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GIS as A Tool for Expansive Soil Detection at Sulaymaniyah City

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ABSTRACT

Geotechnical engineering like any other engineering field has to develop and cope with new technologies. This article intends to investigate the spatial relationships between soil's liquid limit (LL), plasticity index (PI) and Liquidity index (LI) for particular zones of Sulaymaniyah City. The main objective is to study the ability to produce digital soil maps for the study area and determine regions of high expansive soil. Inverse Distance Weighting (IDW) interpolation tool within the GIS (Geographic Information System) program was used to produce the maps. Data from 592 boreholes for LL and PI and 245 boreholes for LI were used for this study. Layers were allocated into three depth ranges (1 to 2, 2 to 4 and 4 to 6) m. A total of 1396 observations were used for producing the maps for both LL and PI, and 371 data for LI. Based on the results, the IDW method gives reasonable predictions depending on the results of R^2 and RMSE. The results also showed that the study area has relatively large zones of high expansive soil that must be taken into considerations before performing any construction activity. These maps are essential for helping geotechnical engineers in making decisions and visualizing soils' behaviors.

Keywords: GIS, liquid limit, plasticity index, liquidity index, expansive soil, swelling pressure, swell index

نظم المعلومات الجغرافية كأداة للكشف عن التربة الانتفاخية في مدينة السليمانية

الخلاصة

الهندسة الجيوتقنية كباقي المجالات الهندسية تحتاج الى التطور ومواكبة التقنيات الحديثة. يهدف هذا البحث إلى دراسة العلاقات المكانية لخواص التربة والتي تتضمن حد الليونة للتربة (LL) ، مؤشر اللدونة (PI) و مؤشر السيولة (LI) لمناطق مختارة من مدينة السليمانية. الهدف الرئيسي من البحث هو دراسة امكانية إنتاج خرائط رقمية لتربة منطقة الدراسة و تحديد المناطق ذات القابلية العالية للانتفاخ لمنطقة الدراسة. لقد تم استخدام طريقة المسافة معكوسة الوزن (IDW) ضمن ادوات التكامل في برنامج نظم المعلومات الجغرافية (GIS) لإنتاج الخرائط. في هذه الدراسة قد تم استخدام بيانات من 592 حفر

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اختبارية لـ(LL) و (PI) و 245 حفر اختبارية ل(LI). تم تقسيم الطبقات إلى ثلاثة مستويات حسب العمق (1 الى2 ، 2 الى 4 و 4 الى 6) م. كان إجمالي عدد المشاهدات المستخدمة لإنتاج الخرائط 1396 قراءة لكل من (LL) و(PI) ، و 371 قراءة لـ (LI) . أظهرت النتائج أن طريقة (IDW) تعطي تنبؤات معقولة بناءًا على نتائج (R^2 وRMSE) . أظهرت النتائج ايضا ان منطقة الدراسة تتضمن مساحات كبيرة نسبيا من التربة الانتفاخية التي يجب ان تؤخذ بنظر الاعتبار قبل اي عملية بناء. من الضروري الاخذ بنظر الاعتبار ان دقة النتائج تتاثر بعدد النقاط ونمط التوزيع على منطقة الدراسة، وهذه الخرائط والتحليلات ضرورية لمساعدة المهندسين الجيوتقنيين في تصور سلوكيات التربة وبالتالي تسهل عملية اتخاذ القرار.

الكلمات الدالة: GIS، حد الليونة، مؤشر اللدونة، مؤشر السيولة، التربة الانتفاخية، ضغط الانتفاخ، دليل الانتفاخ

1. INTRODUCTION

Information on subsurface conditions existing on a site is a critical requirement that is used to plan and design the structure’s foundations and other belowground work **(McCarthy, 2014)**. Construction techniques are planned with the help of data on subsurface conditions **(McCarthy, 2014)**. An in-depth investigation and accurate assessment of the spatial variability of the geological and geotechnical properties of the soils and groundwater are required to manage the planning process of land use in growing cities **(Al-Mamoori et al., 2019a; Masoud, 2015).** One of the adopted methods nowadays in helping to understand soil properties and their behaviors in terms of spatial variation is the Geographic Information System (GIS) **(Suwanwiwattana et al., 2001)**. Researches relating using GIS to study the spatial variability of different soil properties have increased in the recent past years **(Al-Mamoori et al., 2019b; Mohammed, Yahya and Ahmed, 2012).**

Four case studies investigated by **(Hellawell et al., 2001)** considering the use of GIS in analyzing geotechnical data for small scale projects. The first case included an archaeological desk study where GIS used to create a model for possible ground conditions to identify possible sedimentological features, the resulted models were numerically correct but with no real physical meaning. The second case taken by **(Hellawell et al., 2001)** was contaminated land assessment and remediation design of a former industrial area and gas works in the UK, outcomes showed that GIS offered several advantages including cost reduction. The third case included using GIS in the design of a large shopping complex in Prague, Czech Republic. The project demonstrated the ease with which landscaping design appraisals could be conducted using GIS. The final project was evaluating the most suitable technique for the construction of a retaining wall for a new railway in Hong Kong using GIS and according to the results it was successfully used to solve a logistical spatial problem. A case study by **(Kadhim et al., 2013)** for the soil of Basra City showed that it is possible to produce digital geotechnical maps by using ArcGIS software. Many case studies showed the importance and effectiveness of GIS in predicting land cover and groundwater quality **(Dawood, 2018; Kadhim, 2018).** The worldwide geotechnical data must be studied from new perspectives to understand the spatial relationships between geotechnical data.

As geotechnical engineers, one of the most common challenges is the presence of expansive soil which occurs when water is added to plastic clays causing considerable swell and then shrink with the loss of water **(Das, 2016)**. Highly plastic clays throughout the world give rise to engineering problems because of their tendency to undergo volume change with changes in natural water content **(Noble, 1966)**. According to **(Kemal, 2015)** the key to all expansive soil classification systems is the method of measuring swell potential. The swelling behavior of compacted clays is measured with two parameters, free-swell index and swell-pressure, which are the percentage of heave to initial height in one-dimensional condition and the amount of pressure that prevents soil from swelling respectively **(Ashayeri and Yasrobi, 2005)**. In addition to swelling pressure and free swelling, **(AL-Me'amar, 2007)** investigated the effect of dry density and applied load on expansive soil behavior. Expansion indices are dominated by a combination of factors including soil composition and environmental conditions. Several studies have been done on correlating clay content and Atterberg limits to swelling potential of compacted soils **(Seed, Mitchell and Chan, 1962; Chen, 1988; Ashayeri and Yasrobi, 2005)**.

1.1 Aims and Objectives

This article aims to study the spatial variability of geotechnical data related to expansive soil of selected zones of Sulaymaniyah City using GIS techniques and determine high expansive soil for the study area according to the available parameters. Although many researchers have similar investigations regarding soil's different properties in the other cities of Iraq, however, there is a lack of such researches for Sulaymanyiah City. Thus, this research will provide a starting point for researchers in the city to establish a geo-database for the total area of Sulaymanyiah Governorate. As the database grows to become larger, it will be easier to visualize the properties and behavior of the soil of the area.

1.2 Study Area

This study covers an area of 28.5km^2 of selected zones of Sulaymaniyah City in Kurdistan Region of Iraq (**Fig. 1**). Sulaymaniyah is located in the North-east of Iraq on a border with Iran, it is located on a geographic coordinate Latitude 35°33′40″ N and Longitude 45°26′14″ E **(Zakaria et al., 2013)**. The elevation of Sulaymaniyah center is about 847 m above sea level **(Dateandtime, 2020).**

1.3 Expansive Soil Problems

Expansive soils are clay soils that swell by wetting and shrink by drying **(Irshayyid and Fattah, 2019).** These clayey soils contain minerals such as montmorillonite clay that is capable of absorbing water; the volume will increase by absorbing water and decrease by drying. This change in volume makes expansive soil to be considered problematic soil due to the damages that it causes due to the volume change during the swell/shrink cycles. Swelling pressure is the pressure that soil or rock exerts in unyielding support such as a tunnel or basement **(Terzaghi et al., 1996)**. Free swell index is defined as the increase in the volume of soil without any external constraints, on submergence in water **(Patil et al., 2016)**. Swell pressure and free swelling are the two main parameters that are used to determine expansive soils **(Ashayeri and Yasrobi,**

2005). In addition, to some extent, expansive soils can be determined from other parameters such as liquid limit, plasticity index, clay percentage, water content, dry density and swell index **(Idrees et al., 2013)**. Swell index is the ratio of initial moisture content to soil's liquid limit **(Murthy, 2002).** The current study is focused on expansive soil of Sulaymaniyah City and the importance of spotting areas of highly expansive soils to help in decision making for such soils before the construction process. The indicators used in this article are liquid limit. Plasticity index, swell index and swelling pressure.

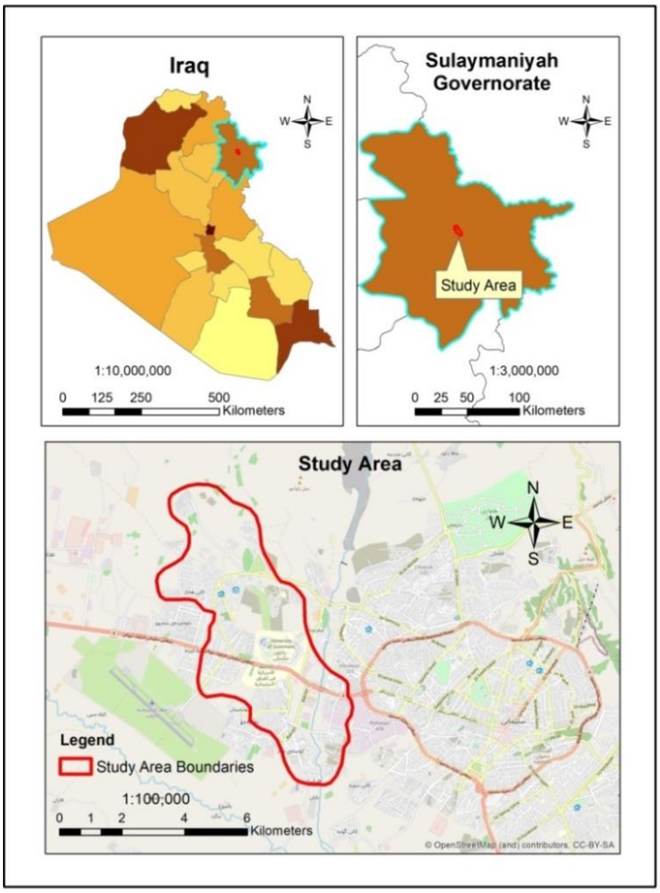


Figure 1. Study area boundaries [Map Source: (**OpenStreetMap, 2020)**]

2. METHODOLOGY

Data were obtained from 93 soil reports prepared by the author between the years 2004 to 2018 for the Engineering Consultancy Bureau of the University of Sulaimani and Khak Soil Lab in Sulaymaniyah City. Data were transported from hard copy data into soft copies by producing excel sheets in formats that can be used within the GIS program.

The coordinates were recorded for each borehole according to the site plan of the projects and then the data were referenced to their exact location by geo-referencing option using ArcMap program.The elevations of the boreholes ranged from 705 m to 898 m above sea level. After completing the process of data organization, a new file Geodatabase was generated for the project and all of the data were entered as point features in the GIS program (**Fig. 2**). The version used for GIS program for the current study is ArcMap10.7.1.

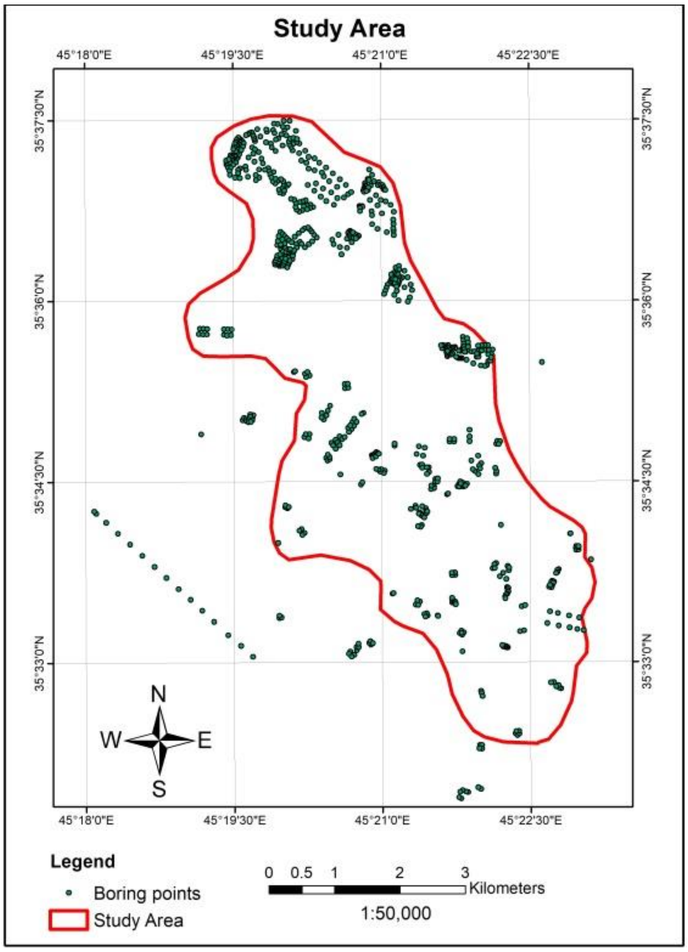


Figure 2. Study area boundaries in ArcMap program

This study has been prepared in two parts:

i. Spatial analysis of geotechnical properties and checking their validation.
ii. Determination of zones of expansive soil.

2.1 Spatial Analysis of Geotechnical Properties

The selected parameters to be investigated in this part include Liquid Limit (LL), Plasticity Index (PI) and Liquidity index (LI). Data for all properties were classified into 3 layers (1 to 2, 2 to 4 and 4 to 6) m. All test data were obtained from laboratory investigations recorded in the soil reports, the number of boreholes and data for each property are listed in **Table 1.**

Table 1. Details of data used in this study

No.	Property	No. of Boreholes	No. of Data
1	Liquid Limit (LL)	592	1396
2	Plasticity Index (PI)	592	1396
3	Liquidity Index (LI)	245	371
4	Swelling Pressure (SP)	205	236
5	Swell Index (SI)	217	324

2.1.1 IDW Interpolation method

Interpolation maps were produced for each property using Inverse Distance Weighting (IDW) interpolation technique. IDW interpolation is a tool within the Spatial Analyst Tools from the Arc-Toolbox which is the main interface to GIS's analytical processing power. In the Inverse Distance Weighting (IDW) method, the data of unknown points from the study area are calculated depending on the distance between these points and the known values. All interpolation methods have been developed based on the theory that points closer to each other have more correlations and similarities than those farther. In the IDW method, it is assumed substantially that the rate of correlations and similarities between neighbors is proportional to the distance between them that can be defined as a distance reverse function of every point from neighboring points **(Setianto and Triandini, 2013)**.

2.1.2 Descriptive statistics

The data used for this study were analyzed and presented using descriptive statistics. Descriptive analytics is considered as the first stage of data analysis in which a summary of the studied data will be presented. This leads to a better understanding of our data **(McCarthy et al., 2019)**. The results of the descriptive statistics of the data used for this study are shown in **Table 2.**

2.1.3 Data validation

The results of the current study were validated using checking points. These points were not entered into the interpolation process. The method used for the validation was the Coefficient of determinacy (R^2) with zero interception and Root Mean Square Error (RMSE). R^2 is the square of the correlation between measured and predicted variables as shown in Eq. (1). RMSE is described in Eq. (2), it is the standard deviation of the predicted errors, it shows how scatter are the prediction errors from the regression line.

$$R^2 = 1 - \left(\frac{\sum(yi - yp)}{\sum(yi - \mu)}\right)^2 \qquad (1)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(yi-yp)^2}{\mathrm{N}}} \qquad (2)$$

Where: yi = measured data, yp = predicted data from the maps, µ= mean of the data, N is the number of data points.

Table 2. Descriptive statistics for the studied data

Statistic	L.L%	P.L%	P.I%	LI	Swelling Pressure (kPa)	Swell Index
Minimum	18.0	12	1.0	-1.71	0	0.21
Maximum	74.0	50	40	0.60	400	0.84
Median	44	25	18	-0.32	25	0.40
Mean	44.05	25.33	18.73	-0.36	62.4	0.41
Range	56	38	39	2.31	400	0.63
Standard deviation	9.62	5.14	7.32	0.32	74.5	0.11

2.2 Determination of Expansive Soil at the Study Area

In this study, the process of expansive soil classification of the area depended on the results of other researchers **(Chen, 1975, 1965; Erzin and Erol, 2004; Holtz and Gibbs, 1956; Holtz, 1959; IS 1498, 1987; Kalantari, 2012; Sapaz, 2004; Van der Merwe, 1964; Chen, 1988)** regarding determination of soil swelling potential. The studied parameters are liquid limit, plasticity index, swelling pressure, and swell index **(Table.3)**. It is important to mention that two soil samples may have the same swelling potential due to these classifications but differ in their amount of swelling **(Seed, Mitchell and Chan, 1962).**

Swelling pressure data achieved according to **(ASTM D4546-08).** Swell index value calculated using Eq. 3 **(Murthy, 2002)** and the classification base on the values presented in **Fig.3**.

$$\mathrm{SI} = \frac{W\%}{L.L} \qquad (3)$$

Where: SI= Swell index, W%= natural water content of the soil, L.L= liquid limit value

Table 3. Properties of high swelling potential soil **[**adopted from **(Abdulla, 2013)**]

Property	Limit for swelling effect	References
Liquid limit	> 40 %	(IS 1498 , 1987) (Chen,1975)
Plasticity index	> 20 %	(IS 1498 , 1987) (Chen,1975) (Holtz and Gibbs,1956)
Initial water content	< 15 %	(Chen, 1988)
Initial dry density	> 16.0 kN/M^2	(Erol, 2004); (Sapaz, 2004)
Clay content	> 28%	(Holtz,1959)
Passing #200	> 60 %	(Chen 1965)
Swell index (Initial water content/liquid limit)	< 0.37	(Kalantari , 2012)
Activity (A=P. I. /Clay content)	PI >23% , Clay content >18% & A =(0.5-2.0)	(Van der Merwe, 1964)

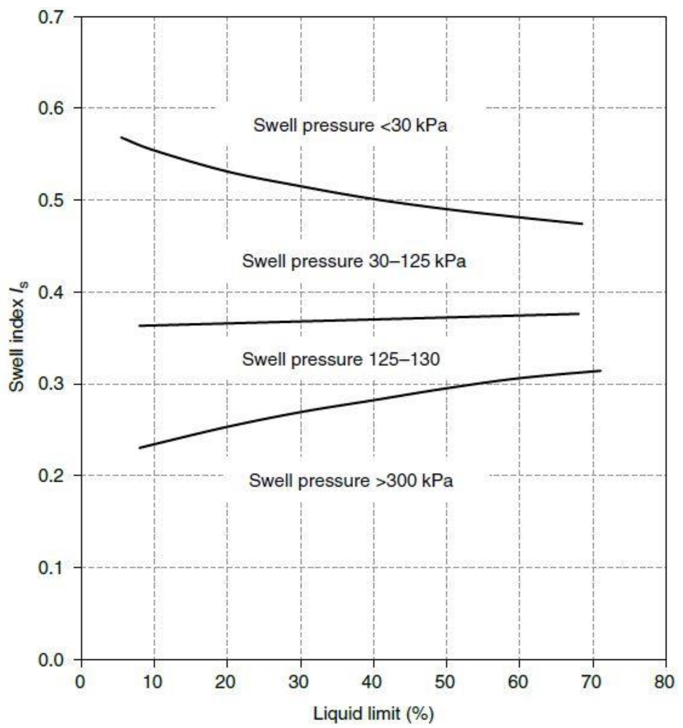


Figure 3. Relationship between liquid limit and swell index for expansive soil **(Murthy, 2002; Chen, 1988)**

3. RESULTS AND DISCUSSION

For the purpose of checking for the accuracy of the results of this study, checkpoints were validated. The validation process depended on the values of Root Mean Square Error (RMSE) and the Coefficient of determinacy (R^2).

3.1 Liquid Limit (LL)

The liquid limit of a soil is the water content, expressed as a percentage of the weight of the oven-dried soil, at the boundary between the liquid and plastic states of consistency of the soil **(Roy and Bhalla, 2017)**. The resulted maps for the Liquid Limit (LL) are shown in **Figs. (4A, 4B, and 4C).** As it is shown through the maps, for each layer the spots that are expected to have high plasticity soils are determined in red color (spots with values greater than or equal 50%) as an indicator for determining high expansive soil, since it is one of the main problems of this area. **Figs. (5A, 5B, and 5C)** show these results from a statistical perspective. Results of R^2 for the liquid limit were (0.47, 0.47 and 0.53) for the layers (1 to 2, 2 to 4 and 4 to 6) meter, respectively. In addition, the RMSE for the three layers is (4.85, 5.95 and 6.08), respectively.

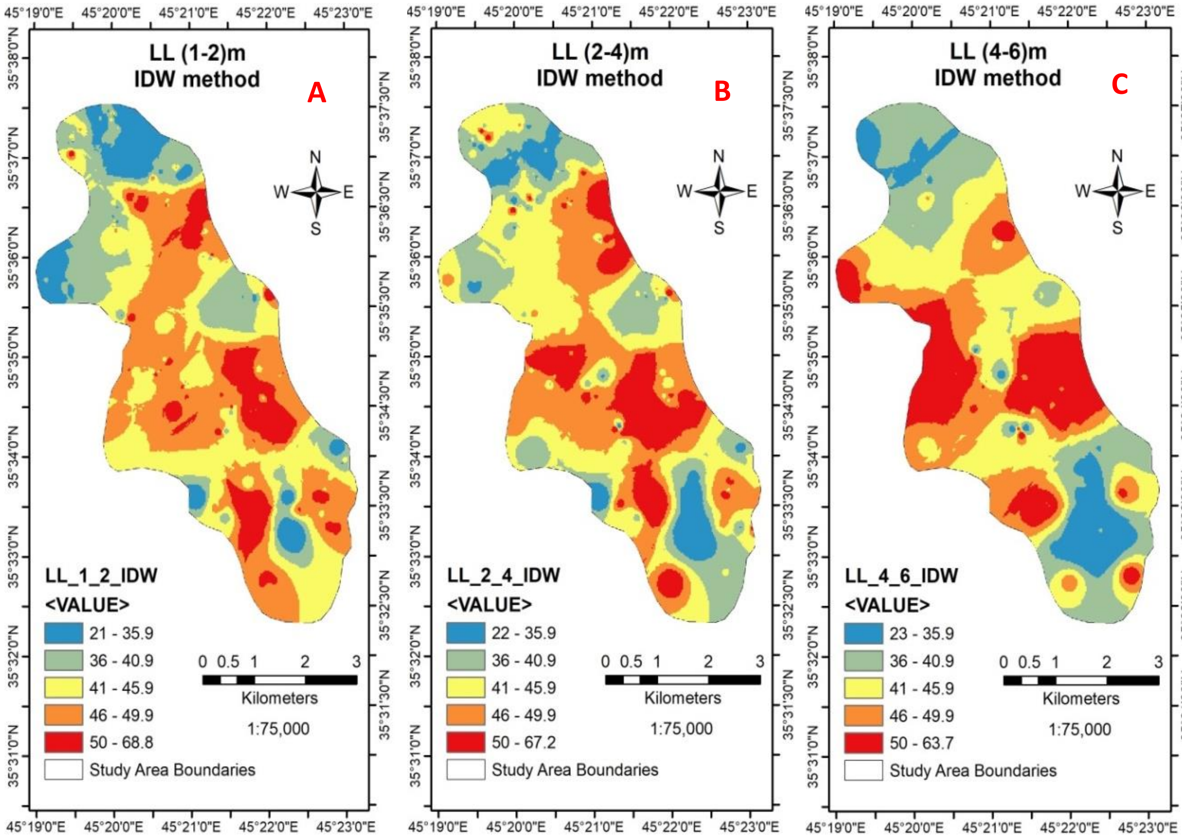
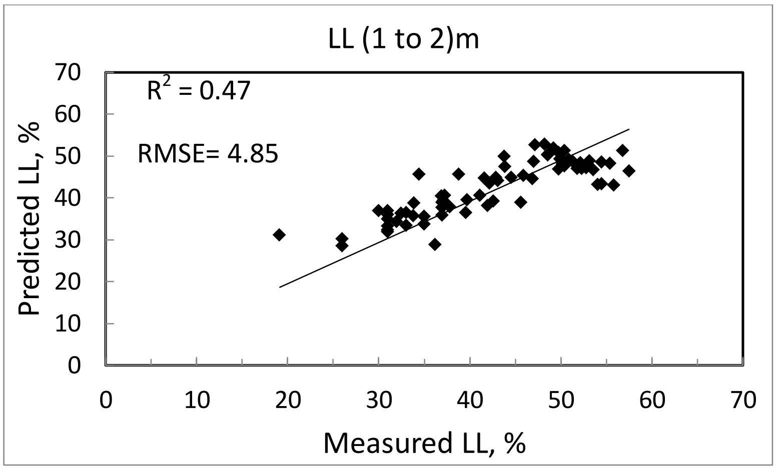
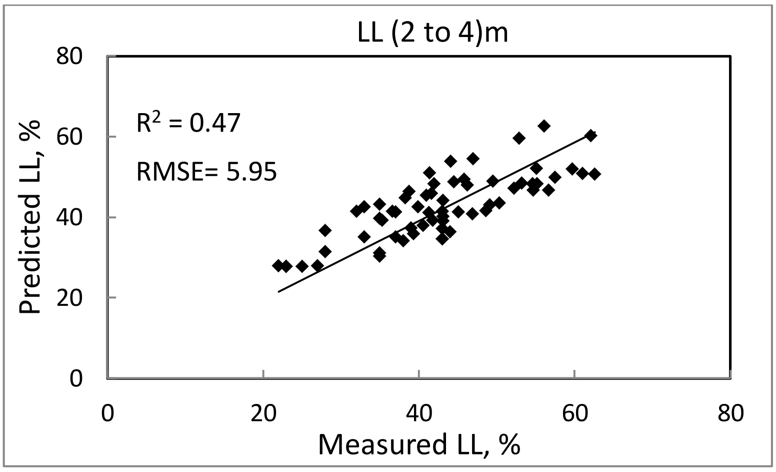


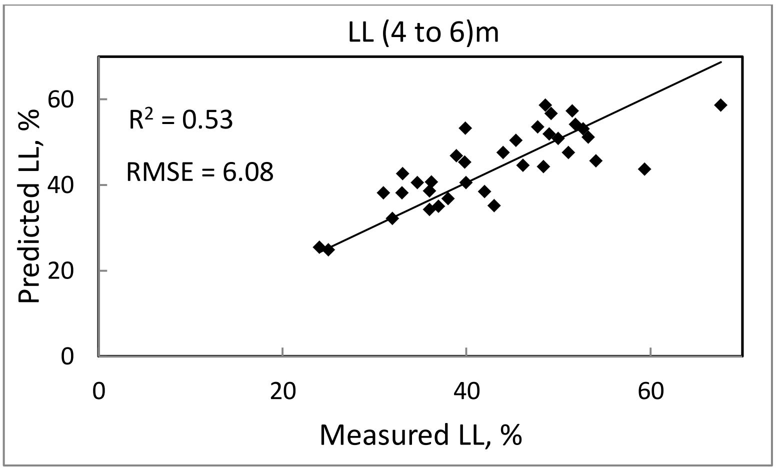
Figure 4. Liquid limit maps for the study area for the depths:
A: (1 to 2) m B: (2 to 4) m and C: (4 to 6) m



(A) Results for (1 to 2) m depth



(B) Results for (2 to 4) m depth



(C) Results for (4 to 6) m depth

Figure 5. Relationship between measured and predicted liquid limit values for the studied layers: A (1 to 2) m, B (2 to 4) m, and C (4 to 6) m

3.2 Plasticity Index (PI)

The range of the plastic state of a soil sample is given by the difference between the liquid limit and plastic limit and is defined as the plasticity index **(Roy and Bhalla, 2017)**. **Figs. (6A, 6B, and 6C)** show the maps produced for the plasticity index and the validation results for this property are shown in **Figs. (7A, 7B, and 7C)**. According to the results, the values of R^2 for the predicted versus measured plasticity index are (0.55, 0.5 and 0.48) for the layers (1 to 2, 2 to 4 and 4 to 6) meter, respectively. The RMSE for the three layers was found to be (3.79, 4.39 and 4.17), respectively.

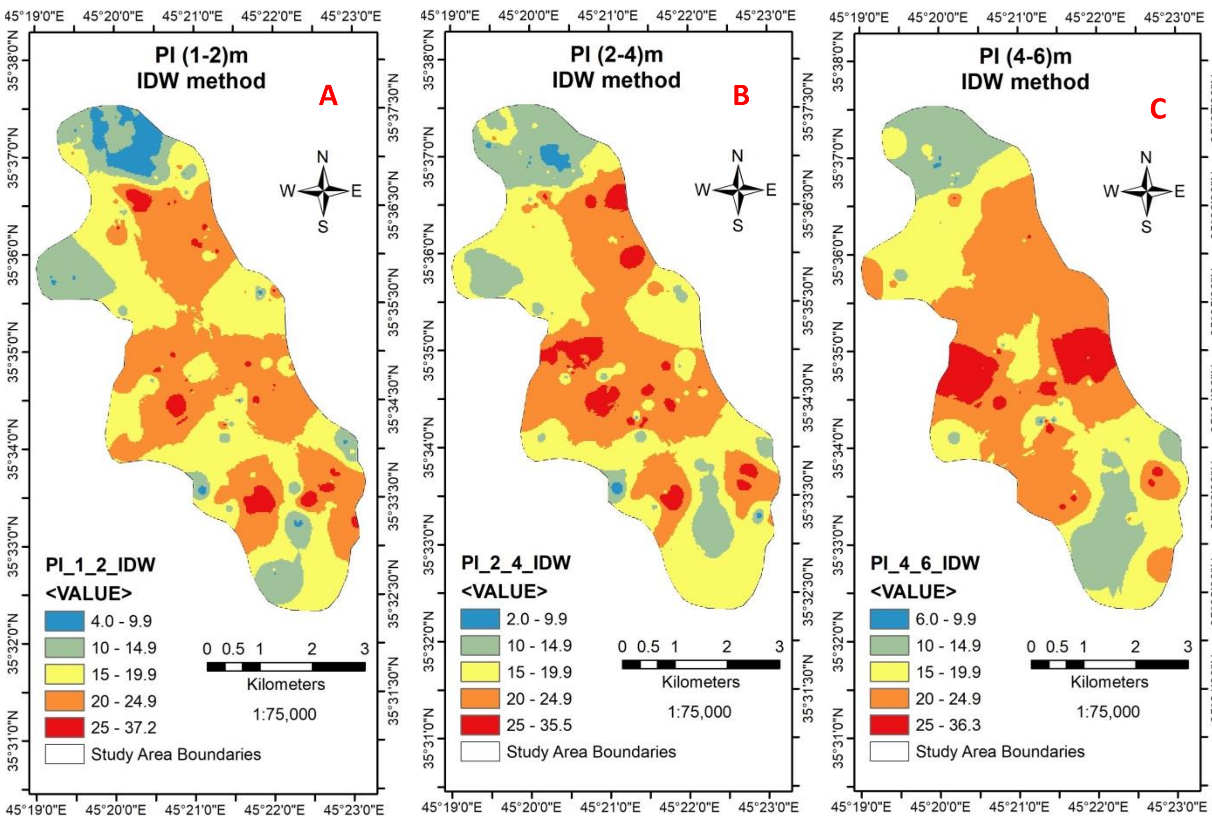
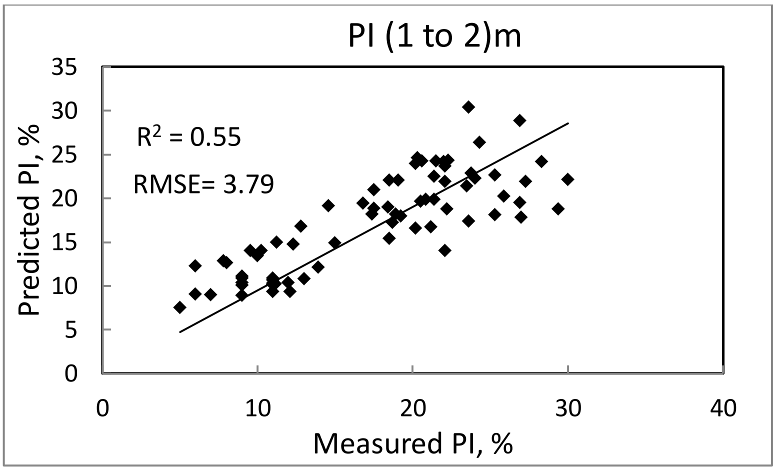
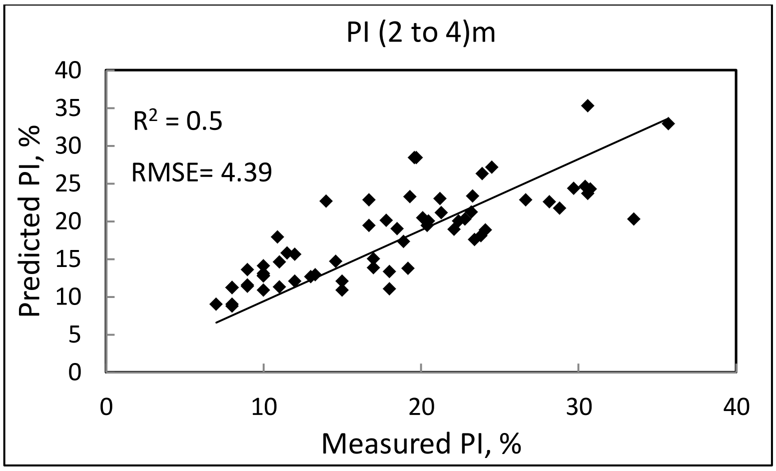


Figure 6. Plasticity index maps for the study area for the depths:

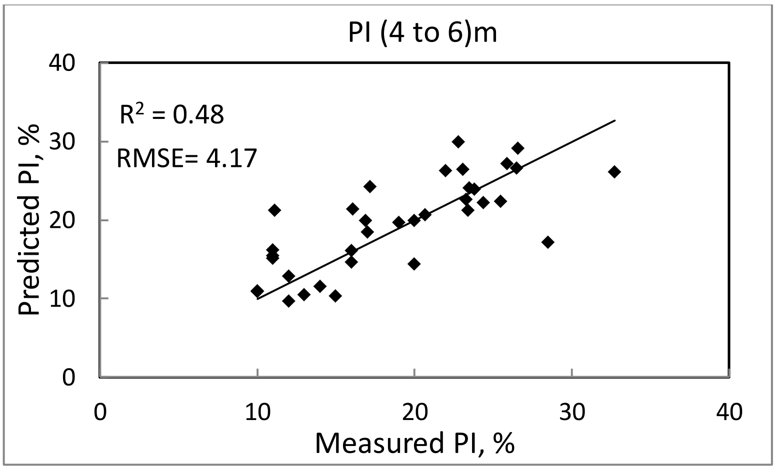
A: (1 to 2) m B: (2 to 4) m and C: (4 to 6) m



(A) Results for (1 to 2) m depth



(B) Results for (2 to 4) m depth



(C) Results for (4 to 6) m depth

Figure 7. Relationship between measured and predicted plasticity index values for the studied layers: A (1 to 2), B (2 to 4), and C (4 to 6) m

3.3 Liquidity Index (LI)

Liquidity index is the relative consistency of a fine-grained soil at its original state in the field and its values range from less than zero to greater than 1. A negative value indicates a soil that is semisolid, whereas values greater than 1 indicate a soil that is in a liquid state, engineers must be cautious in such cases **(Murthy, 2002)**. It is important to identify the consistency of soil in order to visualize how stiff or soft the soil is. **Figs. (8A, 8B, and 8C)** show the variation of the liquidity index in the study area. The resulted maps show that most of the soil of the area is in a semisolid state except for some locations where we have soil ranging from very stiff state to stiff state as spotted by red color. The accuracy of the maps was checked and shown in **Figs**. **(9A, 9B ,and 9C).**

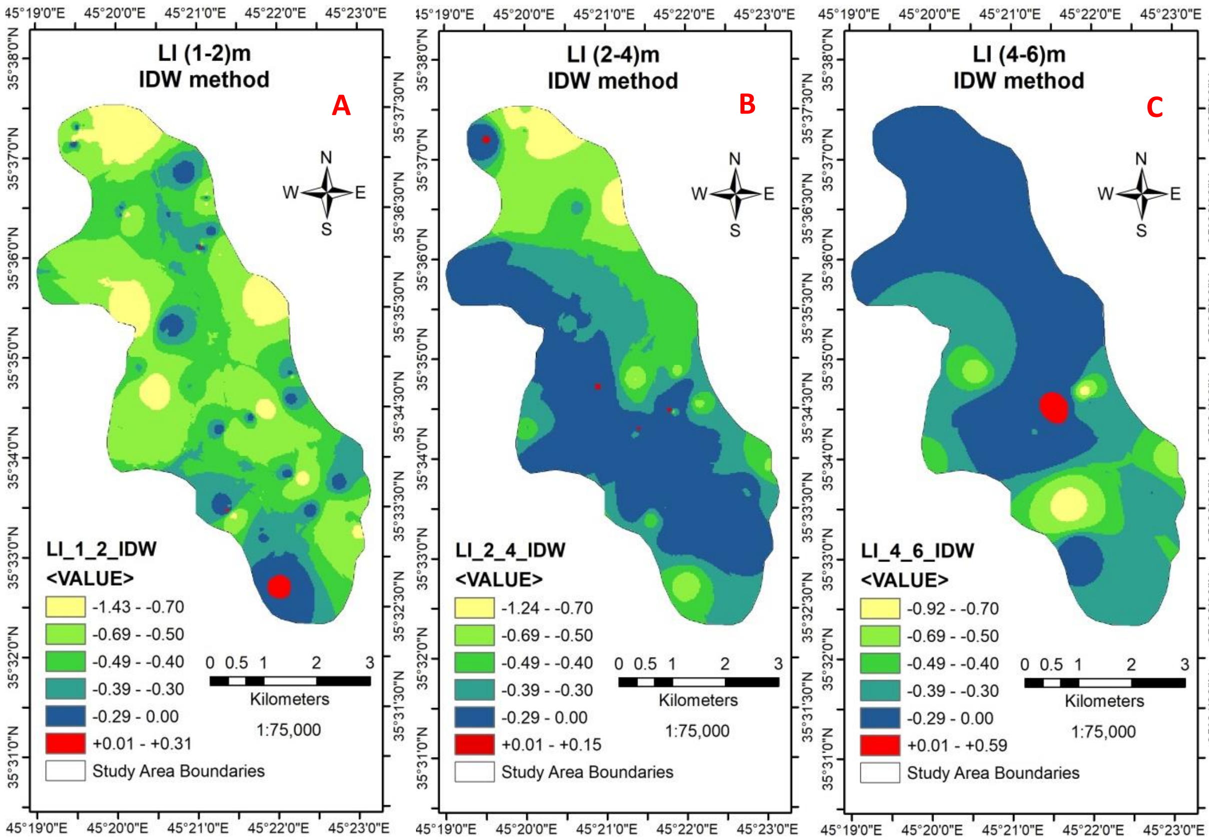
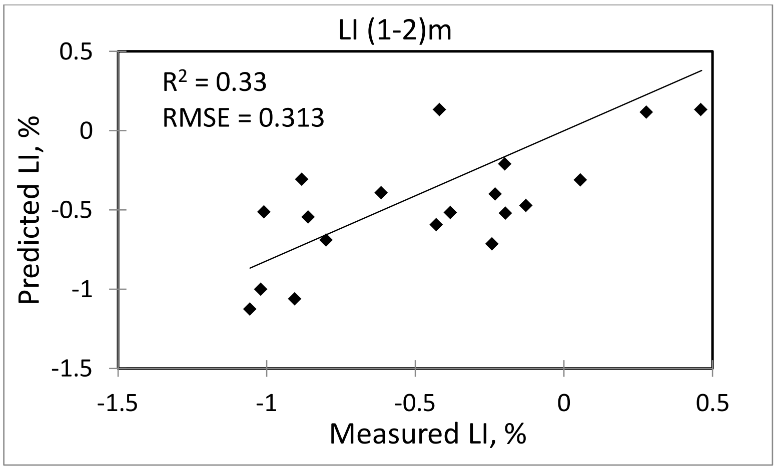
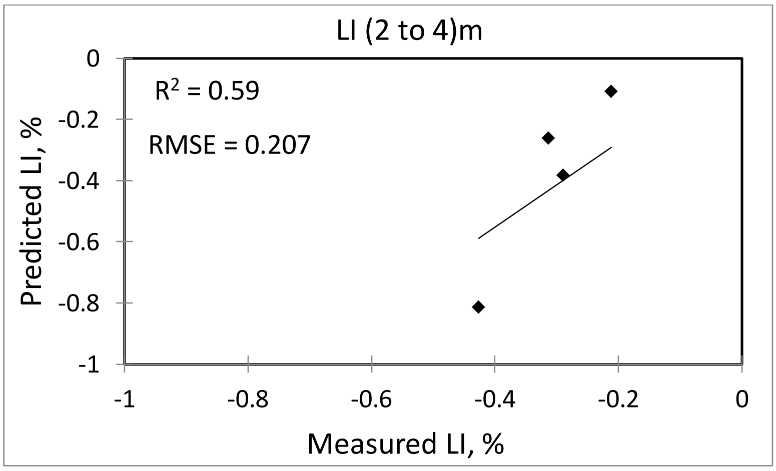


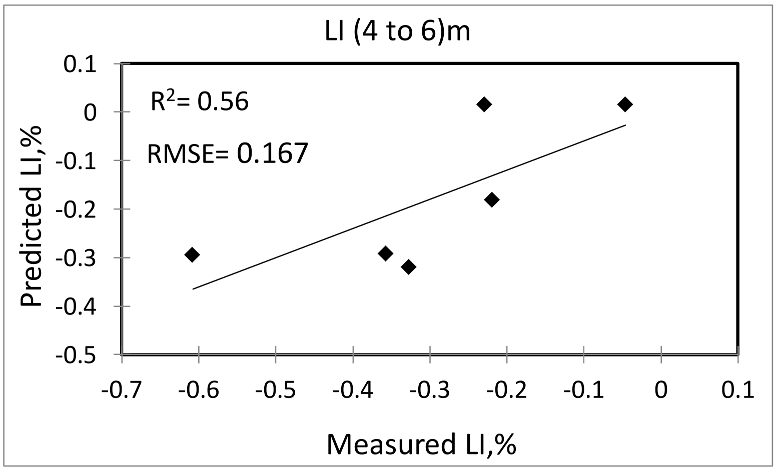
Figure 8. Liquidity index maps for the study area for the depths:
A (1 to 2) m, B (2 to 4) m, and C (4 to 6) m



(A) Results for (1 to 2) m



(B) Results for (2 to 4)m



(C) Results for (4 to 6)m

Figure 9. Relationship between measured and predicted liquidity index values for the studied layers: A (1 to 2) m, B (2 to 4) m, and C (4 to 6) m

All the studied parameters have acceptable results of R^2 and relatively good RMSE values. Among the studied parameters, the liquidity index of (1 to 2) m layer had less R^2 results (0.33) with RMSE value of 0.379. R^2 for layers (2 to 4 and 4 to 6) m are 0.59 and 0.56, respectively. RMSE values for the layers (2 to 4 and 4 to 6) m are 0.207 and 0.167, respectively. Since LI depends on the natural water content value, the fact that the natural water content data were obtained from tests at different temperatures and different seasons may be the reason for not having good predictions. Also, the lack of data at some points can be a cause for the low accuracy results as it is affected by the number of points and the distribution pattern over the study area..

3.4 Expansive Soil at the Study Area

Many researchers divided soils into different ranges of swelling potential according to the values of LL and PI. In this study, the ranges presented by Chen in 1988 and adopted by Das **(Das, 2016)** has been used for a depth range of 1m to 4m in which the values of LL>40% and PI>20% are considered as indicators of high swelling potential soil. The results are shown in **Figs. (10A and 10B)** and layers intersect is shown in **Fig. 10C**.

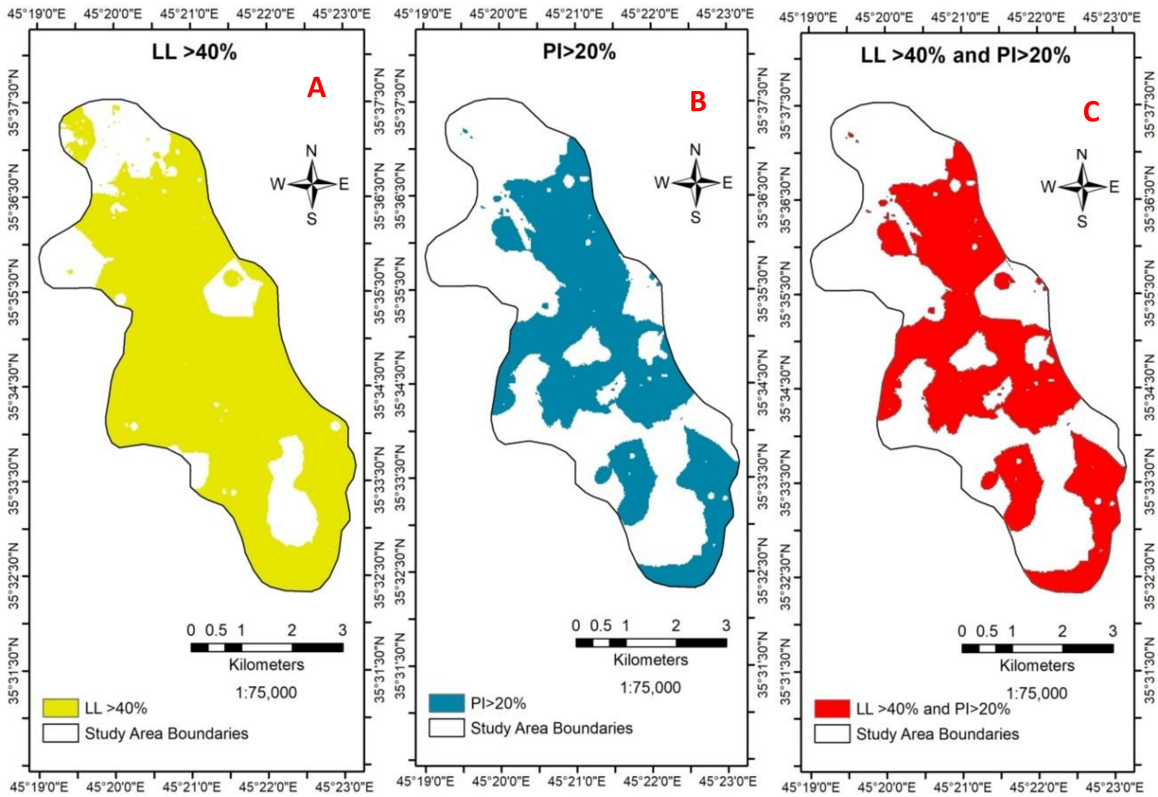


Figure 10. Zones of high swelling potential soil at the study area for A (LL>40%), B (PI >20%) and C (LL>40% & PI>20%)

Dissimilar to other heavy buildings, most of the buildings in the study area are residential houses and schools that are designed to withstand light loads. Since the layers represent depth ranges from 1 to 4 meters, swelling pressure values of lightweight structures are considered in determining critical values of swelling pressure that causes high swelling potential. Therefore, swelling pressure values greater than 50kPa are used in defining high swell potential soil (**Fig.11A).** For the swell index, the values presented by **(Murthy, 2002)** were adopted for this study by taking swell index values less than 0.37 as indicators of high swelling potential soil (**Fig.11B)**. Intersect of swelling pressure layer (>50kPa) and swell index layer (<0.37) with LL>40% and PI>20% are presented in **Figs.(12A, 12B).**

The outcomes of areas of high expansive soils differ according to the selected parameter for the investigation, the zones having all the parameters of high swell potential are shown in **Fig.12C**. These results can help geotechnical engineers in decision making and give an idea of the distribution of such soils.

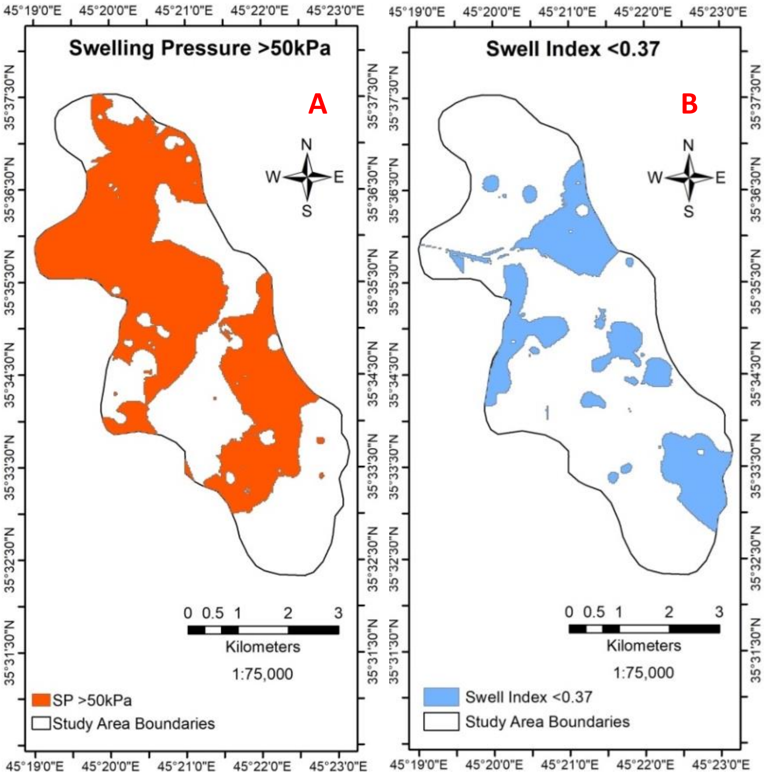


Figure 11. Zones of high swelling potential soil at the study area for A (SP>50 kPa) and B (SI<0.37)

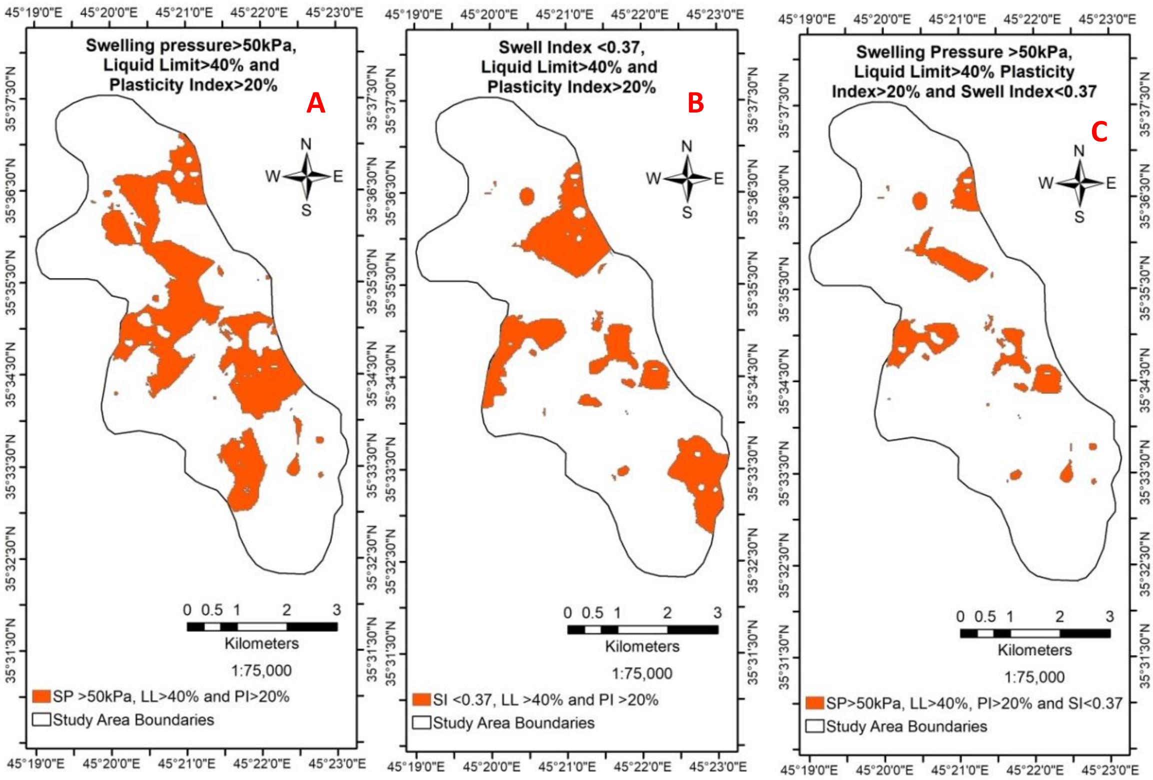


Figure 12. Zones of high swelling potential soil at the study area for A (SP>50kPa, LL>40% and PI>20%), B (SI<0.37, LL>40% and PI>20%), C (SI<0.37, LL>40%, PI>20% and SP>50kPa)

4. CONCLUSIONS

This article aimed to introduce and investigate the benefits of combining Geotechnical engineering data and Geographic Information System GIS to help in visualizing expansive soil's behavior at Sulaymaniyah City. The results led to the following conclusions:

a) By producing interpolation layers for each depth and after checking the validity of the resulted maps depending on the values of R^2 and RMSE, the overall process showed satisfying results.
b) LI maps indicate that the soil of the study area is in the safe side (semisolid state) regarding problems related to soft soils since most of the data are negative and little of data fall within 0 to 0.59 which can be considered as strong soil and it didn't reach soft state.
c) Zones of high swelling potential soil are determined through this study. Different parameters for the determination of high swell potential soil have been presented, these maps share some points and differ at other points. In addition, zones having all the parameters of high swelling potential are presented in this article.
d) The zones having LL>40% and PI>20% occupy large portion of the study area. This indicates that most of the data of the study area fall in these ranges.

e) The zones of intersecting of the different layers must be taken into consideration during construction due to the higher possibility of having soils of high swelling potential and they may cause serious damages in the future.

f) Other indicators must be investigated in determining areas of high swell potential especially free swell values.

g) Such investigations are required to help in better understanding the behavior of the soil underneath the ground.

RECOMMENDATIONS

As a step toward establishing a geotechnical database for Sulaymaniyah’s soil and since this type of researches requires as much data as possible and at nearby areas, it is highly recommended to build a team to work in a group in order to enrich the current database and eventually obtain more accurate results. Also, it is recommended to investigate more criteria for determining high swelling potential soil due to the importance of detecting such soils for engineers.

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NOMENCLATURE

LL= Liquid limit, percentage.
LI= Liquidity index, percentage.
N= Number of data points.
PI= Plasticity index, percentage.
R^2= Coefficient of determination, dimensionless.
RMSE = Root mean square error, dimensionless.
SI= Swell index, dimensionless.
Sp= Swelling pressure, kPa.
W= Water content, percentage.
yi= Measured data.
yp= Predicted data from the maps.
μ= Mean of the data.