Strength Modelling of Soil Geotechnical Properties from Index Properties

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ABSTRACT

This research work presents strength models developed for the class of soils encountered. An empirical, analytical model is developed to predict the CBR and shear stress of soil from its index properties and grade size, with a view to reducing time, effort and cost usually incurred in determining these tests in the laboratory for future planning, design and construction projects. Soil samples were collected from various locations in Ife central local government. Various available index property tests, such as sieve analysis, Atterberg limit test and specific gravity test were carried out and classification of samples performed. Compaction test, California Bearing Ratio test and triaxial test were also carried out with the Optimum Moisture Content (OMC), Maximum Dry Density (MDD), unsoaked California Bearing Ratio (CBR), internal angle of friction φ, cohesion c and shear stress determined. Regression models related to these index properties together were developed and tested to ascertain their effectiveness. The study showed that about 44.4% of the soil mass of the Ife central local government is poorly graded soil with gravel, followed by 33.3% of well graded soil with gravel. Linear and non-linear relationships were generated between various soil indicies and engineering properties through correlation analysis with a reliable coefficient of determination (R). Poorly graded soil with gravel cannot be effectively correlated because of its weak coefficient of determination.

KEYWORDS: Strength models, Regression models, Linear and non-linear relationships.

INTRODUCTION

Bouma (1989) defined translating scientific and engineering data available from soil investigation and survey into what is needed. By translating the known into the unknown, value is added to the relatively available data being transformed into estimates for more laborious and relatively costly soil properties needed. Gaps between properties required for a particular model and quality assessment and available data are filled by correlation equations by utilizing various regression analysis and data mining techniques. Briggs and McLane (1907) derived the first correlation equation by deriving the wilting coefficient equation as stated in the following form:

$$\text{Wilting coefficient} = 0.01\,\text{sand} + 0.12\,\text{silt} + 0.57\,\text{clay}$$

Salter and Williams (1995) with the use of field capacity and permanent wilting concept went further on the work of Briggs and McLane (1907) and derived correlation equations for particle-size distribution, bulk density, organic matter content and soil-water properties. These equations were determined by exploring relationships among different soil texture

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classes and available water capacity. Gupta and Larson (1979) developed 12 functions relating to particle-size distribution and organic matter content to water content. Parameters for power-function water retention curve, sorptivity and saturated hydraulic conductivity for different soil textures were derived by Clapp and Hornberger (1978). Lamp and Kneib (1981) derived Pedo function (PF), while Bouma and Van Lanen (1986) derived the transfer function (PTF) for the development of correlation equations. Wagner et al. (2001) evaluated eight well-known correlation equations used for the estimation of soil hydraulic conductivity using detailed measurements of 63 German soil horizons and found that the PTF developed by Wösten (1997) performed the best for predicting the unsaturated hydraulic conductivity.

Parametric and non-parametric methods are basically the two methods of developing correlation equations. Parametric methods include the use of artificial neural networks (ANNs) and regression models, while non-parametric methods having been successfully used do not use any predefined mathematical functions; they work with similarities instead of fitting equations to data. Nemes et al. (1999) introduced k-Nearest Neighbor (k-NN) algorithm, to estimate soil hydraulic properties and compared the results with those of a neural network model.

The aim of this research is to develop correlation equations for some selected soil samples in Ile-Ife, Nigeria in order to provide a guide that will assist in estimating some engineering properties of soil from some soil index properties. Grant et al. (2006) and Yung et al. (1999) worked on the development of correlation equations in the USA and Europe. However, physical properties of soils in these regions are different from those found in the tropics according to FAO (1990). Moreover, few works have been carried out in these regions, one of which is reported by Tomasella and Hodnett (1998) in Brazil which employed correlation equations for estimating soil water retention capacity. Compilation of works done in some countries on PTF is shown in Table 1. Hence, there is a need for more research on this subject in the tropics, on which this paper was focused, by utilizing correlation equations developed and tested using data of independent variables, such as clay content, moisture content, dry density and bulk density obtained from tests carried out on soil samples found in Ife central local government, Osun State, Nigeria. Statistical regression analysis of the measured soil physical properties will also be carried out in order to come up with locally accurate correlation equations.

Table 1. The top 10 PTF producer countries (Grant et al., 2006)

Country	No. of Papers (1991- August 2006)	Percentage of Total (284 papers)
USA	83	29.2%
Germany	47	16.55
The Netherlands	31	10.9%
Australia	30	10.6%
Canada	23	8.1%
France	19	6.7%
Brazil	18	6.3%
Belgium	15	5.3%
England	14	4.9%
Italy	13	4.6%

MATERIALS AND METHODS

Background

Various tests carried out range from tests involving the determination of both the independent and dependent variables. Independent variables are the index properties which are moisture content, plastic limit, liquid limit, bulk density, silt content, sand content, clay content,… etc., while the dependent variables are California Bearing Ratio (CBR), unconfined compressive strength, permeability,… etc. The results from the tests will be used to develop Pedo transfer/ correlation functions relating the dependent variables to the independent variables.

Location of the Study Area

The area from which the soil samples were collected for laboratory tests was at Ife central local government area, Ile-Ife, Osun state, Nigeria. The local government has within it the Obafemi Awolowo University, which covers a considerable land area in the local government. The locations for the collection of soil samples were determined by means of a grid network on Ife central local government map, which was followed as much as possible and divided into locations (A-J), as shown in Table 2. The map of the local government area was gridded at an interval of 5cm in both vertical and horizontal directions. This is to ensure that soil sampling is uniformly distributed over the whole local government area. The Global Positioning System (GPS) readings as shown in Table 2 of the exact locations of sample collection were recorded. The top soil will be scraped off to a depth of about 75 cm in order that the organic soil is gotten rid of.

Table 2. Sample references and their locations

Sample	Position		Altitude	Trip	Track
A1(Road 1)	07° 29.996"N	004°31.499"E	269m	256km	123°
A2(Road 1)	07° 30.017"N	004°31.476"E	269m	250km	297°
B2(Road 1)	07° 30.121"N	004°31.545"E	269m	267km	039°
B1(Road 1)	07° 30.107"N	004°31.570"E	269m	265km	108°
B1(Road 1)	07° 30.305"N	004°31.669"E	269m	275km	045°
B2(Road 1)	07° 30.308"N	004°31.639"E	273m	269km	100°
C2(Road 1)	07° 30.542"N	004°31.527"E	271m	270km	352°
C1(Road 1)	07° 30.563"N	004°31.549"E	268m	270km	330°
D1(Road 1)	07° 30.752"N	004°31.429"E	282m	271km	114°
D2(Road 1)	07° 30.743"N	004°31.401"E	283m	271km	279°
E (Gbooro Village)	07° 32.675"N	004°30.835"E	275m	320km	321°
F (Arowooogun)	07° 33.569"N	004°31.930"E	266m	5.3km	038°
G (Akeredolu)	07° 34.581"N	004°33.913"E	297m	9.7km	105°
H (Olorunda)	07° 34.330"N	004°32.891"E	286m	13.5km	023°
I (Kajola)	07° 33.823"N	004°33.073"E	291m	14.9km	245°
J (Ibagbe)	07° 34.985"N	004°32.053"E	306m	17.3km	099°
K (Aregbe)	07° 35.014"N	004°31.372"E	268m	18.2km	073°
L (Olukotun)	07° 34.516"N	004°30.736"E	251m	19.8km	008°
M (Elegon)	07° 33.530"N	004°30.575"E	264m	21.8 km	193°
N (Agbe)	07° 33.315"N	004°30.306"E	274m	22.6km	280°

Material Collection

Eighteen soil samples were collected from different locations in Ife central local government in Osun state, southwestern Nigeria. The samples were collected along known roads in built up areas at intervals which were decided by the length of the road from which the sample was collected. The Geographical Positioning System (GPS) gave the co-ordinates, as well as the height relative to mean sea level of each location where soil could be collected for future reference.

Equipment for Laboratory Tests

Equipment used for laboratory tests are: California Bearing Ratio (CBR) machine, triaxial testing machine, unconfined compression machine, West Africa compaction moulds and rammer, as well as constant and falling head permeameters. Used were also: a drying oven capable of maintaining a temperature between 105^0C and 110^0C, a glass weighing bottle, a weighing balance, a scoop, a corrosion-resistant container, palette knives or spatulas, Casagrande apparatus, grooving tool and gauge, a wash bottle or beaker, a rod 3 mm in diameter, test sieves, an evaporating dish, sieve brushes, sodium hexametaphosphate, a mechanical sieve shaker, a tray, filter material, measuring cylinders, a calibrated thermometer, a stopclock and silicon grease or petroleum jelly. All laboratory tests have been conducted in accordance to BS 1377 (1990)

Development of Correlation Equations

In the development of correlation equations, the independent variables; i.e., Atterberg limits, moisture content, optimum moisture content, maximum dry density,… etc. were extrapolated to obtain the dependent variables, such as shear strength and California Bearing Ratio. Soil samples in the same classification were grouped and analyzed together. The validity of each function developed was verified by coefficient of determination (R^2). If it is 1, there is a perfect correlation between the samples. If it is close to 1, there is a strong relationship between the estimated value and the actual value. The software used in determining these functions was MATLAB.

RESULTS

Locations of the Collected Samples

The locations of the collected samples are shown in Table 2. For example, sample A1 indicates that the sample was collected from OAU campus along road 1 at positions 07°29.996´N and 03°39.499´E, respectively, from the reference point. It also indicates that it is located 269m above mean sea level and 256km trip.

Determination of Index Properties and Classification of Soil Samples

The index properties that were determined from the laboratory tests are the liquid limit, plastic limit and plasticity index. Particle size analysis was carried out using the wet sieving method in order to carry out the effective classification of the soil samples as presented in Table 3.

Table 3. Particle size analysis results of the samples

SAMPLE NO.	D10	D30	D60	Cu	Cc	Percent passing BS sieve	
						No. 4	No. 200
A1	0.07	0.5	2.9	41.43	1.23	75.73	11.98
A2	0.15	1.5	4.1	27.33	3.66	61.43	4.67
B1	0.07	0.32	2	28.57	0.73	78.44	13.77
B2	0.07	0.13	0.3	4.29	0.80	93.31	13.08
C1	0.15	0.3	0.7	4.67	0.86	92.22	2.12
C2	0.1	0.29	0.8	8.00	1.05	86.21	5.02
D1	0.15	0.7	1.8	12.00	1.81	79.4	2.2
D2	0.15	0.4	1.8	12.00	0.59	82.16	2.05
E	0.2	1.04	3.3	16.50	1.64	72.44	1.42
F	0.2	2		0.00		52.9	1.39
G	0.3	1.9	4	13.33	3.01	64.14	3.93
H	0.1	0.4	0.24	2.40	6.67	80	3.84
I	0.2	1.05	4.5	22.50	1.23	61.15	1.38
J	0.1	0.2	0.7	7.00	0.57	91.87	3.31
K	0.1	0.7	2.1	21.00	2.33	85.37	2.39
L	0.15	0.38	2.3	15.33	0.42	78.54	2.27
M	0.15	0.4	2	13.33	0.53	77.18	2.54
N	0.1	0.22	0.7	7.00	0.69	93.68	3.42

Results of Atterberg Limit Test

The values of the Atterberg limit are presented in Table 4. Sample numbers are as previously stated in Table 2.

Table 4. Sample numbers and Atterberg limit values

SAMPLE NO.	LIQUID LIMIT	PLASTIC LIMIT	PLASTICITY INDEX
A1	36.1	24.74	11.36
A2	31.7	20.49	11.21
B1	33	20.90	12.10
B2	25.8	17.91	7.89
C1	35.25	25.48	9.77
C2	36.3	25.53	10.77
D1	31.6	25.49	6.11
D2	33.8	20.42	13.38
E	30.65	14.47	16.18
G	35	14.32	20.68
H	26.2	35.88	-9.68
I	46	43.28	2.72
J	29	10.66	18.34
K	29.74	23.04	6.70
L	20.15	19.71	0.44
M	32.6	15.32	17.28
N	20.65	16.00	4.65

Results of Soil Classification Test

The values resulting from index properties presented in Table 3 and Table 4 used in classifying the soil samples by using the AASHTO classification system and the USCS classification system are shown in Tables 5 and 6.

Table 5. AASHTO classification of soil samples

SAMPLE NO.	AASHTO CLASSIFICATION
A1	A-2-6
A2	A-2-6
B1	A-2-6
B2	A-2-4
C1	A-2-4
C2	A-2-6
D1	A-2-4
D2	A-2-6
E	A-2-6
G	A-2-6
H	A-3
I	A-2-5
J	A-2-6
K	A-2-4
L	A-2-4
M	A-2-6
N	A-2-4

Table 6. USCS classification of soil samples

SAMPLE	UNIFIED CLASSIFICATION (USCS)
A1	SW-SC (well graded sand with clay and gravel)
A2	SP (poor graded sand)
B1	SC (clayey sand with gravel)
B2	SC-SM (silty clayey sand)
C1	SC (clayey sand)
C2	SP-SC (poorly graded sand with clay (or silty clay)
D1	SW (well graded sand with gravel)
D2	SP (poorly graded sand with gravel)
E	SW (well graded sand with gravel)
G	SW (well graded sand with gravel)
H	SP (poorly graded sand with gravel)
I	SW (well graded sand with gravel)
J	SP (poor graded sand)
K	SW (well graded sand)
L	SP (poor graded sand)
M	SP (poorly graded sand)
N	SP (poorly graded sand)

Determination of Moisture Density Relationship of Soil Samples

The moisture density relationship involves optimum moisture content (OMC) and maximum dry density (MDD) usually determined by compaction test. The sample numbers with the corresponding values of MDD and OMC are shown in Table 7.

Table 7. Maximum dry density and optimum moisture content of collected samples

SAMPLE NO.	OMC	MDD
A1	13.5	1.94
A2	11.5	2.09
B1	15.5	1.91
B2	11.6	1.68
C1	12.5	1.95
C2	15	1.885
D1	9	2.045
D2	9	2.05
E	11.5	1.955
F	16.5	1.93
G	11.2	1.98
H	12.5	1.64
I	8.4	2.085
J	11.5	1.68
K	10.8	1.72
L	7	1.84
M	14	1.635
N	7.5	2.085

MDD is the maximum dry density in Mg/m^3; CBR in kN.

Determination of Engineering Properties of Soil

In this research, the tests used to determine engineering properties are the California Bearing Ratio (CBR) test and the undrained triaxial test. The values needed from tri-axial tests are that of cohesion C and that of angle of internal friction Φ, which are presented in Table 8.

Table 8. The values of cohesion and angle of internal friction of the soil samples

SAMPLE NO.	Cohesion(kN/m^2)	Angle of internal friction (φ°)
A1	54.9	13
A2	37.7	23
B1	19.5	17
B2	25.8	25
C1	10.9	33
C2	32.3	35
D1	20.9	15
D2	38.1	23.5
E	22	13
G	21.1	14
H	37.7	23
I	21.6	13.5
J	25.5	29
K	73.5	4
L	37	26
M	39	22
N	37.7	23

DISCUSSION

Correlations between Various Soil Properties

The predominant soil types encountered during this project are A-2-6 and A-2-4 according to AASHTO classification and SP (poorly graded sand with gravel) and SW (well graded sand with gravel) according to the Unified Soil Classification System (USCS). It was deduced while generating the correlation for SP (poorly graded sand with gravel) that there exists no correlation between the various index properties obtained in this research and the shear strength of the sample. The functions obtained produced a very weak coefficient of determination (i.e., $R^2 < 0.5$), which indicates a very weak relationship between the estimated value and the actual value.

Correlations for A-2-6 Soil Classification

Various correlations were developed for this type of soil classification using optimum moisture content (OMC), maximum dry density (MDD), liquid limit (LL), plastic limit (PL) and plasticity index (PI) to obtain the values of CBR and shear strength of the soil. The samples used were A1, A2 and C2.

a. **Correlation between Optimum Moisture Content, Plasticity Index, CBR and Shear Strength**

$$CBR = 0.5(OMC)^2 + (OMC)(PI) + 0.5(PI)^2 - 24.31(OMC+PI) + 295.86 \quad (R^2=1) \quad (1)$$

$$\tau = 0.021(OMC)^2 + 0.042(OMC)(PI) + 0.021(PI)^2 - (OMC+PI) + 12.022 \quad (R^2=1) \quad (2)$$

CBR in kN and shear strength in kN/m^3.

b. **Correlation between CBR and Maximum Dry Density**

$$CBR = MDD\,[0.252(MDD) - 1] + 0.993 \quad (R^2=1) \quad (3)$$

c. **Correlation between Shear Strength, Maximum Dry Density and Optimum Moisture Content**

$$\tau = 0.3441\,(OMC)^2 + 0.6882\,(MDD)(OMC) + 0.3441\,(MDD)^2 - (OMC + MDD) + 7.65 \quad (R^2=1) \quad (4)$$

τ is the shear strength in kN/m^3.

d. **Correlation between Optimum Moisture Content, Liquid Limit, Plasticity Index, CBR and Shear Strength**

$$CBR = 0.00858[OMC^2 + OMC(LL+PI) + LL^2 + LL(OMC+PI) + PI^2 + PI(OMC+LL)] - (OMC+LL+PI) + 29.162 \quad (R^2=1) \quad (5)$$

$$\tau = 0.00867[OMC^2 + OMC(LL+PI) + LL^2 + LL(OMC+PI) + PI^2 + PI(OMC+LL)] - (OMC+LL+PI) + 28.956 \quad (R^2=1) \quad (6)$$

e. **Correlation between Maximum Dry Density and Shear Strength**

$$\tau = MDD\,[0.03995(MDD) - 1] + 6.74 \quad (R^2=1) \quad (7)$$

Correlations for Well Graded Soil with Gravel Soil Classification

The samples used for this correlation are D1, G, I and E and the properties considered include optimum moisture content, plasticity index, plastic limit, liquid limit, maximum dry density and D60 to obtain the shear strength only.

a. **Correlation between Optimum Moisture Content, Plastic Limit and Shear Strength**

$$\tau = 0.3295\,(OMC+PL)\,[1- 0.129(OMC+PL)] + 29.74 \quad (R^2=0.970) \quad (8)$$

b. **Correlation between Maximum Dry Density and D60**

$$\tau = 2.0335\,(MDD+D60)\,[0.0836(MDD+D60) - 1] + 41.37 \quad (R^2=0.965) \quad (9)$$

MDD is the maximum dry density in Mg/m^3, D60 is the diameter at 60% passing from grain size distribution (in mm) and Ʈ is the shear strength in kN/m^3.

c. Correlation between Liquid Limit, Plasticity Index, Optimum Moisture Content and Shear Strength

Ʈ = 0.4513(OMC+LL+PI) [0.00813 (OMC+LL+PI)–1] + 48.96

(R^2=0.993) (10)

d. Correlation between Optimum Moisture Content, Maximum Dry Density and Shear Strength

Ʈ =10.705(OMC+MDD) [1-0.0420(OMC+MDD)]–27.57

(R^2=0.874) (11)

Ʈ is the shear strength in kN/m^3.

Correlations for A-2-4 Soil Classification

Samples used include B2, C1 and K. Maximum dry density, optimum moisture content, liquid limit, plastic limit and plasticity index are the properties used to obtain the shear strength in various combinations.

a. Correlation between Liquid Limit, Optimum Moisture Content and Shear Strength

Ʈ = $219.4e^{-0.025(LL+OMC)}$

(R^2=0.863) (12)

LL is the liquid limit, OMC is the optimum moisture content (in %) and Ʈ is the shear strength in kN/m^3.

b. Correlation between Optimum Moisture Content, Maximum Dry Density and Shear Strength

Ʈ = $443.6e^{-0.925(MDD+OMC)}$

(R^2=0.966) (13)

Ʈ is the shear strength in kN/m^3.

c. Correlation between Maximum Dry Density and Shear Strength

Ʈ = $426.1e^{-0.96MDD}$

(R^2=0.954) (14)

Ʈ is the shear strength in kN/m^3.

d. Correlation between Plasticity Index, Optimum Moisture Content and Shear Strength

Ʈ = 38.23 – PI + OMC

(R^2=0.888) (15)

OMC is the optimum moisture content, PI is the plasticity index and Ʈ is the shear strength in kN/m^3.

e. Correlation between Liquid Limit, Optimum Moisture Content, Plastic Limit and Shear Strength

Ʈ = 14.973(LL + PL + OMC)[1 – 0.00828 (LL+PL+OMC)] – 366.6

(R^2=1) (16)

Ʈ is the shear strength in kN/m^3.

CONCLUSIONS

The following conclusions are drawn from this research work with respect to its objectives:

- About 44.4% of the soil mass of the Ife central local government is poorly graded soil with gravel, followed by 33.3% of well graded soil with gravel.
- Linear and non-linear relationships have been generated between various soil indices and engineering properties through correlation analysis with the coefficient of determination (R) obtained.
- Poorly graded soil with gravel cannot be effectively correlated as indicated by its weak coefficient of determination.
- Correlations between various soil properties provide a means of time saving through obtaining some engineering properties without carrying out any test in the laboratory.

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