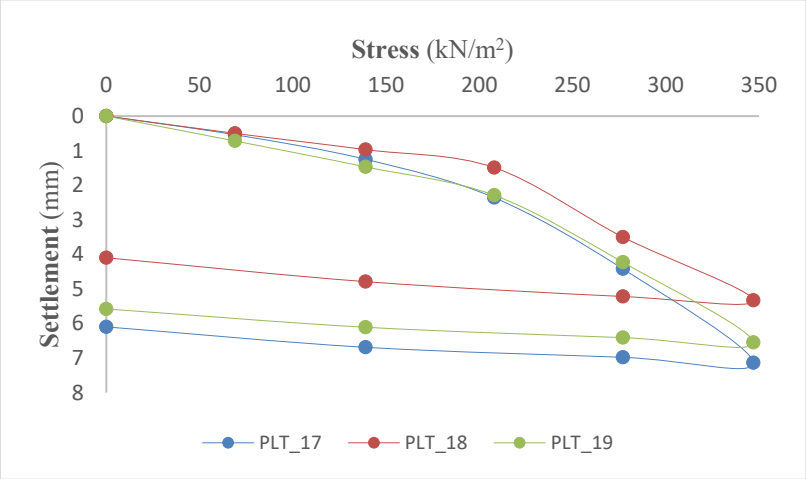


Figure 9. The plate load tests conducted at the Shagaya site (17–19).

3.5. Compaction and Bearing Characteristics

Figure 10 presents the Modified Proctor compaction curves, while Table 8 summarises the compaction and bearing characteristics of the investigated deposits. Maximum dry density (MDD) ranged from 1785 to 1995 kg/m³, with a mean of 1887.8 kg/m³, while optimum moisture content (OMC) ranged from 8.5% to 13.8%, with a mean of 11.3%. California Bearing Ratio (CBR) values ranged from 17.3% to 32.1%, with a mean value of 25.9%.

The test results indicate generally favourable compaction and bearing characteristics, consistent with the predominantly dense calcareous deposits. Variations in MDD, OMC, and CBR reflect differences in fines content and carbonate cementation across the site.

Overall, the compaction and bearing results confirm the deposits' suitability for supporting shallow foundations and associated infrastructure and provide further evidence of the spatial variability identified by the laboratory, SPT, CPT, and PLT investigations.

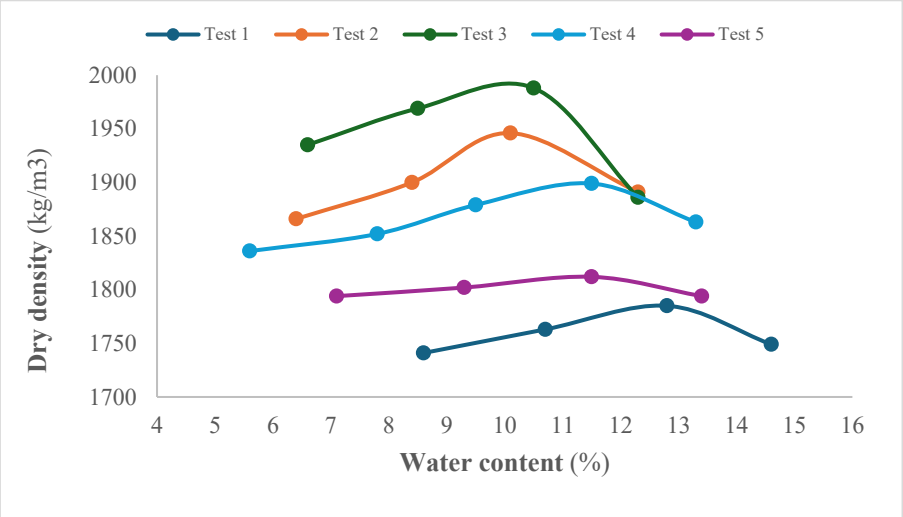


Figure 10. Modified Proctor compaction curves for representative calcareous desert soil samples.

Table 8. Summary of compaction and bearing characteristics.

Parameter	Minimum	Maximum	Mean
Maximum dry density (kg/m³)	1785	1995	1887.8
Optimum moisture content (%)	8.5	13.8	11.3
CBR (%)	17.3	32.1	25.9

3.6. Electrical Resistivity Results

Table 9 summarises the electrical resistivity measurements from the six survey locations, while Figures 11–16 present the corresponding resistivity profiles. Apparent resistivity values ranged from 57.2 to 271.9 Ω·m, with a mean value of 201.6 Ω·m, indicating notable spatial variability within the near-surface calcareous deposits.

The observed resistivity variation reflects differences in soil density, fines content, moisture conditions, and carbonate cementation across the site. Electrical resistivity is influenced by several interrelated factors, including moisture content, degree of saturation, pore-water conductivity, porosity, soil fabric, density, fines content, and carbonate cementation. Consequently, resistivity variations cannot be attributed solely to mechanical properties or cementation effects. In the present study, pore-water conductivity and porosity were not measured at the resistivity survey locations; therefore, the individual contribution of these factors could not be quantified. The resistivity results are therefore interpreted qualitatively within the context of the integrated geotechnical dataset. Given the generally low natural moisture contents observed across the site (1.7–10.0%), differences in density, fines content, and carbonate cementation are considered likely contributors to the measured resistivity variability; however, the influence of other hydrogeological and physicochemical factors cannot be excluded. Accordingly, electrical resistivity was used as a supplementary indicator of subsurface heterogeneity rather than as a direct predictor of mechanical behaviour.

Based on the site-specific interpretation in Table 10, lower resistivity values were generally associated with finer-grained and less cemented materials, whereas higher resistivity values were commonly observed in denser and more strongly cemented calcareous deposits. These observations should be regarded as qualitative trends rather than validated geotechnical–resistivity relationships. Further investigation using spatially coincident geotechnical and geophysical measurements would be required to establish robust predictive correlations. The thresholds in Table 10 are site-specific qualitative interpretations based on an integrated assessment of the available geotechnical and geophysical datasets and should not be treated as transferable classification limits.

Overall, the resistivity results confirm the heterogeneous nature of the subsurface conditions and provide supplementary information that enhances the characterisation of the calcareous deposits between discrete geotechnical investigation points.

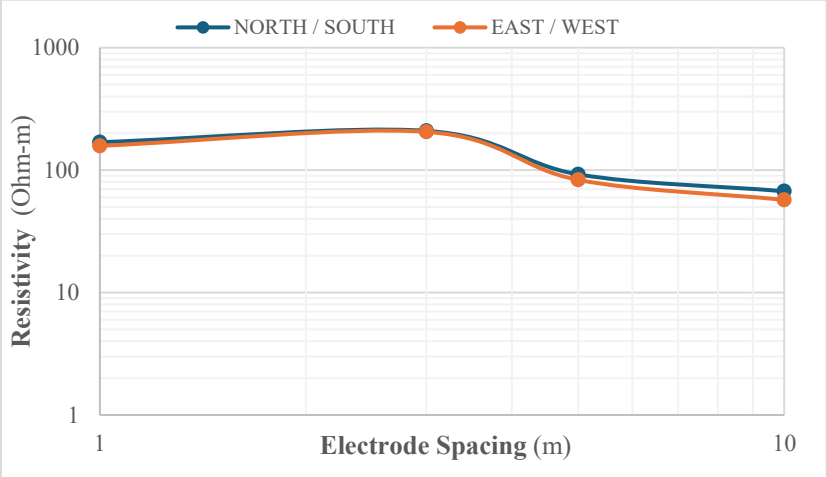


Figure 11. Electrical resistivity profiles in the north–south and east–west directions at ER-01.

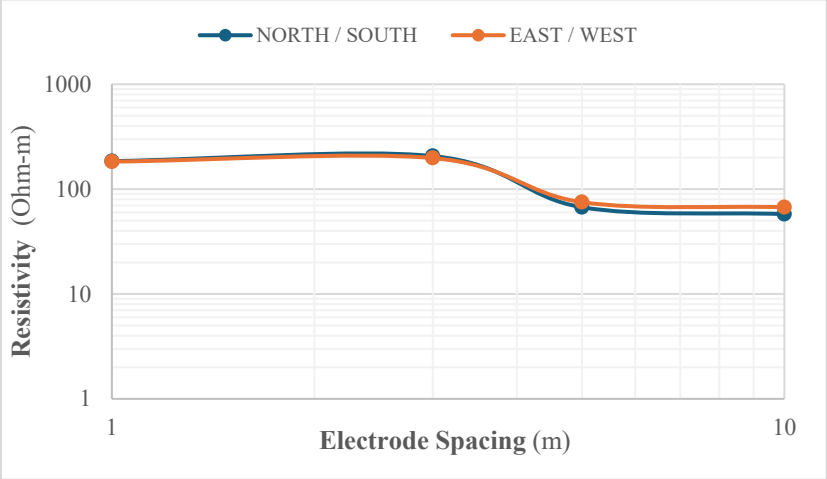


Figure 12. Electrical resistivity profiles in the north–south and east–west directions at ER-02.

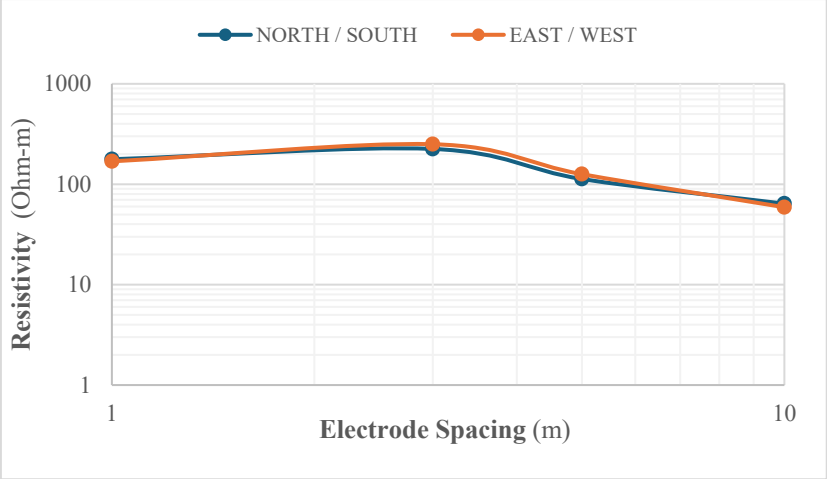


Figure 13. Electrical resistivity profiles in the north–south and east–west directions at ER-03.

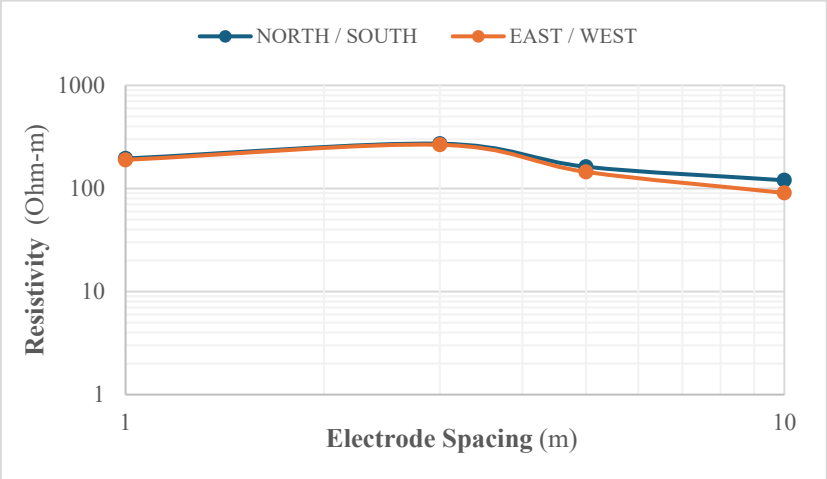


Figure 14. Electrical resistivity profiles in the north–south and east–west directions at ER-04.

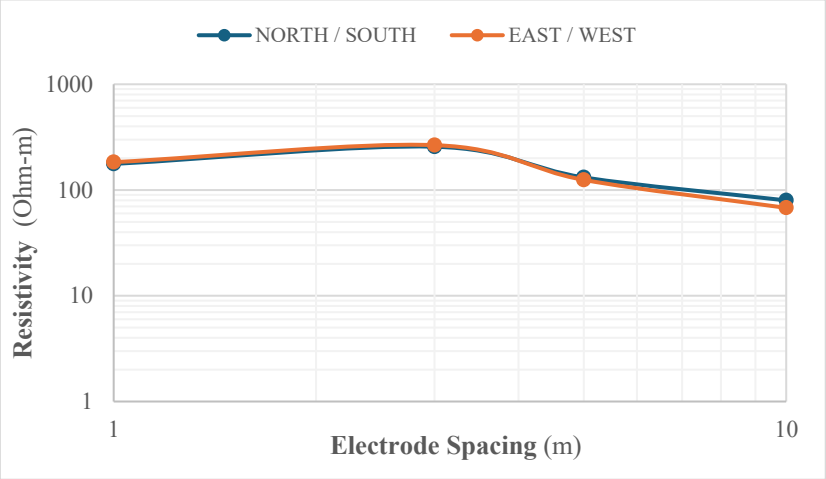


Figure 15. Electrical resistivity profiles in the north–south and east–west directions at ER-05.

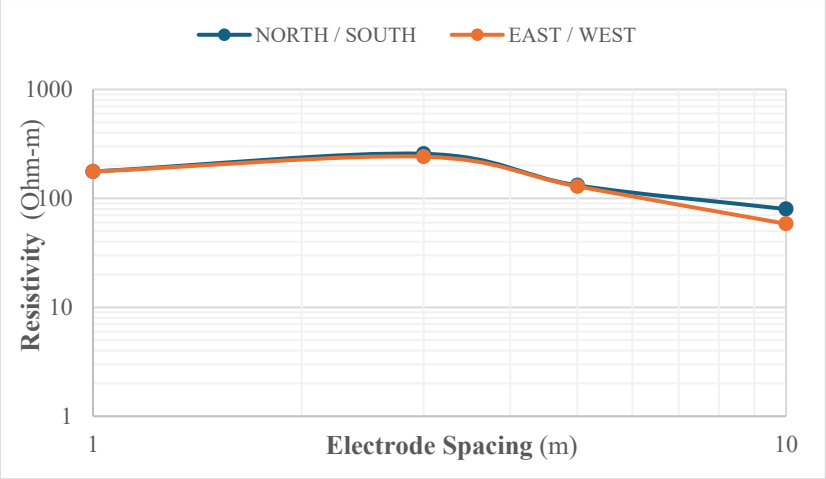


Figure 16. Electrical resistivity profiles in the north–south and east–west directions at ER-06.

Table 9. Summary of electrical resistivity results.

Parameter	Value
Number of Locations	6
Minimum Resistivity (Ω·m)	57.2
Maximum Resistivity (Ω·m)	271.9
Mean Resistivity (Ω·m)	201.6

Table 10. Site-specific qualitative interpretation of electrical resistivity measurements for the Shagaya calcareous desert deposits.

Apparent Resistivity (Ω·m)	Qualitative Interpretation	Likely Geotechnical Characteristics
$\rho < 100$	Low resistivity	Relatively higher fines content, lower density, weaker cementation, potentially lower stiffness
$100 \leq \rho < 200$	Moderate resistivity	Moderately dense calcareous deposits with moderate cementation and intermediate stiffness
$200 \leq \rho < 250$	High resistivity	Dense to very dense calcareous deposits, stronger carbonate cementation, and relatively higher stiffness
≥250	Very high resistivity	Strongly cemented carbonate-rich horizons and potentially enhanced foundation performance

To evaluate directional variability, the north–south and east–west resistivity measurements were compared at each electrode spacing (Table 11). The calculated relative differences averaged approximately 9%, with most values remaining below 15%. Although larger differences were observed at a limited number of measurement points, the overall resistivity trends remained consistent between the two survey directions. These results indicate generally limited directional anisotropy within the investigated calcareous deposits and support the use of resistivity measurements as a supplementary indicator of subsurface variability.

Table 11. Comparison of north–south and east–west resistivity measurements and assessment of directional variability.

Location	Spacing (m)	NS (Ω·m)	EW (Ω·m)	Abs. Diff. (Ω·m)	Relative Diff. (%)
ER-01	1	169.02	157.96	11.06	6.76
ER-01	3	209.23	205.46	3.77	1.82
ER-01	5	92.36	83.25	9.11	10.38
ER-01	10	67.23	57.18	10.05	16.16
ER-01 Mean					**8.78**
ER-02	1	184.73	182.9	1.83	1
ER-02	3	206.59	197.92	8.67	4.29
ER-02	5	67.23	75.08	7.85	11.02
ER-02	10	57.81	67.23	9.42	15.07
ER-02 Mean					**7.84**
ER-03	1	177.44	169.02	8.42	4.86
ER-03	3	224.69	250.32	25.63	10.81
ER-03	5	112.78	125.98	13.2	11.05
ER-03	10	64.09	59.06	5.03	8.17
ER-03 Mean					**8.72**
ER-04	1	195.22	189.44	5.78	3
ER-04	3	271.81	265.21	6.6	2.46
ER-04	5	162.42	144.83	17.59	11.45
ER-04	10	120.01	90.48	29.53	28.01
ER-04 Mean					**11.23**
ER-05	1	176.56	183.28	6.72	3.74
ER-05	3	256.73	265.78	9.05	3.47
ER-05	5	131.63	124.72	6.91	5.39
ER-05	10	79.8	67.86	11.94	16.19
ER-05 Mean					**7.2**
ER-06	1	176.56	176.43	0.13	0.07
ER-06	3	256.73	241.46	15.27	6.13
ER-06	5	131.63	128.81	2.82	2.17
ER-06	10	79.8	58.43	21.37	30.9
ER-06 Mean					**9.82**

The comparison between north–south and east–west resistivity measurements is summarised in Table 11. To evaluate directional variability, absolute and relative differences were calculated at each electrode spacing for all survey locations. The calculated relative differences averaged approximately 9%, with most values remaining below 15%. Although larger differences were observed at a limited number of measurement points, the overall resistivity trends remained consistent between the two survey directions, indicating generally limited directional anisotropy within the investigated calcareous deposits. These findings suggest that the observed resistivity variations primarily reflect spatial changes in subsurface conditions rather than strong directional effects.

3.7. Integrated Interpretation of Geotechnical and Geophysical Results

The combined borehole, laboratory, SPT, CPT, PLT, and electrical resistivity datasets provide a comprehensive understanding of the engineering behaviour of the Shagaya calcareous desert deposits. Despite generally similar soil classifications, the investigated deposits exhibit substantial variability in density, fines content, carbonate cementation, penetration resistance, and foundation stiffness, confirming the heterogeneous nature of the subsurface conditions.

The SPT and CPT results indicate predominantly dense to very dense sandy deposits, with SPT-N values ranging from 10 to 84 and CPT cone resistance values ranging from 15 to 27.5 MPa. These results are consistent with the laboratory findings, which reveal variations in fines content and carbonate accumulation that influence soil density and mechanical behaviour. The PLT programme further shows the significant influence of these factors on foundation response, with Ks values ranging from 24.3 to 210.3 MN/m^3. This wide range highlights the importance of direct stiffness measurements for foundation assessment in calcareous deposits.

Electrical resistivity measurements ranged from 57.2 to 271.9 Ω·m and provided supplementary evidence of subsurface variability. Based on the site-specific interpretation in Table 10, lower resistivity values were generally associated with finer-grained and less cemented materials, whereas higher resistivity values were commonly observed in denser and more strongly cemented deposits. However, these trends should be interpreted cautiously because electrical resistivity is also influenced by moisture conditions, pore-fluid conductivity, porosity, and other site-specific factors. Although direct predictive correlations were not established, the observed geophysical trends were generally consistent with the geotechnical observations.

The integrated interpretation demonstrates that density, fines content, and carbonate cementation are the principal controls on the engineering behaviour of the investigated deposits. The key geotechnical and geophysical indicators summarised in Table 12 collectively confirm substantial spatial variability across the site. Integrating resistivity measurements with borehole, laboratory, SPT, CPT, and PLT data therefore provides a more reliable basis for site characterisation and foundation assessment than any single investigation technique. Table 12 summarises the principal geotechnical and geophysical indicators from the integrated investigation programme.

Table 12. Summary of key geotechnical and geophysical indicators for the investigated calcareous deposits.

Parameter	Minimum	Maximum	Mean	Interpretation
SPT-N	10	84	45	Dense to very dense
CPT qc (MPa)	15	27.5	22	Dense sand
Ks (MPa)	24.3	210.3	107.4	High variability
Resistivity (Ω·m)	57.2	271.9	201.6	Variable cementation

4. Discussion

4.1. Engineering Behaviour of the Calcareous Desert Deposits

The results demonstrate that the engineering behaviour of the Shagaya calcareous deposits is governed primarily by variations in density, fines content, and carbonate cementation. Although the deposits are predominantly sandy and exhibit similar soil classifications, penetration resistance, stiffness, bearing characteristics, and electrical resistivity varied significantly, indicating that soil classification alone does not adequately represent their engineering performance.

Laboratory testing revealed considerable variations in fines content and carbonate concentration, reflecting differences in depositional conditions and natural cementation across the site. These variations are consistent with the spatial changes observed in the SPT, CPT, PLT, and resistivity datasets and demonstrate the heterogeneous nature of the deposits.

The influence of carbonate cementation is evident from the generally high penetration resistance values, favourable bearing characteristics, and wide range of foundation stiffness values measured during the plate load tests. The results indicate that local cementation enhances soil structure and stiffness, resulting in deposits with similar grain-size characteristics exhibiting different mechanical responses and settlement behaviour.

Overall, the investigated deposits provide generally favourable conditions for shallow foundations and renewable energy infrastructure. However, the significant variability across the site highlights the importance of integrated site investigation programmes that capture local variations in density and cementation to improve foundation design and reduce geotechnical uncertainty.

4.2. Relationship Between SPT, CPT, and Soil Stiffness

The SPT, CPT, and PLT results exhibit consistent trends, indicating that penetration resistance is closely related to foundation stiffness in the investigated calcareous deposits. Higher SPT-N values and cone resistance measurements generally corresponded to higher Ks values, reflecting the influence of soil density and carbonate cementation on mechanical behaviour.

SPT-N values ranged from 10 to 84, CPT cone resistance values from 15 to 27.5 MPa, and PLT-derived Ks values from 24.3 to 210.3 MN/m^3, demonstrating substantial spatial variability across the site. The broader range of Ks values suggests that foundation stiffness is influenced not only by density but also by differences in cementation and soil structure.

Overall, the results indicate that SPT and CPT measurements provide useful indicators of relative stiffness variations, whereas PLT testing remains the most direct method for assessing foundation response and settlement behaviour in calcareous deposits.

4.3. Variability of Modulus of Subgrade Reaction

The plate load test results revealed significant spatial variability in the modulus of subgrade reaction (Ks), with values ranging from 24.3 to 210.3 MN/m^3. This nearly ninefold variation indicates that foundation stiffness depends strongly on local subsurface conditions, despite generally similar soil classifications across the site. The variability in Ks is attributed primarily to differences in soil density, fines content, and carbonate cementation. Deposits with higher stiffness are interpreted as dense, partially cemented calcareous horizons, whereas lower Ks values reflect comparatively less competent materials. These trends are consistent with the variations observed in the laboratory, SPT, and CPT datasets. The results also highlight that penetration resistance alone may not fully represent foundation stiffness, as deposits with similar SPT or CPT characteristics can exhibit different settlement responses due to variations in soil structure and cementation. Consequently, direct field measurements remain essential for reliably assessing foundation performance in calcareous deposits. It should be noted that the modulus of subgrade reaction (Ks) obtained from plate load tests is influenced by plate dimensions, loading conditions, stress-bulb development, and subsurface stratigraphy. The PLTs conducted in this investigation were performed using a 0.30 m diameter steel plate in accordance with ASTM D1194 [36]; therefore, the reported Ks values represent localised near-surface stiffness conditions rather than direct design values for full-scale foundations. Scale effects associated with foundation width, embedment depth, contact pressure, and settlement criteria may result in different foundation responses from those measured during plate testing. Consequently, the reported Ks values should be interpreted primarily as

indicators of relative stiffness variability across the site. For actual foundation design, appropriate scale corrections and foundation-specific settlement analyses should be performed using the dimensions and loading conditions of the proposed foundation system.

Overall, the wide range of Ks values demonstrates the site's heterogeneity and emphasises the importance of incorporating stiffness measurements into foundation design and settlement evaluation.

4.4. Bearing Capacity and Compaction Characteristics

The compaction and bearing test results indicate that the investigated calcareous deposits possess generally favourable engineering properties for foundation and infrastructure applications. Maximum dry density values ranged from 1785 to 1995 kg/m^3, while CBR values ranged from 17.3% to 32.1%, reflecting moderate to good bearing performance.

The observed variability is attributed to differences in soil density, fines content, and carbonate cementation, which influence soil structure and resistance to deformation. These trends are consistent with the spatial variability identified from the SPT, CPT, and PLT investigations.

Overall, the compaction and bearing characteristics confirm the deposits' suitability for shallow foundations and provide further evidence that density and cementation are the principal factors controlling the engineering behaviour of the calcareous deposits.

4.5. Role of Electrical Resistivity as a Supplementary Site Characterisation Tool

The electrical resistivity survey provided valuable supplementary information regarding the spatial variability of the calcareous desert deposits and enhanced the interpretation of the conventional geotechnical investigation programme. Apparent resistivity values ranged from 57.2 to 271.9 Ω·m, confirming the heterogeneous subsurface conditions identified from laboratory testing, SPT, CPT, and plate load test (PLT) results. These variations are consistent with the observed differences in fines content, density, carbonate cementation, and foundation stiffness across the study area.

Based on the site-specific interpretation framework in Table 10, higher resistivity values generally correspond to denser, more strongly cemented calcareous deposits, whereas lower resistivity values typically indicate finer-grained, less dense, or less cemented materials. The resistivity classifications in Table 10 were developed specifically for the investigated site and are based on qualitative interpretation of the available integrated dataset. Because electrical resistivity is strongly influenced by geological setting, moisture conditions, soil composition, pore-fluid chemistry, density, and cementation, do not extrapolate the proposed resistivity ranges to other sites without appropriate local calibration and supporting geotechnical investigations.

Although direct quantitative correlations between resistivity measurements and geotechnical parameters were not developed, the resistivity data provided valuable qualitative insight into subsurface variability and supported engineering interpretation.

The resistivity survey did not aim to perform detailed site-wide geophysical mapping or develop predictive resistivity-based models. Instead, the investigation evaluated the practical role of electrical resistivity within a conventional, foundation-oriented site investigation framework. The results show that resistivity measurements can complement borehole, laboratory, SPT, CPT, and PLT data by providing additional information on lateral subsurface variability that discrete investigation points alone may not fully capture.

A key outcome of this study is the integration of electrical resistivity observations with a comprehensive geotechnical database comprising 50 boreholes, 10 CPT soundings, 19 plate load tests, and laboratory investigations. Within this framework, resistivity measurements were interpreted in relation to variations in density, carbonate cementation, and foundation stiffness rather than as a standalone predictive tool. This integrated approach

increases confidence in interpreting heterogeneous calcareous deposits and supports more informed engineering judgement during foundation assessment.

4.6. Implications for Renewable Energy Infrastructure

The results indicate that the investigated calcareous deposits generally provide favourable conditions for renewable energy infrastructure; however, the site shows significant spatial variability in density, stiffness, and carbonate cementation. This variability may affect foundation performance and settlement behaviour, particularly for large-scale developments spanning extensive areas.

The substantial variation in PLT-derived stiffness values highlights the importance of direct field measurements for foundation assessment in calcareous deposits. While SPT and CPT data provide useful indicators of ground conditions, local cementation effects strongly influence stiffness and settlement behaviour.

Overall, integrating laboratory testing, SPTs, CPTs, PLTs, and electrical resistivity surveys improves confidence in site characterisation and provides a more reliable basis for foundation design, reducing geotechnical uncertainty in renewable energy developments on heterogeneous calcareous soils.

4.7. Study Limitations and Future Research

The principal limitation of this study is the absence of direct spatial matching between boreholes, CPT soundings, plate load tests, and electrical resistivity survey locations. Consequently, the interpretation is based on comparison of overall site trends rather than point-by-point validation of resistivity against measured geotechnical properties. While the integrated dataset suggests consistency between resistivity variations and observed differences in density, carbonate cementation, and foundation stiffness, the study does not establish validated predictive relationships between geophysical and geotechnical parameters. Therefore, the interpretation focuses on identifying qualitative trends and improving understanding of subsurface variability rather than developing predictive resistivity-based models. Future investigations should acquire spatially coincident geotechnical and geophysical measurements to enable rigorous quantitative assessment and validation of resistivity–geotechnical relationships.

A second limitation is the relatively limited number of electrical resistivity survey locations compared with the extensive geotechnical database. Although the resistivity data successfully identified subsurface variability, the available dataset was insufficient to support rigorous statistical analysis or site-specific predictive modelling.

An additional limitation of the present study is that the assessment of foundation behaviour was based on conventional geotechnical investigation data and short-term plate load test responses. Time-dependent behaviour, including creep, secondary compression, and other rheological effects, was not evaluated because long-term monitoring data were unavailable. Although the investigated calcareous deposits generally exhibited dense to very dense conditions and low natural moisture contents, future studies incorporating long-term settlement monitoring and rheological testing would be valuable for assessing the potential influence of time-dependent deformation on foundation performance in arid calcareous soils.

No periodic or long-term monitoring measurements were available as part of the original site investigation programme. Consequently, the plate load test results reflect short-term field responses at the time of testing and do not capture potential seasonal or time-dependent variations in settlement behaviour. Given the arid climate, low rainfall, and generally low natural moisture contents observed at the site, significant seasonal effects are expected to be limited; however, this aspect was not specifically investigated and should be addressed in future monitoring studies.

Future research should focus on acquiring spatially matched geotechnical and geophysical datasets to enable direct comparison between resistivity, penetration resistance, and foundation stiffness. Applying advanced geophysical techniques, such as electrical resistivity tomography (ERT), together with larger datasets from calcareous deposits, would further improve understanding of subsurface variability and enhance site characterisation methodologies for renewable energy infrastructure in arid environments.

5. Conclusions

This study evaluated the practical engineering value of electrical resistivity as a supplementary site characterisation tool within an integrated geotechnical investigation framework for the Shagaya Renewable Energy Project, Kuwait. The investigation combined borehole, laboratory, standard penetration test (SPT), cone penetration test (CPT), plate load test (PLT), and electrical resistivity data to assess the engineering behaviour and spatial variability of calcareous desert deposits. The following conclusions can be drawn:

The investigated deposits consist predominantly of medium-dense to very dense calcareous sands exhibiting considerable variability in fines content, carbonate cementation, penetration resistance, and foundation stiffness. This variability demonstrates the heterogeneous nature of calcareous desert deposits and highlights the need for comprehensive site characterisation programmes.

SPT-N values ranged from 10 to 84, CPT cone resistance values ranged from 15 to 27.5 MPa, and PLT-derived modulus of subgrade reaction (Ks) values ranged from 24.3 to 210.3 MN/m^3, indicating substantial spatial variability in engineering behaviour. The observed variations are primarily associated with differences in density, fines content, and carbonate cementation.

Electrical resistivity measurements ranged from 57.2 to 271.9 Ω·m and provided useful supplementary information regarding subsurface heterogeneity. In general, higher resistivity values were associated with denser and more strongly cemented deposits, whereas lower values corresponded to relatively finer-grained or less cemented materials.

Unlike many previous studies, the objective of this research was not to develop empirical resistivity-based correlations. The study focused on how resistivity data can contribute to integrated engineering interpretation and improve understanding of subsurface variability.

The findings demonstrate that electrical resistivity is most effective as a complementary investigation technique that enhances, rather than replaces, conventional geotechnical investigations. When interpreted alongside borehole, laboratory, SPT, CPT, and PLT results, resistivity data can improve confidence in site characterisation and support engineering judgement in heterogeneous ground conditions. The proposed integrated geotechnical–geophysical framework provides a practical approach for reducing site characterisation uncertainty and supporting foundation investigations in calcareous desert deposits. The framework is particularly relevant to large-scale renewable energy infrastructure projects in arid environments where understanding spatial variability is essential for reliable engineering decision-making.

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Abbreviations

The following abbreviations are used in this manuscript:

BH	Borehole
CBR	California Bearing Ratio
CPT	Cone Penetration Test
ERT	Electrical Resistivity Tomography
Ks	Modulus of Subgrade Reaction
LL	Liquid Limit
MDD	Maximum Dry Density
OMC	Optimum Moisture Content
PI	Plasticity Index
PLT	Plate Load Test
qc	Cone Resistance
SPT	Standard Penetration Test
SPT-N	Standard Penetration Test Blow Count
SW	Well-Graded Sand (USCS)
SC	Clayey Sand (USCS)
SM	Silty Sand (USCS)
SP	Poorly Graded Sand (USCS)
USCS	Unified Soil Classification System
Ω·m	Ohm-Metre (Electrical Resistivity Unit)

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