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Prediction of Initial Void Ratio from the Natural Moisture Content of Cohesive Soils

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Abstract
Initial void ratio is an important compressibility parameter needed for the calculation and estimation of consolidation settlement of structural foundations, prediction of pre-consolidation pressure, and the determination of compression in cohesive soils. This initial void ratio is usually determined by a time-consuming process of conducting one-dimensional consolidation tests in the laboratory from undisturbed soil samples recovered from exploratory boreholes. However, not much attention has been given to the prediction of this important consolidation parameter especially for use in situations where undisturbed samples are not available. To address this limitation, one-dimensional consolidation tests were conducted on 319 undisturbed cohesive soil samples which were obtained from exploratory soil boreholes drilled at 29 sites within Lagos and its environs in Nigeria to predict the initial void ratio from their natural moisture contents. The initial void ratio of each sample was determined using the data obtained from consolidation test results and correlation analysis was made with their respective natural moisture content; an index property of the soil. The results showed that the initial void ratio has a strong correlation with the natural moisture content which is a basic soil parameter that is easily determined in the laboratory using disturbed samples. A linear equation was then developed for the estimation of this initial void ratio. This developed equation is practically useful where undisturbed soil samples are not available for laboratory consolidation analysis and so, disturbed soil samples are used to determine the natural moisture content which will then be a useful parameter for the initial void ratio prediction.

Keywords
Initial void ratio; natural moisture content; consolidation settlement; compression ratio; one-dimensional consolidation.

1.0 Introduction

This The initial void ratio is a very important parameter used to estimate consolidation settlement of structural foundations, prediction of pre-consolidation pressure, determination of compression ratio and classification of soil compressibility which is used empirically to determine compression index Cc of cohesive soils (Bowles, 1979, 1996; Coduto, 1999). It is determined by conducting consolidation tests in the laboratory on undisturbed samples collected from field exploration.

When the foundation of any structure is constructed on a compressible soil such as clay, it leads to a settlement whereby the superimposed loads develop pore pressures in the compressible strata which exceed the original hydrostatic pressure. As the pressure gradients force water from the compressible stratum, its volume decreases thereby causing settlement. The compressibility of soils under one-dimensional compression can thus be described from the decrease in the volume of voids with the increase in effective stress. The settlement of a foundation due to structural loads is not expected to exceed permissible limits to mitigate architectural and structural damage (Das, 2014; Murthy, 2002). Settlement magnitudes are computed from the change experienced in a void ratio corresponding to a change in stress from initial field conditions, obtained from e - σ and e – log σ curves which are depicted either as arithmetic plots or semi-log plots. Where the consolidation test results are plotted between void ratio and effective stress arithmetically, the slope of the curve for the pertinent stress range, which is referred to as the coefficient of volume change or the coefficient of volume compressibility m_v can be used in settlement computations. If the void ratio e is plotted against log σ, the slope of the virgin compression curve (the compression index Cc) can also be used in settlement computation (Smith & Smith, 1998). The settlement can be computed either by using the change in void ratio Δe, and the compression index Cc or the change in stress and the coefficient of volume compressibility, m_v, which is itself a function of Δe. Hence, the initial void ratio e_0 is an essential parameter while a_v and m_(v) are obtained for a particular stress range, and Cc is constant across varying stress ranges. The settlement equations can be represented as:

$$S_c = C_c \frac{H_0}{1+e_0} \log \frac{\sigma_0 + \Delta\sigma}{\sigma_0} \qquad 1$$

$$S_c = m_v H_0 \Delta\sigma \qquad 2$$

Where:

$$m_v = \frac{a_v}{1+e_0} \text{ and } a_V = \frac{\Delta e}{\Delta\sigma}$$

$$S_c = \frac{\frac{\Delta e}{\Delta\sigma}}{1+e_0} H_0 \Delta\sigma \qquad 3$$

Where:
$\Delta e = e_0 - e_f$, (decrease in the void ratio),
e_0 = the void ratio of the soil before compression
e_f = the void ratio after primary consolidation is complete
H_0 = original height or thickness of soil layer
σ_0 = present effective overburden stress and
$\Delta\sigma$ = additional stress induced by an imposed load.

Eq. 2 applies only to normally consolidated soils (final stress less than the pre-consolidation stress) otherwise it should be:

$$S_c = C_c \frac{H_0}{1+e_0} \log \frac{\sigma_0 + \Delta\sigma}{\sigma_0} + C_r \frac{H_0}{1+e_0} \frac{\sigma_0 + \Delta\sigma}{\sigma_0} \quad 4$$

The compressibility of soil will determine how much compression shall take place in the soil upon loading, and to assist in classifying cohesive soils in terms of the degree of compressibility, the compression ratio is used for normally consolidated or over-consolidated soils. An important parameter needed to obtain the compression ratio is the initial void ratio, e_0 and is expressed mathematically as:

$$\frac{C_c}{1+e_0} \text{ for normally consolidated soils and} \quad 5$$

$$\frac{C_r}{1+e_0} \text{ for over-consolidated soils} \quad 6$$

Classifications of soil compressibility based on compression ratio for normally consolidated soils or over-consolidated soils are given in **Table 1**.

Table 1: Classification of Soil Compressibility (Coduto, 1999)

$\frac{C_c}{1+e_0}$ **or** $\frac{C_r}{1+e_0}$	**Classification**
0 – 0.05	Very slightly compressible
0.05 – 0.10	Slightly compressible
0.10 – 0.20	Moderately compressible
0.20 – 0.35	Highly compressible
> 0.35	Very highly compressible

Research studies have shown that the initial void ratio of cohesive soils is a very important parameter when soil compressibility and consolidation settlement estimations are required, hence it is a parameter that should be determined from undisturbed soil samples (Coduto, 1999; Sridharan & Nagaraj, 2000; Vinod & Bindu, 2010). Experience has however shown that during soil exploration some drillers either out of negligence or lack of experience fail to recover undisturbed samples from cohesive strata for laboratory determination of strength and compressibility characteristics needed for design and settlement determination of foundations. Since the conventional consolidation test requires undisturbed samples, various attempts have been made to predict compressibility behaviour of soils in situations where undisturbed samples are not available for laboratory analysis. To overcome problems associated with a lack of relevant parameters for settlement analysis such as reliance on assumed parameters, many attempts have been made to correlate the compression index, $C_{c,}$ a parameter also directly used for computation of foundation settlement, with various index properties of the soil. One of such empirical expressions is that of Terzaghi & Peck (1967). The initial void ratio as indicated in Equations 1, 3 and 4 also, is a necessary parameter for settlement and classification of soil compressibility, therefore, its accurate prediction from natural moisture content a standard index test, which is less expensive and relatively less time-consuming would significantly complement the already existing empirical relationship for $C_{c,}$ to easily compute foundation settlement based on reliable compressibility parameters and also minimize the number of consolidation tests that may be carried out in situations where undisturbed samples are available, thereby making the investigation process less expensive.

2.0 Materials and Methods

One-dimensional consolidation tests were conducted on 319 undisturbed clay samples obtained through exploratory percussive borings from depths ranging from 30m – 50m. These samples were obtained from different borehole locations drilled at 29 different sites. These 29 sites were scattered around 15 suburban areas within the city of Lagos, Nigeria. The undisturbed clay samples were collected using 100 mm diameter thin-walled samplers for the determination of natural moisture content and one-dimensional consolidation tests following relevant BS Codes of practice (BS 1377 Part 2, 1990; BS 1377 Part 5, 1990).

The samples were extruded in a standard fixed ring consolidometer using brass rings, 69.18 mm in diameter and 18.6 mm in height and tested under full-saturated conditions. The inner part of the ring was made smooth by lubricating the surface with silicone grease to reduce side friction between the ring and the soil specimen. Load increment was applied at 25, 50, 100, 200. and 400 kN/m^2. Each load increment was maintained for 24 hours and unloaded to zero with a load decrement of unity. At the end of the test, 24 hours after unloading, the sample was removed from the ring and dried in the oven to obtain its final dry weight and water content.

The initial void ratio, as well as other equilibrium void ratio after full consolidation under each pressure increment, was determined from the height of solids method. The relationship used to determine the initial void ratio e_0 is given by as:.

$$e_0 = \frac{H - H_s}{H_s} \quad 7$$

Where,

H = Final specimen thickness under given pressure increment.

$$H_s = \frac{M_s}{G_s \rho_w A} \text{ (Equivalent height of solids)} \quad 8$$

M_s = the dried mass of sample recovered from consolidation apparatus at end of test

ρ_w = Density of water;

A = Cross-sectional area of the test sample.

The natural moisture content which has a profound effect on soil behaviour especially compressibility was determined by oven drying of the clay samples for 24 hours at a temperature of 105°C. This is normally expressed mathematically in a percentage form as the proportion of the mass of water divided by the mass of the dry solid particles.

The relevant parameters considered for compressibility and settlement determination in this study were the initial void ratio and the natural moisture content of the respective clay samples. These parameters were considered as a subset of the laboratory tests results obtained from the various sites. The two parameters were found to give stronger relationship when compared with other index or basic soil properties such as liquid limit, plastic limit or plasticity index. The geotechnical properties of clay samples under study are summarized in **Table 2**, with the map of the research study given in **Figure 1**.

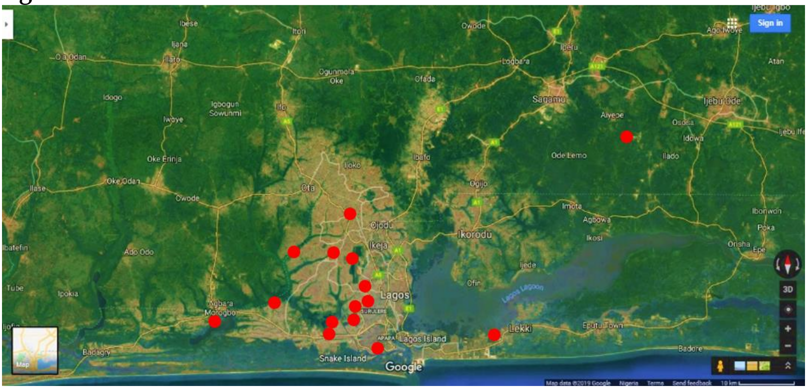

Figure 1. Map showing research study area of Lagos and its environs (Courtesy: Google Maps)

Graphical plots were used to illustrate the relationship between the natural moisture content of the soil samples considered for this study with the initial void ratio obtained from the one-dimensional consolidation test. The coefficient of determination (R^2) was used to evaluate the strength of the relationship between the two parameters considered. It is worthy of note that the higher the coefficient of determination, the stronger the mathematical relationship between the two parameters (Akayuli & Ofosu, 2013; Komolafe et al., 2018; Obaji & Komolafe, 2018). Trendlines were used to indicate how the mathematical relationship established from the graphical plot would behave. Mathematical relationships and expressions are shown for linear, exponential, logarithmic and power trendlines.

Table 2: Summary of laboratory results of data from various locations considered in this study

S/N	Location	Number of Sites	Number of Samples	Range of Natural Moisture Contents (%)	Range of Initial Void Ratios
1	Lekki	1	2	20.5 – 21.7	0.657 – 0.697
2	Ikoyi	5	15	21.8 – 176.2	0.610 – 3.694
3	Iganmu	2	9	13.5 – 44.5	0.497 – 1.077
4	Ijegun	2	4	48.7 – 68.5	1.214 – 1.487
5	Maryland	1	3	17.2 – 67.5	0.672 – 1.453
6	Ijanikin	1	7	17.9 – 70.2	0.586 – 1.569
7	Ebute Metta	1	6	20.5 – 40.7	0.617 – 1.031
8	Ikeja	1	4	16.3 – 21.6	0.419 – 0.680
9	Ijora Badia	3	22	16.7 – 46.5	0.484 – 1.101
10	Akoka	3	59	14.8 – 60.1	0.438 – 1.343
11	Iwaya	4	49	14.7 – 71.2	0.509 – 1.610
12	Odogbolu	1	121	17.3 – 71.2	0.533 – 1.862
13	Makoko	1	8	17.9 – 65.9	0.571 – 1.429
14	Isheri	2	9	16.9 – 59.3	0.547 – 1.328
15	Alimosho	1	1	16.8	0.481

3.0 Results and Discussion

The predicted initial void ratio based on soil indices such as natural moisture content $w_{n,}$ obtained from experimental data for cohesive soils collected from 29 different sites in Lagos and its environs are presented in **Figures 2 - 5** to illustrate various mathematical relationships considered for the most suitable empirical correlation.

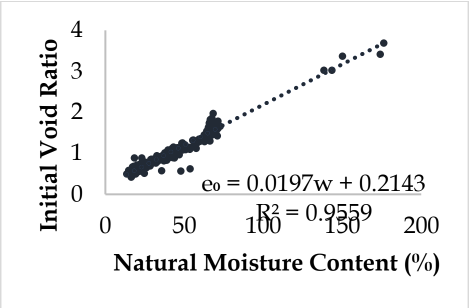

Figure 2. A linear relationship between the initial void ratio and natural moisture content

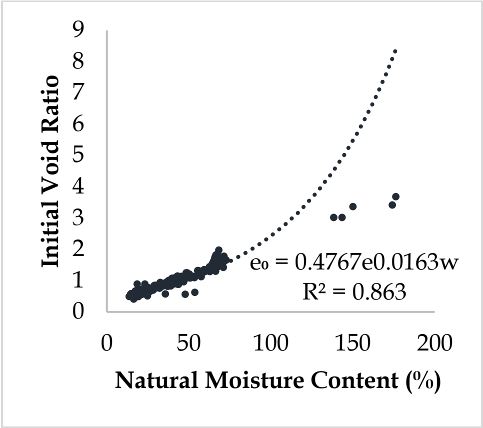

Figure 3. An exponential relationship between the initial void ratio and natural moisture content

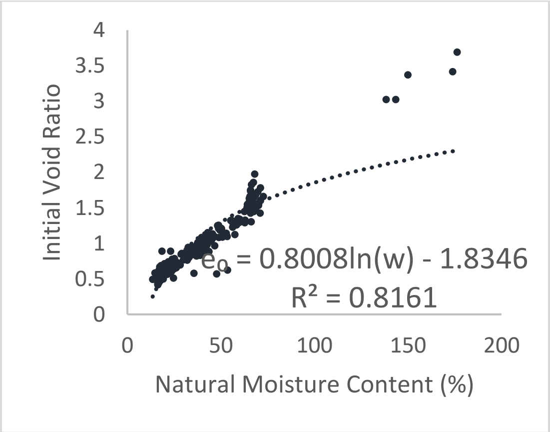

Figure 4. A logarithmic relationship between the initial void ratio and natural moisture content

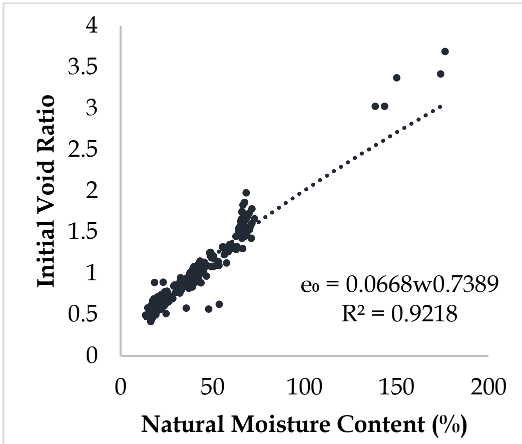

Figure 5. A power relationship between the initial void ratio and natural moisture content

The laboratory test results for the parameters considered in this study classified the soils according to the USCS, commonly used to classify soils for foundations as CL, CS, CM and OH. It is observed from the results presented in Table 2 that the range of natural moisture content considered falls between 13.5% to 176.2%, while the initial void ratio is in the range of 0.419 to 3.7.

Correlation analysis was made using graphical plots to illustrate the relationship between the natural moisture content of the soil samples considered for this study with the initial void ratio obtained from the one-dimensional consolidation test. The coefficient of determination (R^2) was used to evaluate the strength and reliability of the relationship between the two parameters. Linear, Exponential, Logarithmic and Power relationships were performed with the considered variables to develop the most reliable single variable equation with the highest coefficient of determination and acceptable trendline behaviour with the scatter plots as shown in **Figures 2-5**. **Table 3** shows the studied empirical equations and their statistical indices for the mathematical relationships studied.

Table 3: Summary of developed empirical equations and the values of their R²

Mathematical Relationship	Coefficient of determination (R^2)	Equations
Linear	0.956	e_0 = 0.0197w_n+ 0.2143
Exponential	0.863	e_0 = 0.4767$e^{0.0163w_n}$
Logarithmic	0.816	e_0 = 0.8008 In (w_n) + 1.8346
Power	0.922	e_0 = 0.0668$w^{0.7389}$

An evaluation of the studied empirical equations and the values of their coefficient of determination (R^2) as shown in Table 3 reveal that the linear relationship gave the best correlation between the two parameters, having the highest coefficient of determination (R^2) of 0.956 with acceptable trendline behaviour. The linear trend line in Fig. 2 cut across all the regions of the plot almost evenly on either side and reaches an area of high natural moisture contents than the other forms of mathematical relationships and can thus predict the initial void ratio of cohesive soils accurately from its natural moisture content in comparison to the other equations. Thus, the developed mathematical empirical relationship for the prediction of the initial void ratio of cohesive soils from natural moisture content (in %) is given as:

$$e_0 = 0.0197w_n + 0.2143 \quad 9$$

According to Holtz, (2011), the minimum possible range of void ratio *e,* is between zero and infinity, However, typical values of void ratio for clay vary from 0.3 to 1.5 and even higher for some organic soils, Das, (2010) also provides that typical soils in a natural state range from 0.6 to 1.4 for stiff and soft clays respectively and up to about 2.5 – 3.2 for soft organic clays. Predicted values from the developed empirical expression based on Eq. 9 are consistent with the range of given values in literature.

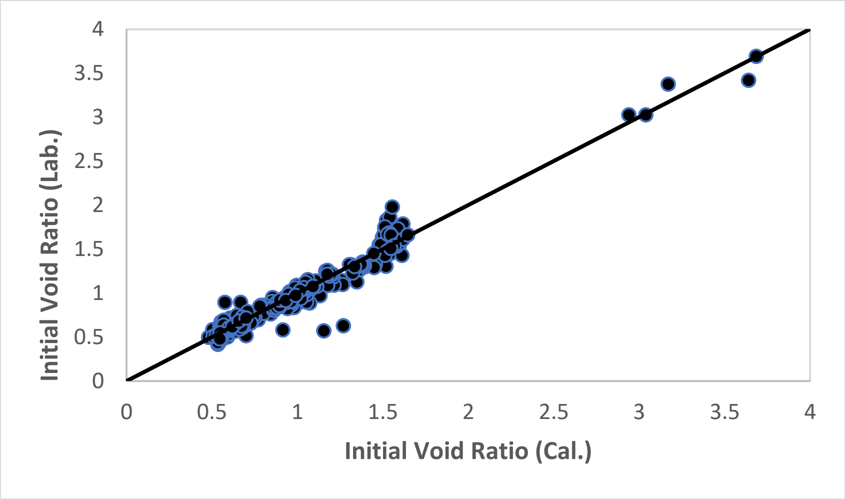

Figure 6. The 1:1 Plot comparing the laboratory and calculated values of Initial Void Ratio

Figure 6 shows a plot comparing the initial void ratio of laboratory values to the calculated values obtained using Eq. (9) about the 1:1 line where the predicted and laboratory determined values are equal. It can be observed that the variations between the two sets of values are not pronounced, as they slightly deviate on either side from the line. This indicates that the developed mathematical empirical relationship is adequate and can reasonably predict the values of the initial void ratio of inorganic and organic clays with a considerable amount of precision.

4.0 Conclusion

In this research study, an attempt has been made to establish an empirical relationship between the natural moisture content (an index soil property) that is easily determinable in the laboratory with the initial void ratio of cohesive soils determined in the laboratory using the one-dimensional oedometer test on undisturbed soil samples recovered from exploratory soil boreholes. The laboratory test results of 319 undisturbed soil samples considered in this correlation studies reveal that a linear relationship is the best form of the mathematical equation relating natural moisture content and initial void ratio of cohesive soils having a strong coefficient of determination (R^2) of 0.956.

The developed empirical relationship is considered straightforward and very helpful to geotechnical professionals in reliably predicting the initial void ratio using the natural moisture content. Predicted values from the developed expressions can be used in conjunction with values also derived from existing empirical correlations of compression index C_c, and index soil properties to classify soil compressibility and estimate foundation settlement. The developed equation would be practically useful where undisturbed clay soil samples are not available for laboratory consolidation analysis and disturbed soil samples can be obtained to determine natural moisture contents especially for clay soils having similar properties with those used for this study.

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