



Geostatistics of strength, modeling and GIS mapping of soil properties for residential purpose for Sulaimani City soils, Kurdistan Region, Iraq

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Abstract

The main objective of the present study is to measure the soil properties of the study area, Sulaimani City (35° 33' 26" N 45° 26' 08" E) and their spatial variability. A combination of conventional analytical methods and geostatistical methods were used to analyze the data for spatial variability. This study was focused on the correlations between the physical and mechanical properties and geostatistical analysis of the Sulaimani City soils based on the experimental data and the data collected from various research studies. The study was also focused on presenting the Atterberg limits, and the mechanical properties such as undrained shear strength of extruded soils using ArcGIS mapping. A total of 85 boreholes with depth up to 6 m underground were drilled and the physical and mechanical properties of the soils were tested. The index properties, compressibility properties, free swelling, and compressive strength of the soils were investigated and quantified with over 1000 data records collected from the literature. The field-tested data were compared with the data from literature and qualified using Vipulanandan correlation model. Using the mean, standard deviation, and coefficient of variation, the parameters of soils properties such as density (γ), index properties, swelling index, initial void ratio, compression index (Cc) and undrained shear strength (S_u) properties were also studied. Undrained shear strength (S_u) of Sulaimani City soils varied from 10 to 119 kPa and quantified very well as a function of liquid limit, plasticity index, moisture content and dry density using the experimental data and data collected from the literature. Statistical analyses and ArcGIS zonation maps based on soil type are presented. Thus, these data are speedily available and can be valuable and provide suggestions for engineers and planners.

Keywords Atterberg limits · Undrained shear strength · ArcGIS map · Statistical analysis · Modeling

Introduction

The geotechnical properties of soils are important parameters to sketch better engineering designs. These geotechnical properties can be grouped into the physical and engineering properties of the soil. Physical properties are which represent the behavior of the soils at the in situ level; generally, these properties are influenced by the geology of the area, while the engineering properties are mostly used in engineering design calculations. The testing procedures were selected based on the accuracy of the results, the cost for the testing, method and accepted a degree of disturbance during

the sampling, soil type, project requirements, and time limitation (O'Neill et al. 1995; Vipulanandan et al. 2006, 2007a, b; Siraruban 2008; Mohammed 2018a, b, c, d). The availability of better correlations between geotechnical properties minimizes the cost of experiments as well as speeds up the design steps. Hence, many researches are being conducted to investigate the relationship between important geotechnical properties (strength, modulus, density) and easily measurable soil properties (liquid limit, plastic limit and moisture content) (Ganstone 1971; Bilgin et al. 2013; Arulrajah et al. 2008). Dennehy (1978), investigated relationship between S_u with LL for remolded marine clay soil samples which were prepared at different moisture content. There are many relations reported in the literature between undrained shear strength (S_u) and index properties for field deposits of clay soils (Duncan 2005; Ganji 2006). Ganji (2006) investigated the linear relationship between the physical and engineering properties of Houston clay soils. Vipulanandan et al. (2007a, b) have developed linear relationships between the

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geotechnical properties of clay soils. It is considered that Atterberg limit tests are not only convenient but may also provide a cheaper method of assessing the quick undrained shear strength of clays (Yilmaz 2000). Since undrained shear strength (S_u) is considered as the main strength parameter, in this study, nonlinear relations between S_u and the index properties of Sulaimani soils are investigated with better correlations of coefficients (R). Both the deltaic and marine clay deposits are bounded by the U-line and A-line in the plasticity chart. In the past, many researchers have developed correlations between the soil index properties, strength parameters and consolidation parameters for various clayey soils (Arulrajah et al. 2008).

This study focused on characteristics of the consolidation and strength properties of soils using the results of 85 boreholes with depth of 6 m underground and presents the experimental results using ArcGIS map. Horpibulsuk et al. (2007) investigated the relationship between the PI and LL of Bangkok marine clay, as mentioned in Eq. (1), with R^2 of 0.94.

$$PI = 0.79 \times LL - 10.27. \quad (1)$$

The behavior of fine soils is defined based on their index properties such as liquid limit (LL), and plasticity index (PI). A major stage in geotechnical engineering is to establish geotechnical properties of soil models based on the empirical equations using the experimental test data. Undrained shear strength (S_u) and compression index (Cc) are the main parameters in the state design of the footings, pavements, or stability assessment of existing structures or slopes. However, S_u is not a fundamental soil property but depends on factors such as the moisture content, index properties and density (Westerberg et al. 2015). The undrained shear strength (S_u) and compression index (Cc) were used to predict the amount of bearing capacity and consolidation settlement of the footings, respectively (Sridharan et al. 2000). The engineering behavior of soils mostly depends on the constitution of the controlling parameters of clay soils, such as moisture content and index properties, strength, and density. There are several soil property relationships that have been quantified in the literature, which are summarized in Table 1. Vipulanandan et al. (2007a, b) investigated relations between undrained shear strength (S_u) of the soft deltaic clay to the moisture content of the soil. It is considered that Atterberg limit tests are not only convenient but may also provide an easy procedure method for assessing the quick undrained shear strength of soils (S_u) (Yilmaz 2000; Tiwari et al. 2011). Geotechnical investigation contributes predominantly to the total cost of the project. Therefore, this aspect is overlooked due to the absence of an abundance of sufficient funds available for this important task. Geotechnical data gathered from various governments and private organizations in the midst

Table 1 Literature review on geotechnical properties correlations of the clay soil

Reference	Correlations	R^2
Federico et al. (1983)	$S_u = 182.93 \times e^{-2.37\left(\frac{MC}{LL}\right)}$	Not available
Nagaraj et al. (1993)	$Cc = 0.274 \times e_L$	Not available
Sridharan et al. (2002)	$S \text{ (kPa)} = 8.2 - 0.06 \text{ MC}$	Not available
Sridharan and Rao Raghuvveer (2004)	$S_u = 8.2 - 0.06 \times \text{MC}$	Not available
Lee (2004)	$S_u = 182.93 \times e^{-2.37\left(\frac{MC}{LL}\right)}$	Not available
Berilgen et al. (2007)	$S_u = 145 \times e^{-2.86\left(\frac{MC}{LL}\right)}$	Not available
Horpibulsuk et al. (2007)	$PI = 0.79 \times (LL - 13)$	Not available
Sivaruban (2008)	$S_u/PI = 64.27LL^{(-1.30)}$	0.43
Sivaruban (2008)	$S_u/LL = 0.49e^{(-0.02PI)}$	0.29
Edil et al. (2009)	$S_u = 191.4/e^{-0.03LL}$	0.38
Bilgin et al. (2013)	$Cc = 0.0092 \times (LL - 10.34)$	0.49
Asik et al. (2016)	$Cc = 0.5562e_o - 0.1453$	0.89
	$Cc = 0.0158MC - 0.179$	0.85
Mohammed (2017)	$PI = 0.75 \times LL - 7.7$	0.97
	$\frac{1}{Cc} = 30.5 - \left(\frac{MC}{0.24 + 0.03MC}\right)$	0.81
	$\frac{1}{Cc} = 20 - \left(\frac{\gamma_d}{0.003 + 0.05\gamma_d}\right)$	0.80
Current study	$S_u = 26.3 \times (\gamma_d)^{1.9} \frac{(LL)^{0.5}}{(PI)^{0.3} \times (MC)^{0.2}}$	0.87

of project planning are accepted to be a fundamental part in the framework of building and foundation works.

Geographical information system (GIS) is an extremely powerful tool for catching, showing and examining topographically referenced information (Sivaruban 2008; Mahar et al. 1983; Keller et al. 1985). This work has been performed in the field of Sulaimani City soil mapping zones, utilizing GIS tools. Also, in this study, interest was in the correlations and statistical variation of Sulaimani City soil properties, such as liquid limit, plasticity index, density, and undrained shear strength (S_u), since the method of statistics is a tool used to analyze the special variation of data. Statistical tools including mean, standard deviation, variance, range, and COV were used in the analyses. Since undrained shear strength (S_u) was considered as an important strength parameter, nonlinear relations between (S_u) and the index properties (LL and PI), moisture content (MC) and dry density (γ_d) of Sulaimani City soils were investigated and it correlated well based on the coefficient of determination (R^2) and the root mean square error (RMSE).

Vipulanandan correlation model

For shear thinning fluids, the shear stress–shear strain rate relationship is nonlinear with a limit on the maximum shear stress tolerance. Similar trends have been observed in many

other engineering and environmental applications and have been modeled using the Vipulanandan correlation model (Qadir et al. 2019a, b; Abdulla et al. 2019; Mohammed and Vipulanandan 2014; Mohammed and Mahmood 2018a, b, 2019a, b). Qadir et al. (2019a, b) and Mahmood et al. (2019) used Vipulanandan correlation model to represent the change in grouted sand properties and cement mortar with curing time. Mohammed and Vipulanandan (2014) used the hyperbolic relationship to predict the relation between compressive and tensile strength of sulfate-contaminated CL soils with and without polymer treatment. In addition, Vipulanandan and Mohammed (2014, 2015, 2018a, b) used the Vipulanandan correlation model to predict shear stress versus shear strain rate and the maximum shear stress of drilling mud and oil well smart cement.

Methods and materials

The boreholes were drilled, and the disturbed and undisturbed soil samples were collected from the northwest of the Sulaimani City area as shown in Fig. 1, and then all the data were digitized for analysis. Around 630 soil properties data were collected from 85 boreholes (BH) (Fig. 1b). This data set was extruded, tested and reported by the Ministry of Construction and Housing/Construction Laboratories/Sulaimani City in between 2017 and 2019. Most of the data were taken from the clay type of soil. SC type of soil has the lowest percentage distribution. Every 1.5 m depth up to 6 m were taken into account in this analysis. The mean, maximum, and minimum soil properties were reported for each BH and the standard deviation and coefficient of variance were also reported.

The study area

The area of study is located between two latitudes 29.840 N and 30.54 N and between two longitudes 74.70 E and 75.32 E. The area of study is 1 of the 22 districts of Sulaimani City, Kurdistan Region, Iraq. The total area of study district is 131.227 km².

Georeferencing of boreholes

The georeference tab is a tool in ArcGIS. It is used to georeference a normal borehole map with a known coordinate map. Using this tool, the boreholes were located on the parcel map. This map was georeferenced using the street names with the Sulaimani City parcel maps. The locations of all the boreholes were more concentrated on the northwest part of Sulaimani City as shown in Fig. 1. Atterberg limits and shear strength were taken as the major variables. The spatial

variations of Atterberg limits studies were also performed up to a depth of 6 m underground.

Test methods

The soil samples were extruded, tested, and reported by the Ministry of Construction and Housing/Construction Laboratories/Sulaimani, and all the tests were performed according to ASTM standards.

Particle size distribution (ASTM D 6913)

Both sieve analysis and hydrometer analysis for the field soils were used to determine the particle size distribution of the soils.

Atterberg limits

Liquid limit and plastic limit tests were conducted on the soil samples based on ASTM D 4318.

Unconfined compression tests (UCS)

The test for the undisturbed soil samples was conducted according to ASTM D-5102. The unconfined compressive strengths (q_u) were determined from the stress–strain relationships. The undisturbed soil samples were extruded from the Shelby tubes using a hydraulic jack. Soil samples were weighed to crosscheck the wet unit weight.

Vipulanandan correlation model

Nonlinear relationships between the physical properties, compression properties, and free swelling of the Sulaimani soils were investigated. Based on the inspection of the test data and the data collected from the literature, the following relationship is proposed (Vipulanandan and Mohammed 2014):

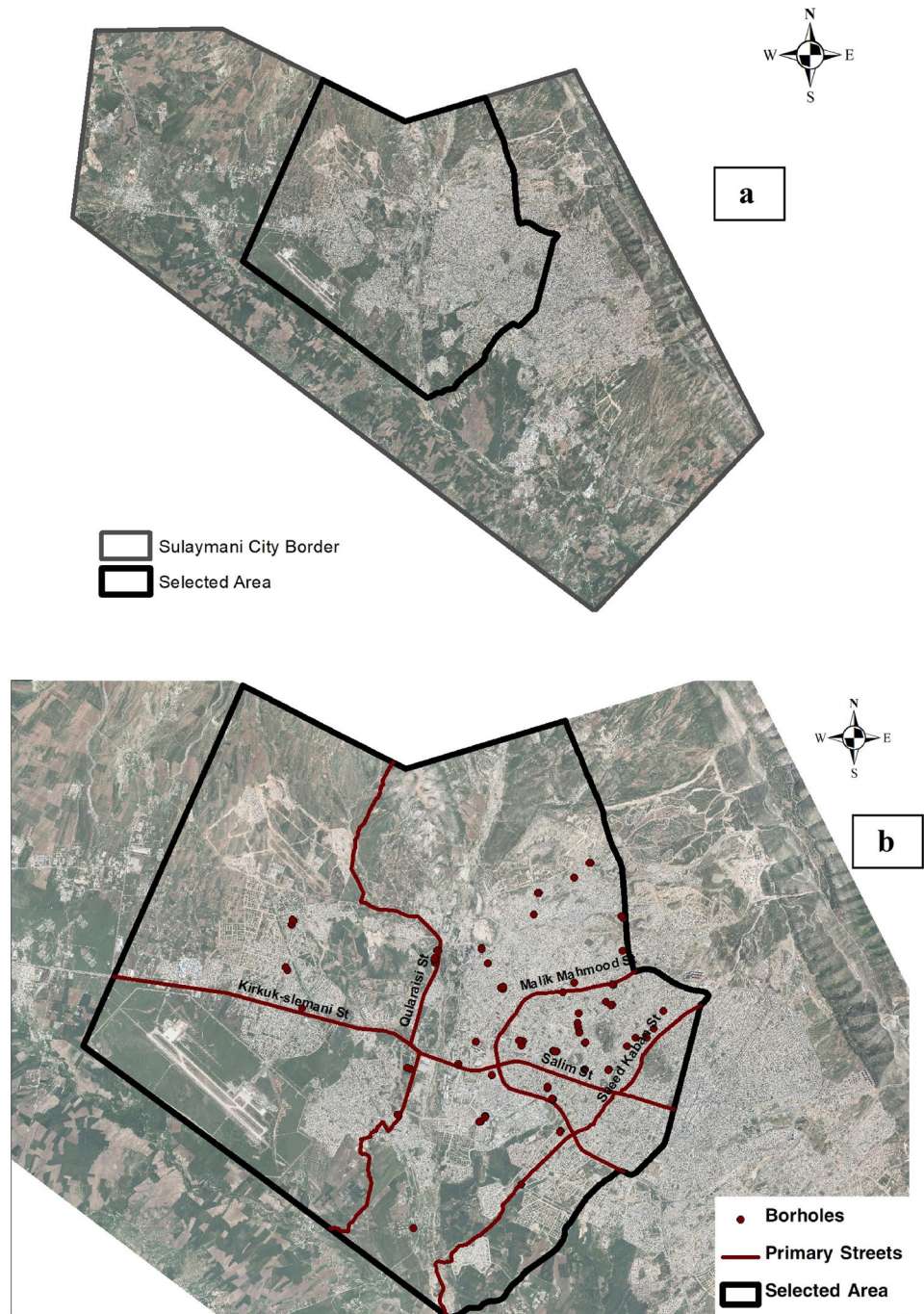
$$\Delta y = Y - Y_o = \frac{X}{(A + B \times X)}, \quad (2)$$

where Y is the soil property (dependent variable); Y_o , A and B are the model parameters (Table 3) and X is the soil property (independent variables).

Results and analyses

The liquid limit, plasticity index, density, moisture content and undrained shear strength values were imported into ArcGIS up to a depth of 6 m. The values were interpolated over

Fig. 1 ArcGIS map of Sulaymani City: **a** study area and **b** main streets and boundary line with BH locations



the selected area to identify the spatial distribution of soil properties. The statistical details and the histograms were developed for each depth data set to identify the distribution. The statistical results are summarized in Table 2. The histograms of liquid limit, plasticity index, density, moisture content and shear strength are as shown in Fig. 2. The liquid limit values are imported into ArcGIS up to a depth of 6 m. The values were interpolated over the selected area to identify the spatial distribution of liquid limit. The statistical

Table 2 Statistical parameters of geotechnical properties for Sulaymani City soils

Statistical parameters	γ_d (g/cm ³)	MC (%)	LL (%)	PI (%)	S_u (kPa)
No. of data	630	630	630	630	630
Range	1.15–1.92	8–32	28–50	11–25	10–119
Mean (μ)	1.65	18	39	18	76
Std. deviation (σ) ^a	0.10	6.0	5.3	3.53	19
COV (%)	0.06	0.28	0.13	0.19	0.24

^aStandard deviation has the same units as the data points

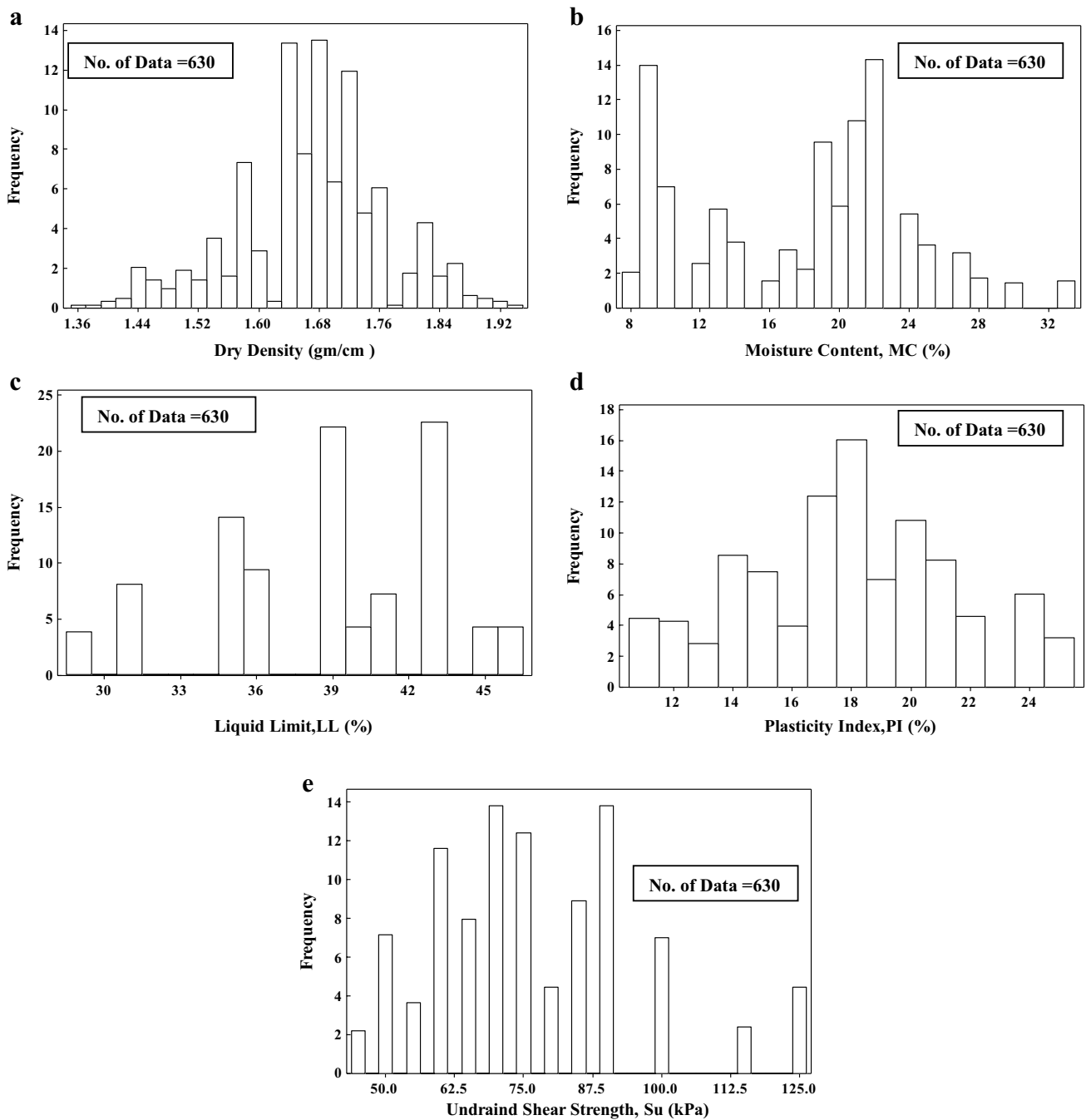


Fig. 2 Histogram of the Sulaimani City soil properties: **a** dry density, **b** moisture content, **c** liquid limit, **d** plasticity index, **e** undrained shear strength

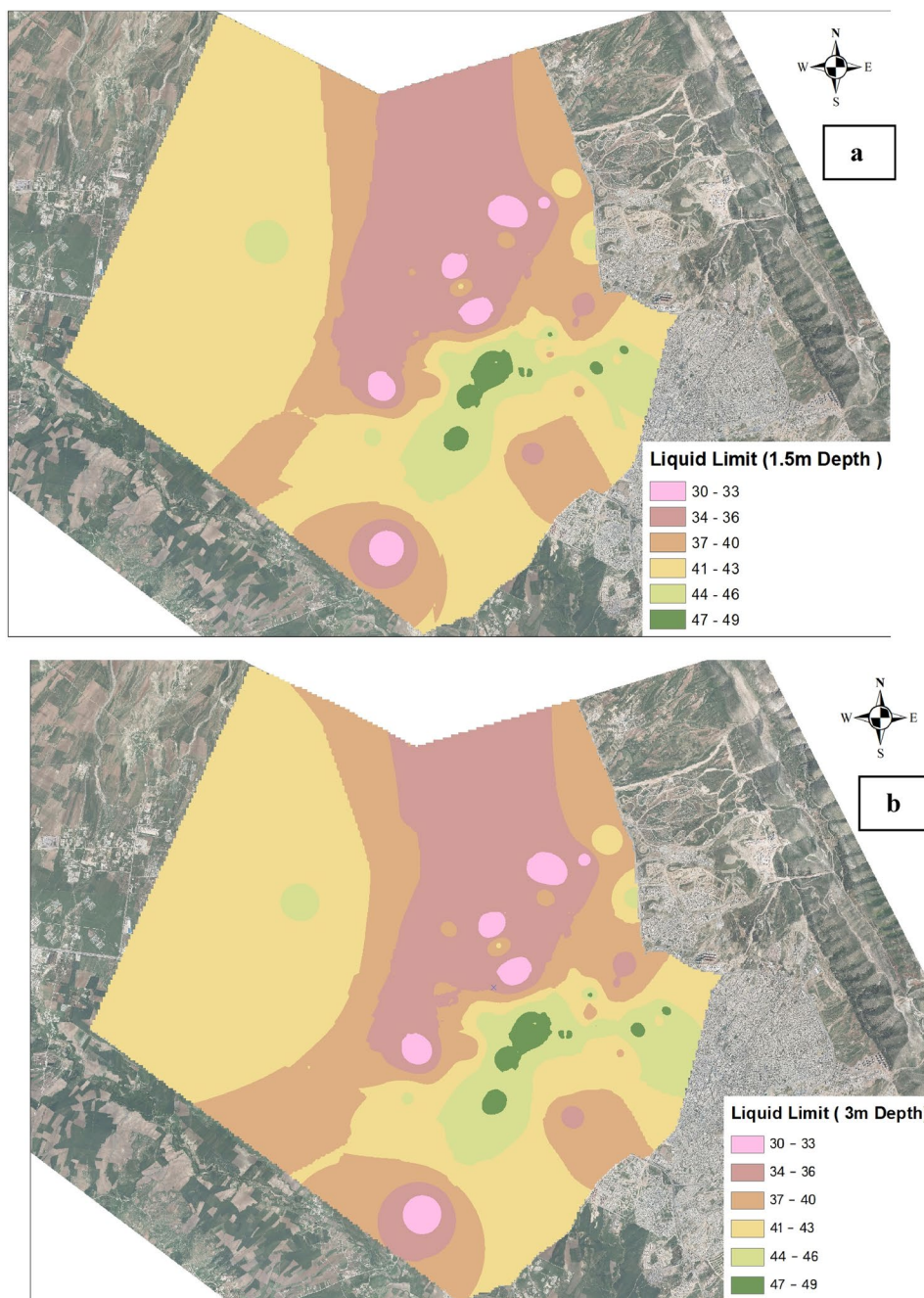
details and the histograms were developed for each depth data set to identify the distribution.

Soil type

Soil type is the most critical issue in geotechnical engineering that is identified with a number of cases. In the study area, the real collection of soil for the most part found was

silt, clay, and sand. The conduct of each type of soil is different, in view of its geotechnical engineering characteristics. Consequently, the motive of soil investigation is truly important to understand the soil types prior to the start of a project. The suitability of the test additionally relies upon the kind of soil. There are two types of results used to present the data, i.e., statistical results and results in the form of zonation maps using ArcGIS tools.

Fig. 3 Spatial variation of liquid limit with depth: **a** 1.5 m, **b** 3 m, **c** 4.5 m, **d** 6 m



Silt and clay contents

Silt and clay content if present in a large percentage is problematic for the foundation of buildings. Therefore, it is necessary to evaluate its presence. The range of percentage of silt and clay at 1.5 m depth is 27–97%, and the minimum silt and clay content go on decreasing as we go deeper into the soil reaching 5% at 6 m depth. The average silt and clay content varies from 97% at 1.5 m to 27% at 6 m depth. The standard deviation of the silt and clay content at 1.5 m depth

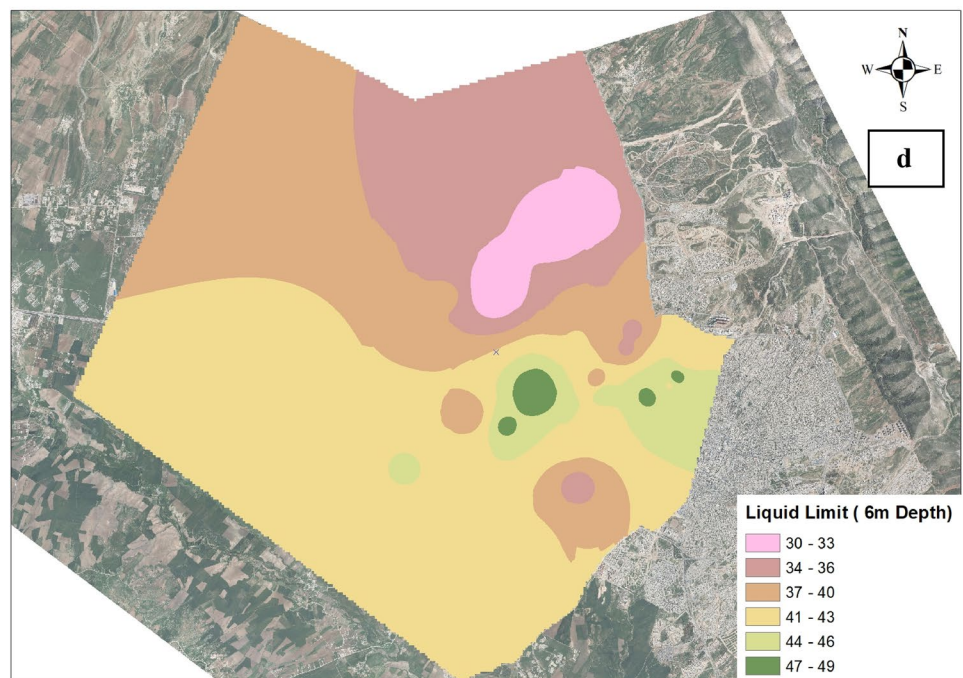
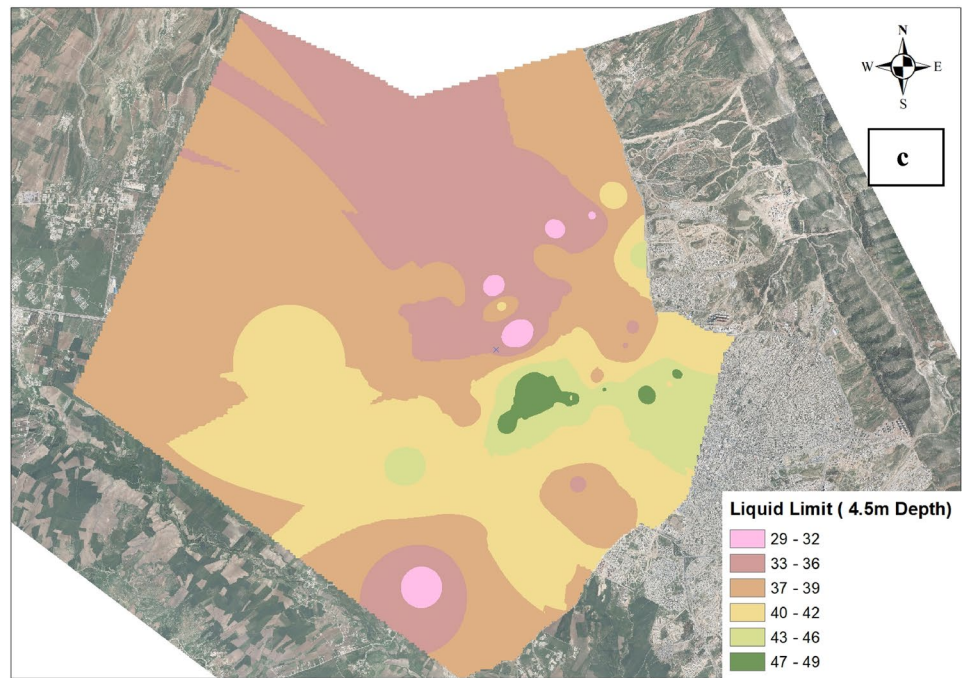
is 18.6 but at 6.0 m depth, its value is 22. The coefficient of variation ranges between 0.28 and 0.82, which signifies that variation goes on increasing with depth.

Data presentation using ArcGIS

Liquid limit

Thematic maps showing the variation of soil type along the 6.0 m depth of soil strata at different locations of Sulaimani

Fig. 3 (continued)



City, Kurdistan Region, Iraq are presented. Four zonation maps have been presented in this paper at depths 1.5 m and 6 m, respectively, as shown in Fig. 3. In all the cases, depth has been taken from natural ground level (NGL). All the maps are divided into six major zones. Each zone is represented by a unique color. The type of soil at 1.5 m depth is shown in Fig. 3a. At this depth, the major portion of map is

covered with yellow and green signifying the presence of silt and clay content (fine content) of more than 50%. The portion under silty sand increases as compared to area at 1.5 m depth, as represented by brown and pink colors in the map as shown in Fig. 3. At a depth of 6 m, it can be viewed that about 50% of the area is brown and pink, which represents silty sand. Liquid limit with a range of 45–50% is presented

Fig. 4 Spatial variation of plasticity index with depth: **a** 1.5 m, **b** 3 m, **c** 4.5 m, **d** 6 m



only at very few locations as represented in green color. Here the area under poorly graded sand increases as clear from ceramic brown color, as shown in Fig. 3d. Similarly, it can be seen from the Fig. 4 that as we move deeper, the area under silty sand in blue color and poorly graded sand in dark color is more and goes on increasing with depth. This depicts that the sand content goes on increasing, and silt content goes on decreasing with depth.

Statistical variation of Sulaimani City soils

The histograms were analyzed and it was found that every depth has a good distribution of data. The maximum and minimum values were in the allowable ranges. The spatial variations of moisture content, Atterberg limits, density and undrained shear strength are shown in Fig. 2.

Fig. 4 (continued)



Dry density (γ_d) (ASTM D 7263)

Based on the total of 630 γ_d data for Sulaimani City soils, the data varied from 1.15 to 1.92 g/cm³ with a mean of 1.65 g/cm³, the standard deviation of 0.1 g/cm³, and the coefficient of variation (COV) of 0.06% as shown in Fig. 3a. The dry density of the Sulaimani City soils was calculated from moisture content and wet density.

Moisture content (MC %) (ASTM D 2216)

Based on the 630 MC data for Sulaimani City soils, the data varied from 8 to 32% with a mean of 18%, standard deviation of 6%, and coefficient of variation (COV) of 0.30% as shown in Fig. 2b.

Fig. 5 Linear variation of liquid limit (LL) and plasticity index (PI) for Sulaimani City soils

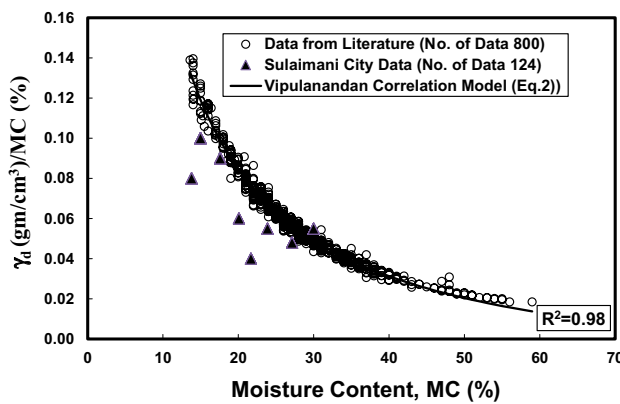
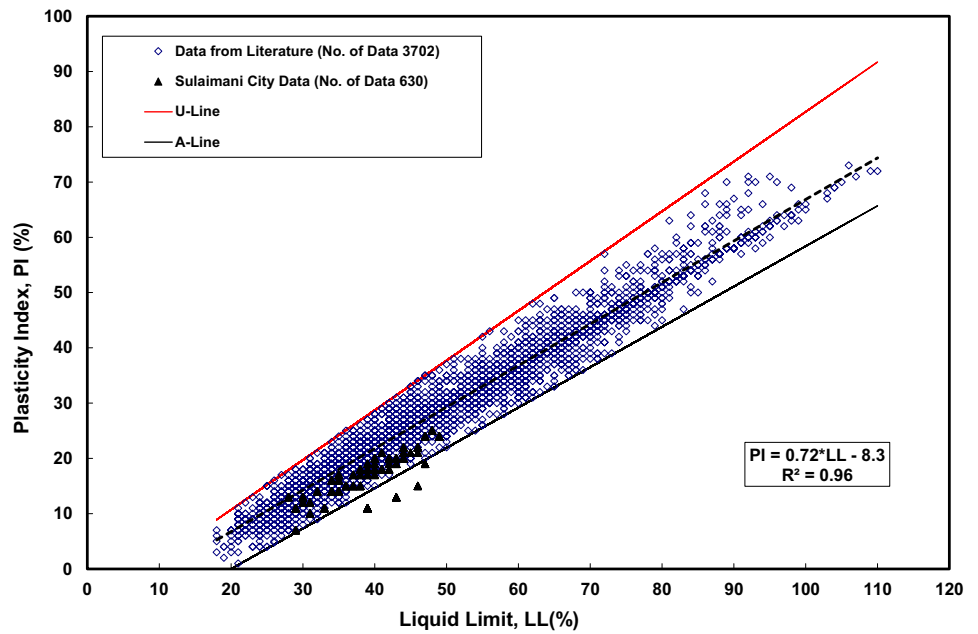


Fig. 6 Non-linear variation of moisture content (MC) and dry density (γ_d) of Sulaimani City soils compared with data collected from the literature

Liquid limit (LL)

Based on a total of 630 liquid limit (LL) data of Sulaimani soil values, the average LL was 39%. The LL varied from 28 to 50%, with a standard deviation of 5.3% and the coefficient of variation (COV) of 0.13% (Table 2). Based on the

tested data for Sulaimani City soils and 3702 data records from the literature, the LL with the plasticity index (PI) was represented using Eq. (3) and the coefficient of determination (R^2) for the relationship was 0.96.

As shown in Fig. 5, Sulaimani City soils are compared with 3702 data records collected from the literature and bounded by U-line and A-line in the plasticity chart. There was a good relationship between PI and LL which was identified as follows with a higher R^2 of 0.96.

$$PI = 0.72LL - 8.3 \quad \text{No. of data} = 3702, \text{ RMSE} = 3.5\%, R^2 = 0.96. \quad (3)$$

Plasticity index (PI)

Depending on the 630 PI data records for the Sulaimani soils, the data varied from 11 to 25% with a mean of 18%, standard deviation of 3.53%, and coefficient of variation (COV) of 0.19% as shown in Fig. 2d and summarized in Table 2.

Table 3 Vipulanandan correlation model parameters for Sulaimani City soils

Dependent variable (Y-axis)	Independent variable (X-axis)	Y_0	A	B	No. of data	RMSE	R^2	Figure no.
$\frac{\gamma_d \left(\frac{g}{cm^3} \right)}{MC(\%)}$	MC (%)	172	4E-05	0.006	800	0.021	0.98	6
FS (%)	LL (%)	197.9	-0.02	0.005	93	0.02	0.81	7
e_0	LL (%)	98.4	-0.005	0.01	62	0.001	0.84	8

Undrained shear strength (S_u)

Based on the tested data and a total of 630 undrained shear strength ($S_u = \frac{q_u}{2}$) data for the CH soil collected from literature, the data varied from 10 to 119 kPa with a mean of 76 kPa, standard deviation of 19 kPa, and coefficient of variation (COV) of 0.24% as summarized in Table 2.

Nonlinear regression model

Based on experimental and collected data from literature, it was assumed that the undrained shear strength (S_u) (kPa) of soils will be influenced by the liquid limit (LL %), plasticity index (PI %), dry density (γ_d) (g/cm^3) and moisture content (MC %). The models were analyzed using multiple regressions; because of nonlinear predictions, logarithmic values were selected for this analysis. The logarithmic multiple regression is:

$$S_u = k \times \frac{(\text{LL})^a \times (\text{PI})^b \times (\gamma_d)^c}{(\text{MC})^d}, \tag{4}$$

where k , a , b , c and d are nonlinear model parameters.

Sulaimani City soil properties correlation

The relationship between moisture content (MC) and dry unit weight (γ_d)

A total of 800 soil data records were collected from various research studies. The tested data and the data collected from the literature were quantified using the Vipulanandan correlation model (Eq. 2), as shown in Fig. 6. The model parameters Y_o , A and B are summarized in Table 3, while the coefficient of determination (R^2) and root mean square error (RMSE) for the Vipulanandan correlation model relationship were 0.98 and 0.021, respectively, as summarized in Table 3.

The relationship between liquid limit (LL) and free swelling (FS)

A total of 93 clay soils data were collected from various research studies. The data collected from the literature were quantified using the Vipulanandan correlation model (Eq. 2) as shown in Fig. 7. The change in the LL with FS of clay soils was represented using Eq. (2) and the model parameters Y_o , A and B are summarized in Table 3. The coefficient of determination (R^2) and root mean square error (RMSE) for the relationship were 0.81 and 0.02, respectively, as summarized in Table 3.

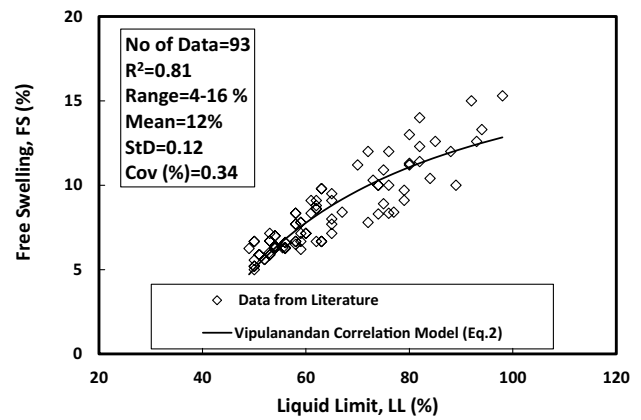


Fig. 7 Non-linear variation of liquid limit (LL %) and free swelling for clay soils

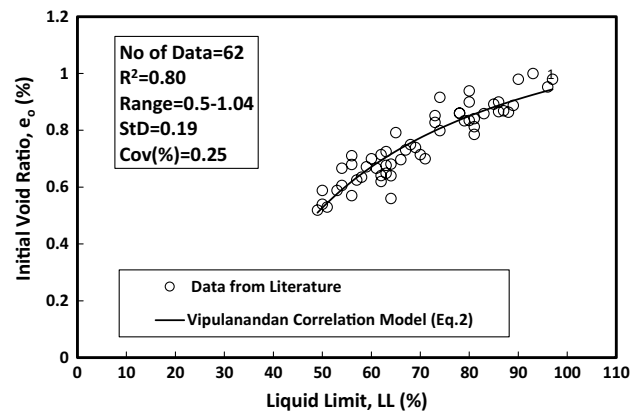


Fig. 8 Non-linear variation of liquid limit (LL) and initial void ratio (e_o) for clay soils

The relationship between liquid limit (LL) and void ratio (e_o)

A total of 62 clay soils data were collected from the various research studies. Based on a total of 62 e_o data records for the soils collected from literature, the data varied from 0.5 to 1.04 with a mean of 0.91, standard deviation of 0.19, and coefficient of variation (COV) of 0.25% (Table 2).

The initial void ratio e_o with LL of the clay soil was represented using inverse Vipulanandan correlation model (Eq. 2) as shown in Fig. 8 and the model parameters Y_o , A and B are summarized in Table 3, while the coefficient of determination (R^2) and root mean square error (RMSE) for the relationship were 0.80 and 0.001, respectively, as summarized in Table 3.

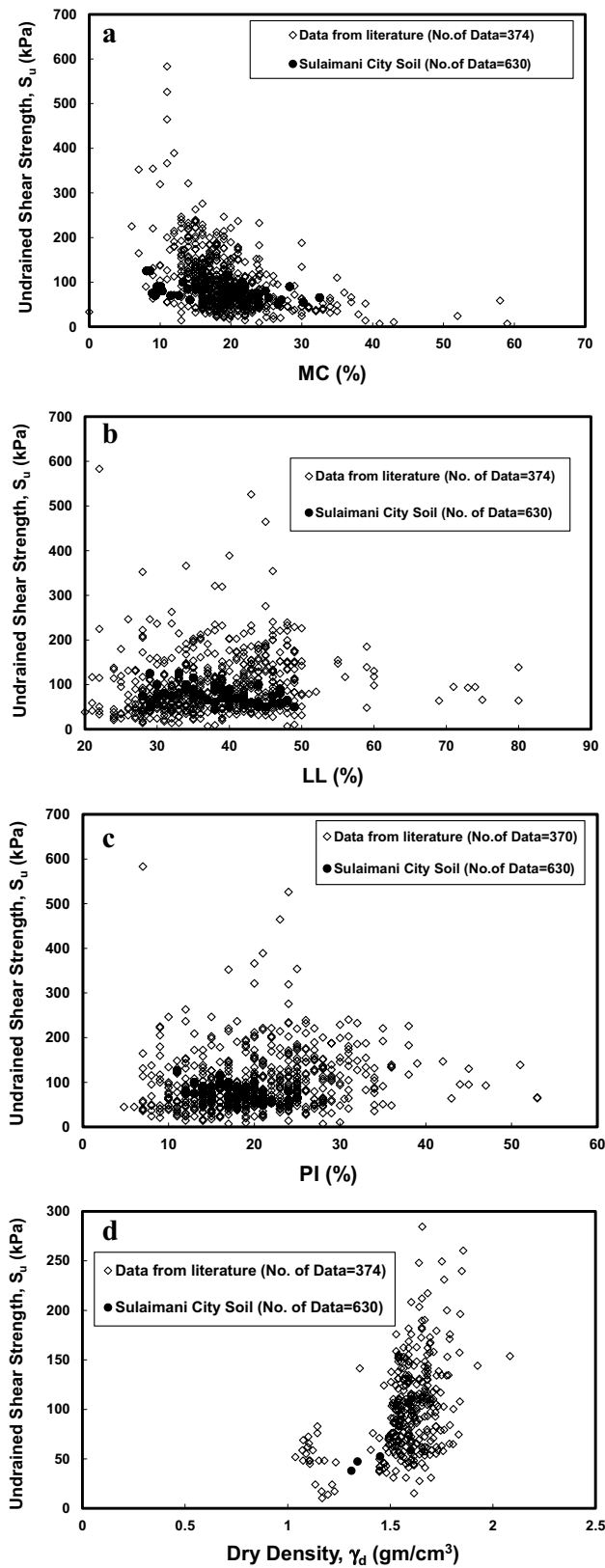


Fig. 9 Variation of undrained shear strength (S_u) for the clay soils with **a** moisture content, MC (%), **b** liquid limit, LL (%), **c** plasticity index, PI (%), **d** dry density

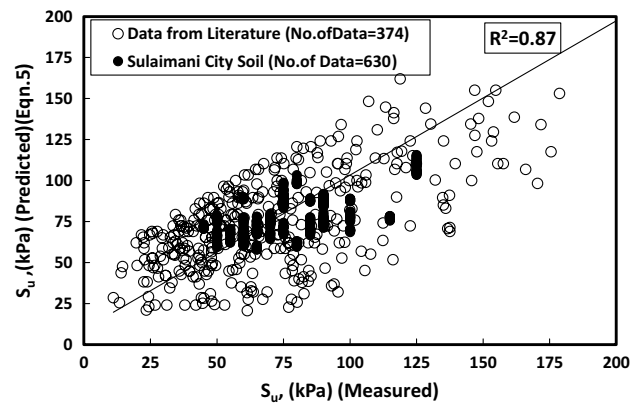


Fig. 10 Comparison between measured and predicted undrained shear strength for soils

The relationship between undrained shear strength (S_u), index properties, moisture content and dry density

The correlation between S_u with MC, S_u with LL and S_u with PI has been studied. Based on the R^2 and RMSE, there were no correlations were observed between shear strength of the soils and LL, PI, MC and density, as shown in Fig. 9. It was assumed that the undrained shear strength (S_u) (kPa) will be influenced by the liquid limit (LL %), plastic index (PI %), dry density (γ_d) (g/cm^3), and moisture content (MC %). The models were analyzed using multiple regression. The nonlinear multiple regression is:

$$S_u = 26.3 \times (\gamma_d)^{1.9} \frac{(LL)^{0.5}}{(PI)^{0.3} \times (MC)^{0.2}} \tag{5}$$

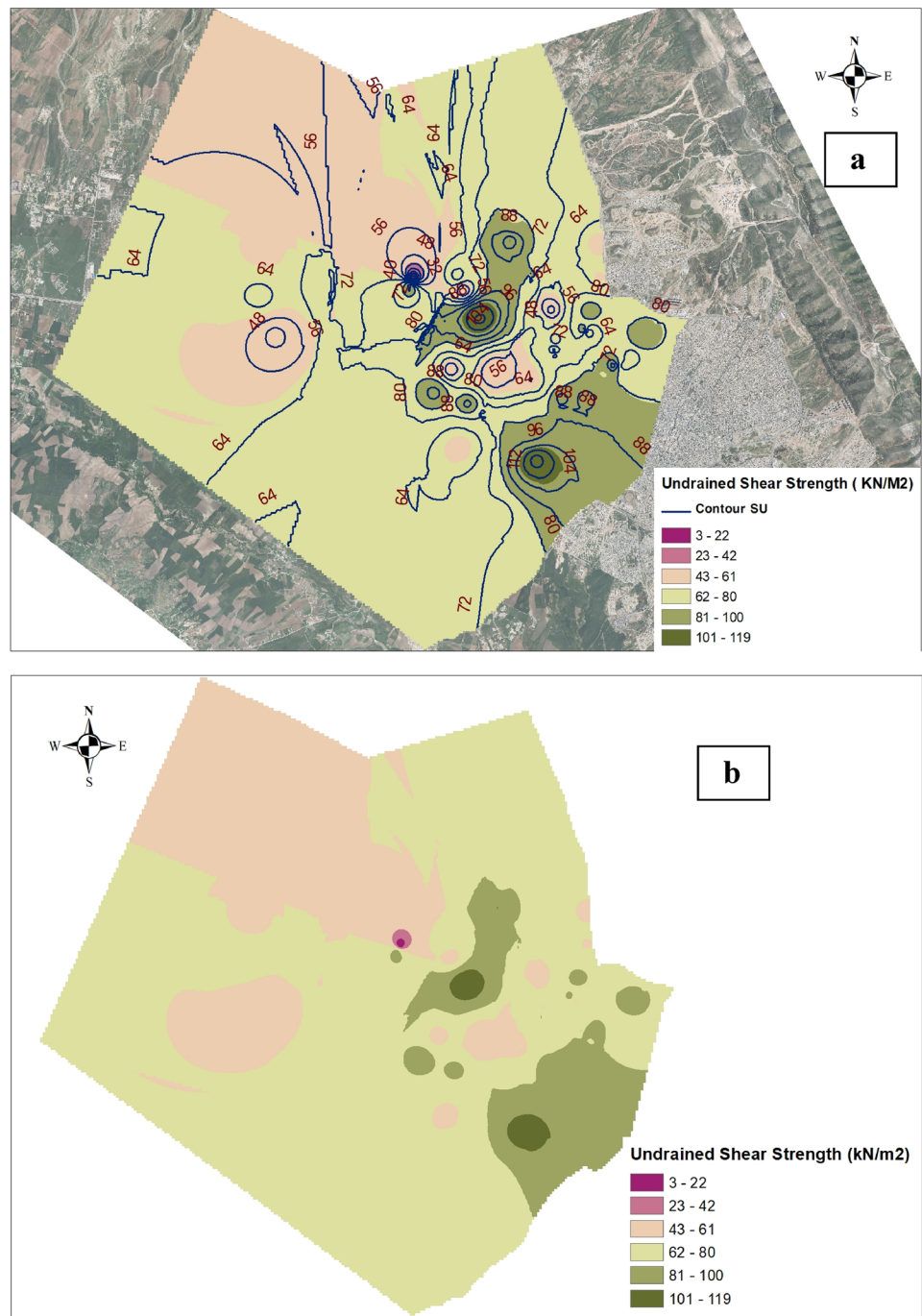
The coefficient of determination (R^2) and RMSE of 376 numbers of data were 0.87 and 1.05, respectively, as shown in Fig. 10. Figure 11 presents undrained shear strength of the Sulaimani City soils at 6 m depth.

Conclusions

The focus of this study was to characterize the Sulaimani soils based on its geotechnical and strength properties. Geo-statistical properties of Sulaimani soils and GIS mapping were also investigated. Correlation between geotechnical properties was examined based on experimental data and collected data from literature and analytical model. Based on this, the following conclusions were advanced:

1. GIS is an effective tool for collecting, displaying and reading geographically documented information. GIS showed numerous uses in geotechnical engineering pro-

Fig. 11 Typical spatial variation of undrained shear strength of the Sulaimani soils at the depth of 6 m



- jects, and interpolation for exploit statistics at inaccessible places through processed graphs, maps, and charts.
2. The majority of soil profile consists of silt of low compressibility to silty sand with few traces of clay, especially for shallow depths to 6.0 m depth. Poorly graded sand was encountered at noticeable locations at a depth of 4.5 m or more.
3. The variation of geotechnical properties of the clay soils showed a good correlation between the compression properties such as undrained shear strength (S_u) and

- compression index (C_c) with easy geotechnical properties measurement of clay soils.
4. Based on the R^2 and RMSE, there were no direct correlations between the undrained shear strength (C_u) and index properties (LL and PL), moisture content (MC) and density (γ) of the clay soils.
5. The undrained shear strength (S_u) of clay soils was in the range of 10–119 kPa. The compression index (C_c) of clay soils was in the range of 0.05–0.55. Undrained shear strength (S_u) of soils quantified very well as a

function of index properties, moisture content and dry density of the soils.

6. These results can help structural and foundation engineers during the process of foundation analysis, estimation of geotechnical investigation cost and planning and execution of different projects associated with civil engineering.

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References

- Abdalla LB, Ghafor K, Mohammed A (2019) Testing and modeling the young age compressive strength for high workability concrete modified with PCE polymers. *Results Mater* 1:100004
- Al-Mhaidib AI (2008) Mathematical model to predict swelling of expansive soil. In: The 12th international conference of International Association for Computer Methods and Advances in Geomechanics (IACMAG), pp 1–6
- Arulrajah A, Bo MW (2008) Characteristics of Singapore marine clay at Changi. *Geotech Geol Eng* 26(4):431–441
- Asik TZ, Matin SI, Rahman M (2016) Correlation of soil parameters and bearing capacity analysis of piled raft foundation for Dhaka-Chittagong elevated expressway. Doctoral dissertation, IUT, CEE
- Berilgen SA, Kılıç H, Ozaydın K (2007) Determination of undrained shear strength for dredged golden horn marine clay with laboratory tests. In: Proceedings of the Sri Lankan geotechnical society's first international conference on soil and rock engineering, pp 5–11
- Bilgin Ö, Mansour E (2013) Variability of soil properties and reliability of empirical equations on soil settlement predictions. In: Foundation engineering in the face of uncertainty: honoring Fred H. Kulhawy, pp 298–307
- Burhan L, Ghafor K, Mohammed A (2019a) Quantification the effect of microsand on the compressive, tensile, flexural strengths, and modulus of elasticity of normal strength concrete. *Geomech Geoen* 1–19
- Burhan L, Ghafor K, Mohammed A (2019b) Modeling the effect of silica fume on the compressive, tensile strengths and durability of NSC and HSC in various strength ranges. *J Build Pathol Rehabil* 4(1):19
- Dennehy JP (1978) The remolded undrained shear strength of cohesive soils and its influence on the suitability of embankment fill. In: Proceedings—clay fills, Institute of Civil Engineers, London, 14–15 Nov 1978, pp 87–94
- Duncan JM, Wright SG (2005) *Soil strength and slope stability*. Wiley, New Jersey
- Edil TB, Benson CH, Li L, Mickelson DM, Camargo FF (2009) Comparison of basic laboratory test results with more sophisticated laboratory and in situ tests methods on soils in Southeastern Wisconsin (no. WHRP 09-02)
- Federico A (1983) Relationships (cu–w) and (cu–s) for remolded clayey soils at high water content. *Riv Ital Geotec* 17(1):38–41
- Ganji PK (2006) Statistical correlations of geotechnical properties, undrained shear strength, Texas cone penetrometer (TCP) blow count values with depth of Houston clayey soil. Thesis. University of Houston, Houston
- Ganstone DG (1971) Statistical correlations of the engineering properties of the Beaumont clays. Master's thesis, Department of Civil and Environmental Engineering, University of Houston
- Günaydin O (2009) Estimation of soil compaction parameters by using statistical analyses and artificial neural networks. *Environ Geol* 57(1):203–215
- Gurtug Y, Sridharan A (2004) Compaction behavior and prediction of its characteristics of fine grained soils with particular reference to compaction energy. *Soils Found* 44(5):27–36
- Horpibulsuk S, Shibuya S, Fuenkajorn K, Katkan W (2007) Assessment of engineering properties of Bangkok clay. *Can Geotech J* 44(2):173–187
- Keller GH, Yincan Y (1985) Geotechnical properties of surface and near-surface deposits in the East China Sea. *Cont Shelf Res* 4(1):159–174
- Lee LT (2004) Predicting geotechnical parameters for dredged materials using the slump test method and index property correlations. DOER Technical Notes collection (ERDC TNDOR-D-1). US Army Engineer Research and Development Center, Vicksburg, Mississippi. <http://www.wes.army.mil/el/dots/doer>
- Mahar LJ, O'Neill MW (1983) Geotechnical characterization of desiccated clay. *J Geotech Eng* 109(1):56–71
- Mahmood W, Mohammed A, Ghafor K (2019) Viscosity, yield stress and compressive strength of cement-based grout modified with polymers. *Results Mater* 100043
- Mohammed AS (2014) Characterization and modeling of polymer-treated and nano particle modified sulfate contaminated soils, drilling muds, and hydraulic fracturing fluids under groundwater. Doctoral dissertation
- Mohammed AS (2017) Effect of temperature on the rheological properties with shear stress limit of iron oxide nanoparticle modified bentonite-drilling muds. *Egypt J Petrol* 26(3):791–802
- Mohammed AS (2018a) Property correlations and statistical variations in the geotechnical properties of (CH) clay soils. *Geotech Geol Eng* 36(1):267–281
- Mohammed AS (2018b) Electrical resistivity and rheological properties of sensing bentonite-drilling muds modified with lightweight polymer. *Egypt J Petrol* 27(1):55–63
- Mohammed AS (2018c) Vipulanandan model for the rheological properties with ultimate shear stress of oil well cement modified with nanoclay. *Egypt J Petrol* 27(3):335–347
- Mohammed AS (2018d) Vipulanandan models to predict the electrical resistivity, rheological properties and compressive stress-strain behavior of oil well cement modified with silica nanoparticles. *Egypt J Petrol* 27(4):1265–1273
- Mohammed AS (2019) Vipulanandan models to predict the mechanical properties, fracture toughness, pulse velocity and ultimate shear strength of shale rocks. *Geotech Geol Eng* 37(2):625–638
- Mohammed A, Mahmood W (2018a) Statistical variations and new correlation models to predict the mechanical behavior and ultimate shear strength of gypsum rock. *Open Eng* 8(1):213–226
- Mohammed A, Mahmood W (2018) Vipulanandan failure models to predict the tensile strength, compressive modulus, fracture toughness and ultimate shear strength of calcium rocks. *Int J Geotech Eng* 1–11
- Mohammed A, Mahmood W (2019) Estimating the efficiency of the sandy soils–cement based grout interactions from particle size distribution (PSD). *Geomech Geoen* 1–18
- Mohammed A, Mahmood W (2019) New Vipulanandan p – q model for particle size distribution and groutability limits for sandy soils. *J Test Eval* 48(5)
- Mohammed AS, Vipulanandan C (2014) Compressive and tensile behavior of polymer treated sulfate contaminated CL soil. *Geotech Geol Eng* 32(1):71–83

- Mohammed A, Vipulanandan C (2015) Testing and modeling the short-term behavior of lime and fly ash treated sulfate contaminated CL soil. *Geotech Geol Eng* 33(4):1099–1114
- Mohammed A, Vipulanandan C (2018) Smart cement compressive piezoresistive, stress–strain, and strength behavior with nanosilica modification. *J Test Eval* 47(2):1479–1501
- Mohammed A, Mahmood W, Ghafor K (2020a) TGA, rheological properties with maximum shear stress and compressive strength of cement-based grout modified with polycarboxylate polymers. *Constr Build Mater* 235:117534
- Mohammed A, Mahmood W, Ghafor K (2020b) Shear stress limit, rheological properties and compressive strength of cement-based grout modified with polymers. *J Build Pathol Rehabil* 5(1):3
- Nagaraj TS, Pandian NS, Narasimha-Raju PSR (1993) Stress state-permeability relationships for fine-grained soils. *Geotechnique* 43(2):333–336
- O'Neill MW, Yoon G (1995) Engineering properties of over consolidated Pleistocene soils of Texas Gulf coast. *Transp Res Rec* 1479:81–88
- Qadir W, Ghafor K, Mohammed A (2019a) Characterizing and modeling the mechanical properties of the cement mortar modified with fly ash for various water-to-cement ratios and curing times. *Adv Civ Eng*. <https://doi.org/10.1155/2019/7013908>
- Qadir W, Ghafor K, Mohammed A (2019b) Evaluation the effect of lime on the plastic and hardened properties of cement mortar and quantified using Vipulanandan model. *Open Eng* 9(1):468–480
- Qadir W, Ghafor K, Mohammed A (2019) Regression analysis and Vipulanandan model to quantify the effect of polymers on the plastic and hardened properties with the tensile bonding strength of the cement mortar. *Results Mater* 100011
- Roy S, Dass G (2014) Statistical models for the prediction of shear strength parameters at Sirsa, India. *Int J Civ Struct Eng* 4(4):483
- Sivaruban N (2008) Construction and maintenance issues related to transportation infrastructure. Master's thesis, Department of Civil and Environmental Engineering, University of Houston
- Sridharan A, Nagaraj HB (2000) Compressibility behavior of remolded, fine-grained soils and correlation with index properties. *Can Geotech J* 37(3):712–722
- Sridharan A, Rao Raghuvver P (2004) Characterization of Ariake and other marine clays. In: International symposium on lowland technology (ISLT-2004), pp 53–58
- Sridharan A, El-Shafei A, Miura N (2002) Mechanisms controlling the undrained strength behavior of remolded Ariake marine clays. *Mar Georesour Geotechnol* 20(1):21–50
- Tiwari B, Ajmera B (2011) A new correlation relating the shear strength of reconstituted soil to the proportions of clay minerals and plasticity characteristics. *Appl Clay Sci* 53(1):48–57
- Vipulanandan C, Mohammed AS (2014) Hyperbolic rheological model with shear stress limit for acrylamide polymer modified bentonite-drilling muds. *J Petrol Sci Eng* 122:38–47
- Vipulanandan C, Mohammed A (2015a) Smart cement modified with iron oxide nanoparticles to enhance the piezoresistive behavior and compressive strength for oil well applications. *Smart Mater Struct* 24(12):125020
- Vipulanandan C, Mohammed A (2015b) Smart cement rheological and piezoresistive behavior for oil well applications. *J Petrol Sci Eng* 135:50–58
- Vipulanandan C, Mohammed A (2015c) Effect of nanoclay on the electrical resistivity and rheological properties of smart and sensing bentonite drilling muds. *J Petrol Sci Eng* 130:86–95
- Vipulanandan C, Mohammed A (2015d) XRD and TGA, swelling and compacted properties of polymer treated sulfate contaminated CL soil. *J Test Eval* 44(6):2270–2284
- Vipulanandan C, Mohammed A (2015) Hydraulic fracturing fluid modified with nanosilica proppant and salt water for shale rocks. In: AADE national technical conference and exhibition, AADE-15-NTCE-38
- Vipulanandan C, Mohammed A (2017) Rheological properties of piezoresistive smart cement slurry modified with iron-oxide nanoparticles for oil-well applications. *J Test Eval* 45(6):2050–2060
- Vipulanandan C, Mohammed A (2018) New Vipulanandan failure model and property correlations for sandstone, shale and limestone rocks. *IFCEE* 2018:365–376
- Vipulanandan C, Mohammed A (2019) Magnetic field strength and temperature effects on the behavior of oil well cement slurry modified with iron oxide nanoparticles and quantified with Vipulanandan models. *J Test Eval* 48(6)
- Vipulanandan C, Kim MS, Harendra S (2006) Microstructural and geotechnical properties of Houston-Galveston area soft clays. In: Proceeding, Geo Denver, Denver, USA
- Vipulanandan C, Ahossin Guezo Y J, Bilgin Ö (2007) Geotechnical properties of marine and deltaic soft clays. In: Advances in measurement and modeling of soil behavior, pp 1–13
- Vipulanandan C, Guezo YJ, Bilgin O (2007) Geotechnical properties of marine and deltaic soft clays. In: Proceedings of the Geo Denver, Denver
- Vipulanandan C, Mohammed A, Qu Q (2014) Characterizing the hydraulic fracturing fluid modified with nano silica proppant. In: AADE fluids technical conference and exhibition, Houston, pp 15–16
- Vipulanandan C, Krishnamoorti R, Mohammed A, Boncan V, Narvaez G, Head B, Pappas JM (2015) Iron nanoparticle modified smart cement for real time monitoring of ultra deepwater oil well cementing applications. In: Offshore technology conference
- Vipulanandan C, Mohammed A, Ganpatye AS (2018) Smart cement performance enhancement with nano Al₂O₃ for real time monitoring applications using Vipulanandan models. In: Offshore technology conference
- Vipulanandan C, Mohammed A, Samuel RG (2018) Fluid loss control in smart bentonite drilling mud modified with nanoclay and quantified with Vipulanandan fluid loss model. In: Offshore technology conference
- Westerberg B, Müller R, Larsson S (2015) Evaluation of undrained shear strength of Swedish fine-grained sulphate soils. *Eng Geol* 188:77–87
- Yılmaz I (2000) Evaluation of shear strength of clayey soils by using their liquidity index. *Bull Eng Geol Environ* 59(3):227–229

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