

Integrated Geotechnical Evaluation of Subsurface Soil Suitability for Bridge Foundations Using Grain-Size Distribution and Standard Penetration Test (SPT) Data

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التقييم الجيوتقني المتكامل لمدى ملائمة التربة تحت السطحية لأساسات الجسور باستخدام بيانات توزيع أحجام الحبيبات واختبار الاختراق القياسي (SPT)

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Abstract:

This study is a detailed geotechnical investigation of subsurface conditions at Al Zahra'a Bridged Intersection, Najaf Governorate, Iraq. The investigation consisted of 8 boreholes (each 30 m deep) supported by Standard Penetration Tests (SPT), soil sampling and laboratory analyses. The subsurface profile is characterised by medium to very dense clayey silty sand from about 1.0 to 26.5 m, below which is hard silty clay and very dense grey sand. Groundwater was found at shallow depths, about 2.9–3.6 m below ground level. Laboratory data showed a high chemical variability with sulphate, total soluble salts and gypsum values of up to 13.750, 30.100 and 29.564%, respectively. Direct shear tests showed friction angles from 34° to 39° with negligible cohesion. Based on the reported geotechnical conditions, the recommended foundation system was bored reinforced-concrete piles with an approximate diameter of 1.25 m and tip depth of 19 m. The results suggest that foundation design and construction should consider subsurface variability, shallow groundwater and chemical soil properties.

Keywords: Geotechnical Characterization, Standard Penetration Test (SPT), Direct Shear Strength, Bored Piles, Gypsiferous Soil, Al Zahra'a Intersection, Najaf.

الملخص

تُقدم هذه الدراسة تقييماً جيوتقنياً مفصلاً للظروف تحت السطحية في موقع تقاطع "الزهراء" (الذي يضم جسراً) في محافظة النجف بالعراق. شملت الدراسة حفر 8 آبار استكشافية (بعمق 30 متراً لكل منها) مدعومة باختبارات الاختراق القياسية (SPT)، وأخذ عينات التربة، وإجراء التحاليل المخبرية. يتميز المقطع الطبقي تحت السطحي بوجود رمل طيني تتراوح كثافته بين المتوسطة وشديدة الكثافة على

عمق يمتد من 1.0 إلى 26.5 متراً تقريباً، وتليها طبقات من الطين الطميي الصلب والرمل الرمادي شديد الكثافة. وقد رُصدت المياه الجوفية على أعماق ضحلة تتراوح بين 2.9 و 3.6 متر تحت مستوى سطح الأرض. وأظهرت البيانات المخبرية تبايناً كيميائياً كبيراً، حيث وصلت نسب الكبريتات، وإجمالي الأملاح الذائبة، والجبس إلى 13.750% و 30.100% و 29.564% على التوالي. كما أظهرت اختبارات القص المباشر زوايا احتكاك تتراوح بين 34 و 39 درجة مع قيمة تماسك (Cohesion) تكاد تكون معدومة. واستناداً إلى الظروف الجيوتقنية المرصودة، تمثلت التوصية الخاصة بنظام الأساسات في استخدام ركائز (أوتاد) خرسانية مسلحة محفورة بقطر تقريبي يبلغ 1.25 متر وعمق طرفي يصل إلى 19 متراً. وتشير النتائج إلى ضرورة مراعاة التباين في طبقات التربة تحت السطحية، ومستوى المياه الجوفية الضحل، والخصائص الكيميائية للتربة عند تصميم وتنفيذ الأساسات.

الكلمات المفتاحية: التوصيف الجيوتقني، اختبار الاختراق القياسي (SPT)، مقاومة القص المباشر، الركائز المحفورة، التربة الجبسية، تقاطع الزهراء، النجف.

1. Introduction

Bridges serve as vital elements of contemporary transportation systems as they ensure the continuity of road networks, promote economic growth, and enhance regional connection. The integrity and enduring functionality of bridge systems are determined not solely by the superstructure but also by the efficacy of the underlying foundation system. Hence, bridge foundation construction needs to be backed by comprehensive geotechnical investigations to identify the subsurface conditions and to estimate reliable engineering parameters for foundation evaluation and design (Modeer & Bharil, 2022). Bridge foundation engineering is a cyclic process involving field investigation, laboratory testing, geotechnical evaluation, and soil-structure interaction assessment for safe and economic performance of the foundation (ACI Committee 318, 2019).

Natural soils show considerable regional variability in their physical and mechanical properties due to differences in geological origin, depositional environment, weathering processes and groundwater conditions, unlike synthetic construction materials. This heterogeneity has direct impacts on the bearing capacity, settlement characteristics, compressibility and shear strength, and thus adds uncertainties in the design of foundations. Accordingly, systematic site investigation to accurately characterise the soil stratification and engineering properties is considered a key step for bridge engineering projects. Insufficient subsurface exploration has been often recognised as a significant factor in foundation problems, such as excessive settlement, uneven deformation, and reduced structural integrity (Hassan & Sennah, 2025; Sepúlveda-García & Alvarez, 2025).

The Standard Penetration Test (SPT) as standardised by ASTM D1586 is the most commonly used in-situ test for geotechnical site investigation worldwide. The SPT provides disturbed soil samples for identification and, at the same time, measures the penetration resistance by the blow count (N-value) which has been well correlated with the relative density, consistency, bearing capacity, settlement characteristics and shear strength. Despite the development of advanced in-situ testing techniques, the SPT remains a fundamental investigation tool for bridge foundation design because of its simplicity, cost-effectiveness and extensive empirical database. Hence, the joint analysis of SPT results and laboratory soil classification is increasingly recommended by modern engineering approaches instead of the separate assessment of each dataset (Sepúlveda-García & Alvarez, 2025). Despite the remarkable progress achieved in bridge geotechnical engineering, a comprehensive review of the latest literature shows that most of the published works have focused on the improvement of some aspects of the site investigation, such as the optimisation of the borehole layouts, quantification of geological uncertainty, geostatistical analysis of Standard Penetration Test (SPT) data, or

the development of advanced numerical methods for subsurface characterisation (Zhao et al., 2023; Oluwatuyi et al., 2023). However, a relatively few number of studies have been undertaken to consider the cohesive analysis of traditional geotechnical investigation data such as grain-size distribution, Unified Soil Classification System (USCS) classification, borehole stratigraphy and SPT resistance for evaluating the suitability of bridge foundation soils in real-world field conditions.

Recent studies have emphasised the growing importance of integrating field measurements with laboratory tests to enhance the reliability of the bridge foundation design. Advances in numerical modelling and machine learning have generated sophisticated methods for predicting the behaviour of soils, but the reliability of the predictions is fundamentally dependent on the accuracy of the geotechnical parameters obtained from site investigations. Therefore, traditional research methods, especially borehole logging, grain-size distribution assessment, and the Standard Penetration Test (SPT) are still the primary source of data for foundation design in transportation infrastructure projects (Fan et al., 2025; Modeer & Bharil, 2022).

The present research endeavours to fill the research gap by combining the results from laboratory and field tests into an integrated geotechnical assessment framework for bridge foundation applications. Previous studies focused on individual geotechnical parameters or a single in-situ testing method, whereas the present study integrates grain-size distribution, USCS classification, borehole stratigraphy and SPT data from multiple boreholes to provide a comprehensive assessment of subsurface conditions. Past bridge foundation studies and FHWA recommendations have highlighted the need for the integration of various sources of geotechnical information for foundation engineering, suggesting that the use of a single investigative parameter may not sufficiently characterise complex subsurface conditions (Mayne & Dumas, 1997; FHWA, 2016). The combination of laboratory soil classification and in situ penetration resistance gives a more reliable evaluation of the soil variability than the analysis of each dataset separately. Grain-size distribution is used to define the physical composition and classification of soil deposits. SPT blow counts represent the in-situ mechanical behaviour of the soil. The combined analysis improves the identification of competent bearing strata, enables a more robust assessment of settlement features and reduces ambiguity in preliminary foundation design (Robertson et al., 1983; Mayne & Dumas, 1997). The Al Zahra'a Bridged Intersection is located in Najaf Governorate in an area affected by the transition zone between the Mesopotamian Basin and the Arabian Platform. The area is dominated by Quaternary deposits associated with fluvial and evaporitic environments. The site studied is characterised by clayey silty sand with variable gypsum, gravel, and cemented sand over hard silty clay and very dense grey sand. The presence of gypsum and these heterogeneous deposits are important factors controlling the geotechnical behaviour of the site and the foundation conditions.

2. Materials and Methods

2.1: Study location

The study area was the proposed site of the Al Zahra'a Bridged Intersection, Najaf Governorate, Iraq. The project area is in Najaf city at a distance of about 500 m from the Culture Palace. Eight boreholes, labeled BH1, BH2, BH3, BH4, BH5, BH6, BH7, and BH8, were strategically placed along the proposed bridge route to examine the spatial heterogeneity of the subsurface soil conditions. Figure 1 illustrates a geographical map of the boreholes inside the research region and delineates the locations of the boreholes.

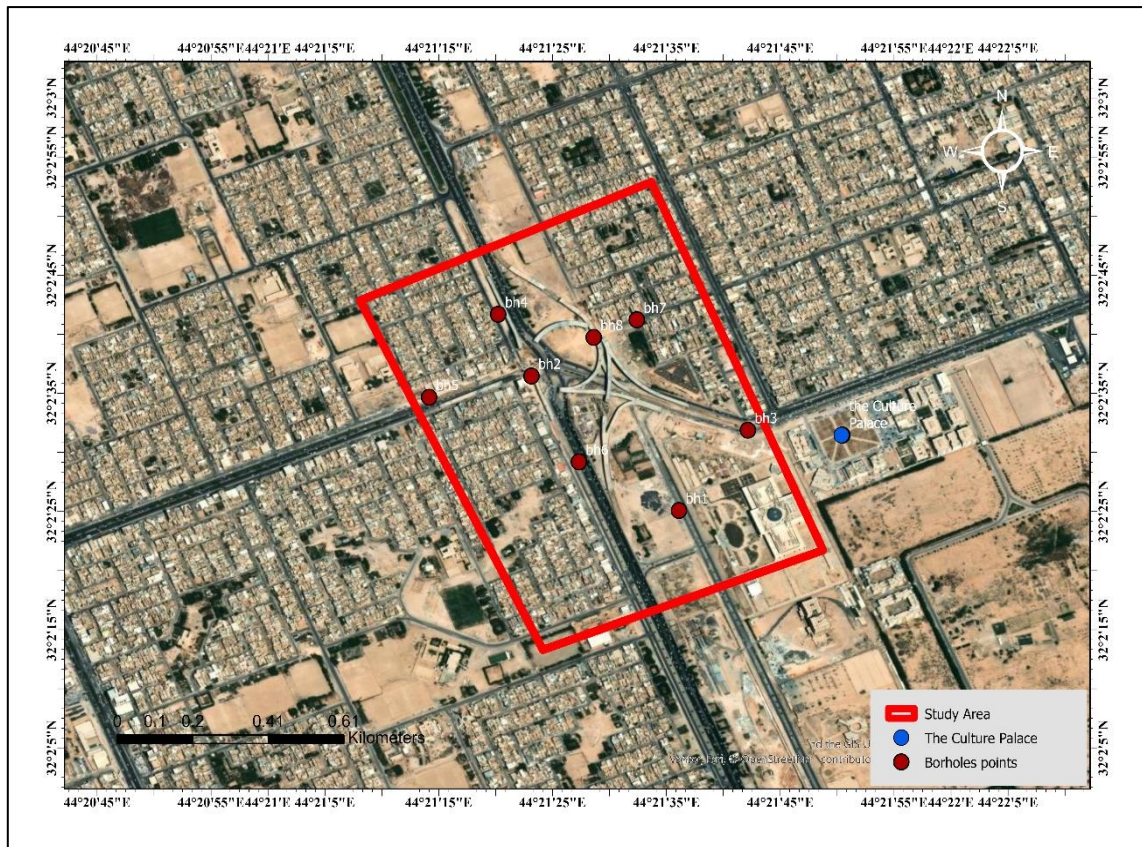


Figure 1: The location of the study area and borehole points layout.

2.2 Site Assessment Initiative

The field study involved drilling eight boreholes to sufficient depths to discern the underlying stratigraphy and evaluate the engineering characteristics of the soil layers. Standard Penetration Tests (SPT) were performed at regular depth intervals during drilling, according to ASTM D1586 standards, to evaluate the in-situ penetration resistance of the soil (ASTM, 2021). Disturbed soil samples were collected from the boreholes and transported to the laboratory for geotechnical analysis.

Laboratory analyses included: grain size distribution analysis, determination of sulphate content (SO_3), evaluation of total soluble salts (TSS), gypsum quantification, determination of calcium carbonate (CaCO_3), chloride content analysis and soil classification based on Unified Soil Classification System (USCS). Soil classification was carried out as per ASTM D2487 and particle-size distribution was determined as per ASTM D6913/D6913M (ASTM, 2021a; ASTM, 2021b). The laboratory results were combined with drill data and SPT information to formulate a complete geotechnical assessment of the subsurface profile (Das & Sobhan, 2018). The conducted research project allowed evaluating the soil stratification, particle size distribution, soil consistency and density as well as the chemical properties that could influence the durability and stability of bridge foundations (Coduto et al., 2016; FHWA, 2016).

2.3 Analysis of Grain-Size Distribution

The representative soil samples from the examined boreholes were subjected to grain-size distribution analyses to determine the relative proportions of gravel, sand and fine fines. The results from the tests were used to determine the soil texture, the changes in soil composition with depth and to classify the soil according to the Unified Soil Classification System (USCS). Particle size distribution is the basic parameter to the drainage characteristics, permeability, compressibility and engineering characteristics of foundation soils (ASTM D6913/D6913M; Das & Sobhan, 2018).

2.4 Standard Penetration Test (SPT)

The Standard Penetration Test (SPT) was conducted at specified depth intervals while drilling in accordance with ASTM D1586. The recorded blow counts (N-values) were utilized to assess the relative density of non-cohesive soils and the consistency of cohesive soils. The SPT findings also yielded significant insights into the fluctuation of soil strength with depth and were utilized to pinpoint suitable bearing strata for bridge foundation support (ASTM, 2021; FHWA, 2016; Bowles, 1996).

2.5 Comprehensive Geotechnical Assessment

The subsurface soil suitability was evaluated on the basis of the borehole stratigraphy, the results of the grain size distribution, the laboratory soil classification and the SPT data.

The integrated evaluation of laboratory and field investigations offers a more reliable assessment of the subsurface conditions than a single testing approach, and therefore enhances the selection of foundations and reduces the uncertainty in geotechnical design (Robertson et al., 1983; Mayne & Dumas, 1997; FHWA, 2016).

2.6 Direct Shear Examination

Direct shear tests were performed on representative soil samples retrieved from the boreholes under investigation to determine the shear strength parameters, namely, cohesion (c) and angle of internal friction (ϕ). Tests were carried out according to ASTM D3080/D3080M for drained loading conditions. The obtained values of shear strength were used to study the shear resistance of the underlying soils and to establish their applicability for the support of bridge foundations. These indicators are important for the evaluation of the bearing capacity, stability of the slope and performance of the foundation in the case of static loading (ASTM, 2020; Das & Sobhan, 2018; Bowles, 1996).

2.7 Chemical Assessments

Selected soil samples were chemically analysed for sulphate (SO_4), total soluble salts (TSS), gypsum, calcium carbonate (CaCO_3) and chloride levels. The assessments were conducted to evaluate the chemical nature of the subsurface soils and to identify any potentially hazardous conditions that could affect the long-term integrity of concrete foundations and reinforcing steel. The chemical properties were investigated following the existing geotechnical and roadway engineering standards (FHWA, 2016; Das & Sobhan, 2018) to assess the possible risks related to the construction of a foundation.

2.8 Examination and Elucidation of Data

The geotechnical assessment involved the synthesis of borehole logs, grain-size distribution studies, laboratory classifications, direct shear testing, chemical analyses, and Standard Penetration Test (SPT) data. Soil profiles were analysed to determine the vertical and horizontal diversity of materials below the studied bridge site. The combination of laboratory and field data enabled recognition of competent bearing layers, analysis of engineering soil characteristics and appraisal of the overall suitability of the subsurface soils for construction of bridge foundations.

Furthermore, the integrated analysis reduced the uncertainty related to the use of a single investigation method and gave an in-depth understanding of the geotechnical conditions affecting the foundation performance. The approach has been widely recommended for road infrastructure projects where subsurface variability significantly impacts foundation design and construction (Robertson et al., 1983; Mayne & Dumas, 1997; FHWA, 2016).

3. Results

3.1 Borehole Stratigraphy and General Soil Composition

The subsurface conditions were evaluated from eight boreholes (BH1–BH8), each extending to approximately 29.3–31.0 m. The available borehole descriptions indicate a predominantly sandy subsurface profile, with variable amounts of gravel and fine material. The reported

descriptions also show vertical variability, with denser granular strata occurring at greater depths in several boreholes. This variability indicates that the bridge alignment cannot be represented adequately by a single uniform soil profile Figure 2.

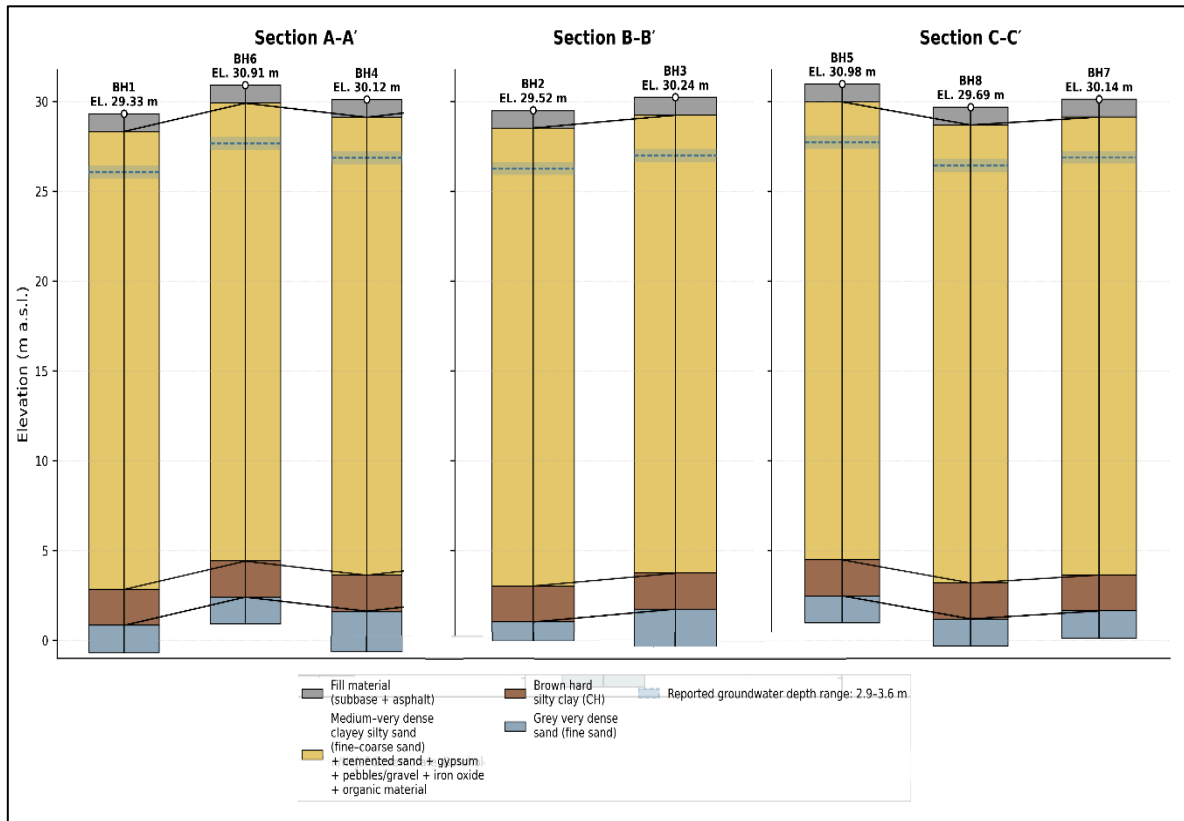


Figure 2: Generalized geological soil profile.

3.2 Grain-Size Distribution and USCS Classification

The reported grain-size results confirm the predominance of sand in the investigated samples Figure 3. Representative reported samples include approximately 63% sand at 3.0–3.5 m in BH2, approximately 72% sand at 3.5–4.0 m in BH3, approximately 94% sand with 4% gravel and 2% fines at 7.5–8.0 m in BH4, approximately 90% sand with 5% gravel and 5% fines at 5.5–6.0 m in BH7, and approximately 90% sand with 4% gravel and 6% fines at 3.5–4.0 m in BH8. The BH2 sample at 3.0–3.5 m is explicitly classified in the manuscript as poorly graded sand (SP), based on $D_{10} = 0.094$ mm, $D_{30} = 0.170$ mm, $D_{60} = 0.393$ mm, $C_u = 4.18$, and $C_c = 0.78$. The available text does not provide complete numerical grain-size parameters for every reported sample; therefore, USCS classifications should only be assigned where the laboratory data support them directly. Most of the samples are grouped near the “Sand Vertex” which indicates the homogeneity of the soil with classification from poorly graded sand (SP) to silty sand (SP-SM) according to the Unified Soil Classification System (USCS) Table 1. Soils (clay/silt) are practically absent, limited to very small zones. The few samples deviating from this base cluster are characterised by an increased gravel content, particularly in surface samples Figure 3.

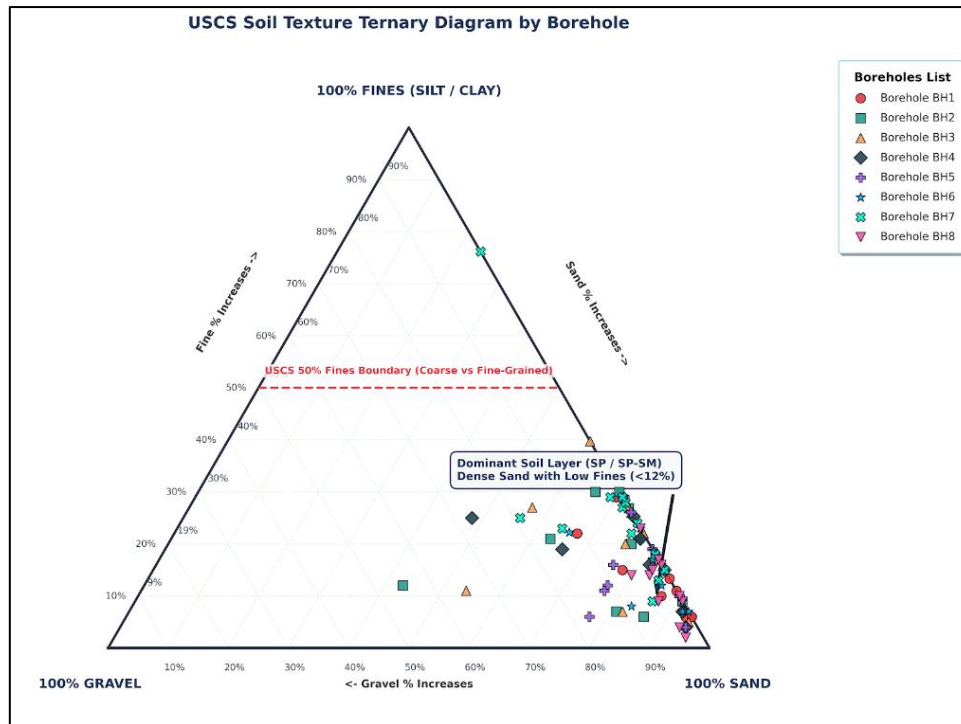


Figure 3: Ternary soil textural classification diagram (BH1-BH8).

Table 1: Subsoil Stratification and USCS Soil Classification

Depth Range (m)	Soil Description	USCS Symbol	Key Characteristics & Remarks
0.0 – ~1.0	Fill Material	-	Surface layer consisting of asphalt and subbase materials.
~1.0 – 26.5	Clayey Silty SAND	SM / SC(or SM-SC)	Medium to very dense; contains pebbles, gravel, high gypsum content (up to 29.5%), organic matter, and iron oxides.
26.5 – 28.5	Brown Hard Silty CLAY	CH	High plasticity clay; hard state, Liquid Limit (LL) ranges from 55.6% to 89.8%.
28.5 – 30.0	Grey Fine SAND	SP / SM(or SP-SM)	Very dense state.

3.3 Standard Penetration Test (SPT) Results

The SPT results show substantial variation in penetration resistance with depth and between boreholes Figure 4. The reported representative values include $N = 50$ at 3.5–4.0 m in BH3, $N = 40$ at 7.5–8.0 m in BH4, $N = 28$ at 2.0–2.5 m in BH6, $N = 33$ at 5.5–6.0 m in BH7, and $N = 30$ at 3.5–4.0 m in BH8. The manuscript also reports SPT values greater than 50 blows in deeper strata of several boreholes. These results indicate that the subsurface contains medium-dense to dense and locally very dense granular layers. Because SPT values can be affected by testing and overburden conditions, the reported N -values are interpreted here together with the borehole descriptions and laboratory results rather than as stand-alone design parameters.

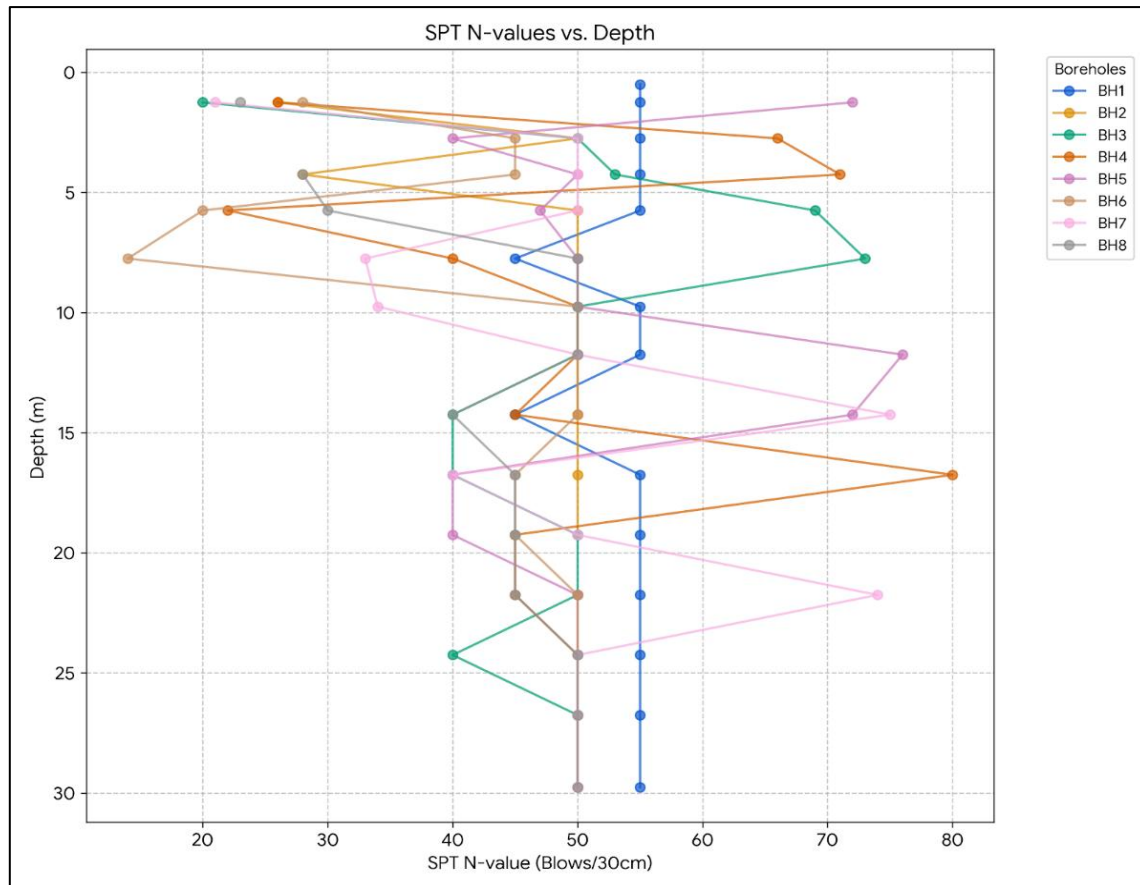


Figure 4: SPT N-value versus depth for Boreholes BH1–BH8.

3.4 Direct Shear Test Results

Direct shear testing was reported for representative samples from BH2–BH8. Measured cohesion was 0 kN/m² for all listed samples, while the angle of internal friction ranged from 34° to 40°. The highest reported value was 40° at 22.0–22.5 m in BH4, while the lowest was 34° at 29.5–30.0 m in BH4. The consistently zero measured cohesion and the relatively high friction angles are consistent with the predominantly granular nature of the reported samples Table 2. These parameters provide useful supporting evidence for evaluating shear resistance, but they should be interpreted at the tested depths and should not be generalized automatically to all strata.

Table 2. Summary of direct shear parameters

Borehole	Depth interval (m)	c (kN/m ²)	φ (°)
BH1	14.5–15.0	0	35.0
BH1	19.0–19.5	0	37.5
BH2	4.5–5.0	0	38.0
BH2	20.5–21.0	0	38.5
BH2	28.0–28.5	0	35.5
BH3	3.5–4.0	0	35.6
BH3	7.5–8.0	0	38.5
BH3	24.5–25.0	0	36.5
BH4	4.0–4.5	0	37.5
BH4	5.5–6.0	0	36.5
BH4	22.0–22.5	0	34.0
BH4	29.5–30.0	0	34.0

BH5	13.5–14.0	0	36.4
BH5	21.0–21.5	0	38.5
BH6	5.0–5.5	0	37.0
BH6	13.5–14.0	0	38.5
BH6	21.0–21.5	0	38.5
BH7	5.5–6.0	0	38.5
BH7	7.5–8.0	0	39.0
BH8	3.5–4.0	0	39.0
BH8	25.0–25.5	0	37.0
BH9	18.5–19.0	0	37.5
BH9	11.0–11.5	0	37.5

3.5 Groundwater

Groundwater was encountered at about 2.9–3.6 m below ground surface during drilling Figure 2.

The relatively shallow groundwater level is significant in the construction of bored piles, as groundwater can influence the stability of the borehole, removal of fine particles, concrete placement, and quality of construction.

3.6 Chemical Properties

The chemical properties of the investigated soils were analysed for 40 samples, except calcium carbonate and chloride, for which 39 and 36 samples were analysed, respectively. The results suggest considerable variation in the chemical composition of the subsurface soils. The water-soluble sulphate (SO₃) content ranged from 0.012% to 13.750%, with a mean value of 2.080%, a standard deviation of 3.082% and a median of 0.399%. The large standard deviation and the considerable difference between the mean and median values point to a highly heterogeneous distribution of sulphate concentrations and the occurrence of locally elevated sulphate contents. Total soluble salts (TSS) also varied widely from 0.150% to 30.100% with an average of 4.688%, a standard deviation of 6.644%, and a median of 0.985%. Gypsum content ranged from 0.025% to 29.564%, with a mean of 4.473%, a median of 0.859%, and a standard deviation of 6.626%. The results show that the soluble and gypsum-bearing constituents of the soils studied vary considerably in space and composition. The calcium carbonate ranged from 2.000–45.000% with an average of 11.718%, a standard deviation of 8.994%, and a median of 8.000%. This illustrates the variable concentrations of carbonates within the investigated subsurface materials.

Chloride (Cl⁻) content was relatively low, ranging from 0.017% to 0.077%, with an average of 0.019%, a standard deviation of 0.010%, and a median of 0.018%. In general, the chemical tests show high variability in sulphate, total soluble salts, gypsum and carbonate contents and relatively low chloride concentrations. The observed chemical heterogeneity is an important factor in the assessment of the interaction between the subsurface soils, groundwater and foundation materials, especially where elevated sulphate and gypsum contents may influence the long-term durability of buried concrete elements Table 3.

Table 3: Statistical Summary of Soil Geochemical Parameters

Parameter	No. of Samples	Mean	Std. Deviation	Median	Minimum	Maximum
Water-Soluble Sulphate (SO ₃) (%)	40	2.080	3.082	0.399	0.012	13.750
Total Soluble Salts (TSS) (%)	40	4.688	6.644	0.985	0.150	30.100

Gypsum Content (CaSO ₄ ·2H ₂ O) (%)	40	4.473	6.626	0.859	0.025	29.564
Calcium Carbonate (CaCO ₃) (%)	39	11.718	8.994	8.000	2.000	45.000
Chloride Content (Cl ⁻) (%)	36	0.019	0.010	0.018	0.017	0.077

3.7 Foundation Suitability and Foundation Recommendation

The integrated geotechnical interpretation indicates that dense to very dense sandy and gravelly strata occur within the investigated profile and represent the more competent materials for foundation support. The manuscript reports a geotechnical recommendation for bored reinforced-concrete piles with a diameter of 1.25 m and a founding depth of 19 m, with an allowable capacity of approximately 500 tons per pile and an ultimate capacity of approximately 1,500 tons per pile using a safety factor of 3. These values are presented as recommendations from the underlying geotechnical report rather than as newly calculated pile capacities in the present study. Final pile design should therefore be based on the project's detailed load requirements, pile analysis, groundwater conditions, construction method, and applicable design code.

4. Discussion

4.1 Importance of the Subsurface Profile to Engineering

The most important feature of the site is the predominance of a thick sandy deposit from about 1 to 26.5 m depth. The material is medium to very dense with variable amounts of cemented sand, gypsum, gravel, pebbles and iron oxides.

From a foundation-engineering viewpoint, the presence of a thick dense granular deposit represents a very different foundation environment than that of thick soft cohesive deposits. The relatively high friction angles obtained from the direct shear testing support further the interpretation of the sandy sequence as a friction-dominated material.

But the heterogeneity of the deposit should not be ignored. Cementation, gravel, gypsum accumulation and local variations in grain size can cause significant variations in both SPT resistance and pile-soil interaction.

4.2. Definition of Shear Strength

The direct shear results show negligible measured cohesion and relatively high friction angles. This behaviour is consistent with the expected response of granular soils, in which the shear resistance is largely controlled by the interparticle friction, arrangement, density and effective stress of particles.

The range of about 34–39° indicates relatively strong friction behaviour. However, a single representative value for design should only be used if accompanied by a proper statistical evaluation and consideration of the specific foundation depth.

4.3. SPT and Relative Density

The SPT results are generally consistent with the classification of the main sandy unit as medium to very dense.

The agreement between SPT interpretation and direct shear results is significant because the two datasets provide complementary information:

- SPT denotes in-situ penetration resistance;
- direct shear gives laboratory shear strength parameters.

Their integration therefore provides a more robust basis for interpreting the engineering behaviour of the soil than either dataset taken alone.

4.4. Implications for groundwater

The groundwater level of 2.9–3.6 m is of particular importance for bored-pile construction.

For bored piles going down to approx 19 m the excavation of the piles will be significantly lower than the observed groundwater level. Construction procedures must therefore be designed to avoid borehole instability and uncontrolled inflow.

The original investigation recommended pumping through sumps and side ditches where foundation excavations extend below the groundwater. It also proposed use of filters at intake pipes to reduce removal of fine soil particles.

The final construction methodology for bored-pile construction should be determined by the contractor and geotechnical engineer based on actual groundwater conditions and borehole stability during construction.

4.5 Chemical Aggressiveness

One of the main results of the investigation is the reported variability and local elevated sulphate and gypsum contents.

Soil sulphate content varies up to 13.75 % and gypsum content varies up to 29.564 %. Groundwater sulphate concentration is up to approximately 203.433 mg/L.

Such values justify the consideration of chemical exposure as a major durability factor for underground reinforced-concrete elements.

The original investigation therefore recommended sulphate-resisting cement and specified further protective measures including limiting water penetration into the foundation zone and applying protective coatings to concrete surfaces in contact with soil.

4.6. Appropriateness of Bored Piles

The original report proposed bored reinforced-concrete piles with a diameter of 1.25 m and an approximate tip depth of 19 m.

The proposed depth places the pile toe within the deeper competent soil sequence as identified by the investigation. This recommendation is also consistent with the requirement of transferring structural loads through near-surface fill and upper soil zones into deeper, stronger materials.

However, the reported capacity of approx. 500 tonnes should be regarded as a design recommendation of the original geotechnical investigation, and not an independently verified capacity. The report itself recommended pile load testing to determine actual capacity and length required.

This distinction is important when you convert an engineering investigation to a scientific paper.

4.7. Study Limitations

It is important to explicitly acknowledge several limitations.

First, the groundwater observations are conditions observed during drilling, and are not necessarily the maximum seasonal groundwater elevation.

Second, the original report is largely graphical in relation to SPT information. To do a quantitative statistical analysis of the SPT data set, one would have to digitise or otherwise directly access the original numerical records.

Third, the original investigation indicates a pile capacity of approximately 500 tonnes, but the report recommends field pile load testing to confirm this. Thus, the value reported should not be interpreted as an independently validated ultimate or allowable capacity.

These limitations do not detract from the engineering value of the investigation, but rather set the level of certainty that can be attached to its interpretation.

5. Conclusions

The integrated interpretation of the geotechnical investigation resulted in the following conclusions for the Al Zahra'a Bridged Intersection:

1. The subsurface profile consists of approximately 1 m of fill material overlying a thick sandy sequence to a depth of approximately 26.5 m.

2. The main soil unit is predominantly clayey silty sand, varying from fine- to coarse-grained, with variable amounts of cemented sand, gypsum, gravel, pebbles, organic material, and iron oxides.
3. SPT and direct shear results were interpreted to show the principal sandy unit to have a relative density varying from medium dense to very dense.
4. Direct shear tests indicate mainly frictional behaviour, with measured cohesion values close to zero and friction angles typically in the range of about 34° to 39°.
5. A hard brown silty clay layer (CH) between approximately 26.5 and 28.5 m depth, overlain by very dense grey sand.
6. In the drilling work conducted, groundwater was struck at a depth of approximately 2.9 to 3.6 m below the surface.
7. Parts of the investigated soil profile and also concrete durability are important design considerations, as chemical analyses show significant sulphate and gypsum contents.
8. The original geotechnical investigation suggested bored reinforced-concrete piles of 1.25 m diameter with approximate pile tips at 19 m depth.
9. A factor of safety of 3.0 indicated an approximate pile capacity of 500 tonnes; however, it was recommended that pile load testing be conducted to verify the actual field capacity and required pile length.
10. The overall findings demonstrate the significance of considering subsurface stratigraphy, SPT response, direct shear strength, groundwater conditions and chemical characteristics in developing foundation solutions for major bridge infrastructure.

6. Recommendations

- Foundation design should use the complete borehole and SPT dataset together with laboratory soil classification and shear-strength results.
- Dense to very dense granular strata identified at depth should be evaluated as potential bearing zones, with the founding level verified against the final structural loads and settlement criteria.
- The reported 19 m founding depth and pile capacities should be treated as recommendations from the underlying geotechnical report and independently verified during final pile design.
- The complete numerical chemical test results should be added to the manuscript and assessed against the durability requirements of the selected concrete and reinforcement system.
- Complete grain-size and USCS results should be tabulated for all representative samples so that the spatial and vertical variability of the site can be reproduced and independently evaluated.
- Where design decisions depend on SPT-derived parameters, appropriate corrections and project-specific correlations should be documented.
- Future investigations may incorporate CPT, geophysical methods, and numerical analyses to improve the characterization of lateral variability and pile–soil interaction.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no conflict of interest.

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