Estimation of compaction characteristics of soils using Atterberg limits

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Abstract. Soils are mostly used construction materials. Naturally occurring soils when are used as a construction material their engineering properties need to be determined and they mostly need to be compacted for the improvement of their engineering properties. The determination of these engineering properties becomes a vital process for the successful design of any geotechnical structure. Testing the properties of compaction, optimum water content (OWC), and maximum dry density (MDD), requires high amount of work and consumes a large amount of time in the laboratory. In this paper, an attempt to develop predictive models between liquid limit, and compaction test parameters is made. To achieve this purpose, 8 samples of North Nicosia Kythrea group soils in North Cyprus were subjected to Atterberg limits and compaction laboratory tests. The soils were tested using standard Proctor compaction tests. Stepwise multiple linear regression analyses were carried out on the experimental data and predictive models were developed in terms of liquid limit (LL). Their compaction results were used to validate the proposed models. According to the findings, the R² values of the models suggested are over 75% and the error variation between the predicted and experimental compaction characteristics values was found to be below ±1. It has been shown that these models will be useful for a preliminary design of earthwork projects which involves Nicosia soils in Cyprus.

1. Introduction

Compaction of soil is the artificial improvement of the mechanical properties of the soil. The soil is densified by the removal of pore spaces and the particles are rearranged. Since the soil particles are closely packed together during this process, the void ratio is reduced thus making it difficult for water or other fluid to flow through the soil. The type of soil and the grain sizes of the soil play a significant role in the compaction process as a reduction in the pore spaces within the soil increases the bulk density. Soils with higher percentages of clay and silt have a lower density than coarse-grained soils since they naturally have more pore spaces. The compaction curve obtained in the laboratory tests or field compaction represents the typical moisture-density curve which explains the compaction characteristics theory.
Soil compaction investigations started during the 20th century due to the automobile invention along with the paved roads. Since then, many efficient and cost effective methods came up; different compaction methods were used for different type of soils. Proctor, a pioneer in soil compaction established this fact in 1933. It was also established that the moisture content affected the degree of compaction for any compaction method used. Soil compaction only affects the volume of air and has no effect on the water content or the size of the solids. Air ratio in the void ratio is removed completely effective during the compaction process, but in practice, it is not. The diminution of pore spaces lead to a rearrangement of the soil particles making them more intense.

The importance of this property is the subject of a good estimate in the construction of earth dams and other projects to fill the ground. And is a vital process and is employed through construction projects such as: highways, and pavements, railways etc. The main goals of soil compaction are: reduction in permeability of the compacted soil, increase in the shear strength of the soil, and to reduce the subsequent settlement of the soil mass under working loads.

In the laboratory, soil compaction is conducted using Procter compaction device test. And in the field are compaction of soil by different equipment with different compression energy. The characteristics of the compaction test of an optimum water content (OWC), and maximum density (ρdmax), which is used to determine the shear strength and bearing capacity of the natural soil. Proctor test which is a laborious and time consuming method. Therefore, there is a need of correlating the compaction characteristics with consistency limits as they are easy to determine. Plastic limit bears a good correlation with OMC than any other consistency limits.

2. Previous work
Alluvial soils and overconsolidated (OC) clays constitute the most soils of Cyprus. Alluvial soils Holocene to recent in age containing gravel, sand, silt and clay are widespread in the Mesaoria plain, especially at Nicosia, Famagusta, and Limassol and at the east and west coast. They comprise loose - medium dense gravel and sand, and soft - firm silt and clays. The alluviums mostly contain low amounts of clay size material. The alluviums also contain high amount of montmorillonite. These alluviums show relatively high apparent strength in their dry state. However, with saturation their strength decreases. These clayey soils have low to medium swelling potential. The silting of the ancient harbours created very soft soils especially at the east and west coastline of the Mesaoria plain. Old stream beds filled with alluviums are found at the coastline and at the interior [1].

The Kythrea group mostly contains turbiditic rocks. It consists, from bottom to top, gravel, conglomerates, greywacke, marl, and mostly abyssal turbidites with a shallow environmental chalk, marl, limestone, and gypsum finishing. Alternation of sandstone-siltstone-marl-claystone is widespread within it. The group is only observed in North Cyprus and has a complete coverage of the northern and southern slopes of Kyrenia range from east to west. It consists of Mia Milia, Skylloura, Lapatza (Pre-evaporitic) and Lapatza (evaporitic) formations. The clayey units of several m thickness to tens of meters thickness in the different formations of the group exhibit different swelling potential. Pre-evaporitic and Skylloura formations exhibit high to very high, Mia Milia intermediate to high swelling potential [2].

Many researchers have made attempts to predict compaction test parameters from several factors such as soil classification data, index properties, and grain size distribution. Gurtug and Sridharan studied the compaction behaviour and prediction of its characteristics of three cohesive soils taken from the Turkish Republic of Northern Cyprus and other two clayey minerals based on four compaction energy namely, standard Proctor, modified Proctor, Reduced standard Proctor and Reduced modified Proctor to develop relationship between maximum dry unit weight and optimum water content and plastic limit with particular reference to the compaction energy [3].

They proposed the Equations 1 and 2 below.

\[ OMC = 0.92PL \]  \hspace{1cm} (1)
\[ MDD = 21.61 - 0.26 OMC \]  \hspace{1cm} (2)
Recently, Sridharan and Nagaraj conducted a study of five pairs of soils with nearly the same liquid limit but different plasticity index among the pair and made an attempt to predict optimum moisture content and maximum dry density from plastic limit of the soils. They developed with the following Equations 3 and 4 [4]:

\[
\text{OMC} = 0.92\text{PL} \\
\text{MDD} = 21.46 - 0.23\text{PL}
\]

Sivrikaya et al correlated maximum dry unit weight and optimum water content of 130 fine-grained soils using standard Proctor compaction test with a plastic limit. They developed the following Equations 5 and 6 [5]:

\[
\text{OMC} = 0.94\text{PL} \\
\text{MDD} = 21.97 - 0.27\ \text{OMC}
\]

Sivrikaya’s work as summarized by Sivrikaya and Soycan showed the following correlations using standard Proctor data with index properties of fine-grained soils [6]:

\[
\text{OMC} = 0.92\text{PL} \\
\text{MDD} = 20.90 - 0.21\ \text{PL} \\
\text{MDD} = 21.84 - 0.27\ \text{OMC}
\]

Most recently, Jyothirmayi et al used nine types of fine-grained soils like black cotton soil, red clay, china clay, marine clay, silty clay etc. which were taken from different parts of Telengana and Andhra Pradeshin, India to propose a correlation Equation 10 using plastic limit (PL) in order to determine the compaction characteristics namely, optimum water content (OMC) of these soils [7].

\[
\text{OMC}=12.001e^{0.0181\text{PL}}
\]

3. Methodology
The soil samples were obtained from depths of between 1 to 10 metres from the North Nicosia soils. In total, 8 samples were collected and they were subjected to particle size analysis test, Atterberg limit tests, and compaction test. The tests were performed in accordance to American Society for Testing and Materials (ASTM) standard specifications to determine the physical and compaction properties of the soils. Mechanical sieve analyses were performed on each soil sample according to ASTM D6913-04 to determine the grain size distribution. Sieve analysis was conducted using U.S. Sieve sizes; #40, #60, #100, and #200. A sample of the soil was dried in the oven at a temperature of 105°C - 110°C for overnight. The whole specimen sample was allowed to cool and the test was done [8].

The Atterberg limits (plastic and liquid limit) were determined on all the 8 samples using distilled water as the wetting agent. The liquid limit test was done on the soil fraction passing through the U.S. No. 40 (0.425mm) sieve in accordance with ASTM D4318-10. This method involves finding the moisture content at which the groove cut in the wet sample with a standard grooving tool closes. In accordance with ASTM D4318-10 procedure, the plastic limits were determined on the soil fraction passing the U.S. No. 40 sieve. This method involves finding the moisture content at which the wet soil just begins to crumble or break apart when rolled by hand, into threads of 3mm diameter [9].

Standard Proctor tests were conducted manually on the soil samples. Standard Proctor test was performed on 8 soil samples. This was used to determine the maximum dry unit weight and optimum moisture content of the soil. Compaction of the soil was done using the mechanical energy obtained from an impacting hammer. The mechanical energy is a function of hammer weight, height of the hammer drop, the number of soil layers, and number of blows per layer. The parameters of the standard Proctor tests in accordance to ASTM D 698-12 [10].
Stepwise multiple linear regression analyses were carried out on the experimental data and predictive models were developed in terms of liquid limit (LL). Their compaction results were used to validate the proposed models.

4. Results and discussions


The test results of sand, silt, clay contents, Atterberg limits and compaction characteristics are given in the Table 1.

Table 1. Laboratory test results for regression analysis of standard Proctor compaction test.

| TEST NO | SAND  | SILT  | CLAY | LL   | PL   | PI    | OMC%  | MDD (KN/m³) | Soil Type |
|---------|-------|-------|------|------|------|-------|-------|-------------|-----------|
| 92      | 48.02 | 14.98 | 37   | 48.8 | 18.5 | 30.3  | 17.5  | 17.26       | CL        |
| 93      | 30    | 16    | 54   | 60   | 22.6 | 37.4  | 19    | 16.42       | CH        |
| 94      | 17.73 | 20.27 | 62   | 76.8 | 25.7 | 51.1  | 22.5  | 15.76       | CH        |
| 95      | 54.32 | 12.68 | 33   | 48.5 | 19.5 | 29    | 18    | 17.76       | CL        |
| 97      | 67.75 | 7.25  | 25   | 43.2 | 20.3 | 22.9  | 15.5  | 19.25       | OL        |
| 98      | 21.35 | 19.65 | 59   | 63   | 21.7 | 41.3  | 19    | 16.36       | CH        |
| 99      | 21.35 | 28.65 | 50   | 49.2 | 18   | 31.2  | 18    | 17.82       | CL        |
| 100     | 22.55 | 19.45 | 58   | 65.7 | 23.9 | 41.8  | 21    | 15.63       | CH        |

Graphs are plotted to correlate optimum moisture content with liquid limit and maximum dry density with optimum moisture content as shown in Figure 1 and Figure 2 respectively.

\[ y = 0.1809x + 8.5179 \]
\[ R^2 = 0.9108 \]

Figure 1. Scatter plot and best-fit curve of liquid limit and OMC.
The equation obtained by the relation is,

\[
OMC = 0.1809 \times LL + 8.5179 \quad (11)
\]

The equation obtained between the OMC with MDD is,

\[
MDD = 26.811 - 0.5198 \times OMC \quad (12)
\]

The measured and predicted OMC and MDD are shown in Table 2.

**Table 2.** Validation of standard Proctor compaction parameters models.

| Optimum Water Content OMC% | Maximum Dry Unit Weight MDD(KN/M3) |
|----------------------------|-----------------------------------|
| Measured                   | Predicted | Abs. Error | Measured | Predicted | Abs. Error |
| 17.5                       | 17.3458   | 0.15418    | 17.26    | 17.7145   | 0.4545     |
| 19                         | 19.3719   | 0.3719     | 16.42    | 16.9348   | 0.5148     |
| 22.5                       | 22.411    | -0.089     | 15.76    | 15.1155   | 0.6445     |
| 18                         | 17.2916   | 0.70845    | 17.76    | 17.4546   | 0.3054     |
| 15.5                       | 16.3328   | 0.83278    | 19.25    | 18.7541   | 0.4959     |
| 19                         | 19.9146   | 0.9146     | 16.36    | 16.9348   | 0.5748     |
| 18                         | 17.4182   | 0.58182    | 17.82    | 17.4546   | 0.3654     |
| 21                         | 20.403    | 0.59697    | 15.63    | 15.8952   | 0.2652     |

5. **Conclusion**

Based on the analysis of laboratory data, it is obtained that the correlation between optimum moisture content with liquid limit and maximum dry density with optimum moisture content for fine grained soils. The correlations based on the investigation in this study are given below:

\[
OMC = 0.1809 \times LL + 8.5179 \quad R^2 = 0.911
\]

\[
MDD = 26.811 - 0.5198 \times OMC \quad R^2 = 0.833
\]
The results showed that these proposed models had $R^2$ values greater than 75% and the variation of error between the experimental and the predicted values of compaction characteristics was less than ±1.

It has been shown that these models will be useful for a preliminary design of earthwork projects which involves Nicosia soils in Cyprus.

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