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Spatial Variation of Shallow Soil Bearing Capacity Using SPT Data and MATLAB Analysis

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Abstract

The current research examines the spatial distribution of shallow bearing capacity in Al-Najaf City through the use of Standard Penetration Test (SPT) data supplemented with advanced computational tools in MATLAB. A high-quality geotechnical survey of 464 boreholes was carried out, with drilling performed at depths ranging from 18 m to 35 m below the current ground surface. To assess the shallow foundations, the top 12 m of the soil profile was analyzed. To measure in-situ soil resistance, SPT measurements were taken at specified depth intervals in every borehole. The raw SPT N-values were adjusted for overburden pressure, an energy-correction parameter, and groundwater effects; other minor adjustments were considered negligible based on their minimal impact on the final dataset. These corrected N-values formed the basis for calculating both ultimate and allowable bearing capacities using empirically developed correlations. MATLAB surface-interpolation procedures were used to generate georeferenced thematic maps that depict the lateral variation of bearing capacity within the 0–12 m depth interval. The resulting spatial analysis shows a significant increase in the bearing capacity of the northern and western regions of Al-Najaf, correlating with increases in urbanization and infrastructure density. The predictive geotechnical maps developed in this study can be considered a highly robust, cost-effective, and timely tool for initial subsurface engineering surveys to guide sustainable city development, infrastructure design, and optimization of foundation engineering.

Keywords: Spatial Variation; Bearing Capacity; Shallow Foundation; Al-Najaf; SPT; MATLAB.

1. Introduction

Accurate determination of soil bearing capacity is an essential requirement under soil structure design and civil engineering safety analysis [1]. Traditional methods tend to rely on large-scale field research and laboratory studies that can often be costly and time-consuming, particularly in highly dynamic urban environments. This has led to an increased literature that has explored empirical and spatial techniques with the objective of coming up with reliable geotechnical parameters to form preliminary design.

The Standard Penetration Test (SPT) is one of the most common in-situ testing techniques because of its simplicity, low cost, and universal standardization. However, SPT itself is always a point-based tool, which suggests that the outcomes of the test do not necessarily reflect the spatial heterogeneity of the subsurface conditions on large scales. The recent studies to overcome this shortcoming have synthesized SPT data with Geographic Information Systems (GIS) and computational modeling systems to generate continuous thematic maps of bearing capacity. Similarly, Karkush et al. (2020) [2] and Sabaa et al. (2023) [3] combined GIS with the SPT measurements in Basrah to create bearing-

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capacity maps, but Salman et al. [4] modeled the compositions of Baghdad using MATLAB interpolation. Other contributions to the region, such as Al-Mirza et al. (2024) [5] in Baghdad, Karkush et al. [6] in Al-Basrah, Amini et al. [7] in Kabul City, and Hassan et al. (2022) [8] in Pakistan, have proven the effectiveness of geostatistical analysis and interpolation (e.g., kriging, inverse distance weighting) in determining spatial variation of soil strength. Outside Iraq, Sharo et al. (2019) [9] applied kriging in GIS to generate geotechnical zonation maps (including SPT-N, cohesion, friction angle, bearing capacity, and pile capacity at 3, 6, and 10 m) based on 222 boreholes in the northern Dead Sea area in Jordan, and Aqeel et al. (2023) [10] used both 2-D geospatial and 3-D geospatial modeling in Khobash, Saudi Arabia, to map These research findings highlight the increased importance of the incorporation of spatial data in geotechnical engineering.

Although these improvements have been made, there are still some gaps in research. Current literature has limitations of small datasets with sparse borehole spacing, thus reducing the accuracy of the ensuing maps. Furthermore, few studies explicitly adjust SPT values to include variables like overburden pressure, groundwater level, and hammer energy efficiency that are necessary in the pursuit of a sense of consistency in the geotechnical interpretation. Even though Geographic Information Systems (GIS) have widely been used in the field, very few studies have utilized MATLAB-based interpolation techniques to simulate the spatial variation of shallow bearing capacity in large urban areas.

This study aims at overcoming these gaps by developing an elaborate geotechnical database of 464 boreholes that were acquired across the entire region of Najaf, Iraq. The top 12 m of the subsurface has been used as the analysis limit, as it is most relevant to the design of shallow foundations. The value of the overburden-corrected Standard Penetration Test (SPT) is used to estimate ultimate and allowable bearing capacities, and the MATLAB-based spatial meters are used to create depth-specific thematic maps. This methodology has the potential to not only augment the accuracy of initial foundation design but also to provide planners and engineers with a practical decision-support tool towards sustainable urban development.

The rest of this manuscript is structured as follows. Section 2 outlines the field where the research was carried out and gives a detailed description of the field studies. Section 3 elaborates the Standard Penetration Test (SPT) procedure and the corrections towards it. Section 4 contains the estimation of the bearing capacity of the soil based on the corrected SPT data, and Section 5 provides the description of the numerical meters and spatial interpolation methods implemented in MATLAB. Section 6 explains the spatial analysis, and Section 7 concludes, summarizing the key findings and providing directions for further research.

2. Description of Study Area and Field TESTS

The city of Al-Najaf is one of the major urban centers in the southern part of Iraq, geographically aligned at about 32.00°N latitude and 44.32°E longitude (see Figure 1). The area is characterized by a semi-arid climate and a topography that is uniformly flat, which in turn has a high lack of yearly precipitation of about 100 mm, and the continuous high-rate urban sprawl due to residential infrastructure, commercial infrastructure, and religious infrastructure necessitates the emphasis on the need to adopt a sustainable and high-resolution method of geotechnical characterization [11, 12]. Alluvial deposits of Quaternary age are predominant in the subsurface profile with interlaced sequences of clayey silts, sandy clays, and isolated layers of silty sands [12]. The groundwater table varies seasonally, and its depth is typically 2-4 m below the natural ground surface [13, 14]. The restricting conditions of the ground, which have an arid climatic regime coupled with spatially variant land use and loading conditions, require complex restrictions on foundation design, which therefore require proper site-specific geotechnical studies in order to make cost-effective and safe development.

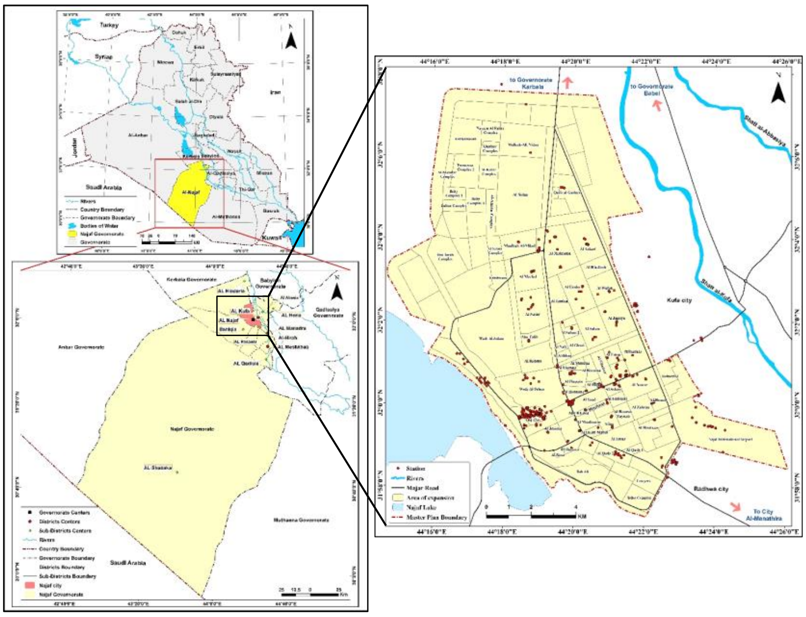
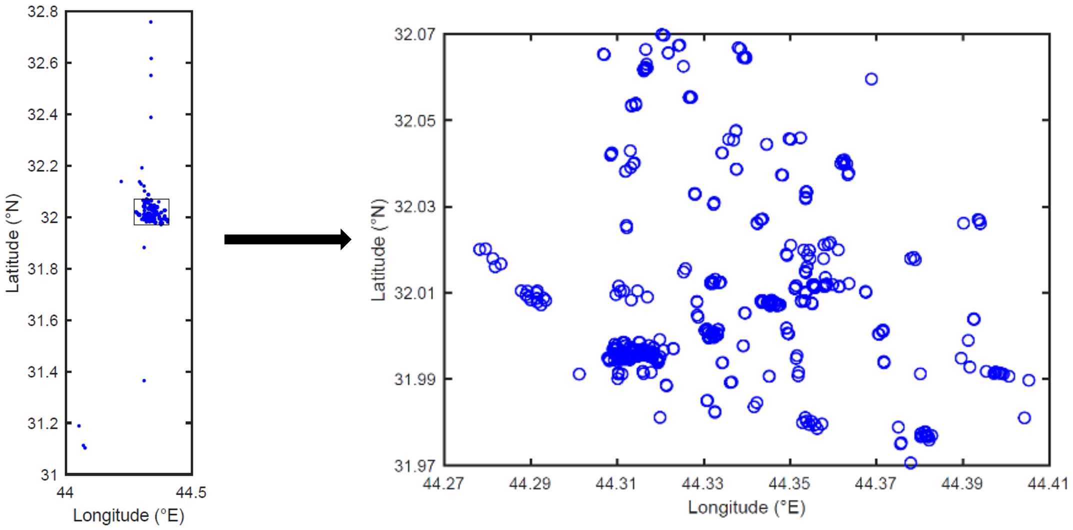


Figure 1. Locations of the drilled boreholes in Najaf City

Data from 464 boreholes were used in this study. Figure 2 gives their spatial distribution. Figure 2-a demonstrates the geographical coverage of all the boreholes, with some scattered and clustered distributions. Figure 2-b shows the zoomed view of the urbanized region, which has the greatest concentration of boreholes, which is sufficient to assess the geotechnical representation of shallow foundations. The analysis was, however, limited to the top 12 m of the soil profile, which is the most applicable depth range in understanding shallow foundation performance, given the fact that most of the low- to mid-rise buildings have shallow footing, which is in this range. The location of the boreholes was planned systematically so that the coverage of the different geological formations and urban land-use categories was evenly spread, covering residential areas, commercial, as well as infrastructural areas.

Such a distribution allowed capturing lateral and vertical variability in subsurface conditions affecting bearing capacity. Standard Penetration Tests (SPTs) were systematically performed at regular vertical intervals of 1.5 meters, corresponding to testing depths of 1.5, 3.0, 4.5, 6.0, 7.5, 9.0, 10.5, and 12.0 meters. The SPT, a widely adopted in-situ testing method, provides a measure of soil resistance to dynamic penetration, expressed as the number of blows (N-value) required to drive a standard sampler 30 cm into the soil after an initial seating drive of 15 cm. These N-values serve as proxies for soil strength and stiffness and are commonly used in empirical formulations for estimating bearing capacity and settlement characteristics.



(a) Regional-scale distribution (b) Zoomed-in view of the main concentration within the urbanized zone

Figure 2. Locations of boreholes used in the analysis

Disturbed soil samples were collected by piston sampling using split-spoon samplers during drilling and sent to the laboratory. The principal tests have been aimed mainly at establishing intrinsic index properties, e.g., natural moisture content and specific gravity, which are central in the classification and indirect measure of solid behavior under loading [15]. The groundwater level measurements were taken again after an equilibration period of 24 hours following drilling to minimize transient effects of both drilling and pumping operations, and the nature of the measurements represented the hydrogeologic steady state. Such readings are critical in the interpretation of good stress conditions and the correction of overburden pressure of SPT results [16, 17].

Field and laboratory data have been gathered and are being prepared, digitized, and incorporated into a computational construct based on MATLAB. Complex geostatistical and interpolation methods, including inverse distance weighting (IDW) and kriging, were applied to get a picture of the spatial distribution of the corrected N-values and to estimate the values of the shallow bearing capacity in the whole study region. To account visually and quantitatively for the variable bearing capacity with depth and location, three-dimensional (3D) models of the surface were created. Such geospatial products provide a significant means of pre-constructing evaluation, helping to exploit ideal location, structural design, and risk management in the city design.

The workflow adopted in this study is summarized in Figure 3, which outlines the sequence from data collection and processing to numerical modeling, spatial analysis, and interpretation.

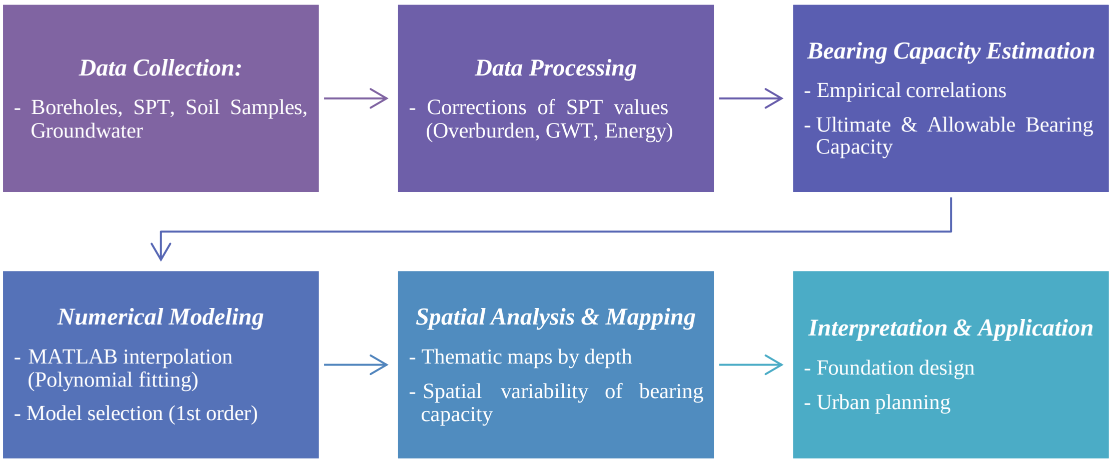


Figure 3. The workflow of the Study

3. Standard Penetration Tests and Corrections

The Standard Penetration Test (SPT) remains one of the most extensively employed in-situ geotechnical investigation techniques, particularly advantageous in granular or mixed soil conditions where undisturbed sampling is difficult or impractical. The procedure yields a penetration resistance index, commonly referred to as the "N-value," which quantifies the number of blows required to advance a split-spoon sampler 300 mm into the soil using a standardized free-fall hammer of known weight and drop height.

While the raw N-value provides a practical measure of soil resistance, it is inherently influenced by a range of procedural and site-specific variables that may introduce significant variability or systematic errors. Therefore, uncorrected N-values often do not conform to reference standards, and their direct use in engineering design may yield misleading estimations of geotechnical parameters such as bearing capacity, relative density, and settlement potential.

To mitigate these discrepancies, a series of empirical correction factors is typically applied to standardize the N-value for use in analytical and design frameworks. These corrections accommodate deviations arising from borehole diameter, drill rod length, hammer energy efficiency (often referred to as the energy ratio), the type and condition of the sampling equipment, and confining pressure effects, particularly due to overburden stress and groundwater table (GWT) location. The corrected N-value (commonly denoted as N_{60}) serves as a more reliable basis for applying empirical correlations in geotechnical analyses.

Burrough et al. [18] highlighted several common sources of error that can compromise the integrity of SPT measurements. These include deviations from the standard hammer drop height of 30 inches (76 cm), use of drill rods exceeding the recommended diameter of 2.5 cm, excessive rod lengths (typically over 50 meters), impediments to the free fall of the hammer, deformation or wear of sampler tips, premature driving of the sampler before formal blow count initiation, improper seating of the sampler on undisturbed soil layers, and human errors in blow count recording or penetration depth measurement. Given the widespread reliance on SPT-derived parameters in empirical geotechnical design methods such as those used for estimating shallow and deep foundation capacities, liquefaction potential, and settlement behavior, ensuring the accuracy and repeatability of corrected N-values is critical. Incorporating rigorous quality control and adherence to standardized testing protocols (e.g., ASTM D1586) significantly enhances the reliability of soil characterization and, by extension, the safety and economy of civil engineering infrastructure founded on these assessments [6, 19].

To standardize the results, the raw blow count (N) is adjusted to obtain the corrected blow count, denoted as N1(60), as shown in Equation 1 [20]. This corrected value is essential for reliable correlation with soil properties.

$$N_{1(60)} = N. C_{WC}. C_{NC}. C_{EC}. C_{BC}. C_{RC} \quad (1)$$

where $N_1(60)$ is SPT value corrected to 60% hammer energy efficiency; N is Field-recorded SPT blow count; C_{WC} is Coefficient of the groundwater table correction; C_{NC} is Coefficient of overburden pressure correction; C_{EC} is Coefficient of energy ratio correction; C_{BC} is Coefficient of borehole diameter correction; and C_{RC} is Coefficient of drill rod length correction.

In the context of this study, the drill rod length during SPT testing exceeded 6 meters. Consequently, the rod length correction factor (CR) was set to 1.0, consistent with the recommendations of Lutenegger [21], who indicate that this correction becomes negligible for rod lengths exceeding 6 meters. Conversely, a CR value of approximately 0.75 is typically applied for rod lengths shorter than 3 meters, reflecting the higher energy transmission efficiency due to reduced mass and inertia. Regarding borehole diameter, the drilling convention employed resulted in a borehole diameter of 10 centimeters. This value falls below the critical threshold at which borehole size significantly influences penetration resistance.

As such, the borehole diameter correction factor (CBC) was also conservatively assumed to be 1.0. It is well-documented that larger borehole diameters tend to reduce confinement around the sampler, resulting in artificially lower N-values due to the decreased lateral support provided by the surrounding soil matrix. Although multiple correction factors can theoretically be applied to the raw SPT N-values to account for procedural and environmental variability, in practical geotechnical applications, only a select subset of these are routinely implemented. The most frequently applied adjustments include:

- C_{NC}, which corrects for overburden pressure to normalize the confining stress acting on the soil during testing,
- C_{WC}, which accounts for the presence and position of the groundwater table, as saturation can significantly affect soil behavior during dynamic loading, and
- C_{EC}, which corrects for variations in the actual energy transferred from the falling hammer to the drill rods, relative to the nominal energy level assumed in standardized testing conditions.

The addition of correction factors is critically important to enhance the comparability as well as the reliability of the Standard Penetration Test (SPT) data taken under different field conditions.

A sensitivity analysis was performed with limited factors to determine the effect of the factors of correction on the calculated bearing capacity. The alteration of the allowable bearing capacity over a range of about 1020 per cent was obtained with changes in the energy correction factor (CEC), overburden pressure correction (CNC) and groundwater correction (CWC) used in the range that had been reported in literature. The highest effect which was felt was CNC especially at depths that were shallow, unlike CEC and CWC which had modest effects. Notably, the general patterns of spatial distributions did not change much implying that the thematic maps are strong enough to give an initial geotechnical zoning despite the change in correction parameters. Prospective studies can be carried out with a more rigorous probabilistic sensitivity analysis to measure with more certainty the limits of uncertainties.

These specific parameters of correction will be discussed in detail in the following sections along with their theoretical foundation and implications.

3.1. Coefficient of Overburden Pressure Correction (CNC)

When a series of Standard Penetration Tests (SPTs) is conducted at a series of increasing depths of a comparatively uniform soil deposit, the Ns measured tend to increase in the direction of increasing depth. This gradual build up is strongly related to the influence of the high levels of vertical effective stress which strengthens the lateral confinement of soil particles around the sampler. The resultant constraint makes the soil hard to drill into and hence exaggerates the number of blows recorded. Nevertheless, these depth variations are not necessarily associated with changes in the intrinsic strength or density of the soils but rather depend on the existing in-situ stress conditions. The overburden correction is used to enable a significant comparison of the SPT results of different depths or locations, and to separate the effect of overburden pressure and penetration resistance. This correction normalizes the observed (or raw) N-values to a standardized effective overburden pressure commonly set at 100 kPa, which serves as a reference stress level in many geotechnical correlations.

Fenton & Griffiths [22] introduced a widely accepted correction methodology, particularly applicable to cohesionless soils exhibiting a relative density in the range of 40% to 60%. The correction involves the application of an overburden correction factor (denoted as C_{NC}), which adjusts the field N-value to a corrected value (N_{60}) as follows:

$$C_{NC} = \frac{200}{100+\sigma'_o} \tag{2}$$

where σ'_o is the effective overburden pressure in kPa. In the current study, subsurface conditions across all sites consist predominantly of soft to stiff silty clay layers. To calculate overburden stress, the dry and saturated unit weights of the soil are assumed to be 15 kN/m³ and 17 kN/m³, respectively.

3.2. Coefficient of Groundwater Correction (CWC)

Peck et al. [23] suggested a groundwater correction mechanism of Standard Penetration Test (SPT) data to overcome the impact of pore water pressure in the measured penetration resistance. Their method uses a linear interpolation model to calculate a correction factor that modifies the raw N -value depending on the location of the groundwater table with respect to the depth of the testing and foundation level. Directly related to groundwater presence, effective stress in saturated soils, especially granular material, becomes less so and thus, interparticle friction and thereby, penetration resistance is also reduced. Consequently, the N-values will be underestimated (using saturated conditions of the soil i.e., when the groundwater table is below the soil) in the calculations used on the design of the soil in the unsaturated or semi-saturated conditions. Boundary conditions of the correction are defined in the following way by the method:

- When the groundwater table is present at the ground surface (i.e., completely saturated at the surface), a 50% decrease in the measured N -value is advisable to represent the corresponding decrease in effective stress.

- When the groundwater table is at or below that depth, which equals the footing width beneath the base of the foundation, no correction is made since the effect of the saturation has been found to be negligible at that depth.

The corrected N, which is referred to as N′, considers the effect of the groundwater table in the occurrence of the SPT beneath the phreatic surface. That in that circumstance, proper precautions must be put in place regarding the field to avoid the intrusion of water into the borehole at the bottom of the borehole. Uncontrolled ingress of water may disturb the in-situ soil structure, create upwards forces on seepage, and invalidate the test results by artificial attenuation of effective stress and mobilization of loose matter around the sampler. Furthermore, in cases where the Standard Penetration Tests are done below the groundwater table and especially in granular soils, it can be justified to take an extra corrective action when the raw or initially adjusted N-value is more than about 15. This situation is associated with situations where dynamic loading caused by the SPT drive creates the temporary decrease in porewater pressure, which is also known as negative excess porewater pressure, in the mass of the saturated soil. The short-term suction amplifies effective stress adjacent to the sampler, hence augmenting resistance and swelling N-values which might be unsuitable in any long-term portrayal of the N-value under steady conditions. In order to explain this overestimation, a second adjustment is done to refine the penetration resistance. The adjusted N-value, which is more realistic in such situations to indicate more realistic soil strength parameters, can be determined through the empirical relation as follows [24]:

$$N' = 15 + \frac{1}{2}(N - 15) \text{ for } N > 15 \tag{3}$$

During the drilling, groundwater table measurements were recorded and re-recorded after a 24-hour time lag to exclude the transient effect. These stabilized values were employed in the application of the groundwater correction factor (CWC) to raw SPT N-values according to methodology of Peck et al. [23]. Although regional hydrogeologic monitoring shows that the groundwater table of Najaf can vary seasonally at 2-4m range, the semi-arid climate restrains the extreme variations. The current study, accordingly, indicates the balance of groundwater state that existed during the study period, and which can be regarded to represent the groundwater state during a provisional foundation design. Future studies may incorporate multi-seasonal monitoring to assess the temporal sensitivity of bearing capacity estimates.

3.3. Coefficient of Energy Correction (C_{EC})

The coefficient of energy correction factor (C_{EC}) is employed in the interpretation of Standard Penetration Test (SPT) results to compensate for variations in energy transfer efficiency associated with different hammer types and operational procedures. Since the amount of energy imparted to the drill rods during testing directly affects the measured N-value, normalization to a standard reference energy level is essential for ensuring the reliability, consistency, and comparability of test data across different sites and equipment configurations. Empirical studies have shown that commonly used hammer types exhibit varying energy transfer efficiencies. For example, safety hammers, which operate by allowing the hammer to fall freely along a guided track, typically achieve an energy transfer efficiency of approximately 60–70% of the theoretical free-fall energy. In contrast, donut hammers, due to their heavier mass and less efficient drop mechanics, generally deliver only 45–50% of the theoretical energy. These discrepancies can lead to systematic deviations in measured N-values if not properly corrected. To standardize the measured blow counts, the field N-value must be adjusted to a reference energy efficiency, commonly set at 60% or 70% depending on the adopted design standard. Therefore, the correction factor C_{EC} was taken as 0.7 throughout this study.

4. Estimation of Soil Bearing Capacity Based on SPT Results in Najaf City

Bearing capacity is highly significant design parameter in geotechnical engineering, as it directly determines the performance, cost and safety of the foundation systems. It is the final pressure which the underlying soil is to experience before shear failure or excessive settlement occurs. Since the soils utilized underground are naturally heterogeneous, anisotropic and stratified, the values of the bearing-capacity can vary dramatically within a short distance through space and, therefore, site-specific studies can be required to ensure the supply of precise and dependable input design data. However, loading of the structure or unnecessary infrastructure not too great may make the geotechnical site investigation economically feasible or even technically necessary to be exhaustive. Such cases can therefore be estimated through empirical or regression-based estimation methods in order to approximate but reasonably conservative estimates of bearing capacity in these cases particularly where field-test results are well documented. They are normally simplified procedures that rely on readily available geotechnical parameters and are calibrated by field data that has been obtained under controlled conditions.

Among the existing variety of field methods, the most commonly used is the Standard Penetration Test (SPT) due to its simplicity, international standardization (e.g., ASTM D1586), and the quality of generating interpretable data with relatively low operational complexity [25]. Technicians administer the test well and the test has minimum training and gives a direct data on the soil resistance which is N -value, a proxy of the soil strength and soil stiffness. Consequently, SPT information is widely applied in preliminary foundation design, feasibility studies and zoning of geotechnical studies, particularly where more comprehensive studies have time or budget constraints. In the present study, 464 boreholes were drilled throughout the city of Najaf and data of the upper 12m of the boreholes in terms of SPT were only used in the analysis.

The chosen range of depths is aligned with the objective of investigation, namely to measure the behavior of shallow foundations, and it also has the effect of reducing numerical dispersion caused by irregular or aberrant N-values due to higher depths found in some areas of the city.

Though the boreholes were originally drilled to a depth of 35 meters, only the top 12 meters Standard Penetration Test (SPT) data were processed and analyzed at standard levels of test .5, 3.0, 4.5, 6.0, 7.5, 9.0, 10.5, and 12.0 meters. The raw SPT N -values were adjusted using three main coefficients to ensure that the values used to compute bearing - capacity values are true reflections of subsurface conditions:

- Correction for overburden pressure (C_{NC}), as defined by Equation 2, which accounts for the variation in effective stress with depth and normalizes the N-values to a reference overburden pressure.
- Energy correction factor (C_{EC}), which standardizes the energy delivered to the sampler. In this study, although safety hammers with a nominal energy efficiency of 70% were used, a conservative C_{EC}= 0.7 was uniformly applied to ensure methodological consistency.
- Groundwater correction factor (C_{WC}), calculated via Equation 3, which adjusts for the reduction in effective stress and increased pore pressure in saturated soil layers.

Taking into account the very heterogeneous subsurface environment at Najaf, i.e., variable groundwater level, some layers of organic nature, and uncontrolled fill areas, it was considered that a global factor of safety (F.S.) of 3.0 would be used in all computations of allowable bearing capacity. This conservative design approach is able to add reliability to a structure, especially in those geotechnical control areas that are weak.

After these corrections, it was estimated using empirically developed regression equations that relate the corrected N -values of SPT with either the ultimate bearing pressure in each borehole location. Since the quantity and level of data is too broad to depict in a specific database, more intensive numerical deliverables are not given here but can be provided on request to develop further analysis or use.

The empirical relationship that has been suggested by Duncan [26], and Fenton & Griffiths [27] can be used to approximate the net ultimate bearing capacity of small raft foundations.

$$q_{ult,net} = \frac{N_{1(60)}}{0.08}\left(\frac{B+0.3}{B}\right)^2 F_d\left(\frac{S_e}{25}\right) \tag{4}$$

For a raft foundation of large width, Equation 4 can be approximated [26].

$$q_{ult,net} = \frac{N_{1(60)}}{0.08} F_d\left(\frac{S_e}{25}\right) \tag{5}$$

$$F_d = 1 + 0.33(\frac{D_f}{B}) \leq 1.33 \tag{6}$$

where $q_{ult,net}$ is net ultimate bearing capacity of soil (kN/m^2), $N_{1(60)}$ is corrected SPT blow count, B is foundation width or diameter (m), Se is allowable settlement (mm), assumed as 25 mm in this study, D_f is depth of footing placement, it is assumed D_f/B=1, which gives a higher value for F_d=1.33.

The allowable bearing capacity (q_{all}) is then derived using the following steps:

$$q_{all,net} = \frac{q_{ult,net}}{FS} \tag{7}$$

$$q_{all} = q_{all,net} + \gamma' D_f \tag{8}$$

where $q_{all,net}$ is net allowable bearing capacity (satisfying both bearing capacity and specified settlement), FS is safety factor (taken as 3 for silty clayey soils), γ' is effective unit weight of soil = γ_{sat}-$\gamma_{w,}$, q_{all} is final allowable bearing capacity including effective overburden pressure effects, γ_{sat} is saturated unit weight of soil, and γ_w is unit weight of water.

5. Numerical Modeling of Field Data

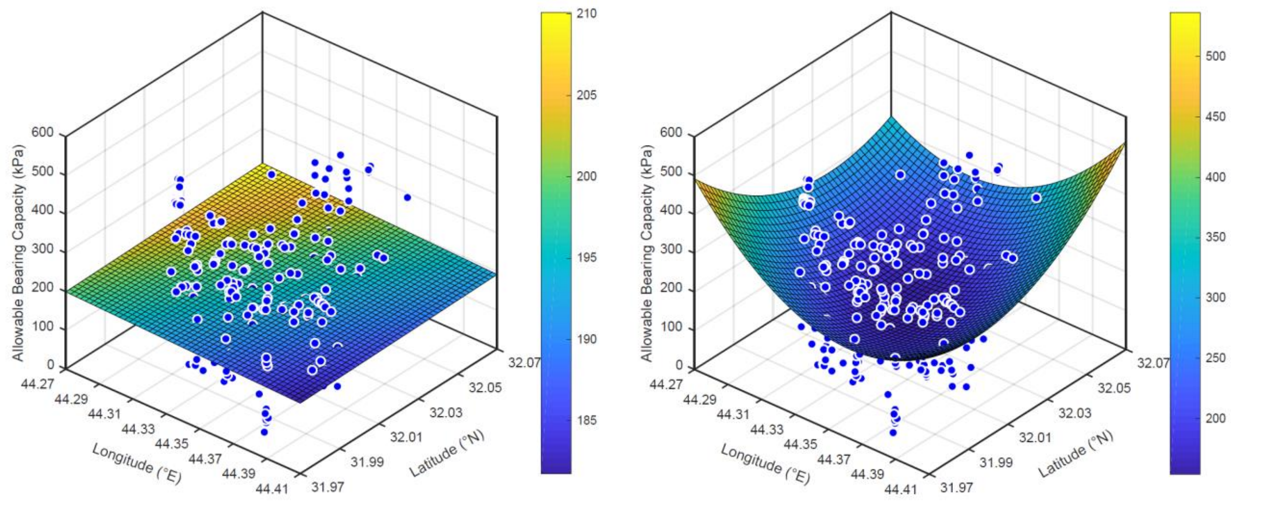
To describe the spatial distribution of the permissible bearing capacity of the area in Najaf City, geotechnical borehole (n=464) data were organized and computed in the computational environment provided in MATLAB. Initial screening and visual analysis of the statistical has shown a group of Standard Penetration Test (SPT) measurements that has an anomalous behaviour which may be due to low spatial borehole density, localised heterogeneities or non-uniform subsurface stratigraphy. Such anomalies were deemed to be non-representative of the overall geotechnical context of the research location; then, a fined dataset of 446 boreholes was used as the final geospatial model. Political surface fitting was carried out to spatial interpolate and model the permissible bearing capacity, where the values derived after correction in SPT were regressed with spatial coordinates and depth.

Instead of geostatistical methods like kriging or inverse distance weighting (IDW) to perform spatial interpolation, polynomial regression was used. Geostatistical techniques are able to model the localized heterogeneity; however, dense data coverage is required and variogram modeling must be very careful, and these techniques can oscillate unrealistically in areas with sparse sampling. Polar surfaces, on the other hand, are more efficient to compute, more stable, and can give geotechnical interpretations that are applicable to map out an area at a regional level. In line with Salman et al. (2024) [4] findings in Baghdad and Sabaa et al.(2023) [3] in Basrah, the first-order model was chosen in this study due to its minimal root-mean-square error (RMSE) values at the expense of overfitting, which, consequently, offered a reasonable balance between accuracy and engineering convenience.

First-order, second-order, third-order, and fourth-order polynomial surfaces were created and compared to determine their capability to explain the variability of shallow soil strength throughout the region. As anticipated, raising the order of the polynomials improved the ability to fit locally around more complex changes in the data, though at the price of more complex computation, more regression parameters, and a greater tendency to overfitting, in regions with sparse or disproportional distributions of data. Increasing the polynomial degree from first- to fourth-order led to a substantial rise in model parameters (from 3 to 15), yet yielded only marginal improvements in model accuracy, as quantified by the Root Mean Square Error (RMSE).

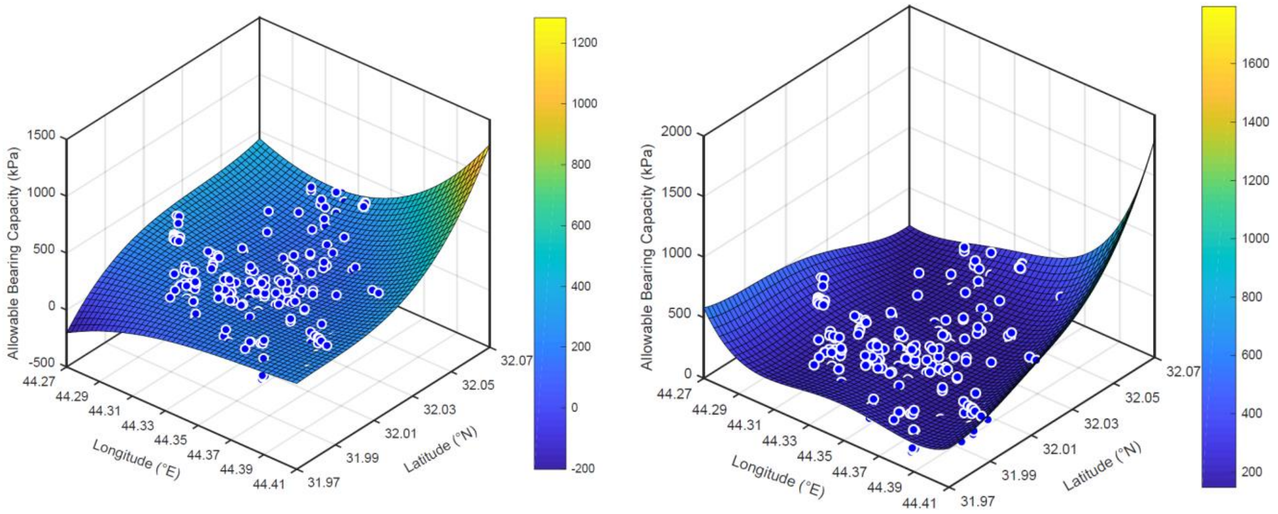
Despite the improved local precision of higher-order surface models, as well as their ability to resolve finer-scale processes such as localized peaks and troughs, interpretation of these processes is unclear, and may be due to either natural processes of a subsurface heterogeneity or artefacts of the sparsity of the borehole data. In addition, the propensity of higher-order polynomials to create spurious oscillations and inflexions makes them less reliable in terms of a strong, generalized characterization of sites. Visual comparison of interpolated bearing-capacity surfaces at a depth of 2 m as in Figures 4 and 5 highlights the differences between the different order polynomials. First-and-second order surfaces develop smoother and easily interpretable trends, which makes them viable when applied at the regional scale. Conversely, third and fourth-order surfaces have better spatial detail but are less stable and interpretable in areas with low data. Numerically, the coefficient of determination (R2), which can be used as a measure of the quality of the model-fit, exhibited a diminutive improvement with the increase in the aspect of the polynomial order between 0.0019 and 0.0514 within the depth ranges studied (Table 1).

This trend, even in the light of this incremental tendency, does not warrant the extra complexity of higher-order models. As a result, it was determined that the first-order polynomial surface would be the best choice of the interpolation technique, and it would represent a good compromise between the simplicity of the model, computing power, and the geotechnical interpretation. Its application in a MATLAB-based framework made it easy to produce thematic maps that represent the spatial variation of bearing capacity across the City of Najaf. As a conclusion, the combination of the revision during SPT results, interpolation by means of a polynomial regression equation and the use of geospatial-analytics represents a successful approach to zone identification of soil strengths. The method significantly advances the initial geotechnical evaluations and permits urban planners, engineers, and decision-makers to maximize infrastructure development, recognizing locations with favorable soil characteristics and reducing risks in the locations with less favorable soil characteristics.



First Order_D_0_2 Second Order_D_0_2

Figure 4. Variation of the Allowable Bearing Capacity of Soil at 0-2 m Depth Using 1st and 2nd Order Interpolation



Third Order_D_0_2 Fourth Order_D_0_2

Figure 5. Allowable Bearing Capacity Variation of Soil at a Depth Range of 0–2 m, Determined Using 3rd- and 4th-Order Interpolation

Table 1. Parameters of Generated 1st, 2nd, 3rd, and 4th Order Polynomial Models at Depth 2 m.

Parameter	First-Order Model			Second-Order Model			Third-Order Model			Fourth-Order Model		
	Min	**Max**	**Av.**	**Min**	**Max**	**Av.**	**Min**	**Max**	**Av.**	**Min**	**Max**	**Av.**
P00	70.54	112.1	91.32	58.17	210.7	134.4	-122.6	294.02	85.71	-940.8	941.6	0.4011
P10	-121.9	6.075	-57.91	-415.9	322.5	-46.7	-1663	1520.7	-80.13	-11050	4316	-3367
P01	-126.5	-29.15	-77.83	-819.2	-157.2	-488.2	-1704	2029.2	162.6	-5762	15330	4784
P20				-997.2	-64.92	-531.1	-1574	4941	-416.9	-4106	60206	28050
P11				207.7	2245	1226.4	-5942	6871	464.5	-10372	73400	-15160
P02				-194.3	526.1	165.9	-6488	3326	-1581	-53500	7010	-23090
P30							-1744	7286	2771	-156000	19820	-68090
P21							-2060	2210	-214	-24140	188200	32900
P12							-3252	24432	10.59	-92260	343600	75200
P03							-4748	1912	-113.4	-35590	121000	-12600
P40										-121000	52700	52700
P31										-473600	397760	-37920
P22										-231460	106000	-62730
P13										-58040	22200	-17920

Though second-, third-, and fourth-order polynomials surface model(s) were created and later evaluated on the basis of the statistical distribution, first order service model was finally chosen to apply practically in the geospatial mapping. This was based on the fact that its root mean square error (RMSE) is relatively small and that it has better stability because it exhibited minimum overfitting tendencies thus giving a more accurate expression in the areas where there are few boreholes. Table 2 shows the regression coefficient and the goodness of fit measures of the first-order model used to generate variations of shallow bearing capacity at various depths.

Table 2. Regression Coefficients and Goodness of fit of the first-Order Model for Different Depths

Depth (m)	P00	P10	P01	R^2	RMSE
0–2	199.4	-125.8	107.3	0.0019	105.63
2–4	207.2	338.5	233.2	0.0154	74.66
4–6	194.3	362.3	293.6	0.0318	59.26
6–8	229.3	61.23	-54.86	0.0030	36.06
8–10	212.7	299	-144.2	0.0514	32.75
10–12	226.5	70.15	-21.22	0.0042	27.80

To explore more on the spatial variability of permissible bearing capacity in the study area, successive regression analyses were performed using the corrected Standard Penetration Test (SPT) data. In order to obtain empirical predictive equations to establish a relationship between the estimated bearing capacity and the spatial location of boreholes, a first-order polynomial surface fitting method, which relates to the P11 model, was used in each of the predetermined depth intervals.

The original geographic coordinates were changed to normalized Cartesian coordinates (along east-west (x) and north-south (y)) according to the min. and max. bounding geographic coordinates of the study area to standardize spatial input variables and also to increase numerical stability. The transformation will maintain consistency throughout all levels of depth and will enable the integration into geospatial mapping solutions.

These regression-based models are computationally efficient at interpolating allowable bearing capacity at unsampled points and form the mathematical basis of the generation of thematic bearing capacity maps in the MATLAB environment. The equations fitted and the regression coefficients of each depth interval is displayed in the following section along with the statistical measures of performance like the Root mean square error (RMSE) and coefficient of determination (R^2), which measure the predictive power of respective models..

6. Results and Discussion

6.1. Spatial Distribution of Bearing Capacity

Figures 6 to 11 illustrate the spatial variation of allowable soil bearing capacity across Najaf soils at different depth intervals. A consistent pattern emerges across all depths: higher capacities concentrate in the northern and western parts of the city, while lower capacities dominate the southern and eastern sectors.

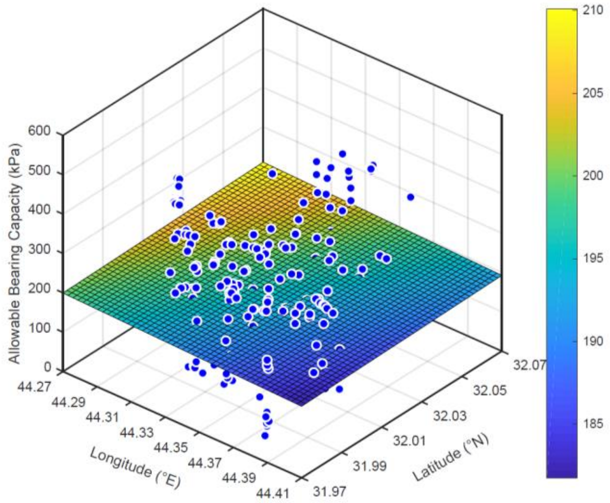


Figure 6. Spatial Distribution of Allowable Soil Bearing Capacity at a Depth Range of 0–2 m

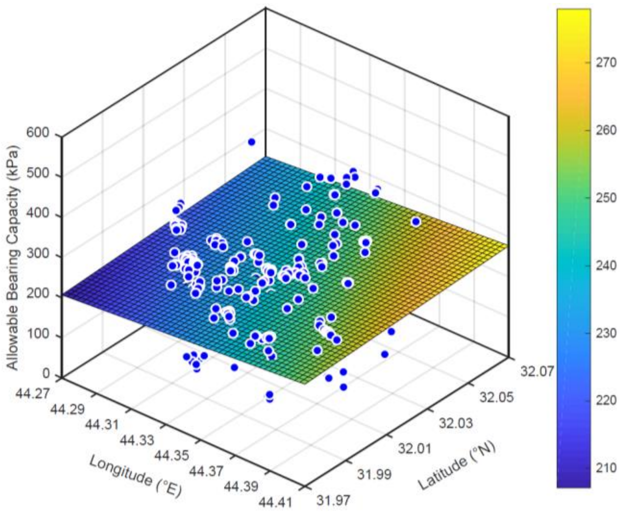


Figure 7. Spatial Distribution of Allowable Soil Bearing Capacity at a Depth Range of 2–4 m

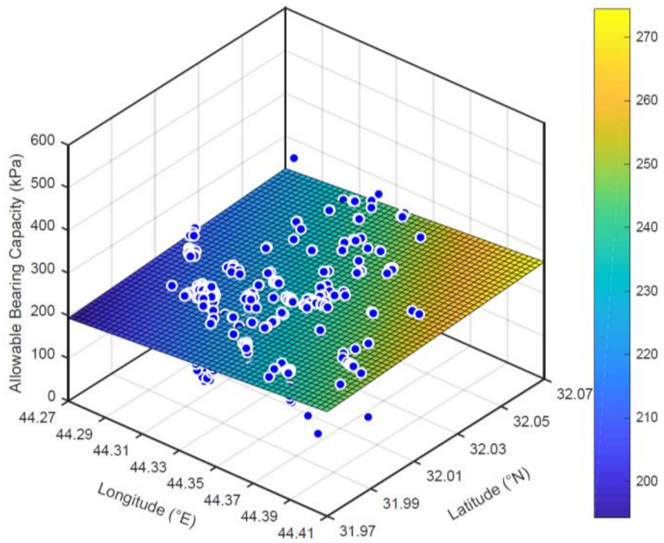


Figure 8. Spatial Distribution of Allowable Soil Bearing Capacity at a Depth Range of 4–6 m

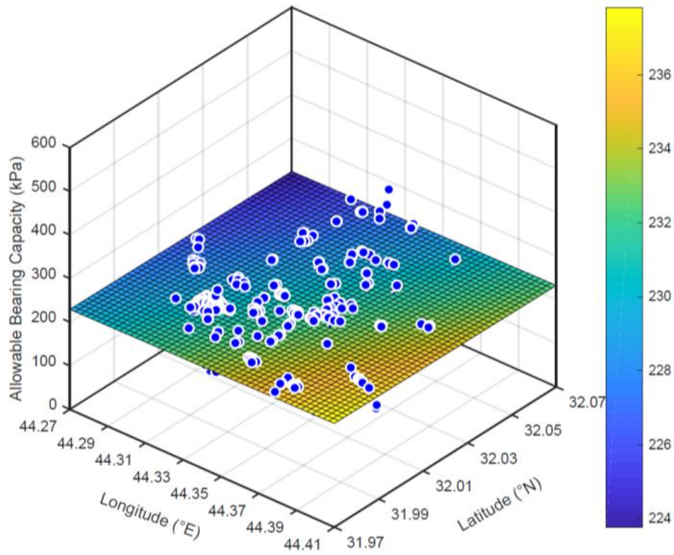


Figure 9. Spatial Distribution of Allowable Soil Bearing Capacity at a Depth Range of 6–8 m

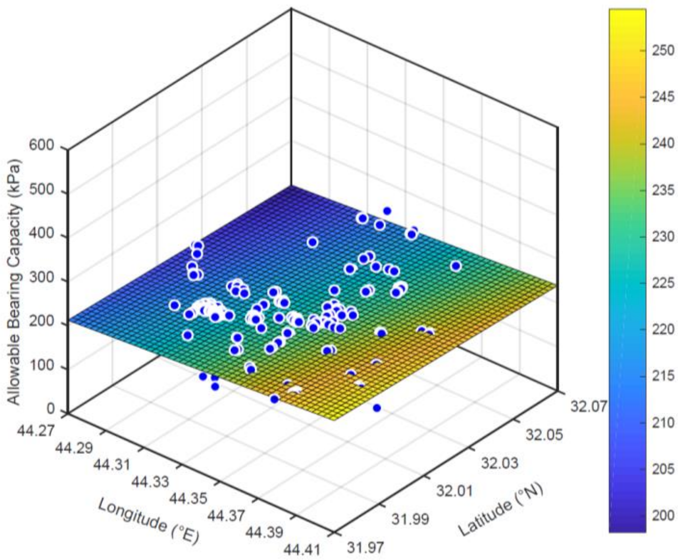


Figure 10. Spatial Distribution of Allowable Soil Bearing Capacity at a Depth Range of 8-10 m

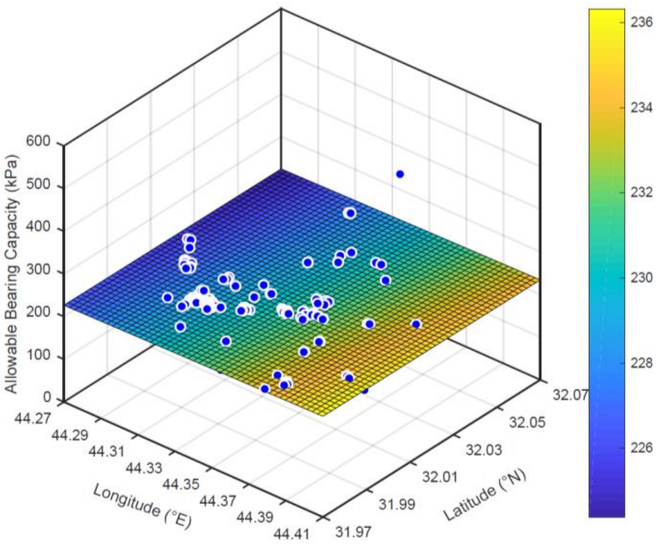


Figure 11. Spatial Distribution of Allowable Soil Bearing Capacity at a Depth Range of 10-12 m

This spatial gradient reflects the subsurface geology. The northwest zone is characterized by sandy clays and silty sands, which typically produce higher corrected SPT values due to greater density and lower compressibility. Conversely, the southeast zone contains more fine-grained clayey silts with higher plasticity, resulting in reduced bearing capacities. Shallow groundwater levels (≈2–4 m) further reduce effective stress in these weaker zones, accentuating the contrast between the strong and weak sectors.

The observed distribution also correlates with urban development patterns: denser infrastructure exists in the stronger-soil zones, consistent with historical reliance on favorable geotechnical conditions for construction. Thus, the spatial patterns not only align with geological mapping but also with the practical footprint of urban expansion.

6.2. Depth-Wise Variability

The depth-wise analysis reveals a transition from heterogeneous shallow soils to more uniform deeper layers:

- At 0–2 m, the maps show highly variable capacities, with localized weak pockets corresponding to recent surface deposits and groundwater-affected soils.
- By 4–6 m, the values stabilize, indicating denser and more competent strata with reduced organic content.
- Beyond 8 m, the variability diminishes further, suggesting relatively uniform strength characteristics at depth.
- The highest allowable capacities are generally observed between 8–12 m, implying that foundations extending into these layers will achieve more consistent and improved performance compared to very shallow foundations.

The depth-based pattern clearly indicates the practical engineering guideline according to which foundations that are located at 8-12m depth of the soil are recommended in Najaf in order to have stability and to avoid settlement

6.3. Evaluation of Regression Models

First-order polynomial regression models were developed to measure spatial differences in each interval in depth using normalized east-west (x) and north-south (y) spatial distances as variables. Third and fourth order polynomials were also experimented but, with higher order, they added spurious oscillations and unnatural surface undulations in regions of the sparse data.

The first-order models chosen had rather small coefficients of determination (R^2 = 0.0019-0.0514) but lower Root Mean Square Errors (RMSE = 27.8=105.6) than the higher order models. The regression equations will be shown in Equations 9 to 15: the results of the regression will be the RMSE and R^2, which will be given to each depth.

$$q_{all}(x, y) = P00 + P10 * x + P01 * y \quad (9)$$

Depth 0–2 m: $q_{all}(x, y) = 199.4 - 125.8 * x + 107.3 * y$ R^2 = 0.0019, RMSE = 105.63 (10)

Depth 2–4 m: $q_{all}(x, y) = 207.2 + 338.5 * x + 233.2 * y$ R^2 = 0.0154, RMSE = 74.66 (11)

Depth 4–6 m: $q_{all}(x, y) = 194.3 + 362.3 * x + 293.6 * y$ R^2 = 0.0318, RMSE = 59.26 (12)

Depth 6–8 m: $q_{all}(x, y) = 229.3 + 61.23 * x - 54.86 * y$ $R^2 = 0.0030$, RMSE = 36.06 (13)

Depth 8–10 m: $q_{all}(x, y) = 212.7 + 299 * x - 144.2 * y$ $R^2 = 0.0514$, RMSE = 32.75 (14)

Depth 10–12 m: $q_{all}(x, y) = 226.5 + 70.15 * x - 21.22 * y$ $R^2 = 0.0042$, RMSE = 27.80 (15)

Even though the R^2 values are represented as low as seen in normal statistical conventions, this is normal in geotechnical interpolation since soils are normally heterogeneous. The mineralogy, depositional history, groundwater variation and anthropogenic fill are complex and non-linear factors that affect the underworld, and explanatory power is inaccessible to spatial coordinates only. In this context, therefore, both RMSE and engineering interpretability are more significant measures of adequacy than R^2.

The regression equations of each depth interval are presented in Equations 9 to 15 along with the metrics of statistical performance (R^2 and RMSE). These equations are used to define the allowable bearing capacity (q all) linearly in terms of spatial coordinates (x, y). Despite low R^2 coefficients (0.00190.0514), which indicate the stochastic heterogeneity of soils, RMSE values confirm the predictive aptitude and steadiness of the initial order model to map the region.

The summary statistics of the regression coefficients for selected depths are presented in Table 3, offering a comparative overview of the interpolation model's behavior and guiding the interpretation of spatial patterns in geotechnical capacity.

Table 3. Summary of minimum, maximum, and average values of first-order interpolation parameters at selected depths

Depth (m)	P00 Min.	P00 Max.	P00 Av.	P10 Min.	P10 Max.	P10 Av.	P01 Min.	P01 Max.	P01 Av.
2	58.17	210.7	134.4	-415.9	322.5	-46.7	-819.2	-157.2	-488.2
4	103.3	148.3	125.8	-135.1	3.569	-65.74	-193.4	-87.96	-140.7
6	136.8	195.7	166.2	-168.4	12.88	-77.74	-260.8	-122.9	-191.9
8	150.2	248.4	199.3	-102.5	164.3	41.9	-145.6	92.4	-26.6
10	173.6	264.5	219.6	-85.2	299	299	-220.3	-30.6	-144.2
12	182.4	270.1	226.5	-65.7	70.15	70.15	-21.22	-21.22	-21.22

To interpret the model more comprehensively, the regression coefficients P00 (reflecting the intercept) and P10 (reflexing the east-west gradient) and P01 (reflecting the north-south gradient) were analyzed in the systematic manner, i.e., at various depth ranges. The key findings of Table 3 consist of minimum, maximum, and mean referring to these coefficients, which only emphasize the spatial heterogeneity that is inherent in the mechanisms of soil properties. Specifically, elevated variability in the coefficients, particularly in the depths with weaker soil is associated with variability in soil characteristics. On the other hand, the smaller values of coefficient which are achieved at the deeper levels, indicates a more homogenous behavior of the subsurface.

Finally, first-order-polynomial approach was concluded to be the strongest, computationally effective and geotechnically explainable methodology of regional-scale mapping in Najaf. This has been found to be in tandem with the results of Salman et al. [4] in Baghdad and Sabaa et al. [3] in Basrah, all of which promoted the use of low-order models in large-scale geotechnical zoning.

In a geospatial meters perspective, the utilized first-order trend model has a number of unique benefits. It is computationally efficient, the interpretability of spatial gradients is well-preserved, and it is insensitive to the sparsity of data, which is highly important when constructing MATLAB-based thematic layers to make initial geotechnical assessments. Though this model is not able to cover micro scale variability or sudden lithological changes, it still provides a good macroscopic approximation of the spatial trends. The representation is very appropriate in regional planning projects and initial stage foundation design evaluations. In spite of its usefulness, the study proffers the naturally present limitations connected with the application of the deterministic and low-order regression models to the spatially sophisticated geotechnical data.

6.4. Engineering and Planning Implications

The thematic maps generated in this study provide practical value for engineering design and urban planning:

- In zones with high allowable bearing capacity, shallow foundations such as isolated footings and raft foundations can be adopted confidently, leading to cost and time savings.
- In zones with low capacities, soil improvement techniques (e.g., compaction, stabilization) or deep foundation solutions (e.g., piles) may be required to ensure structural safety.

For urban planners, the maps highlight safe corridors for expansion and zones of elevated risk where development should proceed with caution. Importantly, these outputs are intended for zoning-level planning and preliminary assessment, not as replacements for site-specific investigations. Final design must still be supported by dedicated field and laboratory testing.

6.5. Comparison with Previous Studies

Compared to earlier works in Basrah, Baghdad, and other Middle Eastern cities, this study contributes a more comprehensive and corrected dataset (464 boreholes analyzed, with SPT corrections applied).

- Basrah (Sabaa et al. 2023 [3]): Used SPT–GIS workflows but relied on limited correction protocols; higher-order or kriging surfaces sometimes introduced noise.
- Baghdad (Salman et al. 2024 [4]; Al-Mirza et al. 2024 [5]): Found that first-order polynomials produced stable maps with competitive RMSE values, consistent with the findings of this study.
- Regional analogs (Jordan, Egypt, Iran): Employed kriging, IDW, and GIS–remote sensing approaches, but their accuracy was sensitive to borehole density.

A cross-study comparison (Table 4) shows that Najaf's maps emphasize depth-specific zoning (2 m bands), corrected SPT data, and RMSE-driven model selection, ensuring both accuracy and stability. Where Najaf diverges is in the northwest high-capacity trend, reflecting its distinct depositional and groundwater regime.

Table 4. Cross-Study Comparison of Scope, Methods, and Engineering Implications

Study / City	Data Scope	Depth Focus	SPT Corrections Applied	Interpolation / Model Choice	Reported Performance	Engineering Implications
This study (Najaf)	464 boreholes	0–12 m (2 m bands)	Overburden, groundwater, energy	1st–4th order tested → 1st order selected	Lowest RMSE; low R^2 expected for soils	Clear N/W high-capacity zones; depth-wise stabilization beyond 8 m supports reliable shallow foundation design
Basrah (Sabaa 2023)	Citywide SPT	to ~10 m	Varies by report	GIS surfaces (IDW, kriging, polynomials)	Effective for zoning; local noise in sparse areas	Thematic maps useful for preliminary foundation choices, but corrections less consistent
Baghdad (Salman 2024)	Citywide SPT	Fixed depths (1.5, 6, 9 m)	Consistent processing emphasized	MATLAB polynomials; 1st order competitive	1st-order RMSE ≈ higher-order; more stable	Low-order surfaces recommended for stability and interpretability
Baghdad (Al-Mirza 2024)	>80 studies	Citywide	GIS harmonization	GIS Geostatistics	City-scale utility demonstrated	Maps support land-use and policy-level screening
Regional (Jordan, Egypt, Iran)	City/region datasets	Shallow-intermediate depths	Mixed approaches	Kriging, IDW, GIS + remote sensing	Accuracy sensitive to borehole density	Advanced interpolants add value but require careful QA to avoid artifacts in sparse datasets

7. Conclusions

The current study has effectively generated a set of MATLAB applications of thematic maps defining the spatial distribution of permissible soil bearing capacity of Al-Najaf City based on the corrected Standard Penetration Test (SPT) data and geospatial regression modeling. Using geotechnical data and spatial interpolation methods of the data gives the resultant maps a cost-effective and viable decision-support system in the initial design of the foundation and urban planning, especially where extensive site investigations are either too expensive or too logistically impractical. Results of this study identify the point of view of such paramount importance of spatial analysis in geotechnical engineering that combining field-like subsurface material with spatial models can contribute to the availability and readability of soil behavior in the region. Such maps offer useful information that is site-location based and can assist in the process of guiding sustainable urbanization, enhancing land-use patterns, and preliminary design without necessarily involving the workload of carrying out rigorous testing on site. Besides that, the study also indicates the potential of utilizing fixed empirical field information at the time of spatial meter operations and therefore legitimizes the performance of the initial-order regression surfaces in characterizing geotechnical fluctuation at extensive levels in areas with complex subsurface settings. Future research should be oriented on:

- Validating the interpolated bearing capacity values through comparison with field-based load test results (e.g., plate load tests or cone penetration testing), thereby improving model calibration and reliability;
- Incorporating additional geotechnical variables, such as soil classification, moisture content, consistency limits, and groundwater fluctuation patterns, can enrich the predictive capacity of the model.
- Exploring advanced spatial modeling techniques, including geostatistical interpolation (e.g., kriging) and machine learning approaches, which may better accommodate non-linear interactions and enhance the fidelity of spatial predictions in highly variable soil environments.

These developments are sure to further enhance the relevance of MATLAB-based geotechnical meters as an innate element of contemporary urban infrastructural design and risk-driven engineering design.

The methodology utilized in this study is replicable in other semi-arid cities with fast urbanization, though only as long as there is sufficient borehole/SPT data available. Transportability of the method is achieved since it is founded on fixed SPT values, and is computationally inexpensive based on space interpolation; this can be applied to other regions with analogous geological and climatic attributes, including southern Iraq, Jordan, or northern Egypt. Although the resultant thematic maps are aimed at being more of a zoning-scale planning tools, they may be of significant benefit to preliminary foundation design as well as to preliminary urban land-use allocation, thus facilitating sustainable development on a larger scale than in the context of Al-Najaf.

In addition to its geotechnical relevance, the methodology and outputs of this study can be readily integrated into urban planning GIS platforms. By exporting the generated thematic maps into standard geospatial formats, soil bearing capacity can be combined with land-use, zoning, and infrastructure datasets. This integration would enable planners, engineers, and decision-makers to access and apply geotechnical information directly in multidisciplinary planning environments, thereby enhancing the role of geotechnical data in sustainable urban development.

7.1. Limitations and Future Work

The surfaces generated (Figures 6 to 11) are the images which illustrate the spatial variation of the allowable bearing capacity of Najaf soils at their incremental depths, which are as follows: (0-2 m, 2-4 m, 4-6 m, 6-8 m, 8-10 m and 10-12 m). These are interpolated maps that, with the help of geographic coordinates and depth, give a practical framework to estimate approximate allowable capacities to provide fast initial preliminary estimates without necessarily off-site-specific testing. These spatially resolved data can be useful decision-support-data to engineers and planners working in foundation design and urban development.

Future studies may advance predictive fidelity with data driven and geostatistical methods that include the following:

- Ordinary and universal kriging, which account for spatial autocorrelation and provide error estimates.
- Machine learning techniques (e.g., GIS-based Random Forest, XGBoost, Support Vector Machines) that can capture complex, non-linear soil–property interactions.
- Hybrid models that integrate SPT data with auxiliary variables such as soil classification, moisture content, or remote sensing indices.

Adopting these methods would help address heterogeneity in Najaf soils, reduce model uncertainty, and support risk-informed decision-making in rapidly urbanizing environments.

8. Declarations

8.1. Author Contributions

Conceptualization, S.K.A. and M.K.; methodology, S.K.A. and W.H.A.; software, A.A.R.; validation, M.K. and A.A.R.; formal analysis, S.K.A. and W.H.A.; investigation, S.K.A.; resources, M.K.; data curation, W.H.A.; writing—original draft preparation, S.K.A.; writing—review and editing, M.K. and A.A.R.; visualization, S.K.A. and M.K.; supervision, S.K.A.; project administration, S.K.A. All authors have read and agreed to the published version of the manuscript.

8.2. Data Availability Statement

The data presented in this study are available in the article.

8.3. Funding

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8.4. Conflicts of Interest

The authors declare no conflict of interest.

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