PREDICTING BEARING STRENGTH CHARACTERISTICS FROM SOIL INDEX PROPERTIES

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ABSTRACT

The bearing strength of foundation soil is a major design criteria for civil engineering structures. This study aims to estimate the bearing strength, namely California Bearing Ratio (CBR) and ultimate bearing capacity, from simple and easy measured soil index properties. Comprehensive literature concerning bearing strength characteristics and their prediction equations proposed by previous researchers were reviewed. Laboratory investigation was conducted on two different soils compacted at various placement conditions (i.e. moisture content and dry density) and tested using CBR and triaxial tests. Based on test results, linear relationships of unsoaked CBR and ultimate bearing capacity with the consistency factor which is formed by combining placement conditions and soil intrinsic parameters had been developed. To verify the validity of the developed linear relationship, data reported by some previous researchers were analyzed. The results revealed that the proposed relationships could predict unsoaked CBR and ultimate bearing capacity precisely with a coefficient of linearity (R2) more than 0.9. This result confirms that the proposed equations are reliable and useful to predict bearing strength parameters for different soils.

Key words: Bearing Capacity, CBR, Consistency Factor, Linear Relationship

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1. INTRODUCTION

Civil engineering works in highways, buildings, dams and other structures have strong relationship with soil. These structures need a strong and stable layer of foundation soil to build on. Therefore, soil must be able to carry imposed loads from any structure placed upon it without shear failure or destructive unallowable settlements [1]. Furthermore, any weakness or failure in soil may lead to severe damage or collapse of structure. Thus, proper estimation of bearing strength of foundation soil is very essential for safety and performance of the structure.

In pavement design, the California Bearing Ratio (CBR) is a common test currently practiced to predict the bearing strength of subgrade soil. Due to its simplicity and relatively low cost, this method has been widely used across the world for flexible pavement design. Even though, highway engineers encounter some difficulties in obtaining representative CBR value for pavement design.

In geotechnical engineering, the bearing capacity of underlying soil plays a vital role in foundation design. The bearing capacity is governed by shear strength of the soil. Terzaghi [2] was the first researcher to propose a comprehensive theory for measuring the ultimate bearing capacity of shallow foundations. After Terzaghi, many researchers such as Meyerhof [3], Hansen [4], Vesic [5], and others have offered theories for predicting the ultimate bearing capacity. However, the different bearing capacity formulae show wide degree of variability while estimating bearing capacity of different type of soils.

The purpose of this study is to establish correlations for unsoaked CBR and ultimate bearing capacity with simple and easy measured soil index properties. These correlations can be used in prediction of the bearing strength parameters for design and evaluation purposes.

2. LITERATURE REVIEW

The bearing strength of soil is quite important for stability and performance of any structure founded on it. Therefore, foundation soil must be capable to withstand the structural loads placed upon it without undergoing shear failure and consequent large settlements [6]. Rupture surfaces are formed in the soil mass upon exceeding a certain stress condition. The bearing strength of foundation soil is characterized by California Bearing Ratio (CBR) and bearing capacity.

2.1. California Bearing Ratio (CBR)

The California Bearing Ratio (CBR) test was first introduced by the California State Highway Department in the 1920’s. The US Army Corps of Engineers then adapted the method in the 1940’s for military airfields. After the Second World War, the CBR method was also used in the UK and its use spread to European countries [7], [8]. CBR is defined as the ratio of the resistance to penetration of a material to the penetration resistance of a standard crushed stone base material. The CBR test is essentially a measure of the bearing resistance of a soil at certain moisture and dry density conditions. It can be carried out both in laboratory and field and the method of measuring CBR is standardized in ASTM [9], [10].

The CBR has been known as an important parameter to characterize the bearing capacity of earth structures such as earth dams, road embankments, bridge abutments and pavements. The CBR is the most widely used strength parameter for fine-grained subgrade soils in flexible pavement design, while research into the use of the resilient
modulus in pavement design continues [11]. Several countries have developed or 
adopted pavement design methods based on the CBR value of the materials. The 
design of pavement thickness requires the strength of subgrade soil, subbase and base 
materials to be expressed in terms of CBR, so that stable and economical design 
achieved. The value of CBR is an indicator of the type of subgrade soil. If the CBR 
value of subgrade is high, it means that the subgrade is strong and as a result, the 
design of pavement thickness can be reduced. Conversely, if the subgrade soil has low 
CBR value it indicates that the thickness of pavement shall be increased in order to 
spread the traffic load over a greater area of the weak subgrade or alternatively, the 
subgrade soil shall be subjected to stabilization.

2.2. Soil Bearing Capacity

The soil bearing capacity is defined as the capacity of the underlying soil to support 
the loads applied to the ground without undergoing shear failure and without 
accompanying large settlements [6]. The theoretical maximum pressure which can be 
supported without failure is called ultimate bearing capacity (UBC). While the 
allowable bearing capacity (ABC) is the UBC divided by the factor of safety (FS). 
The established theory on ultimate bearing capacity is based on ideal condition of soil 
profiles. In reality, the soil profiles are not always homogenous and isotropic. 
Therefore, rational judgment and experiences are always necessary in adopting proper 
soil parameters to be used in calculations of ultimate bearing capacity. The pioneer to 
propose the early theory to evaluate bearing capacity of soil is Terzaghi [2]. The 
ultimate bearing capacity expressed by Terzaghi, using equilibrium analysis is shown 
below:

\[ q_u = C N_C + q N_q + 0.5 \gamma B N_f \] (1)

Where \( N_C, N_q, N_f \): are Terzaghi bearing capacity coefficients obtained from 
friction angle (\( \phi \)); \( C \): Cohesion of soil; \( q \): overburden pressure; \( \gamma \): density 
of soil; \( B \): width of foundation.

Failure due to bearing capacity occurs as the soil supporting the foundation fails in 
shear, which may involve either a general, local or punching shear failure mechanism 
[1]. The mechanism of bearing failure depends on the density of soil. Denser soil fails 
along a well defined slip plane, loose soil fails locally, and very loose soil exhibits 
punching shear failure. For these different failure types, different methods of analysis 
are used [1]. Estimation and prediction of the ultimate bearing capacity of a 
foundation is one of the most significant and complicated problems in geotechnical 
ingenengineering [1].

2.3. Previous Correlations

Over the years, many correlations have been developed for the bearing strength 
parameters for different type of soils. Most of the correlations were applied according 
to the particular circumstances of the soil such as soil type, water content, dry density 
and other soil properties.

Field CBR testing is a time-consuming operation requiring a skilled operator, 
and can be hazardous for the evaluation teams in hostile environments. Engineers 
always experience some difficulties in obtaining representative CBR values for 
design. On the other hand, the laboratory CBR test is not only laborious and time 
consuming, but, sometimes, the results are not accurate due to the sample disturbance 
and poor quality of the laboratory testing conditions. Therefore, the development of
prediction correlations might be useful and become a base for the judgment of the validity of the CBR values. Many correlations have been developed by various researchers for the prediction of CBR, including the dynamic cone penetrometer (DCP), undrained shear strength and Clegg impact hammer [12]-[14]. In addition, there have been several attempts to predict CBR values based on the soil index properties [15]-[17]. Some of the correlations are presented as follows:

Kleyn and Harden [12] established a relationship between the field CBR and the DCP as follows:

\[
\log \text{CBR} = 2.628 - 1.273 \log (\text{DCP}) \tag{1}
\]

A study was carried out to correlate the CBR and the unconfined compression strength \(\sigma_c\) (MPa) by Behera and Mishra [13] on fly ash-lime mixture at 7 and 28 day curing periods. The correlations proposed are written in equation (2) and (3) respectively:

\[
\text{CBR} = 108.8 \sigma_c + 14.14 \tag{2}
\]

\[
\text{CBR} = 56.45 \sigma_c + 39.12 \tag{3}
\]

Al-Amoudi et al [14] studied the efficacy of the Clegg impact hammer (CIH) for estimating the CBR value of compacted soils. They performed CBR and CIH tests for soils compacted with three different compactive efforts and different molding moisture contents (see Fig 1). They developed a general model to predict CBR values from CIV data.

\[
\text{CBR} = 0.1691 (\text{CIV})^{1.695} \tag{4}
\]

\[\text{Figure 1 CBR test results for the various compactive efforts (source [14])}\]

Agarwal and Ghanekar [15] tried to develop a correlation between the CBR and the liquid limit, plastic limit or plasticity index. However, they were not able to find any significant correlation among these parameters. Instead, they found an improved correlation when optimum moisture content (OMC) and liquid limit were included. Hence, they suggested a correlation that was only of sufficient accuracy for the preliminary identification of material. This correlation is:

\[
\text{CBR} = 2 - 16 \log(\text{OMC}) + 0.07 LL \tag{5}
\]
The National Cooperative Highway Research Program [16] had developed a correlation for soils contain 12% fines and exhibit some plasticity. The soil index properties chosen to correlate CBR are the percentage passing 0.075mm size sieve (w) and plasticity index (PI). The suggested equation by NCHRP is given below.

\[
CBR = \frac{75}{1 + 0.728(w \times PI)}
\]  

(6)

A correlation of CBR with plasticity and grading using the concept of suitably index was developed by de Graft-Johnson and Bhatia [17] on the Ghana lateritic soil. The soil samples were compacted to maximum dry density at optimum moisture content and soaked for 4 days according to the Ghana standard of compaction. In this case, the relationship between CBR and suitability index is shown as follows:

\[
CBR = 35 \times SI - 8
\]  

(7)

\[
CBR = \frac{A}{LL(\log PI)}
\]  

(8)

where: SI: Suitability Index value of de Graft-Johnson and Bhatia; A: Percentage passing 2.0 mm sieve size; LL: Liquid Limit; PI: Plasticity Index.

Black [18] and Black [19] proposed a correlation between the ultimate bearing capacity (qu) and the CBR of cohesive soil. Black suggested that the developed correlation depends on the type of soil and method of compaction (static or dynamic). The proposed correlation is:

\[
q_u(kPa) = 70 \times CBR
\]  

(9)

A correlation between CBR and Bearing Capacity was proposed by the Portland Cement Association (PCA) [20] as given in equation (10) below.

\[
q_u(psi) = 26.16 \times CBR^{0.664}
\]  

(10)

Attempts have been made to predict CBR using a single factor that combines placement parameter. Mohamed [21] introduced the placement condition factor (F) which combines two placement parameters, dry density (γd) and moisture content (w) and is defined as:

\[
F = \frac{γ_d}{w}
\]  

(11)

Mohamed [21] applied "F" to unsoaked CBR data of compacted cohesive soils from Sudan and found that "F" predicts very well the unsoaked CBR value. Zumrawi [22] modified the placement factor (F) to a new one called the initial state factor, Fi and is defined by:

\[
F = \frac{γ_d}{γ_w \times e \times w}
\]  

(12)

where γw: is density of water and e : is the void ratio. A linear relationship was found between "Fi" and unsoaked CBR for the same soil, the coefficients of which depends on plasticity index and clay content. It is noted that the two factors (F and Fi) considered only placement parameters, i.e, moisture content, dry density and void ratio. Therefore, this study aims to combine both the placement conditions and the soil intrinsic properties such as liquidity index in a factor and to investigate its relationship with CBR and ultimate bearing capacity values.
3. EXPERIMENTAL INVESTIGATION

To achieve the research objective, laboratory investigation was conducted on two different soils. Soil 1 is fine-grained soil and was obtained from Halfayah in Khartoum north whereas Soil 2 is coarse-grained soil and was obtained from Hatab in eastern Nile.

3.1. Specimen Preparation

Initially, the two soils were air dried and pulverized. The soil samples were subdivided and each sub-sample was mixed with distilled water to bring the sub-sample to the desired moisture content. Each soil was prepared by compacting at five different moisture contents and dry densities. All samples were manually compacted in CBR mould. Soil specimens of 38 mm diameter and 76 mm long and enclosed in thin cylindrical membranes were prepared for triaxial tests.

3.2. Testing Procedure

The tests program started with determination of the basic soil properties such as grain size analysis, Atterberg’s limits, compaction and specific gravity. Then, the compacted specimens at optimum moisture content and maximum dry density were tested using CBR and triaxial tests. The tests results of the two soils are presented in Table 1.

Table 1 The properties of the tested soils

<table>
<thead>
<tr>
<th>Test</th>
<th>Property</th>
<th>Soil 1</th>
<th>Soil 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sieve analysis</td>
<td>Gravel, %</td>
<td>23</td>
<td>67</td>
</tr>
<tr>
<td></td>
<td>Sand, %</td>
<td>14</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>Silt / Clay, %</td>
<td>63</td>
<td>18</td>
</tr>
<tr>
<td>Atterberg’s Limit</td>
<td>Liquid Limit, %</td>
<td>55</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>Plastic Limit, %</td>
<td>27</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>Plasticity Index, %</td>
<td>28</td>
<td>21</td>
</tr>
<tr>
<td>Compaction</td>
<td>Max. Dry Density, g/cm³</td>
<td>1.580</td>
<td>2.202</td>
</tr>
<tr>
<td></td>
<td>Optimum Moisture Content, %</td>
<td>27.7</td>
<td>8.7</td>
</tr>
<tr>
<td>Unsoaked CBR</td>
<td>CBR, %</td>
<td>19.0</td>
<td>37.0</td>
</tr>
<tr>
<td>Triaxial Compression</td>
<td>Cohesion, kN/m²</td>
<td>110</td>
<td>73.0</td>
</tr>
<tr>
<td></td>
<td>Angle of Internal Friction, °</td>
<td>4.5</td>
<td>23.5</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td></td>
<td>2.78</td>
<td>2.70</td>
</tr>
<tr>
<td>Unified Soil Classification System (USCS)</td>
<td>CH</td>
<td>GC</td>
<td></td>
</tr>
</tbody>
</table>

Five test specimens were prepared, for each soil, for the CBR and triaxial tests. The samples were prepared with different water contents and compacted into a standard CBR mould to different dry densities. To relate unsoaked CBR and ultimate bearing capacity results at the same water content and density a pair of identical samples were prepared. The first was subjected directly to the CBR penetration test as unsoaked CBR and the second was used for Triaxial test.

In the CBR test, the compacted sample subjected directly to penetration test to measure the unsoaked CBR. The CBR tests were performed in accordance to BS standard [23]. The penetration resistance load is then plotted against the penetration depth and correction is made for the load-penetration curve. Using the corrected value taken from the load-penetration curve for 2.54 mm and 5.08 mm penetration, the
bearing ratio is calculated by dividing the corrected load by the corresponding standard load, multiplied by 100.

The triaxial test performed in this study is undrained unconsolidated method. The prepared soil specimen subjected to an all round hydrostatic pressure (cell pressure), together with vertical compression load (deviator stress) acting through a piston. The strain dial gauge reading was taken and the corresponding proving ring reading was recorded. The experiment stopped when the soil failed or at 15% strain. The maximum compressive stress at failure and the corresponding strain and cell pressure were recorded. The stress results of the series of triaxial tests at increasing cell pressure were plotted on Mohr stress diagram. Then the shear strength parameters, namely friction angle ($\phi$) and cohesion (C) were determined. The ultimate bearing capacity was computed using Terzaghi equation (1).

The test results and the computed values of ultimate bearing capacity ($q_u$) and unsoaked CBR for the studied soils are presented in Table 2.

<table>
<thead>
<tr>
<th>Soil</th>
<th>Dry density (g/cm³)</th>
<th>Moisture content (%)</th>
<th>Unsoaked CBR (%)</th>
<th>$q_u$ (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil 1</td>
<td>1.505</td>
<td>24.0</td>
<td>17</td>
<td>1124</td>
</tr>
<tr>
<td></td>
<td>1.508</td>
<td>25.0</td>
<td>18</td>
<td>942</td>
</tr>
<tr>
<td></td>
<td>1.547</td>
<td>27.0</td>
<td>19</td>
<td>1073</td>
</tr>
<tr>
<td></td>
<td>1.520</td>
<td>30.0</td>
<td>7</td>
<td>348</td>
</tr>
<tr>
<td></td>
<td>1.480</td>
<td>31.0</td>
<td>6</td>
<td>300</td>
</tr>
<tr>
<td>Soil 2</td>
<td>2.052</td>
<td>6.0</td>
<td>28</td>
<td>1922</td>
</tr>
<tr>
<td></td>
<td>2.166</td>
<td>7.5</td>
<td>36</td>
<td>2588</td>
</tr>
<tr>
<td></td>
<td>2.202</td>
<td>8.7</td>
<td>37</td>
<td>2626</td>
</tr>
<tr>
<td></td>
<td>2.141</td>
<td>9.5</td>
<td>30</td>
<td>2129</td>
</tr>
<tr>
<td></td>
<td>2.059</td>
<td>10.5</td>
<td>27</td>
<td>1426</td>
</tr>
</tbody>
</table>

### 4. ANALYSIS AND RESULTS

The use of soil index properties to predict CBR and ultimate bearing capacity is preferred because it is simple and easy measured and it enables rapid estimation of bearing strength parameters. Several correlations developed to predict bearing strength values are available in the literature. This paper aims to develop correlations of unsoaked CBR and ultimate bearing capacity with soil index parameters. The placement conditions parameters (i.e. water content, dry density, void ratio) and soil intrinsic properties (i.e. Atterberg limits) are combined in away reflecting the influence of each of them on CBR and ultimate bearing capacity. These soil parameters are combined as described by a new concept, factor of soil consistency. This factor was developed from easy measured soil index properties such as water content, dry density, void ratio, liquid limit and plasticity index.

#### 4.1. The Consistency Factor

The consistency factor of compacted soil was introduced by Mohamed [21] and then modified by Zumrawi [22] (see equations (11) and (12)). The consistency factor ($F_c$) is defined as a combination of the soil index parameters such as dry density ($\gamma_d$), moisture content ($w$), void ratio ($e$) and soil consistency index (CI) and can be expressed thus:
The consistency index (CI) is arithmetically 1-LI (where LI is the Liquidity index) as given in equation (14) below.

\[
CI = \frac{LL - w}{PL}
\]

CI is 1.0 when moisture content equals the plastic limit and zero when moisture content equals the liquid limit.

4.2. The Relationship between the Consistency Factor and CBR
To investigate the relationship between the developed consistency factor \( F_c \) (equation 13) and unsoaked CBR, the test results and the data reported by Al-Amoudi et al [14] as shown in Fig. 1 were analyzed. The unsoaked CBR versus the consistency factor are plotted as given in Figs. 2 and 3. From figures, it can be observed that very good linear relationship \((R^2 > 0.90)\) is found for all the data analyzed. This result confirms the dependent of unsoaked CBR on soil index properties which is a combination of placement conditions and intrinsic properties of the tested soils. For the two soils, the linear equations of the best fit are expressed thus:

For soil 1 \( \text{Unsoaked CBR} = 25.99 \ F_c - 33.16 \) \hspace{1cm} (15)
For soil 2 \( \text{Unsoaked CBR} = 2.228 \ F_c + 7.436 \) \hspace{1cm} (16)

![Figure 2 Unsoaked CBR and consistency factor relationship for soil 1 and 2](image-url)
4.3. The Relationship between the Consistency Factor and Ultimate Bearing Capacity

The tests results were analyzed and used to investigate the relationship between the constancy factor, $F_c$ and the ultimate bearing capacity ($q_u$). The data analysis of soils 1 and 2 are drawn in Fig. 4. The plots in this figure clearly indicate that a linear relationship exists between the consistency factor, $F_c$ and the ultimate bearing capacity. The best fit linear equations developed for the two soils are expressed as:

For soil 1  \[ q_u = 1678F_c - 2231 \]  (17)
For soil 2  \[ q_u = 251.5F_c - 585.5 \]  (18)
4.4. The CBR and Ultimate Bearing Capacity Relationship

As a result, the developed linear relationships between the consistency factor and unsoaked CBR and ultimate bearing capacity (equations (15) and (18)) can be used to establish a correlation between them for different soils as expressed by equations (19) and (20) below.

\[ q_u (kPa) = 65 \times (CBR - 1.5) \]  \hspace{1cm} (19)

\[ q_u (kPa) = 113 \times (CBR - 12.5) \]  \hspace{1cm} (20)

The data trend shown in the Fig. 5 below indicate that there is a good agreement between the measured and predicted bearing capacity values and this proved the validity of the developed equations (19) and (20). This result shows that bearing capacity could be predictive from unsoaked CBR value for different types of soils.

![Figure 5 Comparison of measured/predicted ultimate bearing capacity for the tested soils](image)

5. CONCLUSION

In the current study, the relationship of ultimate bearing capacity and unsoaked CBR with the developed factor of soil consistency was investigated. The soil consistency factor \( Fc \) is described by the combination of placement conditions parameters (i.e. dry density, moisture content and void ratio) and intrinsic properties of soil (i.e. liquid limit and plasticity index). For two different soils, the CBR and triaxial tests were conducted at five different moisture contents and dry densities. Based on the test results, the following conclusions are drawn:

- Analysis results demonstrates very clearly that a direct linear relationship exists between the consistency Factor, \( Fc \) and the soil bearing strength measured by unsoaked CBR and ultimate bearing capacity. For all the data studied, the regression coefficient of this relationship was found to be more than 0.9. This result indicates the linearity of the developed relationships and the validity of the soil consistency factor.

- Based on these linear relationships, reliable and strong correlations have been established to predict the unsoaked CBR and ultimate bearing capacity for different type of soils. Furthermore, very good correlations between the unsoaked CBR and ultimate bearing capacity for cohesive and cohesionless soils were developed. Comparison between the measured ultimate bearing capacity and Unsoaked CBR
values and the calculated results using the developed equations clearly indicated the reliability of these equations.

- The developed correlations are reliable and useful in prediction of bearing strength characteristics of foundation soils, subgrade, and embankments for design purposes.

REFERENCES

Predicting Bearing Strength Characteristics From Soil Index Properties