STATISTICAL EVALUATION OF SELECTED METHODS IN FOUNDATION ENGINEERING

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ABSTRACT

In this paper, soil samples were collected from selected locations in Nigeria. Geotechnical properties were determined by using standard methods and evaluated statistically using total error (TE), model of selection criterion (MSC) and statistical reliability (SR). The study revealed that Al Khafaji and Andersland (4.947; 0.570 and 0.984); Nagaraji and Murthy (4.373; 0.606 and 0.983); Wroth and Wood (3.342; 0.694 and 0.980) and mathematical method (3.006, 0.732 and 0.980) are the best techniques for soil settlement determination based on MSC, TE and SR. It was concluded that Skempton, Acar *et al* and Azzouz *et al* techniques should be used only when approximate values are required.

Keywords: Failed Structures, Settlement, Statistical Assessment, Consolidation

INTRODUCTION

Failure and collapse of building and other structures worldwide reported in literature and elsewhere call for failures prevention measures (Liliana, 2007; Johan, 2007; Olajumoke *et al.,* 2009; Ayininuola and Olalusi, 2004; Ephraim, 2006; Salau, 2005). Prevention of structural failures is one of the cheapest and effective ways of protecting the environment and saving lives. It is a well known scenario that structural failures can be caused by many factors such as materials defect (Liliana, 2007; Johan, 2007; Olajumoke *et al.,* 2009); poor engineering practices (Olajumoke *et al.,* 2009; Ayininuola and Olalusi, 2004; Ephraim, 2006); improper settlement/error in consolidation computation (Ephraim, 2006), and natural disasters such as earthquakes and floods (Mattson, 2007; Binci, 2007; Socher and Bohme-Kom, 2008; Bayratar, 2007).

Materials defects and poor engineering practices can be controlled and reduced through the use and adherence to standard code of practices and products monitoring agents respectively. Like other two factors improper settlement/error in consolidation computation can be controlled/corrected by using appropriate methods and techniques of settlement determination. In any event, knowledge of the causes of settlement and a means of computing (or predicting) settlement quantitatively are important to the soil engineer and technologist. Although, there are several possible causes of settlement (dynamic forces, changes in the groundwater table, adjacent excavation, etc.) among others, probably the major cause is compressive deformation of soil beneath the structure. Such compressive deformation generally results from reduction in void volume. This reduction in void volume is accompanied by a rearrangement of the soil grains and a compression of the material in the voids. If the soil is dry, the voids are filled with air and since air is compressible the rearrangement of the soil grains can occur rapidly. If the soil is saturated, the voids are filled with incompressible water, and water must be extruded from the soil mass before the soil grains can rearrange themselves. In civil engineering projects, settlement of soil is calculated using any of the following techniques ranging from Terzaghi's one dimensional consolidation theory to stress path methods (Osinnubi,1993; Bowles, 2006; Gunduz and Arman, 2007):

i. Skempton method(Skempton, 1944),
ii. The square root of time fitting method (Taylor's method) (Osinnubi,1993),
iii. Logarithm of time fitting method (Casagrande's method) (Osinnubi,1993),
iv. The mathematical method (Osinnubi,1993),
v. Acar et al method (Osinnubi,1993;Acar *et*

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*al.,*2008);

vi. Azzouz et al method (Gunduz and Arman, 2007)

vii. Wroth and Wood (Gunduz and Arman, 2007)

viii. Nagaraj and Murthy (Gunduz and Arman, 2007)

ix. Nagaraj and Murthy (Gunduz and Arman, 2007)

x. Al Khafaji and Andersland (Gunduz and Arman, 2007)

Skempton method: Skempton (1944) has documented that compression index can be obtained in terms of the liquid limits as follows (Skempton, 1944):

$$C_c \qquad 0.009(LL \quad 10) \tag{1}$$

Where LL is the liquid limit and C_c is the compression index

The square root of time fitting method (Taylor's method): The theoretical curve on the square root plot is a straight line up to about 60 % consolidation with an error of less than 1 % (Osinnubi,1993). This characteristic of the theoretical curve is utilized to determine a point of 90% consolidation on the laboratory time curve. The coefficient of consolidation for the laboratory curve can be determined from the equation of time factor which can be expressed as:

$$C_c \qquad \frac{1}{60} \; \frac{0.848}{t_{90}} \; H^{2} \qquad \text{or}$$

$$C_c \qquad \frac{0.196}{t_{50}} \; H^{2} \tag{2}$$

Where; t_{50} and t_{90} are 50 % and 90 % settlement respectively and H is the soil sample thickness

Logarithm of time fitting method (Casagrande's method): Like Taylor's method, this method has the same characteristic, but the use of the intersection of the two corresponding tangents (the tangent and asymptote to the theoretical curve) to the laboratory curve was suggested by Casagrande to determine the point of 100 % primary consolidation (compression). The coefficient of consolidation for the laboratory curve can be determined from the equation of time factor at 50 % which can be expressed as (Osinnubi, 1993):

$$C_c \qquad \frac{1}{60} \; \frac{0.196}{t_{50}} \; H^{2} \tag{3}$$

The mathematical method: In this method a linear relationship is established between the void and the logarithms of the stress as follows (Osinnubi, 1993):

$$e_i \qquad e_0 \qquad C_c \log_{10} \frac{i}{0} \tag{4}$$

Where; σ_i is the final normal stress; σ_0 is the initial normal stress; e_0 is the initial void (settlement) and e_i is the final void (settlement)

Acar et al method: Acar *et al* method (2008) reveals that compression index can be obtained in terms of the liquid limit of the soil as follows (Acar *et al.,* 2008):

$$C_c \qquad 0.0045(LL) \quad 0.0798 \tag{5}$$

Azzouz et al method: Azzouz et al (Gunduz and Arman, 2007) reveals that compression index can be obtained in terms of the natural moisture content of the soil as follows (Gunduz and Arman, 2007):

$$C_c \qquad 0.010(M_c \quad 5) \tag{6}$$

Where; M_c is the moisture content

Wroth and Wood method: Wroth and Wood (Gunduz and Arman, 2007) states that compression index can be obtained in terms of the specific gravity and plasticity index as follows (Gunduz and Arman, 2007):

$$C_c \qquad 0.50\, G_s I_p \tag{7}$$

Where; G_s is the specific gravity and I_p is the plasticity index

Nagaraj and Murthy method: Nagaraj and Murthy (Gunduz and Arman, 2007) reported that compression index can be obtained in terms of the natural moisture content and specific gravity of the soil grain as follows (Gunduz and Arman, 2007):

$$C_c \quad 0.2343(G_S M_C) \qquad (8)$$

Nagaraj and Murthy method: Nagaraj and Murthy (Gunduz and Arman, 2007) reported that compression index can be obtained in terms of the specific gravity and liquid limit of the soil grain as follows (Gunduz and Arman, 2007):

$$C_c \quad 0.0023(G_S LL) \qquad (9)$$

Nagaraj and Murthy method: Nagaraj and Murthy (Gunduz and Arman, 2007) documented that compression index can be obtained in terms of the natural moisture content and liquid limit of the soil grain as follows:

$$C_c \quad 0.009M_C \quad 0.002(LL) \quad 0.10 \qquad (10)$$

Al Khafaji and Andersland method: It has been documented that compression index can be obtained in terms of specific gravity, unit weight of the soil and water as follows (Gunduz and Arman, 2007):

$$C_c \quad 0.141G_S \; \frac{w}{s}^{\,2.4} \qquad (11)$$

Where; γ_s is the unit weight of soil grains and γ_w is the unit weight of water

Although, literature have stated various methods and techniques required in the determination of settlement in the soil, but documented works on the assessment of these methods and techniques are rare. With a known importance of settlement in the control of buildings and structural failures, it is essential to evaluate the methods and techniques used in the determination of settlement of soil with a particular attention to accuracy and goodness fit using statistical methods. The main objective of this study is to evaluate the methods and techniques used in the determination of settlement of soil with a particular attention to accuracy and goodness fit using statistical methods.

MATERIALS AND METHODS

Soil samples were collected at random from selected states in Nigeria using standard method stated in literature (ASTM, 1992). The soil samples collected were subjected to laboratory tests. Specifically, sieve analysis, natural moisture content, densities, atterberg limits and consolidation tests using standard methods stated in literature and by using standard equipment such as Oedometer and triaxial machine manufactured ELE Engineering Laboratory equipment. The soil samples were classified using American Association of State Highway and Transportation Officials (AASHTO) and Unified soil classification system (USCS) methods (not presented). Compression index of each of the soil samples were obtained by using the consolidation data and eleven (11) techniques namely Talyor's method, Cassagrade's method, Skempton method, mathematical method; etc. Compressive indices obtained using these techniques were evaluated statistically using total error, model of selection criterion (MSC) and statistical reliability (Oke, 2007; Oke *et al.,* 2009) with a particular attention to accuracy and good fitness.

RESULTS AND DISCUSSION

The index properties of the soil samples were in the range of 10.94 – 24.89 % (natural moisture content); 1575.86 – 1808.85 kg/m^3 (bulk density); 1433.17 – 1708.64 kg/m^3 (dry density) 16.40-41.08 (liquid limit); 0- 21.58 (plastic limit); 2.51 – 14.63 (plasticity index) and 0.03 – 0.309 (void ratio) respectively. Approximately 32-65 % of the soil samples pass 0.075mm (sieve number 200), which indicates that the soil samples were fine graded (clayey soil). Using USCS system the soil samples are designated as low plasticity clay (Figure 1). The relationship between the voids and the stresses are as presented in Figure 2.

Statistical evaluations of data can be conducted using various methods and techniques such as total error, coefficient of determination, model of selection criterion and chi squares. In this study statistical treatment was limited to total error, coefficient of determination and model of selection criterion. The total error, which is the sum of the squares of the errors between the obtained values and the predicted values, can be interpreted as a measure of variation in the values predicted unexplained by the values obtained data (18; 19). The lower the value of total error the higher the accuracy, validity and good fitness of the method. Total error (TE) can be computed using equation (12):

$$Err^2 = \sum_{i=1}^{n} \left(Y_{obsi} - Y_{cali} \right)^2 \qquad (12)$$

Where; Y_{cali} is the average values of each fitting procedure; Y_{obsi} is the obtained (experimental) values and Err^2 is the total error

Table 1 shows the computation of total error for each of the samples. The total error were 0.995, 0.732, 0.758, 0.786, 1.518, 1.011, 0.694, 0.606, 0.918, 0.752 and 0.570 for Skempton, mathematical model, Taylor, Cassangrande, Acar et al, Azzouz et al, Wroth and Wood, Nagaraj and Murthy[a], Nagaraj and Murthy[b] , Nagaraj and Murthy[c] and Al Khafaji and Andersland respectively. These results indicate that Al Khafaji and Andersland method has the least error, next to it is Nagaraj and Murthy[a], method and Acar *et al* method with the highest. Higher errors occur in Acar et al method. It can be attributed to the fact that the method was developed based on liquid limit, which is a function of many factors such soil particle and composition.

The statistical reliability (SR) is interpreted as the proportion of expected data that can be explained by the obtained data. Like coefficient of determination (CD) and model of selection criterion (MSC) the higher the value of SR, the higher the accuracy, validity, confidence level and the good fitness of the method. SR can be computed using equation (13) as follows:

$$SR = 1 - \frac{\left(Y_{obsi} - Y_{Cali} \right)}{Y_{obsi}} \qquad (13)$$

Where; SR is the statistical reliability

Like CD, MSC and TE the SR values using the methods ranges from 0.955 to 0.984 with the lowest SR values coming from Acar et al method and the largest SR values coming from Al Khafaji and Andersland method. Specifically, 0.976, 0.980, 0.980, 0.979, 0.955, 0.972, 0.980, 0.983, 0.973, 0.979 and 0.984 for Skempton, mathematical model, Taylor, Cassangrande, Acar *et al,* Azzouz *et al*, Wroth and Wood, Nagaraj and Murthy[a], Nagaraj and Murthy[b] , Nagaraj and Murthy[c] and Al Khafaji and Andersland respectively.

The model of selection criterion (MSC) has been interpreted as the proportion of expected data variation that can be explained by the obtained data. Like, CD the higher the value of MSC, the higher the accuracy, validity and the good fitness of the method. MSC can be computed using equation (14) as follows (Oke *et al.,* 2009; Babatola *et al.,* 2008):

$$MSC = \ln \frac{\sum_{i=1}^{n} \left(Y_{obsi} - \overline{Y_{obs}} \right)^2}{\sum_{i=1}^{n} \left(Y_{obsi} - Y_{cali} \right)^2} - \frac{2p}{n} \qquad (14)$$

Where; p is the number of parameters; n is the number of data points; MSC is the model of selection criterion; Y_{obsi} is the average of obtained (experimental) values and Y_{cali} is the average values of each fitting procedure

MSC values for these methods were 1.644, 3.006, 2.808, 2.618, 0.724, 1.594, 3.342, 4.373, 1.924, 2.855 and 4.947 for Skempton, mathematical model, Taylor, Cassangrande, Acar et al, Azzouz et al, Wroth and Wood, Nagaraj and Murthy[a], Nagaraj and Murthy[b] , Nagaraj and Murthy[c] and Al Khafaji and Andersland respectively. These results indicate that Al Khafaji and Andersland method has the highest MSC, next to this in MSC values are for Nagaraj and Murthy[a], method and Wroth and Wood, and mathematical model method. These results indicate that for scientific and engineering applications of settlement of soil Al Khafaji and Andersland method should be the first choice and to be followed by Nagaraj and Murthy[a], Wroth and Wood and mathematical model methods. In summary, based on the statistical evaluation these methods can be grouped into three main groups of:

i. The most accurate group which consist of Al Khafaji and Andersland; Nagaraj and Murthy[a], Wroth and Wood, and mathematical model methods. These are methods (techniques) with highest MSC and SR, but with low total error
ii. Medium techniques: these are techniques (methods) with moderate error, but with medium SR and MSC. These are Nagaraj and Murthy[c], Taylor, and Cassangrande
iii. Approximate methods: these are Skempton , Acar *et al*; Azzouz *et al* and Nagaraj and Murthy[b]

It should be emphasized that the values of C_c computed from mathematical model, Talyor and Cassegrade methods are obtained from the field consolidation line, which is based on the results of consolidation tests, while computation of C_c from Skempton and other methods are based on the liquid and plastic limits, natural moisture content, specific gravity and unit weights. Figure 3 (a, b and c) presents relationship between voids from these methods (techniques) and experimental voids.

Table1: Results of Statistical Assessment

Methods/Techniques	Model of selection criterion (MSC)	Total error (TE)	Statistical Reliability (SR)
Skempton	1.644	0.995	0.976
Mathematical model	3.006	0.732	0.980
Taylor	2.808	0.758	0.980
Cassangrande	2.618	0.786	0.979
Acar et al	0.724	1.518	0.955
Azzouz et al	1.594	1.011	0.972
Wroth and Wood	3.342	0.694	0.980
Nagaraj and Murthy[a]	4.373	0.606	0.983
Nagaraj and Murthy[b]	1.924	0.918	0.973
Nagaraj and Murthy[c]	2.855	0.752	0.979
Al Khafaji and Andersland	4.947	0570	0.984

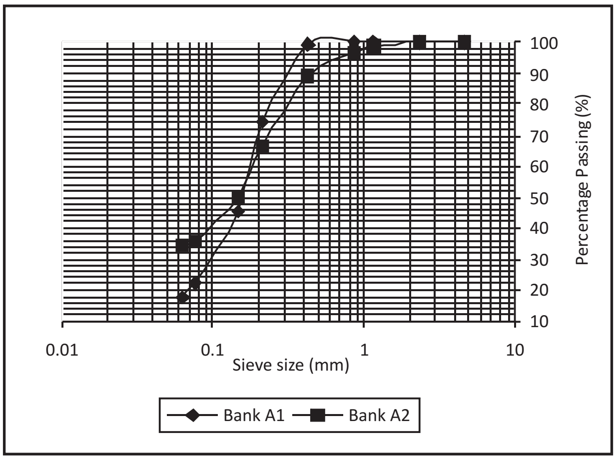

Figure 1(a) Particle Size Distribution of Soil Sample A

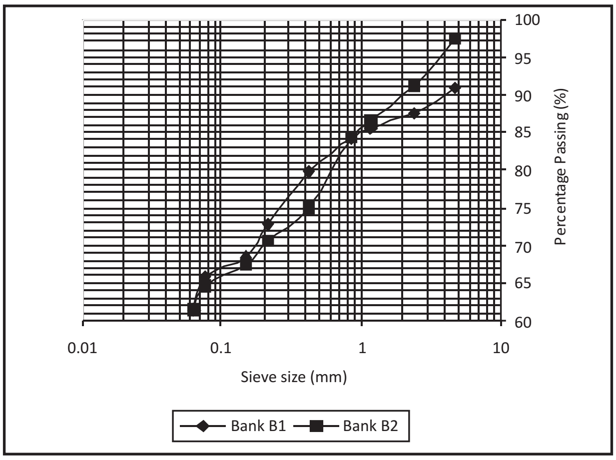

Figure 1(b) Particle Size Distribution of Soil Sample B

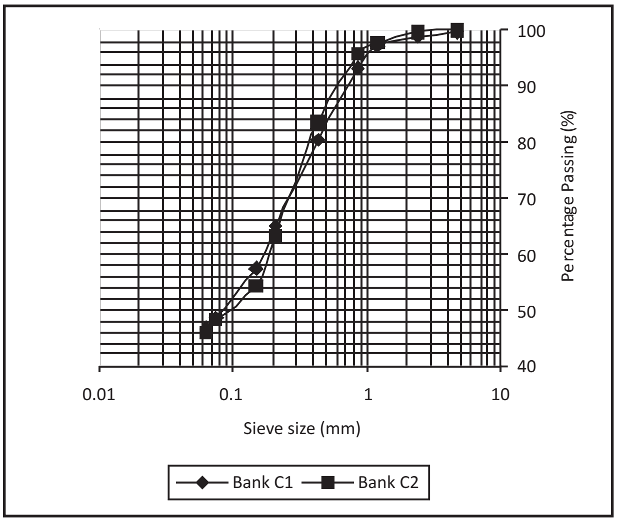

Figure 1(c) Particle Size Distribution of Soil Sample C

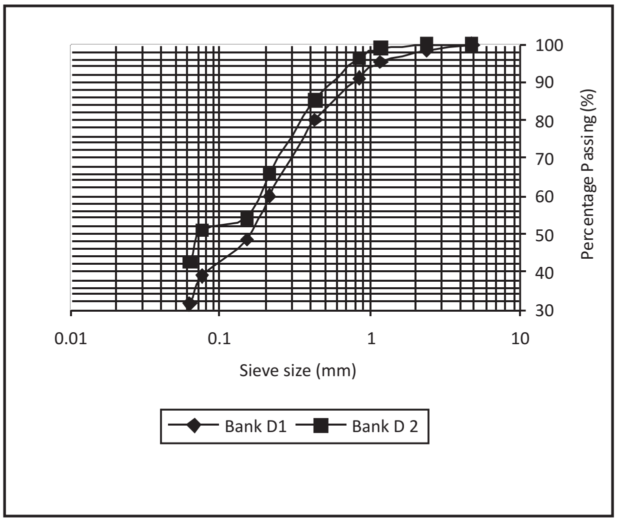

Figure 1(d) Particle Size Distribution of Soil Sample D

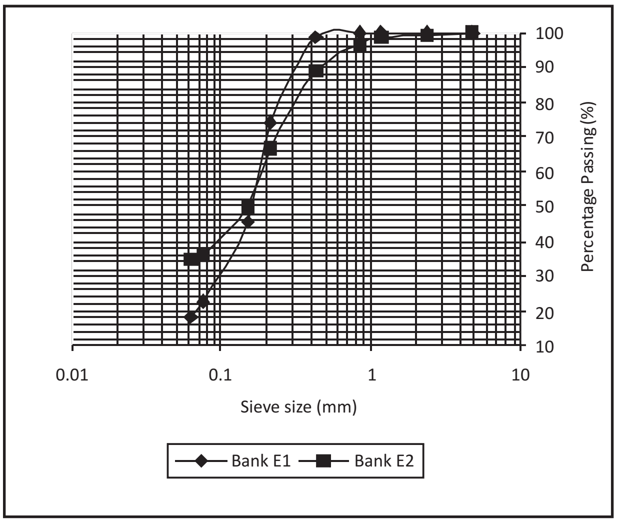

Figure 1(e) Particle Size Distribution of Soil Sample E

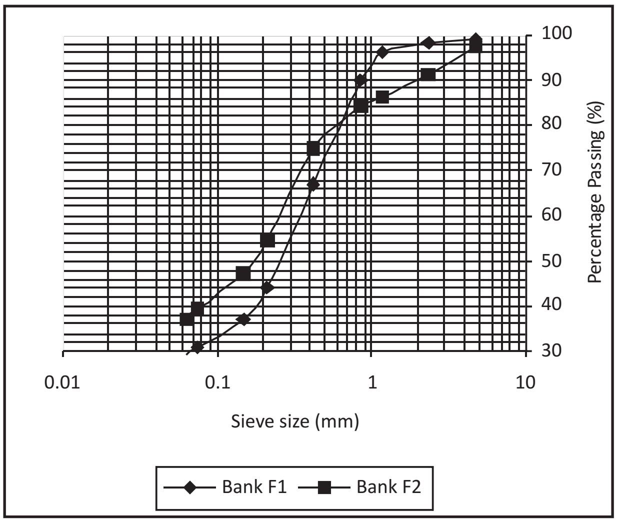

Figure 1(f) Particle Size Distribution of Soil Sample F

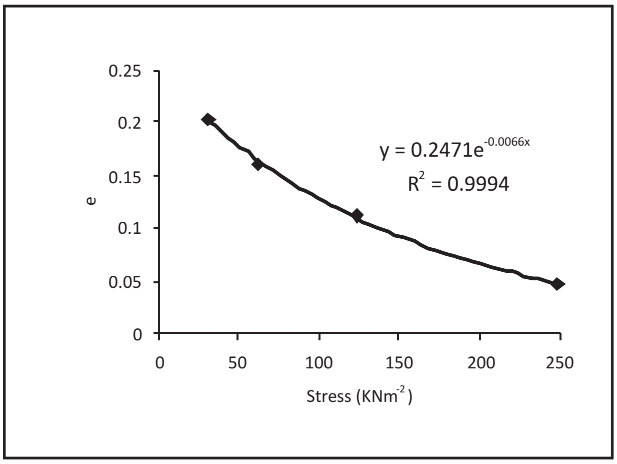

Figure 2 (a) Relationship between the Void Ratio and Normal Stress for Soil Sample A

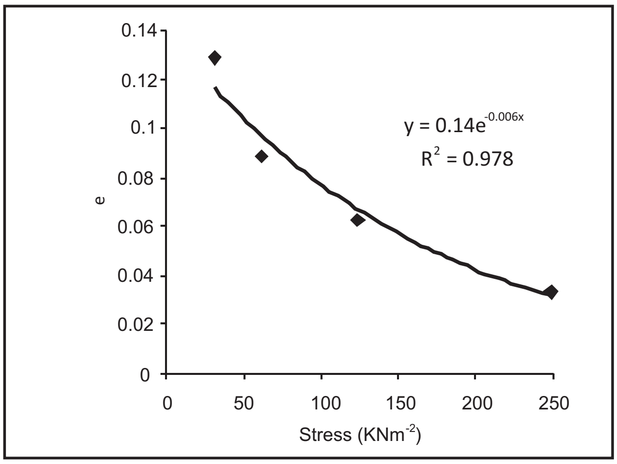

Figure 2(b) Relationship between the Void Ratio and Normal Stress for Soil Sample B

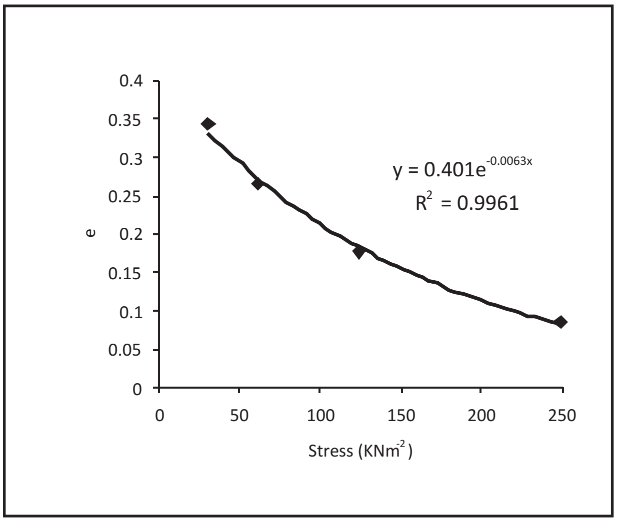

Figure 2(c) Relationship between the Void Ratio and Normal Stress for Soil Sample C

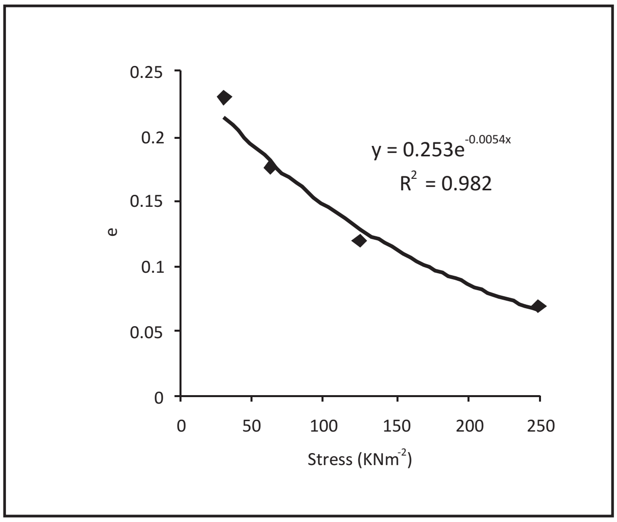

Figure 2 (d) Relationship between the Void Ratio and Normal Stress for Soil Sample D

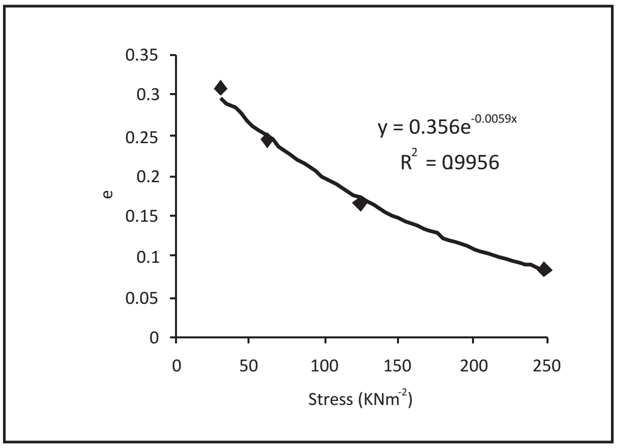

Figure 2 (e) Relationship between the Void Ratio and Normal Stress for Soil Sample E

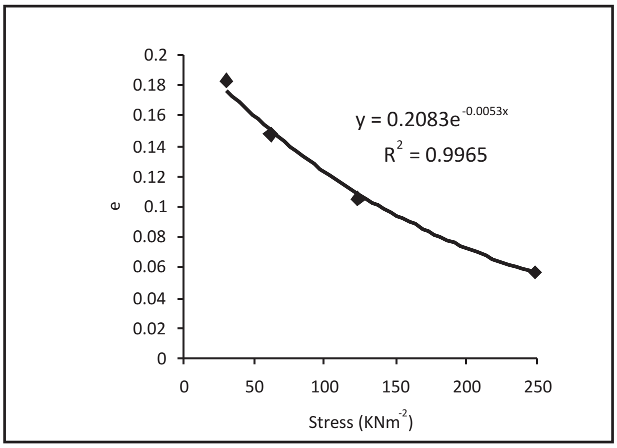

Figure 2 (f) Relationship between the Void Ratio and Normal Stress for Soil Sample F

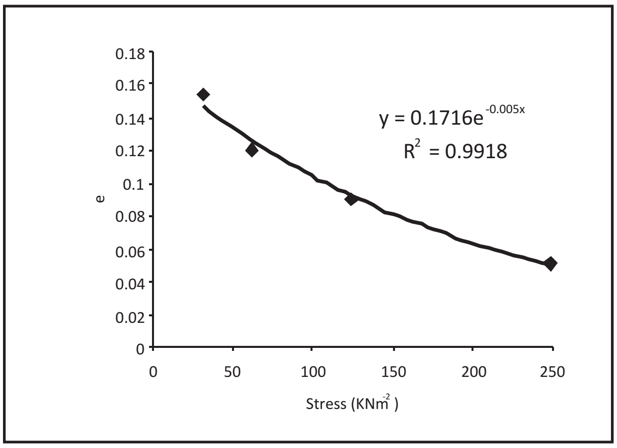

Figure 2 (i) Relationship between the Void Ratio and Normal Stress for Soil Sample I

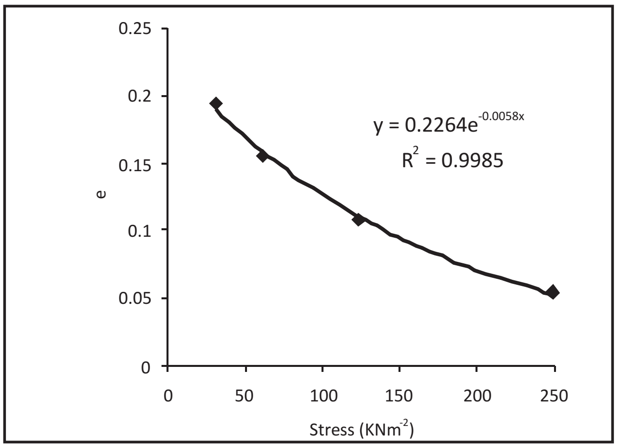

Figure 2 (j) Relationship between the Void Ratio and Normal Stress for Soil Sample J

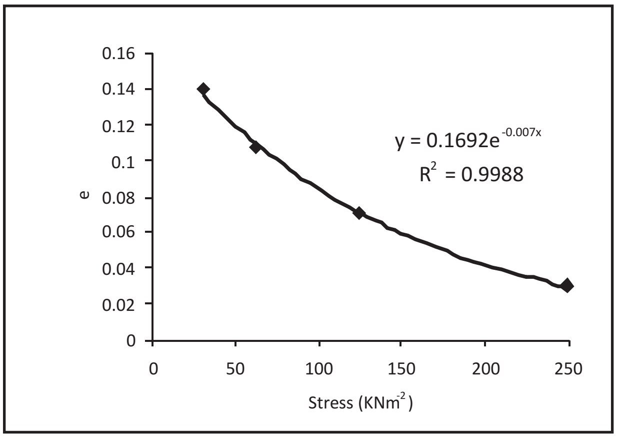

Figure 2 (k) Relationship between the Void Ratio and Normal Stress for Soil Sample K

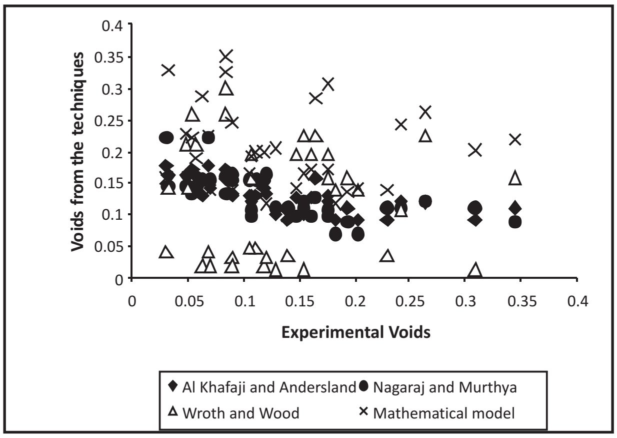

Figure 3(a) Relationship between Experimental Voids and Simulated Voids (The most accurate techniques)

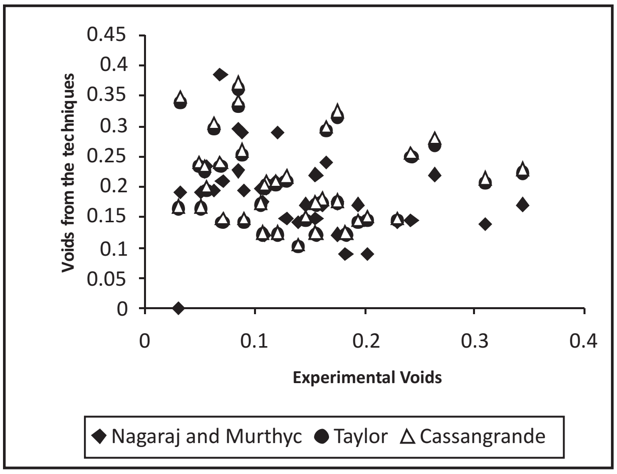

Figure 3(b) Relationship between Experimental Voids and Simulated Voids Medium accurate techniques)

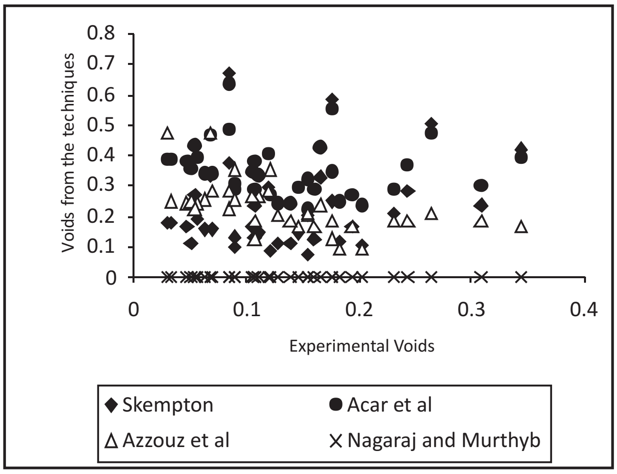

Figure 3(c) Relationship between Experimental Voids and Simulated Voids (Approximate techniques)

CONCLUSION

Based on the study it can be concluded that the:

i. C_c calculated using Al Khafaji and Andersland; Nagaraj and Murthy[a], Wroth and Wood, and mathematical methods are much more accurate than the calculation using Nagaraj and Murthy[c], Taylor, and Cassangrande, and

ii. calculation of C_c using Skempton , Acar *et al.*; Azzouz *et al.* and Nagaraj and Murthy[b] techniques is only an approximation and should be used only when settlement are acceptable or required (such as preliminary design).

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