Correlating Standard Penetration Test (SPT) with Various Soil Properties in Different Kirkuk City Locations: A Case Study Utilizing Inverse Distance Weighted (IDW) for Assessment and Prediction

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Abstract. Due to cost limitations, it is not practicable to experimentally investigate the soil characteristics over the entire city. Given this, the study has focused on using a geographic information system, especially the IDW technique, with linear regression models. The study's data collection was taken from different locations around Kirkuk province. The IDW technique was used to examine the Standard Penetration Testing (SPT) and chemical properties such as total Sulphur content SO_3 (%), total soluble salt TSS (%), organic content ORG (%), chlorine concentration Cl (ppm), free calcium carbonate content $CaCO_3$ (%), Gypsum content GYP (%), and pH. Both single-regression and multi-regression models were utilized to interpolate the SPT and soil properties. Sets of digital maps were created to examine the chemical properties and SPT of Kirkuk soils. SPT values can be predicted more precisely based on integrated physical and chemical soil properties rather than chemical or physical characteristics alone. SPT and physical soil components have been shown to have various positive and negative relationships. While the SPT values have shown favorable relationships with both silt and clay amounts, they have shown negative correlations with gravel and sand contents. The variations of SPT with chemical soil properties have revealed positive correlations with SO_3 (%), TSS (%), $CaCO_3$ (%), GYP (%), and pH contents, while negative correlations were obtained between SPT with ORG (%) and Cl (ppm).

Keywords: Digital maps; standard penetration test; IDW; single and multi-linear regression; soil chemical properties.

1. INTRODUCTION

Data from SPT (Standard Penetration Test), soil tests, and physical and chemical properties can be analyzed and visualized using GIS (Geographic Information System) technology. These data are given as input in GIS according to the corresponding latitude and longitude of borehole points using a typical technique for assessing the geotechnical qualities of soil works. Using GIS technologies, these data can then be examined to map the soil properties, such as bearing capacity, and pinpoint locations that may be vulnerable to hazards. Additionally, GIS can combine SPT data with other spatial data, such as topography, land use, and infrastructure, to better understand how soil conditions may influence decisions about where to build, what will go on there, and how to plan for disaster mitigation. Identifying the soil properties for any agricultural, civil, or geotechnical engineering reasons is always exceedingly difficult and expensive[1]. Corrections are necessary for SPT and their impact on factors such as test field circumstances, the measurement, operation of test equipment, and the diameter and depth of boreholes[2]. These factors have the potential to shift the results from SPT, which will significantly affect the soil's estimated geotechnical properties [3].

GIS can also be utilized to track geoscientific diagramming and cartographic imaging as both depend on generating digital soil maps. These maps offer a quick and accurate way to detect distinguishing traits, which can improve any study. The soil may be inspected, and its potential might be assessed using the ground conduct methodologies employed in creating these digital maps [4]. To reduce earthquake damage and identify safe residential locations, soil engineering characteristics must be recognized. To establish secure residential zones and perform micro zonation, soil properties investigations are required. Alternatively, to being available in spatial data infrastructures like geographic and geomorphologic data, geotechnical data is typically presented and preserved using outdated, inefficient ways. Because of this, geotechnical data for many constructed locations is difficult to access with an acceptable spatial resolution [5]. The geotechnical properties of the ground should be considered when establishing whether the residential area is resistant to seismic effects before building a safe structure [6].

SPT is now the most used technique for gathering information on ground conditions, especially about the depth of the water table and penetration resistance (NSPT) [7]. On the basis of semi-empirical methods, the values are frequently used in foundation design to estimate ultimate load capacity[8]. SPT is a widely used in-situ test because it is simple, fast conducted, and low in cost [9], developed around 1972 [10]. Liquefaction in foundations and associated ground deformations represent geotechnical problems. The post-earthquake reaction and restoration efforts have been difficult and delayed as a result of the damage effect. This is due to the need for a liquefaction hazard map for land use development [11].

The correlation between soil content type (grain size) and SPT can be estimated as larger grain sizes (e.g., sands and gravels) tend to have higher SPT values compared to soils with smaller grain sizes (e.g., clays and silts). This is because larger particles provide more resistance to penetration and compact less easily under the repeated blows of the SPT hammer. Thus, in general, it is expected to see higher SPT values in coarser-grained soils. Gravels are normally better-graded than sands in natural deposits [12]. Soils containing more than 20 percent clay would hardly liquefy unless their plasticity indexes are low [13]. The chemical properties of soil can significantly affect the soil characteristics. These elements can be variable under different conditions; as a result, these properties must be taken into account by engineers when planning and building structures. In addition, some chemical properties may provide a notable indicator for the significance of the SPT values. For example, the shear strength of granular soil is increased with the increase of pH values [14]. Conversely, fine-grained soil has better performance for presenting a correlation between SPT and shear strength [15]. Thus, this study's main target is developing digital soil maps with statistical correlations between SPT values and various physical and chemical soil properties utilizing GIS technique incorporated with the standard Inverse Distance Weighted (IDW) method.

2. SAMPLING

The soil samples were collected from 15 boreholes up to a depth of 10m. The study depth has been set as a shallow depth of 1m for every used soil sample. The samples are distributed in three locations in Kirkuk city-Iraq (Industrial Area 8 samples, Qara Hanjeer 4 samples, and Al Naser 3 samples) as shown in Figure 1. These boreholes had been drilled for geotechnical investigations. Boreholes were drilled using the rotary method. Simple correlations between the Standard Penetration Test and different soil properties were performed using single linear and multi-linear regression methods.

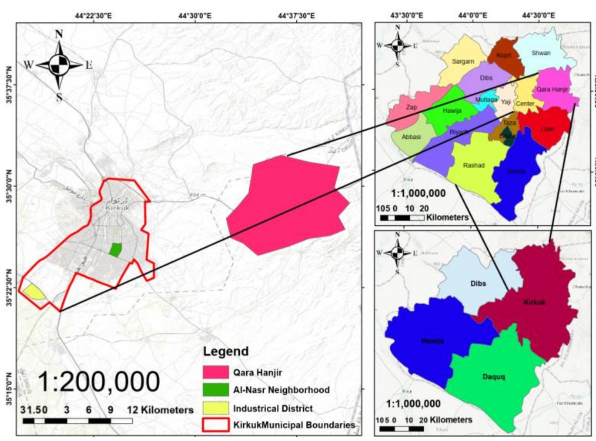

Figure 1: Detailed map of study's location generated by GIS.

3. IDW TECHNIQUE'S RESULT

Using IDW techniques with the surface approximation algorithm as input data, digital maps have been generated in GIS. The input data specifically comprise the provided soil properties at known sites where the unknown points were established by applying IDW methods. The IDW method uses a linear sequence of points in close proximity that are assessed using an inverse function of the distance between the observed and sampled sites to precisely calculate the essential soil parameter at data-missing locations [16]. On the other hand, the technique's hypothesis is that all measured attributes at the sampled and unsampled sites are equivalent.

The IDW approach, as shown in Figure 2(A), was used to generate the SPT map for each studied site. The SPT is split into four zones. Zone no.1 in each location is between very loose and loose classification, which is unsuitable for civil structures or very heavy structures without applying soil improvement methods. Zone No. 2 is between loose and medium dense, which is good for light to moderate bearing structures. Zone no.3 is medium dense, which is appropriate for moderate load-bearing structures; the same is applied to zone no.4 [17]. Similarly, the map of pH distribution in Figure 2(B) revealed that all zones in all locations have similar values ranging between 8.040 to 9.170 that classify under alkaline and indicate low content of organic material [18].

In Figure 2 (C), the GYP (%) of first, second, and most of the third location is non-gypsiferous with very slightly gypsiferous at tiny red spots in the third location. For organic content as predicted by the pH value, the low presence of organic material is observed, as shown in Figure 2 (D). This prediction is suitable for low precision but inaccurate for high precision, as shown in Figures 2 (B) and (D). The percentage of TSS and SO_3 as shown in Figure 2 (E) and (F), are limited to under 3%, and the presence of these small quantities between TSS and SO_3 are almost identical and both converse with $CaSO_3$% content, especially in zone no.2. The round spot area at the top of zone no.2 in Figure 2 (G) exists in the same zone for TSS% and SO_3% but in a contrary

 https://doi.org/10.1051/e3sconf/202342701005

order for each other. Furthermore, all locations have pH > 8, which may predict the type of $CaSO_3$ as a pedogenic carbonate. Figure 2 (H) revealed that all the locations have no chloride present and are safe in terms of corrosion in steel bars inside any possible build project foundations.

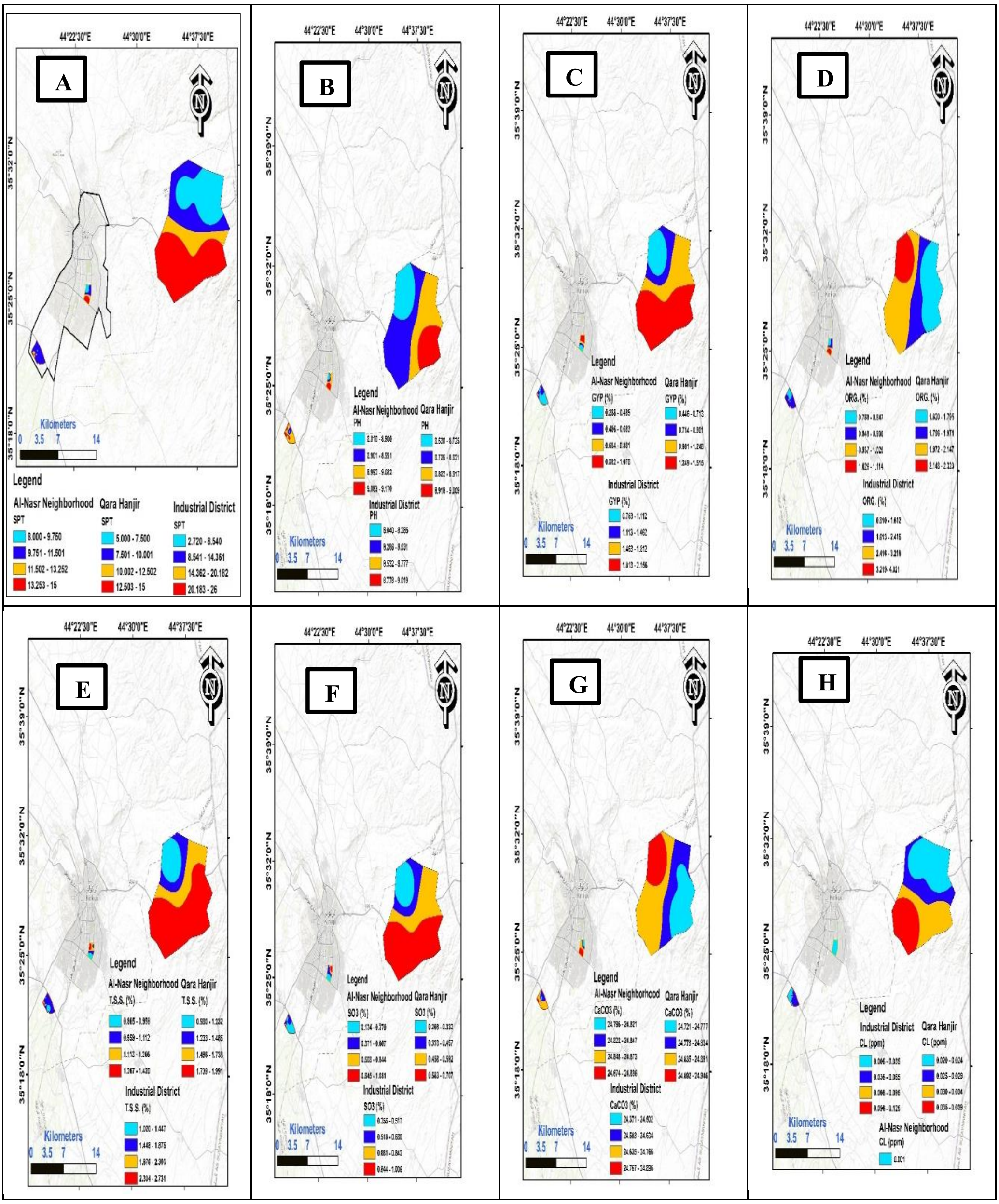

Figure 2: IDW representation of SPT and different soil chemical properties in three studied locations of Kirkuk city, (A) SPT, (B) pH, (C) GYP (%), (D) ORG (%), (E) TSS (%), (F) SO_3 (%), (G) $CaCO_3$ (%), and (H) Cl (ppm).

3.1 Linear Single Regression Model

A linear single regression model was used to estimate the SPT values using field information on the physical and chemical properties of the soil. In Equation (1), the represented SPT values in the linear single regression model are as follows:

$$SPT = L * \text{Physical or Chemical Soil Property } (\%) + M \quad (1)$$

Where L and M are model parameters.

Gravel (%), sand (%), silt (%), clay (%), SO3 (%), TSS (%), ORG (%), Cl (ppm), CaCO3 (%), GYP (%), and pH are physical and chemical model factors that may be directly associated with SPT values. However, SPT necessitates rigorous field analysis and may be the primary indication for the soil strength. As a result, the suggested linear single regression model can estimate SPT using physical and chemical soil parameters.

3.2 Linear Multi-Regression Model

A linear multi-regression model was used to calculate the SPT values using field measurements for physical and chemical soil factors. The linear multi-regression model represents the following SPT values: gravel (%), sand (%), silt (%), clay (%), SO_3 (%), TSS (%), ORG (%), Cl (ppm), $CaCO_3$ (%), GYP (%), and pH. Three distinct linear multi-regression models were employed. Equations (2, 3), and 4 reveal the model forms as follows:

$$\mathrm{SPT} = \mathrm{A} * \mathrm{Gravel}(\%) + \mathrm{B} * \mathrm{Sand}(\%) + \mathrm{C} * \mathrm{Silt}(\%) + \mathrm{D} * \mathrm{Clay}(\%) + \mathrm{E} \quad (2)$$

$$\mathrm{SPT} = \mathrm{F} * \mathrm{SO_3}(\%) + \mathrm{G} * \mathrm{TSS}(\%) + \mathrm{H} * \mathrm{ORG}(\%) + \mathrm{I} * \mathrm{Cl(ppm)} + \mathrm{J} * \mathrm{CaCO_3} + \mathrm{K} * \mathrm{GYP}(\%) + \mathrm{N} * \mathrm{pH} + \mathrm{O} \quad (3)$$

$$\mathrm{SPT} = \mathrm{P} * \mathrm{Gravel}(\%) + \mathrm{Q} * \mathrm{Sand}(\%) + \mathrm{R} * \mathrm{Silt}(\%) + \mathrm{S} * \mathrm{Clay}(\%) + \mathrm{T} * \mathrm{SO_3}(\%) + \mathrm{U} * \mathrm{TSS}(\%) + \mathrm{V} * \mathrm{ORG}(\%) + \mathrm{W} * \mathrm{Cl(ppm)} + \mathrm{X} * \mathrm{CaCO_3} + \mathrm{Y} * \mathrm{GYP}(\%) + \mathrm{Z} * \mathrm{pH} + \mathrm{A_1} \quad (4)$$

Where the model parameters are A, B, C, D, E, F, G, H, I, J, K, N, O, P, Q, R, S, T, U, V, W, X, Y, Z, and A_1, the SPT component can be predicted using varying percentages of physical and chemical soil variables based on the specified multi-regression model characteristics.

4. SPT-SOIL CORRELATION

The relationships between SPT-soil characteristics such as gravel, sand, silt, clay, SO_3, TSS, ORG, Cl, $CaCO_3$, GYP, and pH components and SPT are summarized in Table 1. Positive and negative correlations have been identified between the SPT values and various soil parameters, with degrees of correlation ranging from -0.630 to 0.853. Furthermore, correlations between the gravel and sand, silt, clay, SO_3, TSS, ORG, Cl, $CaCO_3$, GYP, and pH varied from -0.610 to 0.501. Furthermore, satisfactory relationships between sand content and the amounts of silt, clay, SO_3, TSS, ORG, Cl, $CaCO_3$, GYP, and pH substances are observed, with degrees of correlation ranging from -0.630 to 0.655. Positive and negative relationships between silt content and proportions of clay, SO_3, TSS, ORG, Cl, $CaCO_3$, GYP, and pH substances have also been identified, with degrees of correlation ranging from -0.561 to 0.356. Moreover, relationships between clay content and SO_3, TSS, ORG, Cl, $CaCO_3$, GYP, and pH material percentages have been established, with degrees of correlation ranging from -0.467 to 0.389. SO_3 content has been found to have various associations with TSS, ORG, Cl, $CaCO_3$, GYP, and pH, with degrees of correlation ranging from -0.167 to 0.826. TSS content has been determined to have different associations with ORG, Cl, $CaCO_3$, GYP, and pH contents, with degrees of association ranging from -0.286 to 0.853. ORG content has been identified to have different associations with Cl, $CaCO_3$, GYP, and pH contents, with degrees of association ranging from -0.222 to -0.042. Cl content has been identified to have different associations with $CaCO_3$, GYP, and pH contents, with degrees of association ranging from -0.596 to 0.066. $CaCO_3$ content has been identified to have different associations with GYP and pH contents, with degrees of association ranging from -0.147 to 0.601, while GYP and pH have a negative association with a degree of correlation of -0.038. It is essential to establish accurate correlations between SPT and physical and chemical soil contents that may be utilized to determine the ultimate bearing capacity with no cost or effort.

4.1 Linear Single Regression Model

Table 1 summarizes the properties of the proposed linear single regression model Equation (1). The least squares approach was used to solve the proposed linear single regression model. Table 1 shows the model parameters (L and M) as well as the R^2 values for the suggested model for all of the analyzed situations.

Table 1: Linear regression model analysis for SPT values in various Kirkuk City/Iraq places.

SPT Values	Physical & chemical properties (%)	L	M	Equation	R^2
SPT	Gravel	-0.463	21.318	$\mathrm{SPT} = -0.463 * \mathrm{Gravel} + 21.318$	0.048
SPT	Sand	-0.499	23.785	$\mathrm{SPT} = -0.499 * \mathrm{Sand} + 23.785$	0.045
SPT	Silt	0.127	12.751	$\mathrm{SPT} = 0.127 * \mathrm{Silt} + 12.751$	0.012
SPT	Clay	0.558	1.892	$\mathrm{SPT} = 0.558 * \mathrm{Clay} + 1.892$	0.153
SPT	SO_3	9.989	15.862	$\mathrm{SPT} = 9.989 * \mathrm{SO_3} + 15.862$	0.032
SPT	TSS	3.647	15.535	$\mathrm{SPT} = 3.647 * \mathrm{TSS} + 15.535$	0.017
SPT	ORG	-5.930	31.198	$\mathrm{SPT} = -5.930 * \mathrm{ORG} + 31.198$	0.148
SPT	Cl	-105.32	23.791	$\mathrm{SPT} = -105.32 * \mathrm{Cl} + 23.791$	0.049
SPT	$CaCO_3$	5.373	-111.81	$\mathrm{SPT} = 5.373 * \mathrm{CaCO_3} - 111.81$	0.004
SPT	GYP	9.487	11.119	$\mathrm{SPT} = 9.487 * \mathrm{GYP} + 11.119$	0.089
SPT	pH	3.626	-10.68	$\mathrm{SPT} = 3.626 * \mathrm{pH} - 10.68$	0.007

The model's coefficients, L and M, have comparable ranges of -105.32 to 9.989 and -111.81 to 31.198. Furthermore, the R^2 ranges from 0.007 to 0.153. The variation of SPT values with the physical soil properties has been illustrated in Figure 3 (a to d). Different negative and positive associations between SPT and physical soil contents have been observed. The SPT has demonstrated negative correlations with gravel and sand contents, whereas the SPT has demonstrated positive associations with both silt and clay contents. It is obviously indicated that the SPT has positive associations with fine particle contents and negative associations with coarse particle substances. The variation of SPT with the chemical soil properties has been demonstrated in Figure 4 (a to g). The SPT has revealed positive correlations with SO_3 (%), TSS (%), $CaCO_3$ (%), GYP (%), and pH contents, while negative correlations between SPT with ORG (%) and Cl (ppm) have been noticed.

4.2 Linear Multi-Regression Model

Information about the linear multi-regression framework (Equations 2, 3, and 4) is provided in Table 2. The least squares approach was used to solve the linear multi-regression equations. Table 2 shows the proposed model parameters (A to A_1) as well as the predicted values of the model multiple R. The multiple R-value ranges from 0.443 to 0.865.

Table 2: Linear multi-regression model analysis for SPT values in various Kirkuk city/Iraq places.

SPT Values	Equation No.	Linear multi-regression coefficients								Multiple R
		A	B	C	D	E				
SPT	2	-0.161	-0.213	0.095	0.553	-0.748				0.443
		F	G	H	I	J	K	N	O	
SPT	3	-42.959	-20.311	-6.600	-176.322	1.509	49.534	-9.219	81.849	0.679
		P	Q	R	S	T	U	V	W	
SPT	4	1.736	1.561	1.694	1.215	36.791	31.000	11.036	533.503	
		X	Y	Z	A_1					
		39.953	43.833	19.472	827.513					0.865

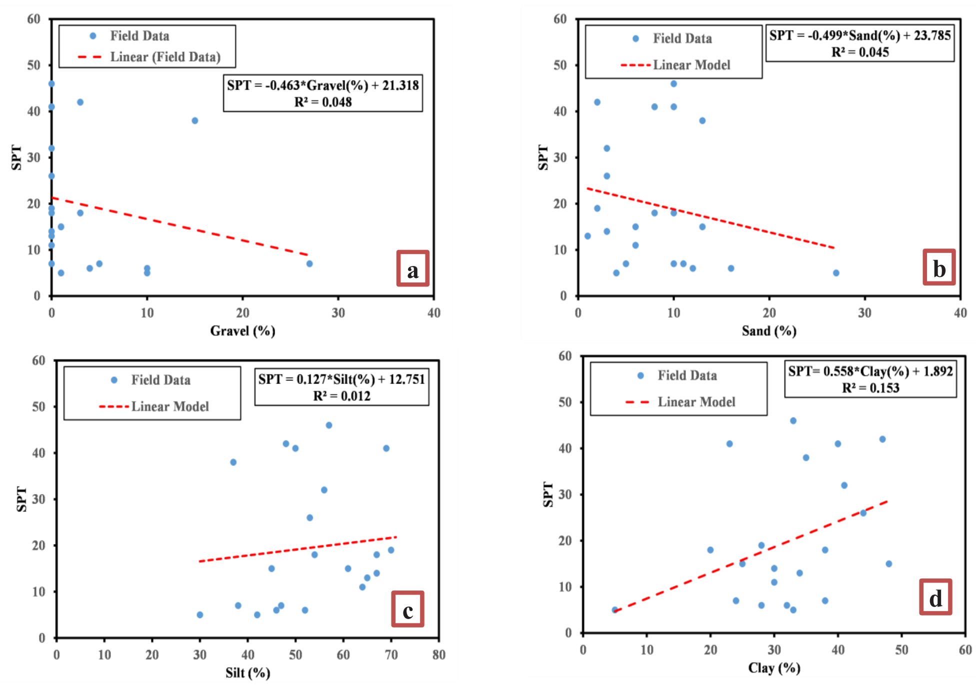

Figure 3: The variation of SPT values with the physical soil contents for various places in Kirkuk city/Iraq using linear single regression model (a) SPT vs. gravel content (%) (b) SPT vs. sand content (%), (c) SPT vs. silt content (%), and (d) SPT vs. clay content (%).

The variations in expected and actual soil SPT values using the multi-linear regression model Equations (2) to (4) are displayed in Figure 5 (a to c). The proposed linear multi-regression analysis of Eq. (4) estimates SPT values successfully in Figure 5 (c) with multiple R values of 0.865. However, a lower multiple R-value of 0.443 has been noticed for the predicted SPT values of Eq. (2), as presented in Figure 5 (a). A moderate multiple R-value of 0.679 has been noticed for the predicted SPT values of Eq. (3), as presented in Figure 5 (b). It is evident that SPT values can be approximated more conveniently based on integrated physical and chemical soil features rather than chemical or physical attributes alone

Table 3: Correlations between SPT-soil characteristics for various places in Kirkuk City/Iraq.

	SPT	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	SO_3 (%)	TSS (%)	ORG (%)	Cl (ppm)	$CaCO_3$ (%)	GYP (%)	pH
SPT	1.000											
Gravel (%)	-0.379	1.000										
Sand (%)	-0.392	0.501	1.000									
Silt (%)	0.438	-0.610	-0.630	1.000								
Clay (%)	0.337	-0.142	-0.003	-0.081	1.000							
SO_3 (%)	0.178	-0.191	-0.308	0.244	0.023	1.000						
TSS (%)	0.131	-0.085	-0.348	0.105	-0.057	0.568	1.000					
ORG (%)	-0.385	0.262	0.655	-0.561	0.389	-0.167	0.112	1.000				
Cl(ppm)	-0.220	-0.007	0.090	-0.520	-0.467	-0.067	0.110	-0.047	1.000			
$CaCO_3$ (%)	0.067	-0.056	-0.142	0.356	0.359	-0.077	-0.119	-0.091	-0.596	1.000		
GYP (%)	0.298	-0.134	-0.306	0.159	0.030	0.826	0.853	-0.042	0.066	-0.147	1.000	
pH	0.084	0.027	0.008	0.120	0.232	0.095	-0.286	-0.222	-0.308	0.601	-0.038	1.000

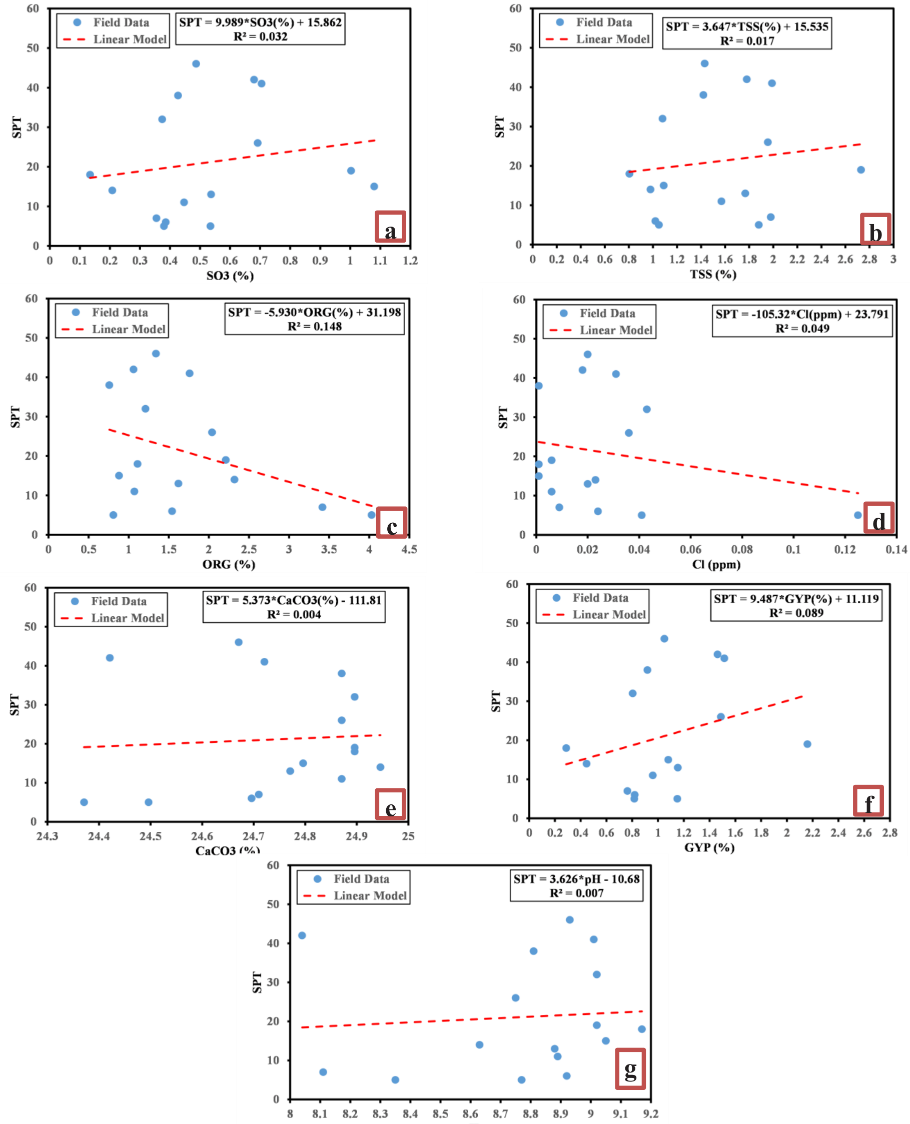

Figure 4: The variation of SPT with the chemical soil contents for various places in Kirkuk city/Iraq using linear single regression model (a) SPT vs. SO_3 (%) (b) SPT vs. TSS (%), (c) SPT vs. ORG (%), (d) SPT vs. Cl (ppm), (e) SPT vs. $CaCO_3$ (%), (f) SPT vs. GYP (%), and (g) SPT vs. pH.

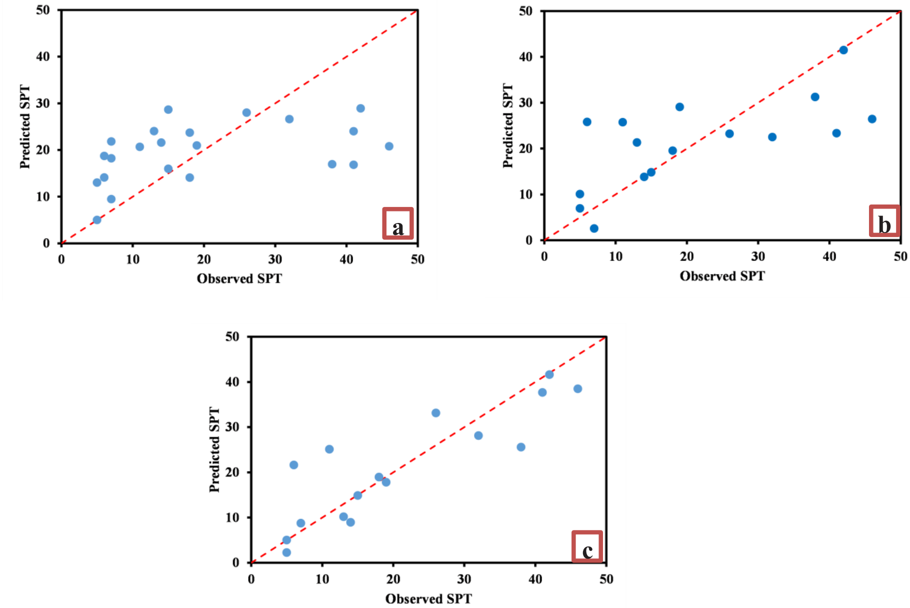

Figure 5: The variation of predicted and observed soil SPT values for various places in Kirkuk city/Iraq using linear multi-regression model (a) Eq. (2), (b) Eq. (3), and (c) Eq. (4).

6. CONCLUSIONS

Based on the results of this study and the data that are currently accessible, the following conclusions have been made:

- According to an overall assessment and by utilizing the IDW approach, the SPT values in different locations of this study were between very loose and loose classification, which is not suitable for heavy or very heavy civil engineering structures, while the SPT values in other studied areas were between loose and medium dense which is good for light to moderate bearing structures.
- SPT values were predicted more precisely using integrated physical and chemical soil properties rather than chemical or physical characteristics alone.
- The pH values predicted organic content, and this prediction is suitable for low precision and inaccurate for high precision.
- SPT and physical soil components have been shown to have various positive and negative relationships. While the SPT values have shown favorable relationships with both silt and clay amounts
- The variation of SPT with the chemical soil properties has revealed positive correlations with SO_3 (%), TSS (%), $CaCO_3$ (%), GYP (%), and pH contents, while negative correlations were obtained between SPT with ORG (%) and Cl (ppm).

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