Evaluating the Spatial Distribution of some Soil Geotechnical Properties Using Various Interpolation Methods (Case Study: Sulaimani Province, Iraq)

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ABSTRACT

Soil geotechnical parameters are important inputs for the prediction of ground suitability for construction projects. The aim of the study is the evaluation of spatial distribution of some soil geotechnical characteristics for Sulaimani governorate, northern Iraq which has a semi-arid climate. Sixty different soil specimens were taken from a distance of 2.0 meters from natural ground surface, around the Sulaimani city which are suitable for resettlement purposes. Several required laboratory experiments were performed to obtain some engineering properties of the collected soils according to ASTM standards, namely field water content, field wet density, initial void ratio (IVR), and degree of saturation (DS). Three different interpolation methods namely Inverse Distance Weighted (IDW), and Thin Plate Spline (TPS), which are deterministic interpolation methods in addition to and one geostatistical method, Ordinary Kriging (OK), were applied. Cross validation and accuracy assessment of model performance are also applied and analyzed. In general, the geostatistical method performance was compared with the deterministic methods. Ok method found to be more accurate and less biased method than the other two methods, which has lower RMSE (1.38%, 11.33%, 0.07 and 0.82 gm cm⁻³) and ME (-0.63%, 0.94%, -0.16 and 0.30 gm cm⁻³) for water content, DS, IVR and wet density respectively. According to the interpolation maps 65 to 70 % of study area is likely suitable for construction purposes compare to the other 30 to 35 %, which need some precautions for the suitability issue for construction projects. The results yielded in the reliability of the obtained soil geotechnical properties from geospatial maps, which may importantly engage to suitable engineering management application and modeling of land use.

Keywords: Soil Geotechnical properties; Interpolation; IDW; TPS; Ordinary Kriging

INTRODUCTION

Traditionally engineers have been trying hard to predict the variation of soil and its properties by sketch maps and manual diagrams. Soil mapping has been done since decades using paper maps by cartographers (using symbols and lines). Most of these old methods are cumbersome and uneconomical (Khatiri, 2018). The knowledge of expert are considered more for other models, where current information is determined based on a clear guideline choice to understand soil kinds and their geotechnical characteristics distribution spatially (Zhu et al., 2001; Wieliemaker et al., 2001; Egli et al., 2005; Egli et al., 2006). According to the cost effective and time consuming of soil sampling and testing for a huge number of samples, it is necessary to find robust alternative methods for soil’s geotechnical properties prediction. Hence, now the use of digital maps using Geographical Information System (GIS) has provided the way out to store and manipulate the soil variation in a most optimum way possible and enhances our capability to map the exact variation of the landscape around the globe (Khatiri, 2018; Abulude et al., 2015). Therefore, accurate interpolations of soil’s geotechnical properties at un-sampled places are necessary in order to be within preferable planning and management (Rahman et al., 1997; Tognina, 2004; Behrens et al., 2005).

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Globally, the most effective and accurate interpolation methods have been significantly considered and used (Kravchenko and Bullock, 1999; Robinson and Metternicht, 2006b; Zhu et al., 2001). These studies evaluated the effectiveness of different interpolation techniques in measuring soil properties, however, few of the techniques were actually related to soil geotechnical properties (Meul and Van Meirvenne, 2003; Karydas et al., 2009; Lieb et al., 2012). For instance, geostatistical methods found to be one of the most accurate ways to study soil characteristics spatial distribution (Saito et al., 2005; Kumar et al., 2012; Kumar et al., 2013; Liu et al., 2014; Behera and Shukla, 2015). Previous studies have used the geospatial techniques to assess the soils spatial association and the soil characteristics changeability geographically (Wei et al., 2008; Egli et al., 2006; Egli et al., 2005), and the relations between soil types and environmental variables (Lagacherie and Holmes, 1997; Behrens et al., 2005; Carré et al., 2007), different soil types for some points in Sulaimani Governorate (Salih, 2020). Moreover, spatial variability is omitted as some studies were conducted at a regional scale. So there is a gap and there is not much information existing on the accurate various soil types’ distribution and their geotechnical properties, usually, detailed spatial distribution maps for soils are not available in developing countries such as Iraq. Hence, this study aim is to evaluate some soil geotechnical properties spatial distribution in a semi-arid region in addition to assess the precision of predicted map based on different interpolation methods and finally evaluate geotechnical properties effect on stability of construction project.

Methodology

1. The study area and soil samples locations

This study was conducted and carried out in Sulaimani Governorate, Iraq (Figure 1). The study region altitude ranges between 633 m to 1706 meters above sea level. The study area climate is hot and dry over summer and cold over winter (Najmaddin et al., 2017b). The mean annual precipitation is between 450-700 mm (Najmaddin et al., 2017a). Site investigations were performed to obtain the required field information and obtain soil natural samples. From various 60 locations, the required soil specimens were collected in March-May 2019. All the collected soil specimens were taken from 2.0 meters depths from natural ground surface. Moreover, in order to discover the soils physical characteristics of around selected sites, collection of undisturbed and disturbed soil samples was carried out. The collected soil samples for all locations were kept undisturbed by extracting them via thin wall tubes to find the real field density of the soil samples. This scenario is carried out to obtain representative samples of the selected sites in order to understand in-situ field properties of the soils of the selected locations. In addition, the collected specimens were directly put in plastic bags in order to save their natural geotechnical properties, especially field moisture content and field density.

2. Laboratory Work

Soils geotechnical characteristics were obtained via both field and laboratory test methods. Several required laboratory experiments were performed so to obtain the collected soils physical properties according to ASTM standards as follow.

Water Content Determination (ASTM D 2216 – 10)

This test was performed according to ASTM standards in order to find the collected soil samples natural moisture content. Soils moisture content is the ratio of water mass in a given soil sample mass to the dry soil solids mass of the same sample. Water content is denoted as percentage.

Density (Unit Weight) Determination (ASTM D 2937-10)

This test is a laboratory experiment, which was implemented to find in-place density of natural soil gotten by a thin-walled cylinder according to ASTM standards. The in-place density is the mass ratio of wet soil sample to the volume of same sample. So, the dry density is the mass ratio of the dry soil sample to total volume of same sample. This test method overall principles have been effectively utilized to gain specimens of some fine-grained soils fields have 4.75 mm as a maximum particle-size for other purposes than determination of density, such as conduction of other laboratory tests for soil’s engineering properties determination.
advantage of the semi-variogram to demonstrate spatial continuity (autocorrelation). As a function of distance the semi-variogram tests the frequency of the statistical association. The range is the distance the spatial correlation, and the sill corresponds to the maximum variability in the absence of spatial dependence. OK estimates \( Z(X_o) \) and the minimum error or variance of \( \sigma^2 \) were calculated as follow respectively.

\[
Z(X_o) = \sum_{i=1}^{n} A_i Z(X_i)
\]  
\[
\sigma^2 = \mu + \sum_{i=1}^{n} \gamma(X_o - X_i)
\]

The weights are \( \lambda_i \); the lagrange constant is \( \mu \); and \( \gamma \) is the semi-variogram value corresponding to the distance between \( X_o \) and \( X_i \) (Vauclain et al., 1983; Agrawal et al., 1995).

The semi-variogram expressed as follow, which were used to inspect the soil characteristics spatial distribution. Based on intrinsic hypotheses and the regionalized variable theory (Nielsen and Wendroth, 2003).

\[
y(h) = \frac{1}{2n} \sum_{i=1}^{n} (Z(X_i) - Z(X_i + h))^2
\]

The semi-variance is \( y(h) \), the lag distance is \( h \), the parameter of the soil characteristic \( Z \), the number of pairs of locations is \( N \), which separated by a lag distance \( h \). \( Z(X_o) \) and \( Z(X_i + h) \) are values of \( Z \) at \( X_i \) and \( X_i + h \) positions (Wang and Shao, 2013).

In current research, the spherical model \( y_\theta(h) \) was considered for the sample variogram fitting changes in the variogram function. Spherical model is defined by:

\[
y_\theta(h) = \begin{cases} 
0 & h = 0 \\
\frac{C_0}{C_2} + \frac{C_1}{C_2} \left( \frac{h}{C_2} \right) - \frac{\left( \frac{h}{C_2} \right)^3}{C_2} & 0 > h \geq C_0 \\
C_0 + C_1 & h > C_0
\end{cases}
\]

The vector of free parameters that fully determines the variogram shape where characterized by \( \theta \). For the considered variogram models, it will often be the case that \( \theta = (C_0, C_1, C_2) \); where \( C_0 \) is the nugget parameter, i.e. the nonzero limit \( \lim h \to 0 y_\theta(h) = C_0 \) in case the variogram model is assumed to be discontinuous in the origin, \( C_1 \) is called sill parameter, that is the limit value \( \lim h \to 1 y_\theta(h) = 0 \); and \( C_2 \) is the range, which is the typical spatial scale associated to significant.

2.3.3. Thin plate splines (TPS)

The TPS interpolation can be used to represent any location in space to a new location given a set of control points in terms of radial basis functions (Duchon, 1977; Wahba and Wendelberger, 1980). The TPS corresponds to the radial basis as

\[
Z(r) = r^2 \log r
\]

\( r \) is the distance between un-sampled places and sample points. More details about the TPS estimation can be found in (Duchon, 1977; Wahba and Wendelberger, 1980; Bachaokwu et al., 2017).

2.4. Cross validation

The performance of spatial interpolation methods were assessed by the Split-data-sets-cross-validation method. It is to divide the points into two collections: the used points in the interpolation operation and the used points to validate the obtained results. In this study we randomly hold 20 points for validation and 40 points for interpolation operation.

To assess the accuracy of the interpolation methods, the Mean Error (ME), Mean Absolute Error (MAE), Root Mean Squared Error (RMSE and determination coefficient (R² value) were calculated.

\[
ME = \frac{1}{n} \sum_{i=1}^{n} (X_i - \hat{X}_i)
\]

\[
RMSE = \sqrt{\frac{\sum_{i=1}^{n} (X_i - \hat{X}_i)^2}{n}}
\]

The interpolated value at the un-sampled place \( i \) is \( \hat{X}_i \) (i.e. place where the sample point was removed or did not use in interpolation operation), \( X_i \) is the right value at place \( i \) and \( n \) is the number of points in the dataset.

RESULTS AND DISCUSSION

Results

1. Moisture content spatial distribution (%)

Figure 2 displays spatial distribution of the water content %, applied three methods IDW, OK and TPS characterizing the bulk of the data have critical water content (12%–18%). Predicted water content is plotted against observed water content (Figure 3), with the linear regression best fit and 1:1 line. RMSE value were 1.38%. For OK and TPS methods and slightly higher for IDW which were 1.5%. A statistical summary between predicted and observed water content is shown in Table 2. The R² value between predicted and observed water comet were low but significant for all methods at \( p < 0.05 \).

Figure 2. Spatial distribution of predicted water content using inverse distance weighting (IDW), Ordinary kriging (OK) and Thin Pate Spline model (TPS) methods.

Figure 3. Scatter plot between observed and predicted water content using (IDW), (OK) and (TPS) methods. The blue line shows the best-fit regression with 95% confidence interval.
Table 1. Statistical summer of cross validation for different soil geotechnical properties using different interpolation methods.

<table>
<thead>
<tr>
<th>Soil Geotechnical Properties</th>
<th>Interpolation methods</th>
<th>ME</th>
<th>MAE</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Content (%)</td>
<td>IDW</td>
<td>-0.77</td>
<td>1.24</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td>OK</td>
<td>-0.63</td>
<td>1.13</td>
<td>0.28</td>
</tr>
<tr>
<td></td>
<td>TPS</td>
<td>-0.68</td>
<td>1.22</td>
<td>0.32</td>
</tr>
<tr>
<td>Degree of Saturation (%)</td>
<td>IDW</td>
<td>1.75</td>
<td>9.8</td>
<td>0.31</td>
</tr>
<tr>
<td></td>
<td>OK</td>
<td>0.94</td>
<td>9.8</td>
<td>0.27</td>
</tr>
<tr>
<td></td>
<td>TPS</td>
<td>0.43</td>
<td>10.7</td>
<td>0.12</td>
</tr>
<tr>
<td>Initial Void Ratio</td>
<td>IDW</td>
<td>-0.15</td>
<td>0.068</td>
<td>0.37</td>
</tr>
<tr>
<td></td>
<td>OK</td>
<td>-0.16</td>
<td>0.066</td>
<td>0.42</td>
</tr>
<tr>
<td></td>
<td>TPS</td>
<td>-0.17</td>
<td>0.07</td>
<td>0.28</td>
</tr>
<tr>
<td>Wet Density (gm cm⁻³)</td>
<td>IDW</td>
<td>0.42</td>
<td>0.71</td>
<td>0.18</td>
</tr>
<tr>
<td></td>
<td>OK</td>
<td>0.36</td>
<td>0.66</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>TPS</td>
<td>0.33</td>
<td>0.81</td>
<td>0.1</td>
</tr>
</tbody>
</table>

3. Spatial distribution of Initial Void Ratio (IVR)

The spatial distribution of the IVR is shown in Figure 6, which demonstrates the predicted IVR values ranged between 0.4–0.67. In Figure 7, the predicted IVR % relation with the observed IVR is drawn, along with the linear regression best fit and 1:1 line. RMSE value were ranged between 0.07 -0.08 for all methods. The R² of predicted IVR % and observed IVR % is shown in in Table 2, which were 0.37, 0.42 and 0.28 for IDW, Ok and TPS respectively.

4. Spatial distribution of Wet density (gm cm⁻³)

Figure 8 represents the spatial variation of the wet density, which illustrates that the predicted wet density ranged from 16.5–195. Predicted wet density is plotted against observed wet density (Figure 9), with the linear regression best fit and 1:1 line. RMSE value were ranged between 0.88 gm cm⁻³ for IDW, 0.86 gm cm⁻³ for OK and 0.95 gm cm⁻³ for TPS. The R² value between predicted wet density and observed Wet density is shown in in Table 2, which were 0.18, 0.12 and 0.1 for IDW, Ok and TPS respectively.
TPS) and deteministic approach with R² value are presented in Table 2. Ok method from the comparative results, found to be more precise for predicting soil properties in the region, initial void ratio and wet density. The lowest error was provided by OK method (ME, MAE and RMSE values) and the highest R² value in the spatial interpolation compared to deterministic methods. This might be because of OK as a geostatistical method include spatial autocorrelation and optimize the masses statistically (Ford and Quiring, 2014). This results is in agreement with previous research which stated that OK method frequently provide superior interpolation for values estimation at the unmeasured places (Bhunia et al., 2018; Nayanaka et al., 2010; Tripathi et al., 2015) and disagree with (Ikechukwu et al., 2017; Yao et al., 2013) who stated that the deterministic models give better interpolation than OK for land study.

The ME, which provided relative error or sometimes refer to as a bias of the predicted data in comparison with the observed data, was lowest for OK method and highest for IDW. This possibly due to IDW utilizes a linear set of values at captured sample locations, by an inverse function assigns weights of the separation among the sample places to be estimated and points captured to estimate values of the unknown place (Robinson and Metternicht, 2006). However masses are identified randomly, we use an ideal mass management function that allocates a mass that is most appropriate for points within the data set that captured. Robinson and Metternicht (2006) Asserted that IDW’s expectations are affected by this mass obligation. This does not imply IDW method is not suitable for soil geotechnical properties mapping. TPS method on the other hand performs better than IDW.

The importance of the carried out soil tests is in the right decision for a proper soil foundation for construction projects. Specifically, the natural soil geotechnical properties. In Figures 2 and Figure 4, which are representing the spatial distribution of the prediction of natural moisture content and the degree of saturation, the places in the study area which have a lower level of degree of saturation and moisture content are more suitable for construction projects compare with the other places. This might be because; increasing degree of saturation and moisture content can lead to more lubrication around soil particles resulting in a damp/wet soil state. This soil state is not preferable for construction foundations, due to its weak capability to resist superstructures loads. For example, grade color bar in these two figures showed that the darkness grade increases the effects on the suitability of the place for construction projects foundations. The majority of the mid-grade is light blue, which means that is better according to lower water content compare to the dark blue places. However, the very dark blue places are quite small percent and distributed randomly in the region. The region potentially might be divided to three places according to the predicted maps, red (5%), light blue (70%), and dark blue (25%), which means that likely the most suitable places yielded in large percent compare with the remain probably unsuitable and hence requires some precautions for the foundation areas of construction projects.

In the same way, soil’s initial void ratio is significant for sustainability of construction project.

In Figure 6, which is representing the distribution of the prediction of the initial void ratio, hence the places with high void ratio are weak and not suitable for construction project. Because, higher initial void ratio can cause more openings to be available in the soil structure, which can be filled either by air and/or water. This lead to less solid proportions to resist the superstructures loads. According to the spatial distribution of IVR. The region potentially might be divided to three places according to the available predicted map, yellow color area (15%), light green (50%), and dark green (35%). The IVR distribution yielded in almost 65 % of likely suitable for construction purposes compare to the other 35 %, which unlikely requires some precautions for the suitability issue for construction projects.

Similarly, soil wet density do the same behavior as the mentioned properties. In Figure 8, which is representing the spatial distribution of the prediction of the wet density. Hence, the places with high wet density are weak and not suitable for construction projects foundations. Because, more wet state can be weak for foundation soil state and might lead to severe structure collapse problems. So, the places with very light yellow color are the most suitable compare with the other places, however they cover a very small part of the region and distributed randomly. On the other hand, the very dark green places representing the worse places compare with the other places, which are lightly concentrated and randomly distributed in the region, and more likely found in the methods of OK and TPS. The wet density distribution yielded in almost 75-95% of probably suitable for construction purposes compare to the other 5-25%, which unlikely requires some precautions in order to be suitable for construction projects.

It is important to be mention here, the majority of natural soil samples were collected in spring time and a very small number of samples were collected at the end on winter seasons. This is means that almost the samples were collected in the wet seasons, which might possibly cause increase in the magnitudes of some geotechnical properties such as water content, degree of saturation and wet density. Unfortunately, the magnitudes of these properties might decrease if the sampling taking place in summer season. However, the effects may be small, as the specimens were extracted from 2.0 meters depthness below natural ground level. In addition, the initial void ratio is related to the type of soil and the season’s wetness is not influence in its magnitude.
CONCLUSION

Understanding the spatial distribution of the geotechnical characteristics of the soils is crucial for sustainable land management. Coefficient of determination (R² value) was used to assess the efficiency, and the root mean square error (RMSE), mean error (ME) and mean absolute error (MAE) were used to represent the errors. The results show that the OK interpolation method gave better results. Compare to TPS and IDW methods. IDW skill is driving higher RMSE and ME compared to other deterministic and geostatistical methods, it has the worst presentations. Based on predicted maps for these properties more than 65% of the study area is likely suitable for construction project. Finally, the outcomes guide to the amplification of reliable soil geotechnical properties maps, which can notably participate in the appropriate application of agricultural and engineering managements and land modeling.

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REFERENCES


Laskar A and Pal SK. (2012) Geotechnical characteristics of two different soils and their mixture and relationships between parameters. EJGE 17: 2821-2832.


تقييم التوزيع المكاني لبعض الخواص الجيوتقنية للتربة باستخدام دراسة حالة: محافظة السليمانية، العراق

تتعدد المعلومات الجيوتقنية للتربة في محاولة تقييم التوزيع المكاني لبعض الخواص الجيوتقنية للتربة في محافظة السليمانية، العراق ذات المناخ شمالي، حيث تم أخذ عينة متداخلة من التربة بمقترح متر من سطح الأرض الطبيعي حول مدينة السليمانية والتي تتمнт أراضي استيطان. وقد تم إجراء عدد من الفحوص المراعية المتصلة للحد من التربة الجيولوجية، ودرجة السطحية، ودرجة المعايرة، ودرجة التربة في حالات توزيعية معينة من التربة، وتم تمكين الطريقة الجغرافية (GS) من تمكين الطريقة الجغرافية (GS) من تمكين الطريقة الجغرافية (GS) من تمكين الطريقة الجغرافية (GS) من تمكين الطريقة الجغرافية (GS). كما تم تمكين الطريقة الجغرافية (GS) من تمكين الطريقة الجغرافية (GS) من تمكين الطريقة الجغرافية (GS) من تمكين الطريقة الجغرافية (GS) من تمكين الطريقة الجغرافية (GS) من تمكين الطريقة الجغرافية (GS). 

تعتبر هذه الدراسة مستقبلاً لتبين بحثية لأراضي مشابهة النبات، وتحديد هذه الدراسة إلى تقييم التوزيع المكاني لبعض الخواص الجيوتقنية للتربة في محافظة السليمانية، العراق ذات المناخ شمالي، حيث تم أخذ عينة متداخلة من التربة بمقترح متر من سطح الأرض الطبيعي حول مدينة السليمانية والتي تتمنت أراضي استيطان. وقد تم إجراء عدد من الفحوص المراعية المتصلة للحد من التربة الجيولوجية، ودرجة السطحية، ودرجة المعايرة، ودرجة التربة في حالات توزيعية معينة من التربة، وتم تمكين الطريقة الجغرافية (GS) من تمكين الطريقة الجغرافية (GS) من تمكين الطريقة الجغرافية (GS) من تمكين الطريقة الجغرافية (GS) من تمكين الطريقة الجغرافية (GS) من تمكين الطريقة الجغرافية (GS). كما تم تمكين الطريقة الجغرافية (GS) من تمكين الطريقة الجغرافية (GS) من تمكين الطريقة الجغرافية (GS) من تمكين الطريقة الجغرافية (GS) من تمكين الطريقة الجغرافية (GS) من تمكين الطريقة الجغرافية (GS). 


