Geotechnical characteristics correlations for fine-grained soils

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Abstract. Compressibility and shear strength are the principal geotechnical engineering properties of soils, which control the stability of a soil mass under structural loads. Therefore, it is always required to be measured before the design of the foundation of any structure. Evaluation of shear strength and compressibility characteristics are time consuming and laborious. Hence, there is a necessity for prediction of those characteristics with the help of correlating them with index properties, initial void ratio, natural moisture content, field densities of soils, which can be determined easily. In this paper, a study is conducted on two sets; two and three geotechnical natural properties together for Barika, Arbat and Hwana fine-grained soils in Sulaimani Governorate, Iraq. In addition, new empirical relationships with single and multiple dependent variables were developed with better estimation capability. The best relationship was observed between plasticity index as a function of liquid limit with correlation coefficient (R) and RMSE equal to 0.874 and 2.18 respectively. Whereas, there was no significant relationship between coefficient of compressibility (compression index, Cc) and consistency properties was noticed.

Keywords: Compressibility, Shear Strength, Fine-Grained Soil, Correlation.

1. Introduction
For every civil engineering stable structure such as building, bridge, highway, tunnel, dam, and towers, a proper foundation soil is necessary. Then, for successful evaluation of the suitability of that soil to construct a safe foundation and as construction materials, information about its properties is frequently necessary. Therefore, understanding soils detailed geotechnical, physical and engineering properties are very much essential.

In the last decay, many researches were performed to correlate the physical properties with the mechanical properties. This approach was adopted for the purpose of time saving and reduces cost of investigations. In addition, it was carried out by the earlier researchers in the field of soil mechanics and foundation engineering.

In 1982, Abdel-Rahman [2] has made a correlation between index properties and the engineering properties of Egyptian clay from different locations along the Nile valley and Delta. For this purpose, and intensive study was carried out to make correlations with simple and multiple regression analysis in spite of the simple regression was enough for estimation. In 2000, Isik [15] performed a study to evaluate clayey soil’s shear strength by using the liquidity index of soils from various locations in Turkey. After that, in 2004, USDA [23] made a correlation between soil plasticity as well as plasticity index and strength parameter (residual strength). In 2009, Al-Busoda [5] also, correlated physical and engineering properties of Baghdad cohesive soil based on Atterberg limits. In 2017, Rashed et al. [17] correlate compressibility properties (Cc and Cr) with index properties of sixty soil samples.

Empirical models related to various index properties correlated with compression index have been presented by many researchers such as Terzaghi and Peck (1967) [22], Skempton (1944) [21], Bowles (1989) [11], Wroth and Wood (1978) [24], Yoon et al (2004) [25], and Abassi et al. (2012) [1]. Moreover, Nagaraj et al. (2012) [16] focused on re-examination of undrained strength conducted at Atterberg limits. The study emphasizes on the uniqueness of strength at liquid limit or plastic limit. The results of Das et al. [12] in 2013 indicate that the rate of decrease of undrained shear strength of high liquid limit soils at higher water content is less compared to that at lower water content.

An empirical correlation is also presented that unsaturated state of compacted soils relates to unconfined shear strength [14]. Moreover, formulation of an expression for predicting undrained shear strength of a remolded soil at any water content based solely on its liquid limit and plastic limit [20]. Some of the equations belong to the compressibility and shear strength properties versus various index properties are presented in Tables 6 and 7, which indicate interpretation strength of correlation.
This paper entails the geotechnical properties correlations of some of the fine-grained soils in Sulaimani City, Northern Iraq. These correlations give emphasis to two sets; two and three geotechnical natural properties together. In addition, new empirical relationships with single and multiple dependent variables proposed to be developed with better estimation capability.

2. Methodology

2.1 Collection of soil samples

In this study, one hundred and seventy undisturbed fine-grained soil samples were collected from different locations in Sulaimani City, Barika, Arbat and Hwana districts. The samples were collected from shallow depths of 1.0 - 2.0 m from the natural ground level and then used for the laboratory testing experiments (field density, one-dimensional consolidation, unconfined compression tests). Same number of disturbed soil samples was collected for determination of the other geotechnical properties listed in Table 1. The carried out laboratory tests include Atterberg Limits (LL & PL), moisture content, unconfined compressive strength, and one-dimensional consolidation tests [6, 7, 8, 9, & 10]. The one-dimensional consolidation tests were performed with the oedometer equipment, and the plasticity index is calculated as the difference between LL and PL.

2.2. Testing methods

For conduction of one-dimensional consolidation tests (ASTM D 2435-11), undisturbed soil samples have been trimmed to the size of a mold of 50 mm in diameter and thickness of 20 mm. After the sample put in the oedometer apparatus, the pressure was applied in the range of 25 – 800 kN/m² by sequencing stages for every 24 hours.

Atterberg limits tests (liquid limit and plastic limit) were done on the soils, which were passed sieve No. 40. The liquid limit was measured through the Casagrande liquid limit equipment. Linear shrinkage limit (ASTM C 356-10) is the proportion of decrease in the length of a soil sample to the original length when the moisture content is reduced from liquid limit (LL) to shrinkage limit (SL). Other soils samples physical properties were also determined according to ASTM standards as shown in Table 1.

3. Results and Discussion

3.1 Soil samples natural properties

The selected soils samples for this study were tested in order to obtain the natural geotechnical properties. Various numbers of trials for each laboratory test were carried out. Table 1 shows the minimum and maximum values and the considered specifications for each conducted laboratory test. The field geotechnical properties were found to be variable.
Table 1. The conducted laboratory experiments to obtain the natural geotechnical properties of the selected soils samples of current study.

| Type of Test                          | No. of Samples | Min. Value     | Max. Value     | Specification No.          |
|--------------------------------------|----------------|----------------|----------------|---------------------------|
| One Dimensional Consolidation        | 81             | $C_c = 0.0469$ | $C_c = 0.381$  | ASTM D 2435-11            |
| Unconfined Compressive Strength (UCS)| 81             | $C_r = 0.0039$ | $C_r = 0.0564$ |                           |
| Dry Density ($\rho_d$)               | 168            | $25.92 \text{ kPa}$ | $929.95 \text{ kPa}$ | ASTM D 2166-16            |
| Liquid Limit (LL)                    | 143            | $1.2723 \text{ gm/cm}^3$ | $2.01957 \text{ gm/cm}^3$ | ASTM D 2937-10            |
| Plastic Limit (PL)                   | 143            | $30 \%$       | $70 \%$       | ASTM D 4318-10            |
| Plasticity Index (PI)                | 143            | $10$          | $32$          |                           |
| Natural Water Content ($w_n$)        | 204            | $11 \%$       | $32.95 \%$    | ASTM D 2216-10            |
| Initial Void Ratio ($e_o$)           | 81             | $0.4493$      | $0.983$       | -                         |

### 3.2 Relationship between liquid limit and plasticity index

In this study, some better relationships among the geotechnical properties of the collected soil samples were found. Plasticity index significantly correlated with liquid limit for the total data of 143 points in the form of linear relationship as shown in Figure 1. This is noticed from the achieved values of $R^2$ and RMSE, which are 0.874 and 2.18 respectively. Logically, this type of soil properties relations can positively work. Liquid limit directly affects plasticity index and can cause notable changes in the plasticity index magnitude.

The figure shows that with the increasing of plasticity index, liquid limit increases for all used soil samples. There is a similarity existed between developed equation in this study for PL and LL with the developed equations by other researchers such as Yukselen-Aksoy et al. (2008) [26]; Al-Ameri & Al-Kahdaar (2010) [4]; and Rashed et al. (2017) [17] as shown in Table 2.
Table 2. Compared empirical equations for current study and the ones obtained from related literature among some of the geotechnical properties of soils.

| Reference                      | Empirical Models                  | R   | R²   | RMSE  | Type of Soil                  |
|--------------------------------|-----------------------------------|-----|------|-------|-------------------------------|
| Yukselen-Aksoy et al. (2008)   | PI = 0.916 LL - 28.01             | 0.995 | 0.9899 | -     | Clay                          |
| Al-Ameri & Al-Kahdaar (2010)   | PI = 0.54 (LL - 0.71)             | 0.894 | 0.8   | -     | CH, CL, MH and ML             |
| Rashed et al. (2017)           | PI = 1.01 LL - 26.73              | 0.974 | 0.948 | 1.83  | Clayey or silty soil with low to high plasticity |
| Current Study (2019)           | PI = 0.6729 LL – 10.036           | 0.935 | 0.874 | 2.18  | CH, CL, MH and ML             |

3.3 Relationship between initial void ratio as a function of dry density and natural water content

The correlation between initial void ratio and few field properties (ρ_d and w_a) were investigated by the total data of 75 points via using simple regression model. The achieved good relationship between e_o and ρ_d was a linear model as presented in Figure 2 with R² and RMSE values equal to 0.77 and 0.076 respectively. This is lower than the developed relations by Sadrekarimi et al. (2006) [18], and Rashed et al. (2017) [17]. It may be resulted from the considered number of data, which can influence the accuracy of the obtained relationship. Also, the method of sampling to determine the soils field density can be responsible for some of the mistakes or non-correct density calculation according to the percent of disturbance.

Significant relationship found between e_o and natural water content as shown in Figure 3 with R and RMSE equal to 0.61 and 0.102 respectively, which is lower than the obtained results by Al-Ameri & Al-Kahdaar (2010), and Rashed et al. (2017) [4 & 17] as shown in Table 3. Correlations among soils geotechnical parameters can vary. Although, after testing collected soil samples with similar particles sizes or similar in some of the geotechnical properties, they may show differences in correlated properties. This may results from the microscopic composition of those soils and has various contents such as clay minerals, particles shapes, voids distributions and shapes, and various minerals.
Figure 2. Initial void ratio relationship with dry density.

Figure 3. Initial void ratio relationship with natural water content.

Table 3. Compared empirical equations for current study and the ones obtained from related literature among some of the geotechnical properties of soils.

| Reference                     | Empirical Models                     | R     | R²     | RMSE   | Soil Type                      |
|-------------------------------|--------------------------------------|-------|--------|--------|-------------------------------|
| Sadrekarimi et al. (2006)     | \( e_0 = -0.162 \gamma_d + 3.30 \)  | 0.9899| 0.9799 | -      | Clay                          |
|                              | \( e_0 = 0.02 W_n + 0.08 \)         | 0.97  | 0.9409 | -      | CH, CL, MH & ML               |
| Al-Ameri & Al-Kahdaar (2010)  | \( e_0 = 0.088 \gamma_d -1.964 \)  | 0.91  | 0.8281 | 0.029  | Clayey or silty soil with     |
|                              | \( e_0 = 0.066 W_n - 0.44 \)        | 0.9   | 0.81   | 0.03   | low to high plasticity        |
| Rashed et al. (2017)          | \( e_0 = -0.7639 \rho_d + 1.9902 \) | 0.77  | 0.5929 | 0.076  | CH, CL, MH & ML               |
| Current Study (2019)          | \( e_0 = 0.00195 W_n + 0.294 \)     | 0.61  | 0.371  | 0.102  | CH, CL, MH & ML               |
3.4 Relationship between dry density and natural water content

Figure 4 shows the used data for a relationship determination between dry density and natural moisture content for the selected soil samples. It is obvious that increasing of natural water content values lead to decrease in dry density. $R$ and $RMSE$ for the relationship were found to be 0.74 and 0.084 respectively, which is lower than the developed relations by Sadrekarimi et al. (2006) [18], and Rashed et al. (2017) [17] as shown in Table 4. This is may be due to the date/time of sampling in the field and quick field water content calculation. Some deductions in the natural water content are expected due to hot weather and delay in testing. Also, the method of sampling to measure the field density can be responsible for some the mistakes or non-correct density calculation. Using a significant number of collected field soil samples in the determination of the geotechnical parameters can be an important factor to increase the accuracy of the obtained correlations among those geotechnical parameters.

![Figure 4. Dry density relationship with natural water content.](image)

| Reference                         | Empirical Models                          | $R$ | $R^2$  | $RMSE$ | Type of Soil                        |
|-----------------------------------|-------------------------------------------|-----|--------|--------|------------------------------------|
| Sadrekarimi et al. (2006)         | $\gamma_d = 0.001 (W_n)^2 - 0.22 W_n + 20.52$ | 0.92| 0.8464 | -      | Clay                               |
| Rashed et al. (2017)              | $\gamma_d = -0.5948 W_n + 24.853$        | 0.89| 0.7921 | 0.34   | Clayey or silty soil with low to high plasticity |
| Current Study (2019)              | $\rho_d = -0.0204 W_n + 2.1016$          | 0.74| 0.5476 | 0.084  | CH, CL, MH and ML                 |

3.5 Relationship between compression index and consistency properties

The correlation between compression index and consistency properties ($LL$ and $PI$) were investigated using the total data of 75 points using linear relationship. There are no good relationships found between $C_c$ and $LL$ and $PI$ as shown in Figures 5 and 6 with $R$ equal to 0.46 and 0.44 and $RMSE$ equal to 0.0318 and 0.0648 respectively. Table 5 shows that the mentioned relations are also reported by many previous authors such as Akayuli & Ofosu (2013) [3], and Dway & Thant (2014) [13]. The latter correlations are similar to the obtained correlations in this study; however, the results of the mentioned previous studies are higher than the current study developed relationships. Regardless clay particles are
important for all conducted tests; the used sampling methods are differing. The weak relationships may result from the disturbance of the disturbed samples for consistency properties determination, while the Cc and Cr samples are undisturbed and have almost the natural properties.

**Figure 5.** Compression index relationship with liquid limit.

**Figure 6.** Compression index relationship with plasticity index.

**Table 5.** Compared empirical equations for current study and the ones obtained from related literature among some of the geotechnical properties of soils.

| Reference               | Empirical Models            | R    | $R^2$ | RMSE  | Type of Soil         |
|-------------------------|-----------------------------|------|-------|-------|----------------------|
| Akayuli & Ofosu (2013)  | $C_c = 0.004 \text{ LL} - 0.03$ | 0.88 | 0.7744| 0.2116| Weathered Birimian Phyllites |
| Dway & Thant (2014)     | $C_c = 0.01 \text{ PI} + 0.01$ | 0.76 | 0.5776| -     | Clayey soils         |
| Current Study (2019)    | $C_c = -0.0022 \text{ LL} + 0.2795$ | 0.46 | 0.2116| 0.0318| CH, CL, MH and ML    |
|                         | $C_c = -0.0049 \text{ PI} + 0.2882$ | 0.44 | 0.1936| 0.0648|                      |
3.6 Relationship between compression index and initial void ratio

A total data of 81 points of the various selected locations for current study were considered. Linear regression model was developed to predict $C_c$ as a function of $e_o$ as shown in Figure 7. It can be seen that the initial void ratio increase caused an increase in the compression index. So, a good relationship was found between those two parameters as the values of $R$ and RMSE for the relationship are equal to 0.65 and 0.0335 respectively. Similar results are reported by Dway and Thant (2014) and Rashed et al. (2017) as shown in Table 6. The obtained relationship shows that the predicted compression index by simple linear regression involving initial void ratio can be used to evaluate the real compression index for clayey soil sample. Logically, compression index is directly dependent on the available voids in the natural clayey soil samples. When the void ratio increases, the compression index will also increase, however, it is not totally linear relation as many other factors can affect the compressibility process such as the natural voids distribution, voids shapes, solid particles shapes, percent of impurities, etc.

![Figure 7. Compression index relationship with initial void ratio.](image)

### Table 6. Compared empirical equations for current study and the ones obtained from related literature among some of the geotechnical properties of soils.

| Reference                      | Empirical Models         | R   | $R^2$  | RMSE  | Type of Soil                        |
|--------------------------------|--------------------------|-----|--------|-------|-------------------------------------|
| Rashed et al. (2017)           | $C_c = 0.72 e_o - 0.21$  | 0.66| 0.4356 | 0.028 | Clayey or silty soil with low to high plasticity |
| Dway and Thant (2014)          | $C_c = 0.2 e_o + 0.21$   | 0.56| 0.3136 | -     | Clayey soils                        |
| Current Study (2019)           | $C_c = 0.2494 e_o + 0.0045$ | 0.65| 0.4225 | 0.0335 | CH,CL, MH and ML                    |

3.7 Relationships between unconfined compressive strength and dry density

This relationship was carried out for the total obtained data of 166 points of the three selected locations in Sulaimani city as shown in Figure 8. Single linear relationship was conducted between unconfined compressive strength and dry density. A little correlation was found according to the values of $R$ and RMSE that equal to 0.56 and 108.66 respectively. Figure 8 shows in general that with the increasing of dry density, UCS value increases. As the used soil samples are fine-grained soils, and the dry density correlated with UCS, it is clear from the obtained relationship that a portion of water is required to add
some saturation among the soil particles. This may enhance the cohesion and show more strength capability and the relation is not totally linear.

\[ y = 580.36x - 720.16 \]
\[ R^2 = 0.56, \ RMSE = 108.66 \]
\[ \text{Data No.} = 166 \]

**Figure 8.** Unconfined compressive strength relationship with dry density.

### 3.8 Relationships between unconfined compressive strength with initial void ratio

The correlation between UCS and \( e_0 \) using the total data of 81 points of the three selected locations in Sulaimani city in the form of single linear equation as presented in Figure 9. There is a relationship between UCS and \( e_0 \), which noticed from the achieved values of \( R \) and \( \text{RMSE} \), 0.54 and 119.13 respectively. From Figure 9, it is clear that with the void ratio values increase, UCS decreases. In geotechnical engineering, initial void ratio is inversely related to strength of soils because of the high void spaces in soil means lower dry density. It affects reducing bearing capacity of structures foundation and slope stability. Table 7 shows that similar results are reported by Shaikh et al. (2014) and Rashed et al. (2017), however, they obtained higher \( R \) values compare with the obtained \( R \) value of the correlation of current study. With the availability of significant void ratio, the soil state can be weak as those voids can be occupied either by water or air. Solid particles decrease means less reaction agents to any action, and importantly compression.
Figure 9. Unconfined compressive strength relationship with initial void ratio.

Table 7. Compared empirical equations for current study and the ones obtained from related literature among some of the geotechnical properties of soils.

| Reference                  | Empirical Models          | R    | R²    | RMSE | Type of Soil                                      |
|----------------------------|---------------------------|------|-------|------|---------------------------------------------------|
| Rashed et al. (2017)       | Su = - 798.5 e₀ + 629.1   | 0.95 | 0.9025| 14.6 | Clayey or silty soil with low to high plasticity  |
| Shaikh et al. (2014)       | S₀ = - 23.62 e₀ + 52.62   | 0.85 | 0.7225| -    | Cohesive soils                                    |
| Current Study (2019)       | UCS = - 577.76 e₀ + 677.88| 0.54 | 0.2916| 119.13| CH,CL, MH and ML                                  |

3.9 Multiple regression analysis

A fair multiple variable empirical equation for predicting compression index as a function of index properties (LL and e₀) was obtained. This is done from the total data of 79 points of the three selected locations to collect natural soils samples in Sulaimani city based on the obtained values of R and RMSE, which were 0.41 and 0.0632 respectively. The obtained multiple empirical equation is presented below, Equation 1. Liquid limit is one of the properties which facilitate assessment of engineering behaviour of a soil. Liquid limit can be determined relatively quickly and easily and it has bearing on important aspects of engineering behaviour of soil such as strength or load bearing capacity. Hence, Liquid limit of a soil can thus be used for predicting its engineering properties, which positively obtained in the relationship of Equation 1.

\[
C_c = 0.159 - 0.0021 \text{ LL} + 0.1696 e_0 \tag{1}
\]

4. Conclusions

Based on the statistical analysis on the obtained test results, the following conclusions were drawn:

1. Based on Root Mean Square Error (RMSE) and correlation coefficients (R and R²) values, the best relationships were observed between plasticity index as a function of liquid limit.
2. Initial void ratio has a good relationship with ρ_d and ρ_n with W_n, in the form of single linear equations as compared to e₀ and W_n and based on the values of R, R² and RMSE.
3. Weakest correlation coefficients were achieved for $C_c$ as a function of LL, PI and $e_o$ in the form of single linear relationships, based on the values of $R$, $R^2$ and RMSE.

4. Fair relationship to predict the recompression index as a function of LL and $e_o$ was proposed using multiple regression analysis with $R$ and RMSE values equal to 0.41 and 0.0632 respectively.

5. There were fair single empirical equations obtained for the estimation of unconfined compressive strength using soil parameters such as $\rho_d$ and $W_n$ with respect to values of $R$, $R^2$ and RMSE, while, those results are better than the relation between UCS and $e_o$.

### List of Symbols

| Symbols | Description |
|---------|-------------|
| ASTM   | American Society for Testing and Materials |
| $C_c$   | Compression Index |
| LL      | Liquid Limit |
| PL      | Plastic Limit |
| PI      | Plasticity Index |
| $R$     | Correlation Coefficient |
| $R^2$   | Correlation Coefficient |
| RMSE    | Root Mean Square Error |
| $W_n$   | Natural Water Content |
| $\rho_d$| Dry Density |
| $e_o$   | Initial Void Ratio |
| UCS     | Unconfined Compressive Strength |

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