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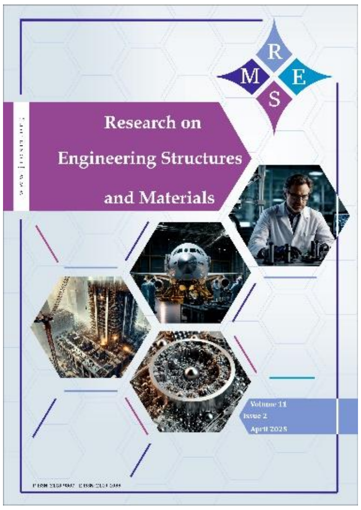

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Research Article

Mapping of elemental soil properties for residential compound in Kirkuk city using GIS technique

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Abstract

Referring to the investment orientation and reducing the housing crisis by establishing residential complexes in mountainous areas adjacent to the city and expanding the city's area to control population growth. This research focused on studying structural cracks that appeared in several residential units of the Garden City complex in Kirkuk, which were attributed to soil subsidence and swelling problems. The study collected data at five locations within a residential complex in Kirkuk City. Utilized the Inverse Distance Weighted (IDW) method for the examination of the ratio of clay to silt, and also the physical attributes of swelling, liquid limit (LL), void ratio (e) and compression index (Cc). Also, the study examined the chemical characteristics of total free calcium carbonate content ($CaCO_3$, %) and total gypsum content (GYP, %). The study used single-regression and multiple-regression models for the interpolation of the plasticity index (PI) and soil attributes. The creation of the digital map sets was for examining the physical and chemical residential compound characteristics in Kirkuk City. PI values can be predicted with greater accuracy by considering integrated physical and chemical soil qualities than g just on chemical or physical factors. PI and physical soil components exhibit a range of both beneficial and detrimental connections. The changes of plasticity index (PI) in connection to physical soil qualities exhibited positive relationships with liquid index (LI), LL, swelling potential, Cc, rebound index (Cr), and e, while PI variations and chemical soil values are positively correlated such as sulfate (SO_3%), gypsum (GYP%), and chloride (Cl%). Linear multiple regression models (LMRM) of physical and combined physical-chemical soil variables reliably PI index values, exhibiting high R^2 value ranges (between 0.072 and 0.018). Elevated clay content, high liquid limit, and swelling signify expansive soils that present hazards for foundations and infrastructure. Minimal silt content: little impact on permeability or erosion. The void ratio (e): Elevated values (0.9+) indicate loose, compressible soils that require stabilization.

1. Introduction

Soil refers to the earth's outermost layer; it is composed of crushed rock that has been weathered and otherwise changed by biological, chemical, and environmental factors, such as erosion. Because of variations in the interaction between the project sit soil layers, aquifer, air, and biosphere, soil differs from its rock-based components [1]. The term "soil" consists of minerals and organic matter suspended in water and air [2, 3]. The soil structure fills the pores in the soil, which are made up of components containing porous granules. Liquid water and gaseous air are both contained in these pores [4]. The typical range for soil types is 1–2 g/cm^3 [5].

Geologists divide time based on observable shifts in the Earth's condition. Recent global environmental changes suggest that the Earth may have entered a new geological epoch dominated

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by humans, the Anthropocene. Here we review the historical genesis of this idea and evaluate human footprints in the geological record against the formal requirements for recognizing a new epoch. The suggests two various proposed dates to meet the criteria for defining the beginning of the Anthropocene: 1610 and 1964. The formal establishment of the Anthropocene epoch would represent a fundamental change in the relationship between humans and the Earth system [6]. This layer that supports life is known as a pedosphere, and it is dynamic, porous, and well-built. It distributes energy, mass flows, and water efficiently. In addition to the fact that pedology, the study of soil science, is helping to lessen environmental pollution. Soil science studies soil as a complex system of interconnected natural components, with an emphasis on its physical, chemical, biological, and evolving properties [7, 8].

Among the several investigations into soil characteristics is the one conducted in the Tuz region [9]. Here, researchers discovered a range of soluble grain percentages (22- 99%) and sulfate proportions (0.04–12.3%). The pH values of the soil for Mosul city range from 7.44 to 7.88, according to [10]'s study of its chemical qualities [11]. Looked at the chemical makeup of various Swiss locations. The percentage of organic materials varied between 3.4% and 7.3%. The grain silo region in Kirkuk city has been the site of soil experiments by the National Center for Structural Laboratories [12].

Soil gypsum concentrations were determined to be between % 0.09and 67.4% [13]. Soil exploration was conducted in the Shorja region of Kirkuk Governorate. The region's sulfate percentage ranged from 0.14 to 44.6 % when soil was examined physically and chemically and based on chemical analysis. Nonetheless, the proportion of carbonates varied from 21.5 to 42.0%, while the gypsum concentration was 0.3 to 95.44 %. Soil tests on the Corniche Street apartment building behind Kirkuk Park were performed by the National Center for Structural Laboratories [14]. Sulfate concentrations in the area are between 0.05% and 6.99%, according to their findings. Identifying geographic information systems as an effective tool for spatial analysis and modelling [15].

Geostatistical methods take into account the study region's spatial scale, sample distance, and the model's spatial pattern to calculate the spatial distribution and variability [16]. In regions where soil sample measurements are unavailable, soil property estimates are derived using interpolation methods. Soil property maps derived from known samples are frequently predicted by IDW interpolation technique. There has extensively evaluated the spatial variability of soil and its spatial correlations and mineral parameters, including physical, chemical, and biological aspects [17], [18].

GIS may be employed to monitor geospatial mapping and cartographic analysis, as both rely on the creation of digital soil maps. These maps provide a rapid and precise method for identifying distinct characteristics, hence enhancing any research. The soil may be examined, and its potential evaluated through the ground conduct procedures utilized in the creation of these digital maps [19]. Soil geotechnical testing for Kirkuk city was therefore a part of this project. Nevertheless, investigating the soil's chemical characteristics in the designated regions is the primary goal of this project. In addition, using the IDW interpolation approach, geotechnical spatial maps of the research area were prepared and predicted. Used spatial analytic methods, including IDW and Kriging, for the integration of 56 soil samples from Kirkuk city pits [20]. The integrated ingredients were categorized by soil properties, including silt, clay, sand, gravel, and initial void ratio, internal friction angle, cohesiveness, and ideal moisture composition. Quantitative methodologies, including geotechnical parameter correlation, linear regression (LMR), and linear multiple regression, were employed. In three zones, third to fifth zones, IDW and Kriging methodologies deviate, indicating they depict the Kirkuk city dissimilarly sand distribution. The linear multiple regression model demonstrates a strong to outstanding connection between fundamental and studied soil parameters, with (R^2) values from 0.77 to 0.97 to 0.86 to 0.98.

Geographic distribution and soil attributes were the study's main emphasis. GIS and IDW projected soil attributes. Over 65 Kirkuk City soil samples were carefully analyzed for physical and behavioral features. Ten digital maps of gravel, sand, clay, silt, specific gravity, dry density, Atterberg limits, and water content by IDW. Different city neighborhoods have different patterns. Sand was the main soil type, gravel was abundant in the north, and silt was diverse. Southern and eastern clay concentrations affect agriculture and pollution control. The LL and PL Atterberg rose with clay, demonstrating a link. Except for the northwest, which had the greatest dry density, most locations had water. Most areas have consistent gravity. The findings improve Kirkuk City engineering and geotechnical operations, backed by cross-validation of fundamental and assessed physical features. IDW maps showed variability in R squared (R^2), with lower RMSE values indicating better accuracy. All categories showed moderate to outstanding correlations [21].

Inverse Distance Weighting and LRMs are used to Multiple Kirkuk were used for research. SPT and chemical parameters (SO_3%, TSS, ORG, Cl ppm, $CaCO_3$%, GYP%, and pH) were evaluated using the IDW method. Multiple- and single-regression models interpolated SPT and soil specs. Kirkuk soil chemistry and standard Penetration Test parameters were mapped digitally. Physical-chemical soil characteristics predict SPT better than chemical or physical components. Soil physical components and SPT have pros and cons. Silt and clay increase SPT values whereas gravel and sand decrease them. SPT chemical soil characteristics are favorably associated with SO_3 and TSS. Positive connections were seen between $CaCO_3$, (GYP%), and pH levels and SPT, (ORG%), and Cl (ppm) [22] are negatively correlated.

Geotechnical engineering is no different from any other branch of engineering in that it must adapt to and make use of emerging technology. The objective of this paper was to examine the spatial correlations among the LL, PI, and LI of soil for certain zones within Sulaymaniyah City. Researching the feasibility of creating digital soil maps of the research area and identifying areas with highly expansive soil is the primary goal. The maps were created using the Geographic Information System (GIS) program's Inverse Distance Weighting (IDW) interpolation function. This study utilized data from 592 LL and PI boreholes and 245 LI boreholes. Each layer was assigned a depth between one and two, two and four, and four and six meters. The LL and PI maps were created using 1396 observations each, whereas the LI maps were based on 371 observations. Based on the R^2 and RMSE results, the IDW approach provides fair forecasts. The research region includes significant areas of expansive soil. Which must be considered before any construction activity can begin, according to the data. Geotechnical engineers rely heavily on these maps to aid in decision-making and to visualize the behaviors of soils [23].

Spectral maps showing the regional distribution and concentration of pollutants indicate a strong correlation between the spectral reflectance recorded by the radiometer and the reflectance resulting from satellite image analysis, thereby improving time, effort and human resources [24]. The research aims at studying the mechanical, chemical, and physical features of the housing project site in Garden City Kirkuk, located on one side of Kirkuk to the northeast. Most of the project structures cracked due to soil problems. The combined properties were analysed and examined by mapping the correlations between the properties in the areas and collecting samples from five different locations for research, and using a method called IDW to combine all the collected data for the soils in the residential complex.

The aim can be depicted as geographical data integration of the amounts of the PI, clay and silt contents, LI, swelling, compression, and swelling indices (Cc and Cr), initial void ratio, and gypsum and chloride contents for the present residential complex investigation in Kirkuk, Iraq. The objective was to examine the link between the plasticity index and physical soil factors with a simple LRMwith discrete correlations. The precise relationships between PI and the physical, chemical, and combined physical-chemical soil parameters were analyzed more utilizing LMRM. In addition, digital maps generated by predictive models may depict the likelihood of soil swelling and mitigate expected hazards for more civil engineering purposes. The site was selected for study after problems appeared in the residential units; cracks appeared, indicating that the foundation had sunk because of soil subsidence. Some cases [2,3]. Unlike previous studies based on geographic information systems and IDW technology conducted in Kirkuk, this study integrates the soil physical and chemical features to predict the plasticity index (PI) with greater accuracy, providing an integrated geotechnical and chemical perspective on soil behaviour.

2. Region of The Residential Complex

The study was conducted in Kirkuk in the Garden City residential complex located at the coordinates (448840-3928757) northeast of Kirkuk city. The project consists of (508) housing units with different sizes (170-200-300) square meters, one and two floors). Different specifications, including service buildings such as a kindergarten, nursery, school, health centers, multiple commercial buildings, and green spaces with no less than 10-15%. The project covers an area of 232,500 square meters. This project was constructed after leveling the land because the area is mountainous consisting of valleys and mountains Cut-and-fill operations were carried out according to the site's geological conditions to achieve suitable ground levels for construction to obtain a suitable terrain for the construction of the residential complex. Figure 1 shown that the project's location in the city of Kirkuk, including the location of the project of our work. Figure 2 at inspection of the residential complex, several fissures of varying sizes and locations have been observed. Field inspections revealed that the cracks observed were mainly caused by foundation settlement due to soil compression in clay layers with high swelling capacity.

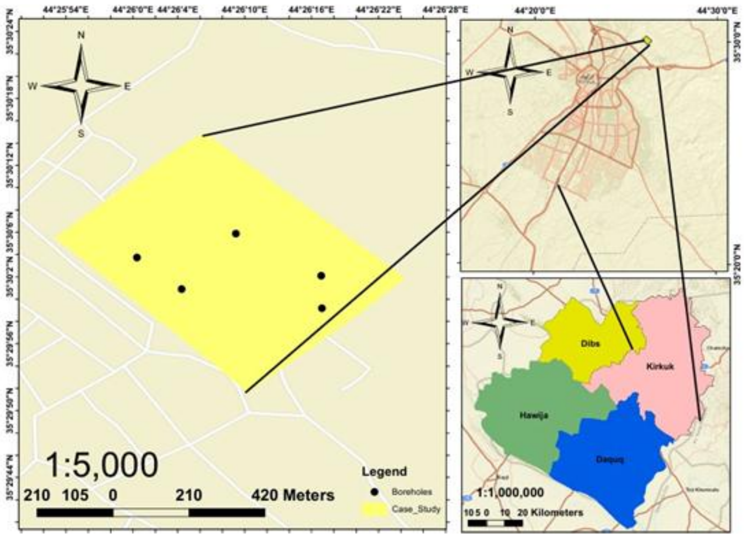


Fig. 1. Detailing the project's location

Fig. 2. Shape and position pisparate fissures in the examined residential compound in Kirkuk, Iraq

3. Methodology

3.1 Laboratory Test Method

Five distinct locations were used to collect samples throughout the project at a depth of 2-3 meters, and the soil consisted of solid clay rock. The samples were processed to get a particle size corresponding to sieve No. 4 (4.75 mm) and subsequently dried in a specialized oven at a 60-70°C for one day. Tables 1 and 2 present the outcomes of mechanical and physical tests aimed at determining the soil features for five selected points in the project. Chemical analyses to ascertain the soil's chemical features. Following ASTM standards ASTM D4318-17E1) for Atterberg limits, (ASTM D4546), all tests were performed y (specifically for swelling potential, ASTM (D698-12-21) for Standard Compaction test, ASTM (D2435), for Consolidation test, and acquired the data presented in Table 3 below were conducted.

Table 1. Coordinates and physical properties of soil in five locations

Location	N	W	Clay (%)	Silt (%)	L.L. (%)	PL (%)	P.I. (%)	L.I. (%)
1	449032.93	3928614.65	87	10	48	35	13	0.9
2	448840.11	3928822.19	88	10	31	21	10	2.33
3	448616.46	3928757.18	93	5	46	36	10	0.89
4	448716.84	3928668.91	93	5	46	36	10	0.89
5	449031.9736	3928703.101	89	11	56	37	19	1.9

Table 2. Mechanical properties of soil samples

Sample No	Swelling (%)	Cc	Cr	e_o
1	4.9	0.19	0.026	0.76
2	1.7	0.2	0.021	0.781
3	3.8	0.13	0.018	0.609
4	5	0.16	0.021	0.574
5	5.5	0.29	0.03	0.963

Table 3. Chemical properties of soil samples

Sample No	SO_3 (%)	Gypsum (%)	Cl (%)	$CaCO_3$ (%)
1	1.34	2.88	0.023	24.246
2	1.43	3.07	0.014	24.396
3	1.61	3.46	0.034	23.046
4	1.07	2.3	0.057	23.971
5	1.2	2.58	0.031	23.845

3.2 Geographic Information System Using IDW Technique

Geographic Information Systems (GIS) serve as a robust instrument for the comprehensive, spatially explicit examination of the Earth's resources [5]. They provide a distinctive capability to integrate geographic data locations and characteristics with tabular data attributes of those features with other data products or outputs. Moreover, Geographic Information Systems have shown to be very effective in the intricate study and interpretation of the interaction dynamics of Earth's natural systems. Advancements in the last decade in cost-effective and user-friendly Geographic Information Systems, particularly tailored for environmental management, have rendered GIS more accessible than ever in the professional sphere.

The data entry procedure begins with designing the database master plan to feature classes, together with their different locations and coordinates. Specific information is manually inputted. Conversely, several types of information may be immediately obtained from point or satellite maps, significantly reducing input time and costs. GIS statistical features can be used to investigate correlations between various data for specific feature classes or between themselves [25]. Soil research has adopted new technologies, facilitating the easier visualization and interpretation of geographical soil data. The amalgamation of GIS and civil engineering made numerous methodologies to depict the earth's surface by three-dimensional models of any global study region. [26].

IDW is one of the most prevalent interpolation algorithms. It was employed for the prediction of the any unmeasured site value for by evaluating the surrounding anticipated location values. It is basically based on two assumptions: first, the influence of an unknown value at a certain location is directly proportional to its closeness to the control point, rather than to more distant locations. The effect magnitude is in an inverse proportion to the distance between locations. Cross-validation was performed for assessing the accuracy of the fit using the root mean square error (RMSE) criterion, which yielded RMSE values ranging from 0.08 to 0.15 for the main physical parameters, indicating satisfactory prediction reliability. It can provide the following equation 1 [27, 28].

$$\frac{\sum_{i=1}^{n} w_i\, z_i}{w_i} = \frac{\sum_{i=1}^{n} zi/D_i^p}{1/D_i^p} \tag{1}$$

Z denotes the interpolated value of the unknown point wi, while the weighting function determines the influence of the control point zi. The value zi represents the observed data at control point i, n is the nearest neighboring points considered in the interpolation process (ranging between 20 and 30 in general IDW applications; however, in this study, n = 4 due to the limited dataset). Di^p denotes the distance between I and the interpolated location, while p represents a weighting exponent, an arbitrary positive real integer.

3.3 Linear Single and Multi-Regression Model

The following sections explain the two models in the analysis.

3.3.1 Single-Regression

Using data collected in the field regarding the soil's physical and chemical features, the study used a linear single regression model for evaluating the soil's plasticity index (PI) feature. The subsequent PI soil characteristics are depicted in the linear simple regression model in Eq. (2):

$$PI\ [\%] = K1\,.physical\ or\ \ chimical\ properties\ [\%] + K2 \tag{2}$$

Where K1 and K2 are parameters. The model's parameters, denoted as K1 and K2 number of physical or chemical model parameters, including LL, clay, silt, gypsum, and organic content percentages, may have a direct correlation with PI content. Although PI might be the main reason for soil swelling, it necessitates a thorough laboratory examination. Accordingly, PI can be estimated from physics and chemistry of soil by the designed linear single regression model.

3.3.2 Multi Regression

Field data of physics and chemistry of soil variables were utilized to compute the PI soil attribute using a linear multi-regression model. The following soil properties are represented by the linear multi-regression model: silt%, clay%, gypsum %, (LL, LI), swelling, Cc, Cr, eo, SO3%, and CL%. The researchers used four separate linear multi-regression models. Independent variables were chosen by a stepwise forward selection method to identify the most statistically significant predictors of PI among the physical and chemical parameters. The following model forms are shown by Eqs. (3), (4), (5), and (6):

The model parameters are A, B, C, D, E, F, G, H, I, J, K, N, O, P, C1, C2, C3, C4, C5, C6, C7, C8, C9, C10,

$$Plastic\ index\ [PI]\%{=}A{+}B{*}\ (silt\%)\ {+}C{*}\ (clay\%)\ {+}D{*}LL{+}E{*}LI \tag{3}$$

$$Plastic\ index\ [PI]\% = F + G * swelling + H * Cc + I * Cr + J * e_o \tag{4}$$

$$Plastic\ index\ [PI]\% = K + N * SO_3\% + O * gypsum\ \% + P * Cl\% \tag{5}$$

$$\begin{aligned} Plastic\ index\ [PI]\% &= C1 + C2 * clay\ \% + C3 * silt\ \% + C4 * LL + C5 * LI\ + \\ C6 *\ swelling &+ C7 * Cc + C8 * Cr + C9 * e_o + C10 * SO_3\% + C11 * gypsum\ \% \\ &+ C12 * Cl\% \end{aligned} \tag{6}$$

C11, and C12. The criteria established by the multi-regression model enable the prediction of the PI component through various ratios of physical and chemical soil factors.

4. Results

4.1 Physical Soil Distribution

Various soil digital maps by GIS technique according to IDW interpolation was performed and using a weighting exponent p = 2 and the four nearest neighboring data points are presented in Figure 3. The Figure includes maps for swelling, clay, silt, LI, compression index, and initial E. It obviously indicated that the clay is concentrated on the western zone of the area under consideration although the silt is concentrated on the eastern zone part. In addition, the highest swelling zone, liquid limit, compression index and void ratio are situated in the southeastern region of the analyzed area. The soils, known for a high clay content (87–93%) and liquid limits LL (31–56) %, are classified as CH (high-plasticity clays) according the Unified Soil Classification System (USCS), signifying significant expansivity. Swelling potential ranged between (1.7-5.5)% (volumetric swelling), presumably volumetric swell or kPa pressure) and increased void ratios (up to 0.96) indicate considerable hazards of heave, subsidence, and diminished bearing capacity, intensified by the semi-arid environment of the region with seasonal moisture variations. The 1:4,000 scale indicates relevance to infrastructure projects (e.g., foundations, roads), where mitigating strategies such as lime stabilization, deep foundations, or moisture control are essential.

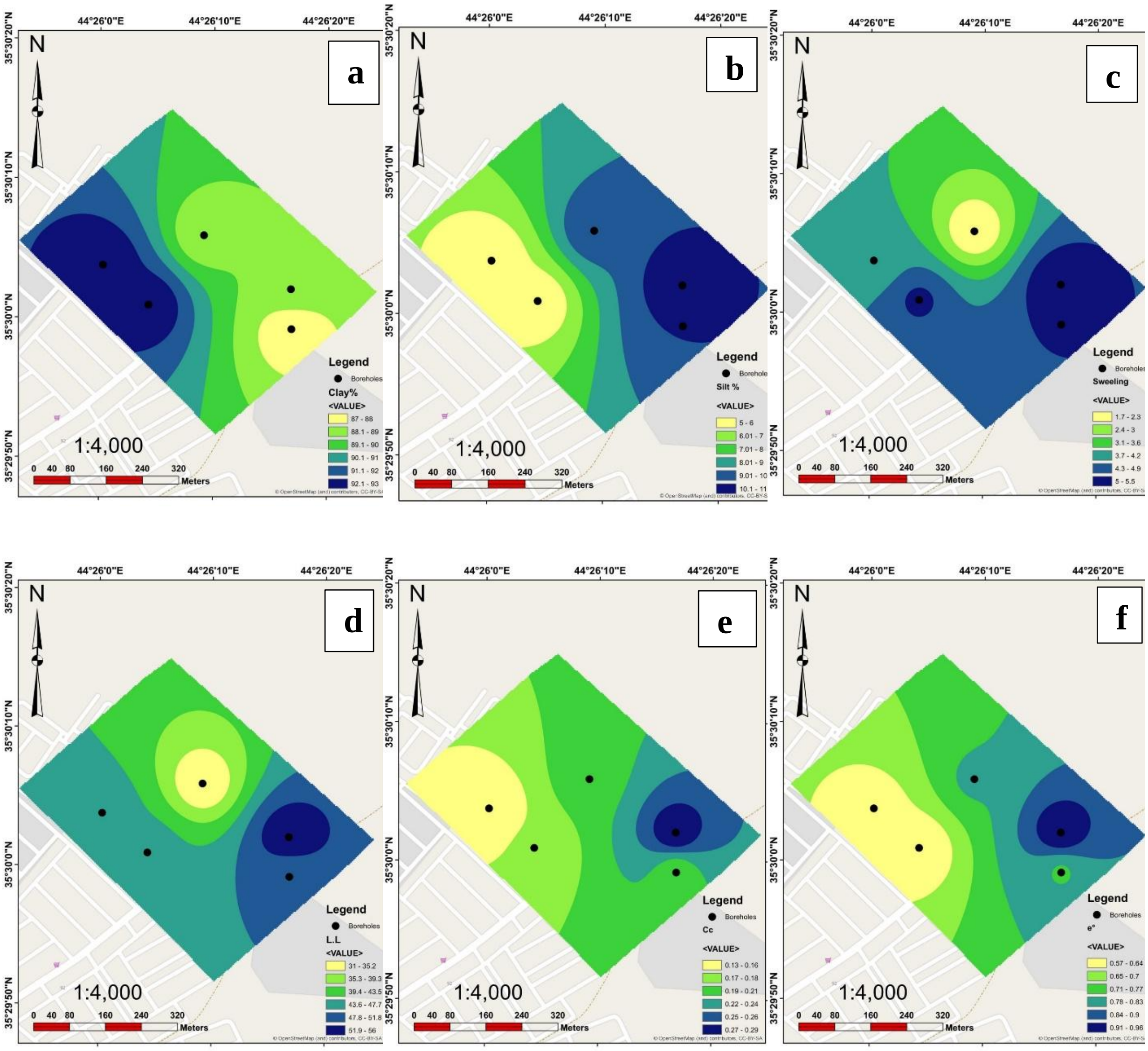


Fig. 3. Inverted distance weighting technique for soil samples collected from Garden, Kirkuk City, Iraq: (a) clay, (b) silt, (c) swelling, (d) LL, €, Cc, and (f) void ratio

4.2 Chemical Soil Distribution

Figure 4 shows soil digital maps by GIS according to the IDW for CaCO3 and gypsum contents. The CaCO3 ratio (23.3-24.4) concentrates in the Middle Eastern area under consideration and the gypsum (2.49-3.46) in the north western part.

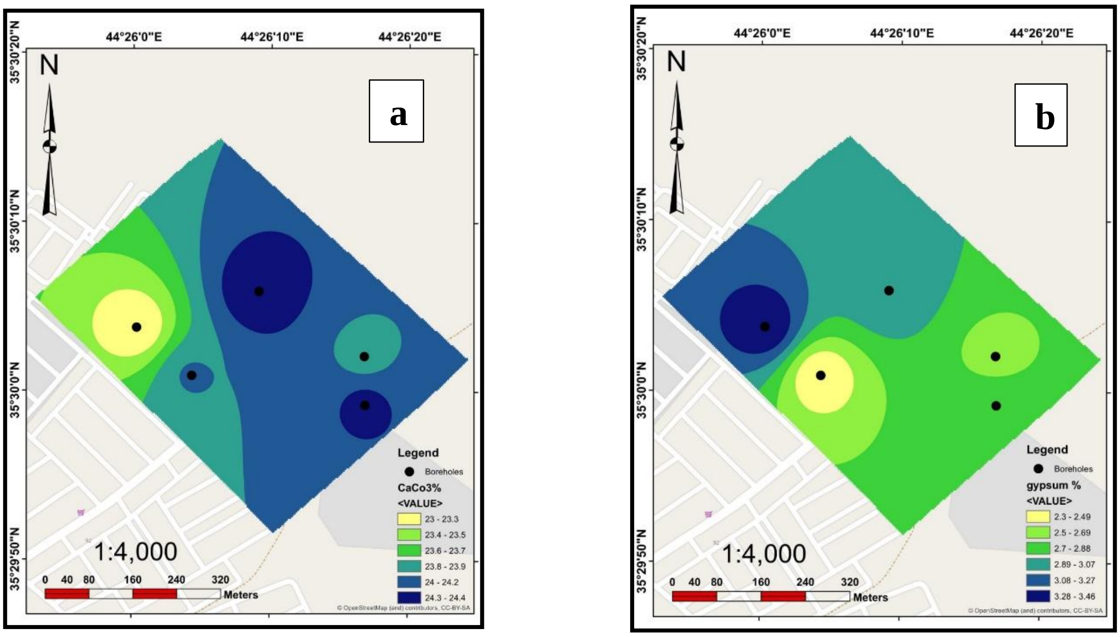


Fig. 4. distributions of IDW methodology for chemical soil in study areas of Garden City, Kirkuk City, Iraq: (a) $CaCO_3$, and (b) gypsum content

4.3 The Relationship Between Plasticity Index and Soil Properties

Table 4 summarizes the relationships between PI and several soil parameters, including silt percentage, clay percentage, gypsum percentage, liquid limit (LL), plasticity index (LI), swelling potential, Cc, Cr) eo, and concentrations of SO3% and Cl% compounds.

Table 4. The correlations between the PI and soil features

Parameter	P.I.	Clay (%)	Silt (%)	L.L. (%)	L.I. (%)	Swelling	Cc	Cr	eo	SO_3 (%)	Gypsum (%)	Cl (%)
Plastic limit	1.0											
Clay (%)	-0.42	1.00										
Silt (%)	0.66	-0.93	1.00									
L.L. (%)	-0.73	0.14	0.04	1.00								
L.I. (%)	0.320	-0.501	0.680	-0.380	1.00							
Swelling (%)	0.59	0.16	-0.05	0.94	-0.52	1.00						
Cc	0.90	-0.57	0.82	0.40	0.65	0.29	1.00					
Cr	0.93	-0.61	0.78	0.62	0.30	0.57	0.90	1.00				
eo	0.86	-0.71	0.92	0.29	0.69	0.13	0.95	0.85	1.00			
SO3 (%)	-0.35	-0.02	-0.09	-0.37	0.01	-0.58	-0.42	-0.49	-0.14	1.00		
Gypsum (%)	-0.35	-0.02	-0.09	-0.37	0.01	-0.58	-0.42	-0.49	-0.14	1.00	1	
Cl (%)	-0.13	0.80	-0.73	0.41	-0.60	0.58	-0.30	-0.19	-0.56	-0.58	-0.57	1

Plasticity index (PI), Compression Index (Cc), and recompression coefficient (Cr)

The PI characteristic is favorably and adversely associated with certain soil parameters, ranging from -0.42 to 0.93. Higher plasticity increases soil porosity and liquid limit, as the PI substantially correlates with the Liquid Limit (LL) (0.73), compression index (Cc) (0.90), and void ratio (eo) (0.86). Clay percentage inversely corresponds with silt percentage (-0.93) and marginally with recompression coefficient Cr (-0.61). The strong correlation between liquid limit and swelling potential (0.94) shows that soils with higher liquid limits expand more, which is crucial for building stability. Cc significantly matches recompression coefficient Cr (1.00) and eo (0.92), showing that the high correlation between PI and Cr may be an indirect result of Cr's strong correlation with Cc and eo. The similar values between SO_3% and Gypsum% are expected because SO_3 is a major component of gypsum, whereas chloride percentage (Cl %) favors clay (0.80) but negatively correlates with LL (-0.73) is logical, as salts cause flocculation of clay particles, reducing plasticity. These links are needed to map elemental values and understand soil behavior using GIS.

4.4 Linear Single Regression Model

Table 5 shows potential linear one-regression model features. One LRM was solved and provided by least squares. Table 5 displays the model's parameters and R^2 values for all scenarios. Additionally, R^2 values range (0.872) to (0.018).

Table 5. Swelling soil property LRM analysis

Swelling Properties (%)	*Equation*	Properties (%)	R^2
Plasticity Index (PI)	0.3151*L.L-1.919	L.L	0.532
	0.879*silt(%)+5.19	Silt	0.440
	-0.563*clay(%)+63.031	Clay	0.165
	-3.0591*GYP(%) + 21.141	GYP (%)	0.122
	-32.47*Cl(%)+13.4331	CI	0.018
	-32.471*Cl(%)+13.433	LI	0.102
	1.522*swelling+6.0451	Swelling	0.350
	58.6791*Cc+1.017	Cc	0.817
	766.52*Cr-5.3801	Cr	0.872
	21.7451*eo-3.634	eo	0.764
	-6.59*SO3(%)+21.1641	SO3	0.123

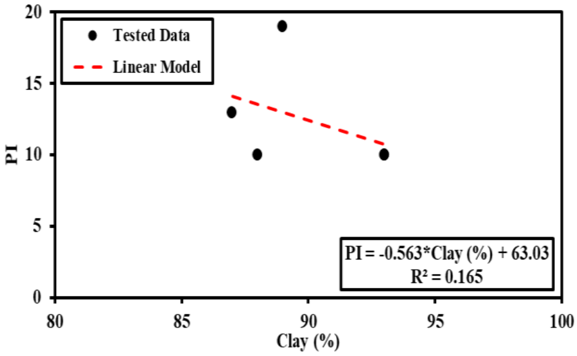
The PI relationship to the physical soil characteristics is illustrated in Figure 5a–d. When it comes to the physical components of soil, PI has both positive and negative relationships. The figures analyze the PI–Clay (%) relationship is weakly negative and scientifically unreasonable due to differences in clay type or imbalance in sample distribution. (R2 = 0.165) with plasticity index. An increase in clay concentration decreases PI somewhat. Shows a moderate positive connection (R2= 0.440) between silt concentration and PI. Liquidity and plasticity. LI has little effect on PI (R2= 0.102).

The relationship between the LL and the PI. In the data, the two variables (R^2 = 0.532) are positively correlated. If LL increases, PI climbs, showing the strongest correlation among the four metrics examined. Figures (e-h) depict the edema relationship to PI. It has a little positive connection (R^2 = 0.351), suggesting that when swelling occurs, PI also rises, albeit to a limited extent. This outcome is characterized by a poor correlation. Figure (d) depicts the relationship between the Cc and the PI. The data exhibits a robust positive correlation (R^2 = 0.8171), indicating that PI significantly increases as Cc rises. Figure (e) illustrates the initial void ratio (eo) in correlation with the plasticity index (PI). It shows that the correlation is positive at (R^2 = 0.746) (R^2 = 0.8723), indicating that the void ratio (eo) and compression ratio (Cr) significantly affect PI, as shown in Figure (5) illustrates the strong positive correlation; as Cr rise, PI also grows significantly, showing that the four parameters analyzed are strongly correlated.

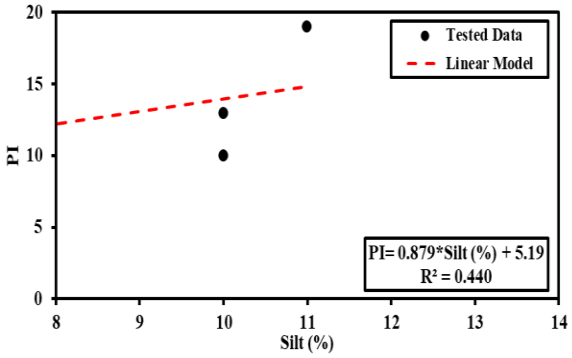
The LRMs used interpret the relationships between chemical properties by linking the independent variables (SO_3%, GYP%, Cl%) to the dependent variable Pl. The results showed a general weakness in the explanatory power of these models, with both SO_3% ($P_1 = -6.59 \times SO_3 + 21.16$, R^2 = 0.123) and GYP% ($P_1 = -3.06 \times GYP + 21.14$, R^2 = 0.122) showed slight negative correlations, meaning that increases in SO_3 or GYP content were accompanied by limited decreases in P_1 values.

In contrast, the Cl% model ($P_1 = -32.47 \times Cl + 13.43$, R^2 = 0.018) a relatively high slope coefficient, but with little explanatory power, possibly due to the narrow range of Cl concentrations in the samples (0.01–0.06%) as mentioned in section (m). The data in section (i) most likely refer to different codes or sample groups, while section (m) clarifies the measurement ranges, confirming the limited variation in the Cl% variable.

Overall, PI–SO_3, GYP, Cl: Very weak relationships (R^2 < 0.13) which have no statistical effect on plasticity and the equation for Cl is unrealistic (very large coefficient versus very weak R^2). Statistically, some models are not valid for prediction due to low R^2 (<0.2). Therefore, it is preferable to exclude them if researchers deem it necessary.



(a)



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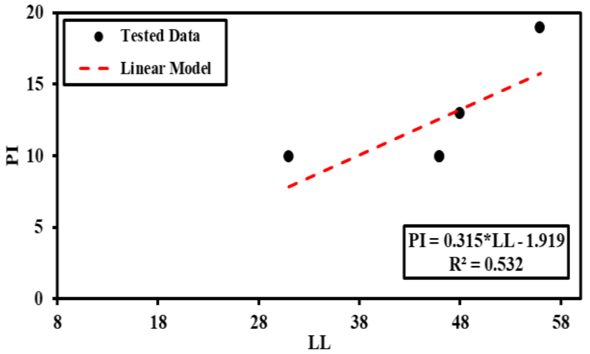
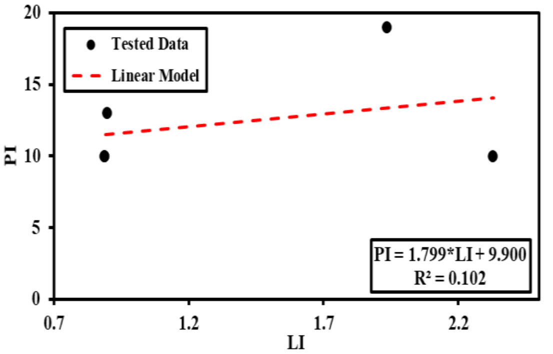
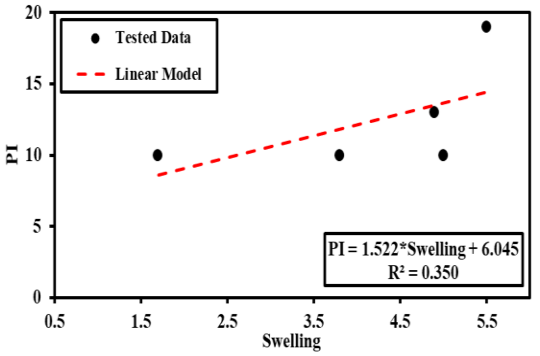


(c)



(d)



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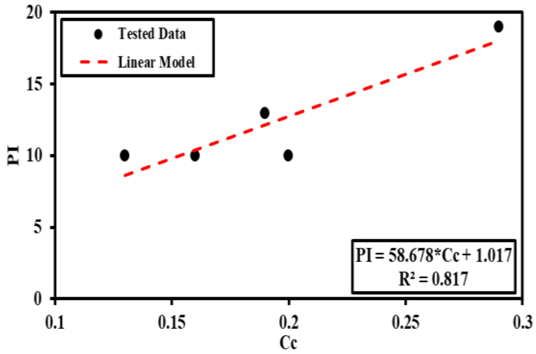

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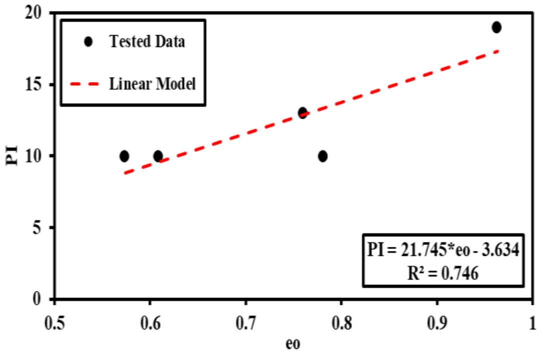
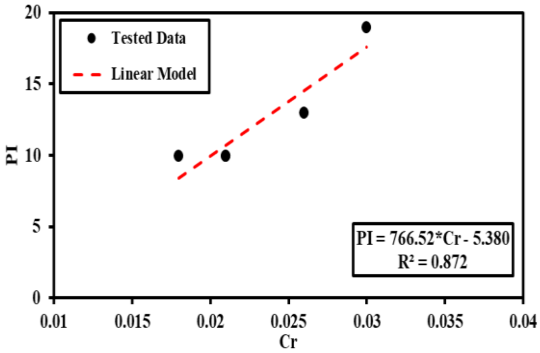


(g)



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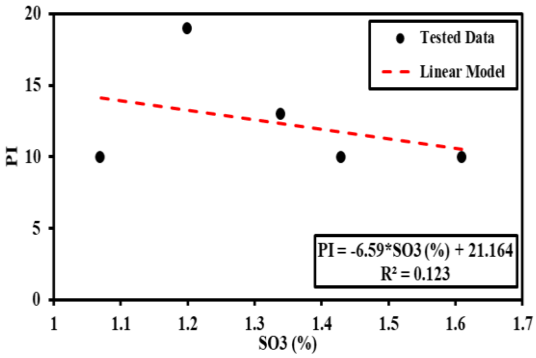
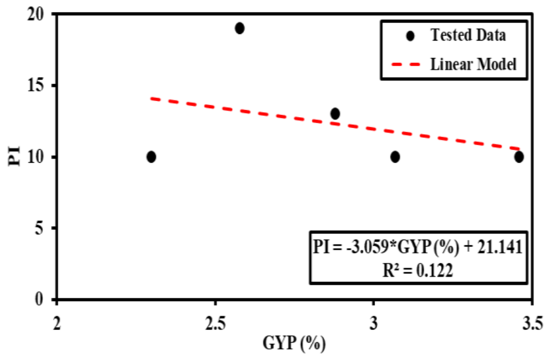
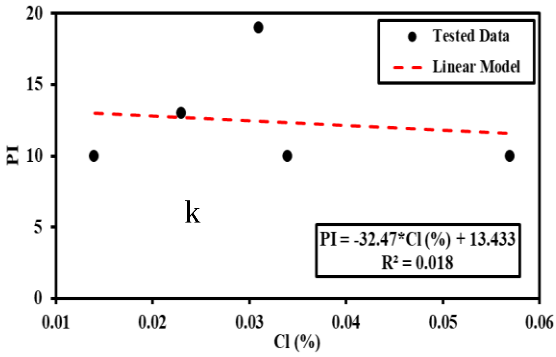


(i)



(j)

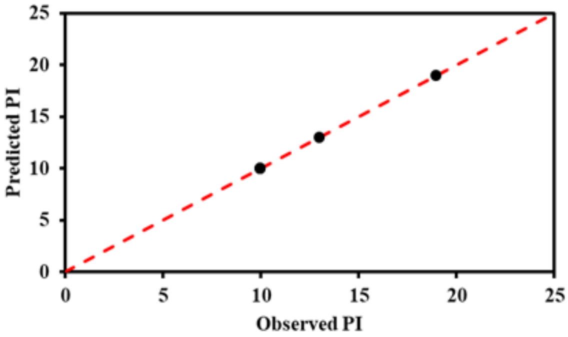


(k)

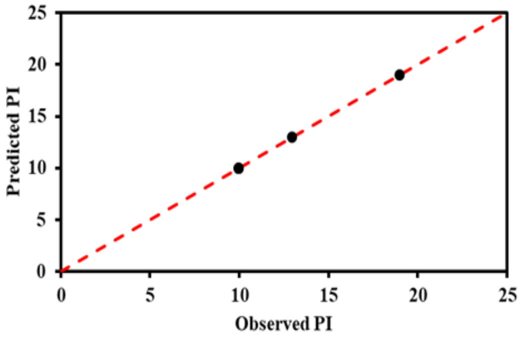
Fig. 5. The variation of PI with different soil compositions in Garden City in Kirkuk City, utilizing a linear simple regression model

4.5 Multiple LRM

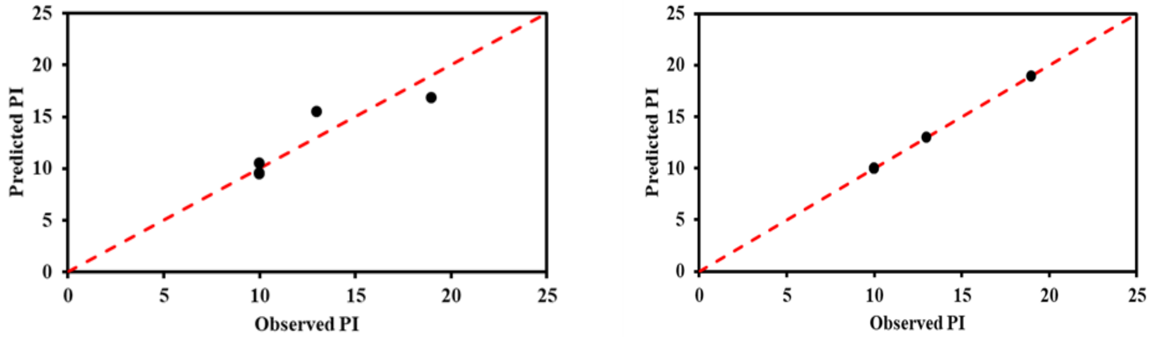
Figure 6 shows the general framework for applying multiple linear regression, where the least squares method was used to find model solutions and estimate its statistical coefficients. The figure shows the predictive values of the model and the coefficients derived from it, where the correlation coefficient (R) ranged between 0.68 to 0.872, confirming a strong but realistic fit to the experimental data. The model was according to a scholarly work on the PI relationship to four chemical features of the soil in the Garden City area of Kirkuk. Figure (6-A) shows a negative relationship between PI and $CaCO_3$%, as calcium carbonate usually contributes to reducing plasticity through its interaction with clay minerals, resulting in a harder and less flexible structure. Figure (6-b) illustrates the relationship between PI and gypsum (GYP%), which is irregular; low gypsum content may help improve soil structure cohesion, while high concentrations contribute to reduced flexibility due to the high solubility of gypsum.



(a)



(b)



(c) (d)

Fig. 6. Variation of PI content for soil ingredients inside Garden City, in Kirkuk City, Iraq, employing a LMRM: a – Eq.3, b – Eq.4, c – Eq.5, d – Eq.6

Figure (6-c) shows a clear positive relationship between PI and clay content (CL%), where high clay content increases soil flexibility by enhancing internal cohesion and water retention capacity. In contrast, Figure (6-d) indicates an inverse relationship between PI and SO_3%, as sulphates cause soil particles to expand and weaken their cohesion when exposed to moisture. In general, clay content (CL%) is the most influential factor in determining plasticity, while calcium carbonate ($CaCO_3$) and sulphate (SO_3) have the opposite effect, reducing it. The effect of gypsum (GYP%) varies depending on its concentration and soil conditions. These results highlight the complexity of the effect of chemical reactions on soil behavior and plasticity.

5. Discussion

Data on the distribution of particles might be helpful in examining the likelihood of soil swelling and in developing appropriate foundation alternatives. In comparison to soils with lower clay content, those with a higher concentration of clay are much more likely to swell. Notwithstanding their diminutive size and elevated surface area to volume ratio, clay particles possess the capacity to absorb and retain substantial quantities of water. Soil expands owing to water absorption, as clay particles absorb greater amounts of water, leading to an increase in volume. Soil clay percentage, clay type, and water absorption rate would all have a role in the swelling. Consequently, the clay content of the soil is a crucial factor to consider when determining the likelihood of soil swelling. Predicting the soil type content in nearby sample locations is possible with the use of the GIS technique and the IDW approach.

LL and PI can be utilized to forecast soil expansion. These two elements provide significant insight into the soil's response to variations in moisture levels. Soils with high concentrations are more prone to swelling because they change size more in response to moisture changes and can generally hold more water. These soils have the ability to expand and even collapse if they hold too much water.

Negative correlations between PI and SO_3%, GYP%, and Cl% indicate that higher chemical content reduces soil plasticity and swelling potential. This is attributed to the flocculating effect of salts, which decrease water adsorption on clay surfaces, thereby lowering plasticity. The integration of physical and chemical parameters significantly enhanced PI prediction accuracy, as indicated by the multiple regression model (R^2 = 0.872). This finding supports the hypothesis that combined modelling yields more reliable results than separate analyses of physical or chemical factors alone.

The southeastern part of the Garden City complex exhibits the highest swelling potential, liquid limit, and void ratio, as indicated by the IDW maps (Figure 3). This zone corresponds spatially to the locations where the most severe foundation cracks were observed, confirming the link between soil expansivity and structural distress.

6. Conclusions

Relying on only five samples limits the accuracy of generalizing clay distribution located in a residential complex in Garden Kirkuk. The geographical analysis for this study used the IDW method. Tests were conducted on cracks in the structures of the compound under study using the physics and chemistry of soil samples taken from the site. The statistical analysis was based on simple and multiple LRMs, as well as correlations between the PI and soil properties. The following conclusions were proposed.

- The residential complex under examination has clay soil at a depth of 2-3 m distributed mostly in three zones, as determined by the IDW approach in conjunction with GIS. The GIS and IDW analysis revealed that the northern half of the residential complex under examination had the highest percentages of clay and silt.
- The bulk of the investigated residential compound is covered by clay soil, in accordance with the IDW methodology integrated with the GIS process.
- GIS and IDW analyses revealed that the central area of the residential compound under consideration contained the highest quantity of gypsum.
- The soil models analyzed using the GIS and the IDW method mainly contain values for the plasticity index and liquidity limit ranging from 21 to 37, respectively, indicating that the soil is expansive clay soil.
- The plasticity index, which indicates swelling, has been found to have both positive and negative relationships with soil physical and chemical factors.
- The accurate prediction PI values were obtained by the physical combined with physical and chemical soil parameters using the linear multi-regression models that were presented. Both models achieved R2-values of 0.872 demonstrating the accuracy and positive correlation of the results.
- Soil classification is clay CL (inorganic silt/low plasticity clay).
- The statistical models in this study comprehensively offer mechanical and geographical insights into the causes of cracks in the residential complex under study.

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