Prediction of undrained shear strength and correlation in between soil parameters

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ABSTRACT: Correlation of soil parameters has undeniable benefit in the determination of engineering properties of soil to solve problems in geotechnical Engineering area. The tests were conducted within geotechnical laboratory. These tested soil parameters, used in the correlation analysis are unconfined compressive strength, bulk unit weight and dry unit weight. The aim of this study is proposing a relationship in between the strength parameter with some of the index properties of soils using statistical regression analysis. The linear regression analyses have been done for prediction of unconfined compressive strength (q_u) from bulk and dry unit weight as model-1 and model-2 respectively. And dry unit weight was predicted from bulk unit weight as model-3. Model-4 represents the multiple linear regression analysis to predict q_u. The health of developed models is measured by coefficient of determination (R²) values. Though, model-1, model-2, model-3 and model-4 have R – squared values of 0.9112, 0.9333, 0.9109 and 0.9452 respectively. Therefore, they are correlated strongly and positively. The prediction of unconfined compressive strength of these soils correlated in linear regression, are fairly determined with Model-2 compared with model-1 and model-4 (MLR).

Key words: Regression analysis, unconfined compressive strength, unit weight

1. Introduction

The undrained shear strengths are determined in the laboratory using unconfined compressive strength apparatus. The undisturbed soil specimens were prepared and ready for tests. The results obtained from this test are unconfined compressive strength (q_u). If it is so, these samples are tested rapidly and it is a special case of the Unconsolidated undrained test in which cell pressure is zero. The unconfined compressive strength (q_u) is widely used for stability analysis of soil foundations under undrained conditions. This is primarily because the mean value of q u/2 accurately describes the undrained shear strength on the failure surface in a particular area, and additionally, the q u-value testing procedure is straightforward and inexpensive. The standard size specimen, 38mm in diameter and 76mm in height, is typically used in this study for unconfined compression tests [1]. Mechanical properties of clayey soils, particularly shear strength, are critical in engineering practise. One of the most important mechanical properties of soil, the undrained shear strength cu, was determined from unconfined
and confined tests under undrained conditions [2]. Another very important soil properties investigated under soil exploration through laboratory tests are bulk unit weight and dry unit weight. The main purposes of testing unit weights are to compute the in-situ bulk and dry density of soils. Empirical correlations are widely used in geotechnical engineering practice as a tool to estimate the engineering properties of soils.

2. METHODOLOGY

2.1. Sampling and Testing

The soil samples were collected from Kemise town, which is located in Amhara region, Northern part of Ethiopia at latitude of 10°43′N and longitude of 39°52′E with elevation of 1450m above mean sea level. Soil samples were acquired from different places in the town. The soil samples collected from this area were prepared for correlating in between some of soil parameters with and unconfined compressive strength. The total numbers of soil samples used for this analysis were twelve. Phases I and II soil samples were subjected to an unconfined compressive test. The results included a stress-strain diagram. The stress-strain diagram was corrected for the initial concave portion of the curve, which is believed to be caused by sample preparation, irregular loading surfaces, and seating loads. The initial tangent modulus was determined by calculating the slope of the tangent to the initial straight segment of the corrected curve drawn through the origin. Finally, the conventional result of a standard UC test is noted as the failure strength. The sample preparation method, such as static versus impact compaction, had an effect on the stress-strain behaviour, and the corresponding data were considered and analysed separately [3]. The soils are classified in to silt, clay and silty sand according to Unified Soil Classification system. The soil properties tested in the geotechnical laboratory and used for this analysis are in-situ bulk unit weight, dry unit weight and unconfined compressive strength values. The methodologies followed under this study were presented in chart 1 below.

Stability analysis of a rock slope requires determination of the rock mass's cohesion (c) and angle of internal friction (φ). Typically, these parameters are estimated without extensive field testing. Su is the shear strength of an undrained soil when sheared at constant volume. A critical state is a state of stress in a soil that occurs when continuous shearing occurs at a constant shear stress to normal effective stress ratio and a constant volume. At the liquid limit, the undrained shear strength of a soil can be estimated to be approximately 1.7 kN/m². As a result, the present work determined both the liquid and plastic limits using a single consistent method, namely the Swedish fall cone method. Composition of the soil: mineralogy, grain size and distribution, particle shape, pore fluid, and so on. Whether loose, dense, or overconsolidated in its initial state. Particle structure refers to the arrangement of particles, whether densely packed or randomly distributed. Conditions of loading: effective stress path (drained and undrained), and type of loading. The bulk density of the soil, its moisture content, texture, organic matter, and management all affect its resistance to metal penetrometers. The final two variables have a long-term but unknown effect on the soil strength of cultivated soil. Predicting the normalised, undrained shear strength of saturated fine-grained soils using plasticity-value correlations... because they quantify the interaction between the solid and liquid phases in soils in a straightforward manner, allowing for the classification of soils with similar mechanical properties.
3. DATA ANALYSIS AND DISCUSSION

According to Unified Soil Classification system, the Soil types found in the study area are clay, silt and silty sand. Most of the soil samples are collected from 1.5m depth but three of them are from 1.6m, 1.7m and 1.9m having similar soil properties with the other samples. The results obtained from the laboratory test are unconfined compressive strength, bulk and dry unit weight. These values are tabulated in Table 1 below.

| Test Pit Location          | Bulk unit weight (kN/m³) | Dry unit weight (kN/m³) | Unconfined Compression Strength (kN/m²) |
|----------------------------|--------------------------|-------------------------|----------------------------------------|
| Zone Administration        | 14.6                     | 10.59                   | 114                                    |
| Gelma Abageda              | 16                       | 13.14                   | 260                                    |
| Kune                       | 18                       | 15.44                   | 400                                    |
| Green Area                 | 20.2                     | 16.32                   | 494                                    |
| Fewoz Factory              | 19.2                     | 15.05                   | 390                                    |
| 02 Elementary School       | 19.5                     | 15.10                   | 342                                    |
| Amerach                    | 16                       | 11.56                   | 120                                    |
| Mickael Church             | 15.8                     | 11.80                   | 174                                    |
| Segno Gebeya               | 13.25                    | 10.35                   | 72                                     |
| High school                | 19.7                     | 15.44                   | 372                                    |
| Preparatory school         | 17.4                     | 13.78                   | 248                                    |
| Around TVET                | 14.35                    | 11.72                   | 140                                    |

Table 1: Presentation of laboratory test results.

Unit weight ($\gamma_b$) is the ratio of the total weight ($w$) to the total volume of the soil aggregate [9]:

$$\gamma_b = \frac{W}{V}$$  \hspace{1cm} (1)

The dry unit weight $\gamma_d$ is defined as the ratio of the weight of soil solids ($W_s$) to the total volume ($V$) [9]:

$$\gamma_d = \frac{W_s}{V}$$  \hspace{1cm} (2)

3.1. Regression Analysis

Numerous studies have been conducted in recent years to predict the physical and engineering properties of various soils, which is generally beneficial for field engineers in terms of preliminary design, proper estimation, and higher quality control planning. Regression analysis is a statistical technique for examining, quantifying, and interpreting simple relationships between variables. The purpose of this article is to attempt to develop a mathematical
relationship between two variables through the fitting of a linear equation to observed test data. Prior to fitting a linear model to observed test data, it is critical to ascertain whether any relationship exists between the variables of interest. The coefficient of determination (R²) is a measure of the relationship's strength. It is the ratio of the sum of squares in the regression to the sum of squares in the total. R² is a value between 0 and 1. The closer the value is to 1, the more accurate the equation [4]. The true test of the quality of the resulting regression relationship is its ability to predict the dependent variable when no independent variables were used to estimate the regression coefficients [5]. The purpose of regression analysis is to determine the relationship between the values of Y and their corresponding values of X. The dependent variable or response is Y, whose value must be predicted, and the independent or regressor variable is X, which is used to predict the dependent variable's value [6].

3.1.1 Correlation
Correlation describes the degree of relationship between two variables. Product moment correlation efficient (r) can be measured to identify the correlation among different important geotechnical parameters. The equation is [5]:

\[ r = \frac{S_{xy}}{\sqrt{S_{xx}S_{yy}}} \]  

(3)

Where: 
\[ S_{xx} = (\Sigma x^2) - n \bar{x}^2 \]  
\[ S_{yy} = (\Sigma y^2) - n \bar{y}^2 \]  
\[ S_{xy} = (\Sigma xy) - n \bar{x} \bar{y} \]

To create valid prediction models, relationships between unconfined compression strength and soil index properties were established. These index properties, such as bulk unit weight and dry unit weight, can be determined more easily and quickly. With this in mind, relationships between unconfined compression strength and the previously mentioned index properties of soil were established. The health of the drawn relationships was determined using the R² value, which is a more accurate indicator of the health of any correlation [7]. The simple linear regression developed models were determined by using x1stat2015 statistical analysis. The results are presented in Figure 1 to Figure 7. For model 1 and model 2 the linear regression has been performed by considering unconfined compressive strength as dependent variable and bulk and dry unit weight as independent variable. And for model 3 consider dry unit weight as dependent and bulk unit weight as independent variable [11].

3.2. Simple Linear Regression

3.2.1. Relationship between unconfined compressive strength and bulk unit weight
The correlation has been developed in between unconfined compressive strength (\( q_u \)) and bulk unit weight (\( \gamma_b \)) with scatter plot.

![Fig 2: Relationship between unconfined compressive strength and bulk unit weight (Model - 1with correlation coefficient (R) of 0.95)](image-url)
3.2.2. Relationship between unconfined compressive strength and dry unit weight

![Graph showing the relationship between unconfined compressive strength and dry unit weight. The correlation coefficient (R) is 0.97.]

**Fig 3:** Relationship between unconfined compressive strength and dry unit weight (Model -21 with correlation coefficient (R) of 0.97)

3.2.3 Relationship between dry unit weight and bulk unit weight

![Graph showing the relationship between dry unit weight and bulk unit weight. The correlation coefficient (R) is 0.95.]

**Fig 4:** Relationship between dry unit weight and bulk unit weight (Model -31 with correlation coefficient (R) of 0.95)

![Comparison between predicted and experimental results (q_u) for Model-1. The percentage error ranges from +19.3 to -17.9%.]

**Fig 5:** Comparison between predicted and experimental results (q_u) for Model-1
3.3. Multi-Linear Regressions

The most usually utilized correlation statistical analysis in the prediction of one soil parameter as dependent variable from other two or more soil parameters as independent variable is multi-linear regression analysis (MLR) [8]. Here, the soil strength is considered to be predicted, and bulk unit weight and dry unit weight are taken as independent variable. From the result obtained from MLR analysis, we can easily visualize the comparison in between predicted and experimental values shown in Fig. 7 below.

All the soil properties tests conducted under this study were according to ASTM standards. The prediction of strength (kN/m²) and dry unit weight are determined quickly from the developed
model equations.[9] For linear regression the predicted values for unconfined compressive strength are determined using Eq. (4) and Eq. (5), but Eq. (6) is used to predict the dry unit weight ($\gamma_d$).

The percentage error for model-1 varies from 6.5 to 19.3 % and -10.1 to -17.9%. For Model-2, the errors vary from 2.7 to 15.8% and -8 to -16.7%. And for model-3 the percentage error is varying from 0.6 to 7.9 and -1.3 to -8.1%. The comparison of observed and predicted values are represented in these three modeled equations and presented in Fig.4, Fig.7 and Fig.8.

$$q_u = 53.9299\gamma_b - 652.9751$$  \hspace{1cm} (4)

$$q_u = 60.6602\gamma_d - 546.4603$$  \hspace{1cm} (5)

$$\gamma_d = 0.8587\gamma_b - 1.2406$$  \hspace{1cm} (6)

Here, the developed equation for multiple linear regressions by using XLStat2015 statistical analysis software is listed below. Therefore, the errors within the developed models-4 for multiple linear regression analysis, is varies from +0.24 to +12.02% and -2.68 to -16.31%.

$$q_u = 20.6309\gamma_b + 38.7767\gamma_d - 604.8687$$  \hspace{1cm} (7)

The validations of the models are evaluated according to the results obtained from the equations and errors obtained from the variation in between observed (experimental) and predicted values.[10] For this correlation the developed models which gives least error for prediction of unconfined compressive strength ($q_u$) is Eq. (2). The prediction models-1, model-2 and model-3 have the coefficient of correlation (r) of 0.9546, 0.9661 and 0.9544.

4. Conclusion

The values of bulk unit weight and dry unit weight of soils are ranges from 14.35 to 20.2kN/m$^3$ and 10.35 to 16.32kN/m$^3$ respectively. The coefficient of determination ($R^2$) obtained from developed models are greater than 0.9. This shows that, the models have a strong relationship and correlated positively. The empirical relationship developed linearly for dependent variable ($q_u$) as a function of bulk and dry unit weight with errors of predicted values verified with experimental values are varies from +19.3 to -17.9%. Model-1 and model-2 have coefficient of determination ($R^2$) value of 0.9112 and 0.9333 respectively. For the model-3 the errors vary from +7.9 to -8.1% with $R^2$ valueof 0.9109. From the equations developed under this linear regression statistical analysis good prediction of unconfined compressive strength is obtained from Eq. (2). In case of multiple linear regression analysis, the percentage errors in the prediction of unconfined compressive strength value verified with the experimental value is within the ranges of +12.02 to -16.31, and with the coefficient of determination ($R^2$) value of 0.9452.

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