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INVESTIGATION OF SHALLOW FOUNDATION SOIL BEARING CAPACITY AND SETTLEMENT CHARACTERISTICS OF MINNA CITY CENTRE DEVELOPMENT SITE USING PLAXIS 2D SOFTWARE AND EMPIRICAL FORMULATIONS

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ABSTRACT
This study investigated the soil bearing capacity and foundation settlement characteristics of Minna City Centre development site using standard penetration test (SPT) data obtained from10 SPT boreholes at 0.6, 2.1 and 3.6 m depths to correlate soil properties. Evaluation of foundation bearing capacity and settlement characteristics for geotechnical preliminary design of foundations was carried out using some conventional empirical/analytical models and numerical modelling. The aim was to investigate and determine the geotechnical parameters required for adequate design of Physical structures of the proposed Minna City Centre, at Minna the capital of Niger state. The SPT N-values were corrected to the standard average energy of 60% (N60) before the soil properties were evaluated. Using the corrected N-values, allowable bearing pressure and elastic settlement of shallow foundations were predicted at 50 kN/m² applied foundation pressure. The numerical analysis results using Plaxis 2D, a finite element code, shows the analytical/empirical methods of estimating the allowable bearing pressure and settlements of shallow foundations that provided acceptable results. Results obtained show that an average bearing capacity value of 100 – 250 kN/m² can be used for shallow foundations with embedment of 0.6 to 3.6 m on the site.

Keywords: *Bearing capacity, Foundation settlement, Standard Penetration Test, Numerical modelling, Plaxis 2D, Finite element method*

1. INTRODUCTION

Some Nigerian soils are problematic and adversely affect foundations of structures there by compromise the stability of the structures. These soil problems have resulted to excessive settlement, tilting and collapse of many buildings not only in Nigeria but also around the world [1 - 4].Numerical modelling method that better represents soil constitutive behaviour is required to develop an improved approximation of foundation soil bearing capacity and settlement. Also, there is need to investigate and determine the most appropriate methods that are most suitable to Nigerian soil peculiarities and distinctions based on SPT results, being the most common and economical geotechnical field test used in Nigeria. The study focused on the prediction of foundation soil bearing capacity and settlement based on Standard Penetration Test (SPT) N-values using empirical/analytical (deterministic) models and Plaxis 2D numerical modelling in the proposed Minna City Centre, at Minna the capital of Niger state of the Federal Republic of Nigeria.

Niger State is covered by two major rock formations, the sedimentary and basement complex rocks. Minna occupies the central portion of the Nigerian basement complex. The Minna area comprises of met sedimentary and meta-igneous rocks which have undergone polyphase deformation and metamorphism. These rocks have been intruded by granitic rocks of Pan-African age. Five lithostratigraphic units have been recognized in Minna area: The schist which occur as a flat laying narrow southwest-northeast belt at the central part of Minna with small quartzite ridge parallel to it, the gneiss occur as a small suites at the northern and southern part of the area forming a contact with the granite. Feldspathic rich pegmatite is bounded to the east, with average width of 65meters and 100 meters long, the pegmatite host tourmaline. Granitic rocks dominate the rock types in the area and vary in texture and composition [2].

When a soil is subjected to an increase in compressive stress due to foundation load, the resulting soil compression is known as settlement of the foundation

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[5].In many parts of the world, Standard Penetration Test (SPT) is still considered one of the most common *in situ* tests used to evaluate the strength of coarse grained soils [6]. Bowles [7] stated that 85–90% of conventional foundation design in North and South America is made using SPT results. SPT data have been used in correlations for unit weight, relative density, angle of internal friction and unconfined compressive strength [8].

The numerical analysis of foundation settlement and bearing capacity were performed using Plaxis 2D, a non-linear finite element software. Plaxis 2D is used for two-dimensional analysis of deformation and stability in geotechnical engineering. It uses advanced soil constitutive models for the simulation of the non-linear, time dependent and anisotropic behaviour of soils and rocks. The input data in Plaxis 2D are index, elastic and strength parameters, obtained from the processed SPT N-values. It generates the unstructured 2D finite element meshes with options of global and local mesh refinements. Using its calculation facilities, Plaxis 2D undergoes a calculation process and presents the calculation and model outputs which can be accessed in animation and/or numerical forms.

The objectives of this research was to estimate the bearing capacity and settlement of foundation soils from measured penetration resistance in terms of the SPT corrected N-values, to evaluate design equations for foundation settlements and bearing capacity using different constitutive models based on SPT results, to model foundation settlement numerically using PLAXIS 2D software and compare the results of the empirical/analytical methods with those of numerical analysis in order to identify the best analytical methods that could be used for the prediction of foundation settlements and bearing capacity in Nigeria considering her peculiar soil properties.

2. RESEARCH METHODS

2.1 Data and Analysis

The research made use of standard penetration test (SPT) data (using Donut hammer type) collected from 10 test holes (30 data set) distributed over the study area. Bearing capacity and foundation settlement estimations were made at depths of 0.6, 2.1 and 3.6 m and settlement was determined at applied foundation pressure of 50 kN/m^2.Based on empirical/analytical methods, bearing capacity and settlement were evaluated using some most commonly used models presented in Tables 1 and 2 of the Appendix.

2.1.1 Bearing capacity

For the allowable bearing pressures of shallow foundations, footing plan dimensions of 2 m by 2 m by 0.4 m for length, breadth and depth, respectively were assumed with safety factor of 3.

2.1.2 Elastic Settlement of Foundations

For the elastic settlement of shallow foundations, plan dimensions of 2 m by 2 m by 0.4 m for length, breadth and depth respectively were assumed.

2.2 Standard Penetration Test

The SPT was conducted in accordance with ASTM D-1586-99 [9]. The standard split tube sampler has an inside diameter of 34.93 mm and an outside diameter of 50.8 mm. The numbers of blows required for a spoon penetration of three 150 mm intervals are recorded. The number of blows required for the last two intervals are added to give the standard penetration number, N, at that depth. This number is generally referred to as the N-value which was a correction to an average energy ratio of 60% (N_{60}). SPT was conducted at intervals of 1.5 m. According to Bezgin [11] a correction to average energy ratio of 60% (N_{60}) is required to SPT N-values because of the greater confinement caused by the increasing overburden pressure. The correction factors used in the study are those proposed by Das [12] to standardize the field penetration number as a function of the input driving energy and its dissipation around the sampler into the surrounding soil.

2.3 Numerical Modelling

Numerical analysis of foundation settlement and bearing capacity were performed using a non-linear finite element analysis with a finite element code. Plaxis, which is a finite element method (FEM) software for deformation analysis and modelling of geotechnical problems was used in the study. [10]

3. RESULTS AND DISCUSSION

3.1 Corrected SPT N-Values (N_{60})

The variation of N_{60} with depth of test is shown in Figure 1. N_{60} increased with depth having the highest value of 74.97at 3.6 m boring depth in BH 3 and the lowest value in BH 5.Such high values of N_{60} are associable to crystalline formations from the basement complex. Details about soil formations in Nigeria can be found in Ola [13]. N_{60} values are needed for more accurate design analyses and have less variability or scatter due to test method.

3.2 Bearing Capacity

Variations of allowable bearing capacity with boring depth are shown in Figures 2 and 3 for BHs 3 and 5 respectively. The results presented herein are for BHs 3 and 5 that respectively has the highest and lowest values of N_{60}.Based on the method proposed by Meyerhof [14] and Plaxis, applied foundation pressures in the range of 100 – 250 kN/m² were proposed for use in the site under investigation at shallow depths (depths in the range of 0.6 - 3.6 m). Atat et al. [15] suggested an average allowable bearing pressure of 154.78 kN/m² for shallow foundations in Akwa-Ibom State. Salahudeen, *et al.* [1] suggested applied foundation pressures in the range of 120 – 200 kN/m² at shallow depths (depths in the range of 0.6 - 3.6 m) for South South geopolitical zone. Also, Salahudeen, *et al* [2] suggested applied foundation pressures in the range of 135 – 260 kN/m² at shallow depths (depths in the range of 0.6 - 3.6 m) for South West geopolitical zone. Based on the numerical modelling results, methods proposed by Meyerhof [14] and Peck et al. [16] were found to give good estimations of allowable bearing capacity of foundation.

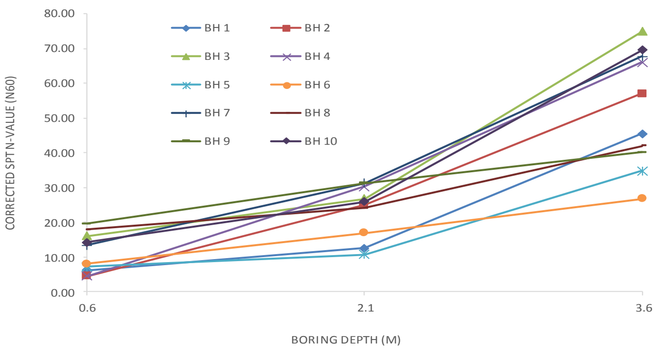

Figure 1: Variation of corrected N-values with boring depth

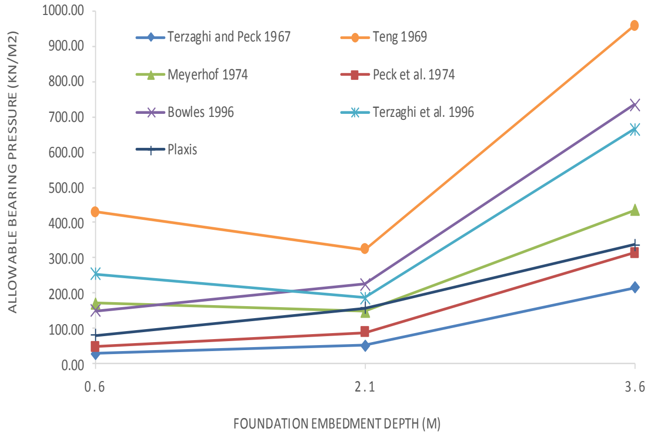

Figure 3: Variation of allowable bearing pressure with foundation embedment depth (BH 5)

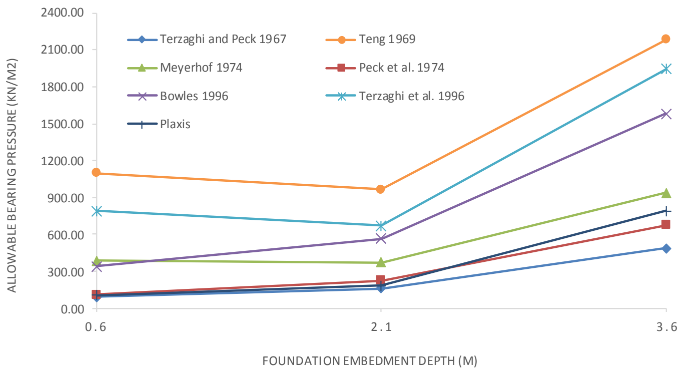

Figure 2: Variation of allowable bearing pressure with foundation embedment depth (BH 3)

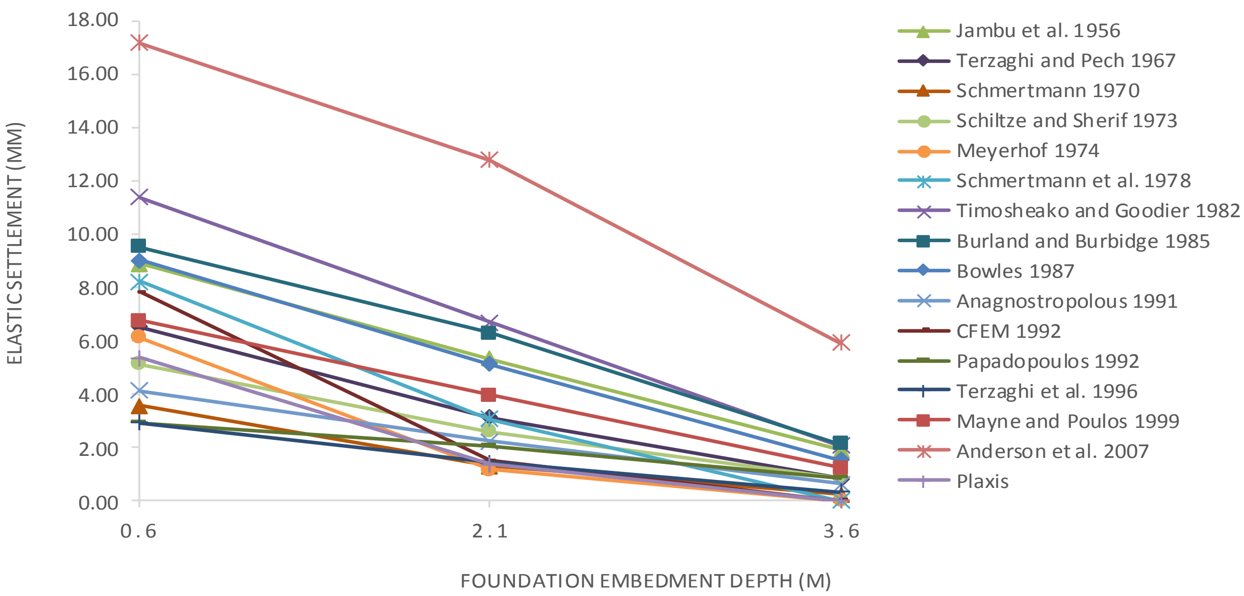

Figure 4: Variation of elastic settlement with foundation embedment depth (BH 3)

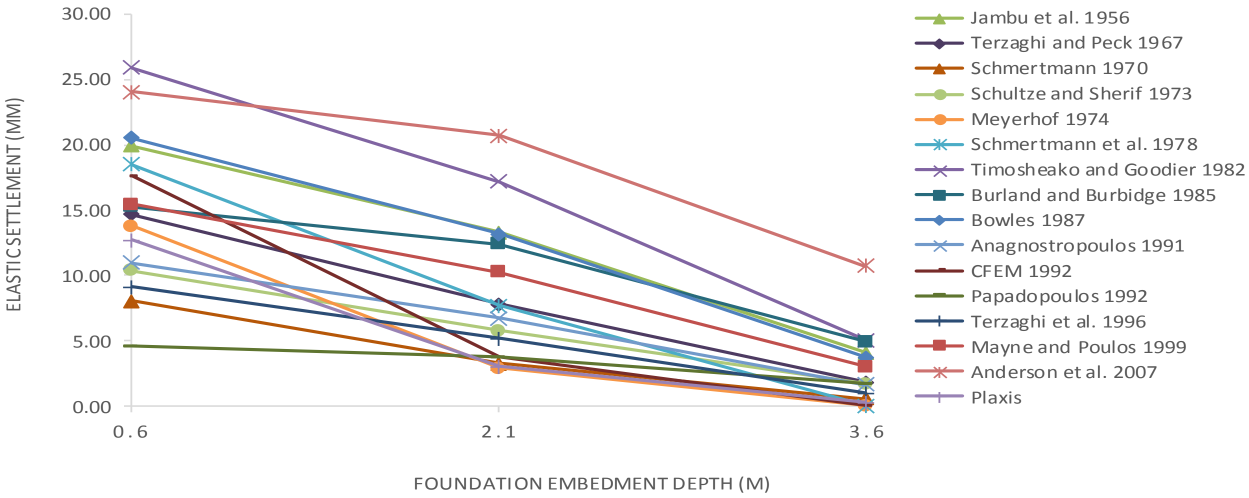

Figure 5: Variation of elastic settlement with foundation embedment depth (BH 5)

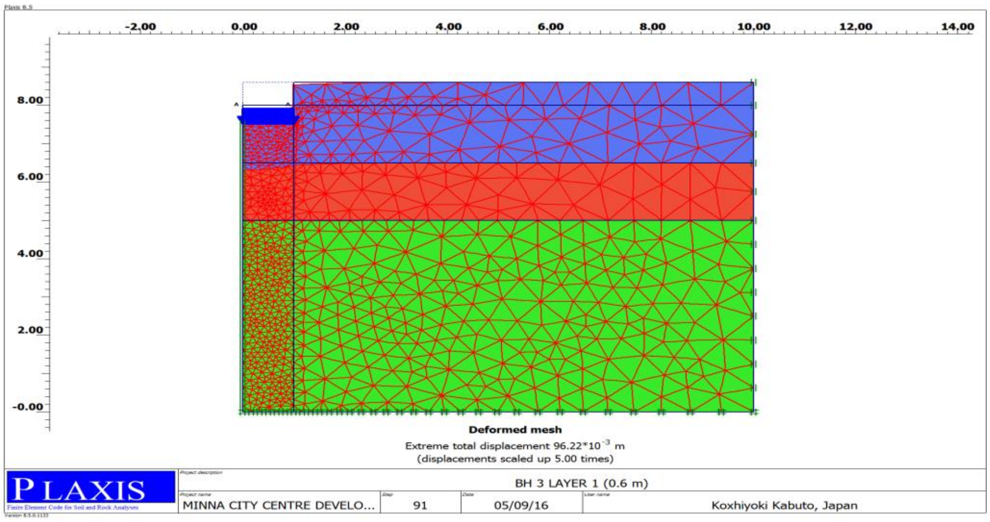

Figure 6: Numerical analysis mesh showing deformation of the soil body at collapse at 0.6 m embedment depth (BH 3)

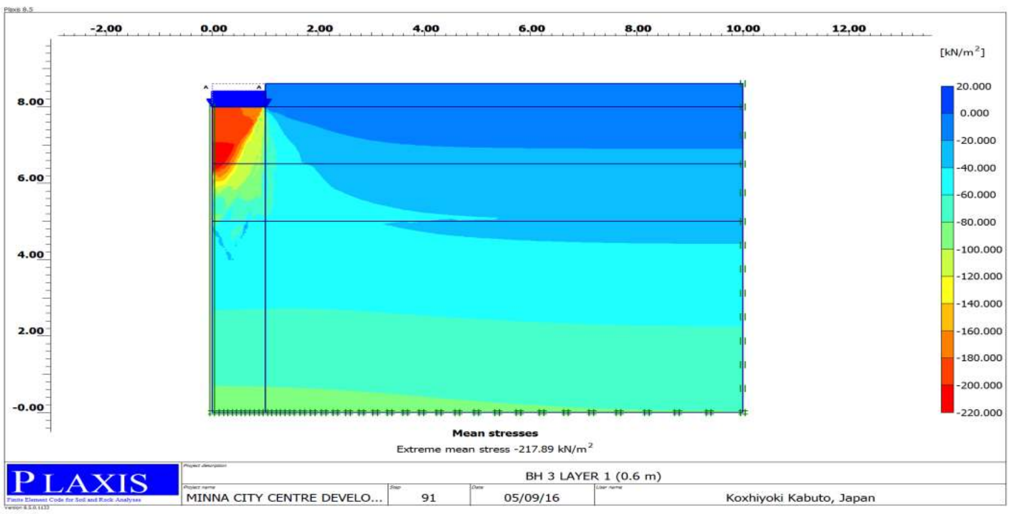

Figure 7: Numerical analysis result of stress distribution up to the collapse of the soil body at 0.6 m embedment depth (BH 3)

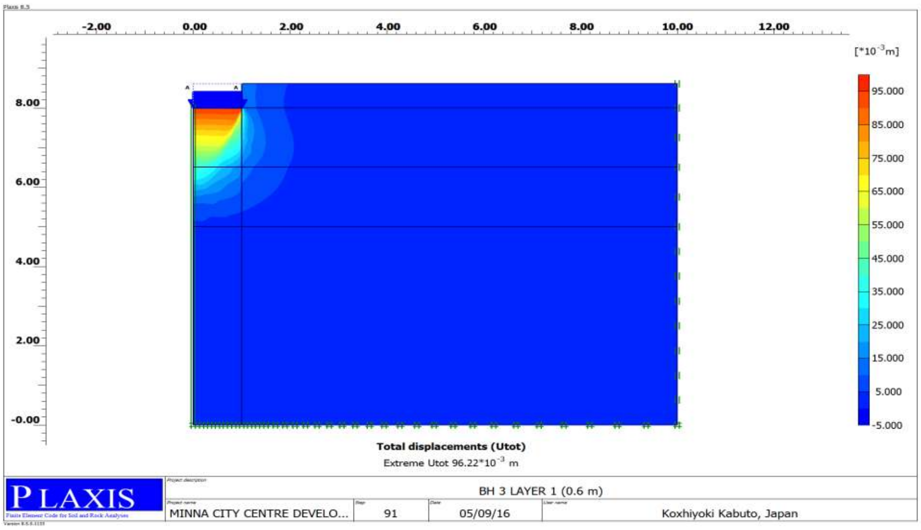

Figure 8: Numerical analysis result of settlement up to the collapse of the soil body at 0.6 m embedment depth (BH 3)

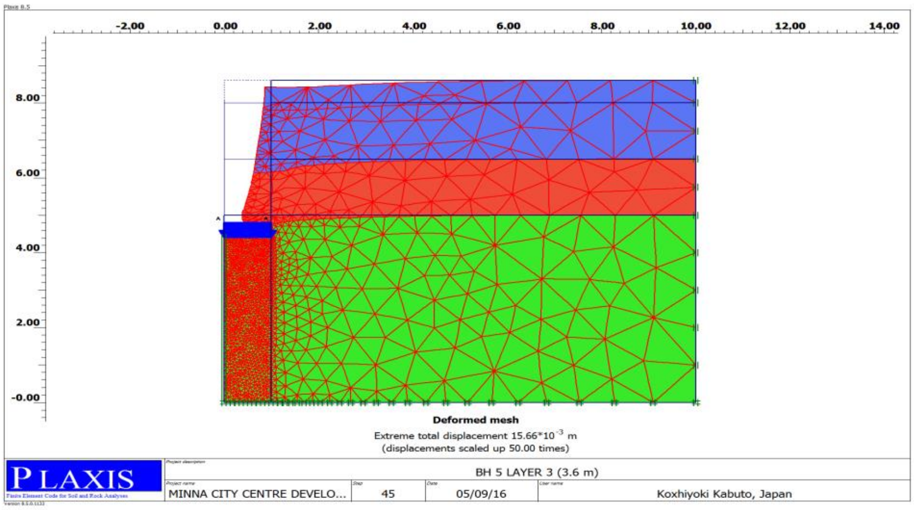

Figure 9: Numerical analysis mesh showing deformation of the soil body at collapse at 3.6 m embedment depth (BH 5)

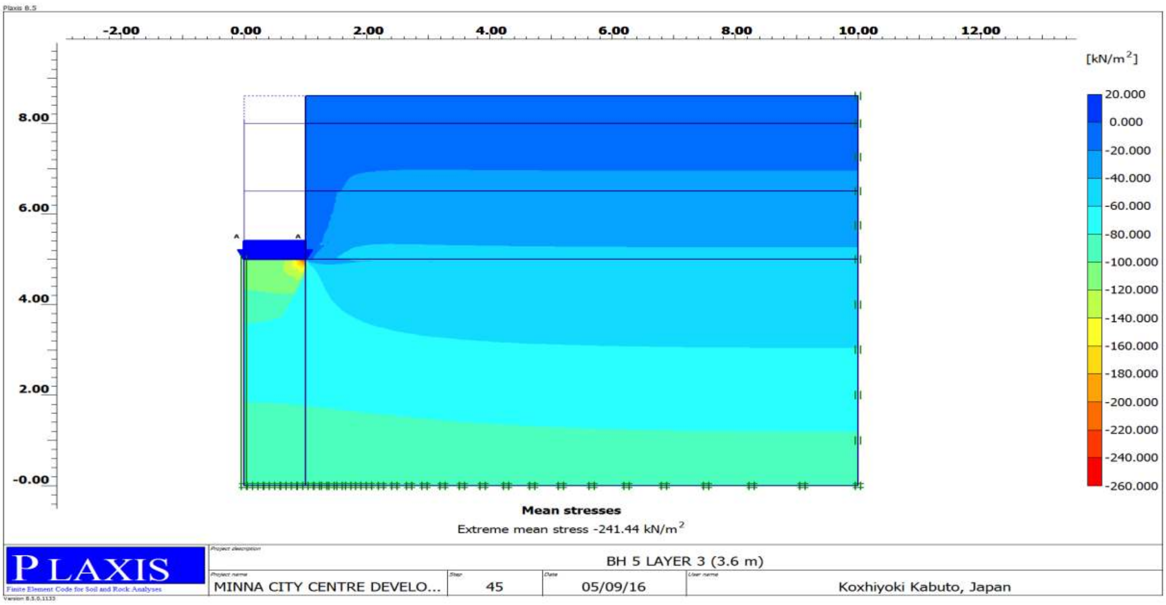

Figure 10: Numerical analysis result of stress distribution up to the collapse of soil body at 3.6 m embedment depth (BH 5)

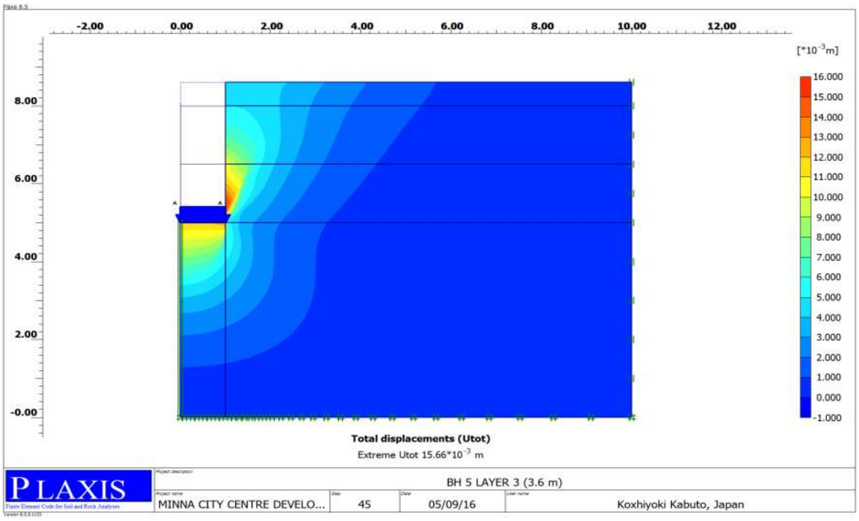

Figure 11: Numerical analysis result of settlement up to the collapse of the soil body at 3.6 m embedment depth (BH 5)

3.3 Elastic Settlement of Foundations

Variations of elastic settlement of foundations with boring depth for various applied pressures are shown in Figures 4 and 5 for BHs 3 and 5 respectively. The figures show the different empirical/analytical models commonly used in computing elastic settlement of shallow foundations. The N_{60} values indicate that settlement values will be highest in BH 5 due to low N_{60} values at thatpoint as confirmed in the elastic settlement results. The recorded trend is consistent with observations of reported by Salahudeen *et al,* [1]. A comparison carried out by Shahin et al. [20] based on field measurement and artificial neural networks (ANN) results among methods proposed by Schmertmann [21], Schltze and Sherif [22] and Meyerhof [23] rated the Schltze and Sherif [22] method as the best for estimating shallow foundation settlements. However, based on the numerical modelling results, comparison of the fifteen empirical/analytical methods considered in this study, showed that the Schltze and Sherif [22],Meyerhof [14], Schmertmann *et al* [23], Canadian Foundation Engineering Manual (CFEM) [24] as well as the Mayne and Poulos [25] methods gave good estimations of foundation settlement.

The numerical analysis results of soil body deformation, stress distribution and settlement respectively at collapse of the soil body for the at 0.6 m embedment depth(for BH 3) and 3.6 m depth (for BH 5)are shown in Figures 6 - 11.

4. CONCLUSIONS AND RECOMMENDATIONS

The study considered N-values corrected to the standard average energy of 60% (N_{60}) as input data in analytical/empirical and numerical models used to predict foundation settlement and bearing capacity for adequate design of Physical structures of the proposed Minna City Centre, at Minna the capital of Niger state. Based on the results of this study, the following conclusions were made.

a) Allowable bearing pressures of 100 - 250 kN/m^2 at depths between 0.6 and 3.6 m are adequate for the site.
b) Settlements of footings embedded at depths in the range 0.6 – 3.6 m and applied foundation pressures of 50 kN/m^{2}are within the limiting value of 25 mm value of allowable total settlement stipulated by Eurocode 7 [33].
c) A comparison of the six empirical/analytical methods considered in this study showed that the Meyerhof [14] and Peck et al. [16] methods gave good estimations of allowable bearing capacity of foundation soils.
d) A comparison of the fifteen empirical/analytical methods considered in this study, showed that the Schltze and Sherif [22], Meyerhof [14], Schmertmann*et al.* [23], Canadian Foundation Engineering Manual (CFEM) [24] as well as the Mayne and Poulos [25] methods gave good estimations of foundation settlement.
e) Shallow foundations in the investigated site should be placed at a minimum depth of 1.0 m to avoid excessive settlement.
f) Results of the study can be used for adequate design of light weight structures on the site.

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6. APPENDIX

Table 1: Empirical/analytical models for soil bearing capacity analysis

Property	Model	Reference
Corrected N-value	$N_{60} = \frac{N_{\eta H}\eta_B\eta_S\eta_R}{60}$	[12]
Allowable bearing pressure of shallow foundations	$q_a = 53((N_1)_{60} - 3)\frac{(B+0.3)^2}{2B}R_w R_d$	[18]
	$q_a = 0.32(N_1)_{60}R_D\frac{(B+0.3)^2}{B}S_a$	[14]
	$q_a = 0.44C_w(N_1)_{60}S_a$	[16]
	$q_a = 0.348(N_1)_{60}R_D\frac{(B+0.3)^2}{B}S_a$	[7]
	$q_a = S_c\frac{((N_1)_{60})^{1.4}}{1.7B^{0.75}}$	[19]

Table 2: Empirical/analytical models for elastic settlement analysis

S/N	Model	Reference
1	$S_e = \mu_1\mu_0\frac{q^B}{E}$	[26]
2	$S_e = \frac{3q}{N_{60}}\left(\frac{B}{N_{60}}\right)^2 C_W C_D$	[17]
3	$S_e = C_1C_2q\sum_0^{2B}\frac{I_z}{E_s}\Delta z$	[21]
4	$S_e = \frac{fq\sqrt{B}}{N^{0.87}\left(1+\frac{0.4D_f}{B}\right)}$	[22]
5	$S_e = \frac{\Delta PB}{2\Delta\hat{C}_r}$	[14]
6	$S_e = q\sum_0^{Z_1}\frac{I_z}{E_s}Z_1$	[23]
7	$S_e = qB\frac{1-\mu^2}{E_s}I_s$	[27]
8	$S_e = 0.14\alpha\left(\frac{1.71}{(N_{60(a)})^{1.4}}\right)\left(\frac{1.25(L/B)}{0.25+(L/B)}\right)^2$	[28]
9	$S_e = q_0\alpha B^1\left(\frac{1-\mu_s^2}{E_s}\right)I_sI_f$	[29]
10	$S_e = \frac{2.37q^{0.87}B^{0.7}}{N^{1.2}}$	[30]
11	$S_e = \frac{q_0Bi_c}{E_s}$	[24]
12	$S_e = \left(\frac{qB}{E_s}\right)f$	[31]
13	$S_e = B^{0.75}\frac{1.7}{\acute{N}_{60}^{1.4}}q$	[19]
14	$S_e = \frac{q_0B_eI_GI_FI_E}{E_0}(1-\mu_s^2)$	[25]
15	$S_e = \frac{12q}{N'}\left(\frac{B}{B+1}\right)^2$	[32]

Where:

N_{60} = Corrected standard penetration number for field conditions

$(N_1)_{60}$ = N_{60} correction for overburden pressure

N = Measured penetration number (N-value)

η_H = Hammer efficiency (%)

η_B = Correction for borehole diameter

η_S = Sampler correction

η_R = Correction for rod length

σ^1_0 = Effective overburden pressure in kN/m^2

P_a = Atmospheric pressure = 100 kN/m^2

E_s = Elastic modulus of soil

μ = Poisson’s ratio of soil

q_n = Net pressure on the foundation (kN/m^2)

Es = Appropriate value of elastic modulus of soil (kN/m^2)

q = Applied foundation pressure (kN/m^2)

S_e = Elastic settlement (mm)

B = Width of foundation (m)

D_f = Depth of embedment (m)

B_R = Reference width = 0.3 m

H = Thickness of the compressible layer (m)

L = Length of foundation (m)