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Original Research Article

Assessment of Foundation Settlement Prediction using Analytical and Numerical Techniques

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ABSTRACT

There is a longstanding problem of disparities among analytical methods used by foundation engineers to predict footing settlement. Thus, this study compared several analytical methods using numerical techniques as basis. Nine footing embedment depths of 0.6, 2.1, 3.6, 5.1, 6.6, 8.1, 9.6, 11.1 and 12.6 m with applied foundation pressure of 200 kN/m² using a 2 m x 2 m x 0.4 m *pad footing were considered. Standard penetration test (SPT) N-values corrected to the standard average energy of 60% (N_{60}) obtained from the six geo-political zones of Nigeria were used to obtain the input parameters used for the prediction of foundation settlement using analytical and numerical modelling techniques. Three analytical methods (each of empirical, semi-empirical and elastic) and three numerical modelling software based on finite element codes were used to model foundation settlements and their results compared. Footing settlement values of 30.48, 27.27, 24.28, 25.46, 31.85 and 56.26 mm were obtained for the North Central at 2.1 m footing embedment depth for the empirical, semi-empirical, elastic, Plaxis 3D, Plaxis 2D and Geo-Studio respectively. The methods considered were rated and the best performance at shallow depths was observed in the semi-empirical method proposed by Schmertmann et al. which was recommended for the prediction of foundation settlements.*

1. INTRODUCTION

Housing demands due to the growing population and migration of people to urban areas in all the six geo-political zones of Nigeria (North Central (NC), North East (NE), North West (NW), South East (SE), South South (SS) and South West (SW)) is a serious challenge to the government. The fact that the limited areas of land suitable for building constructions have been exhausted, construction on less desirable subgrades, such as soft saturated clays and silts is increasing in order to meet the demands of the society (Osinubi, 1992). These demands necessitate the need for alternative construction methods so as to provide fast, safe and affordable quality housing. Efforts have been made to move from the traditional building construction techniques to a more innovative and advanced construction method to meet these demands (Salahudeen and Sadeeq, 2016).

Some Nigerian soils are problematic and pose serious threats and adverse effects to foundation of structures and the structures themselves (Osinubi, 1993a). These soil problems manifest in the form of excessive settlement, tilting and collapse of many buildings not only in Nigeria but also around the world (Osinubi, 1993b; Osinubi 1995; Katzenbach et al., 2005; Salahudeen, 2017). The design procedures in use today can produce unreasonable displacement estimates and incorporate a large amount of uncertainty (Roberts and Misra, 2010). Methods that better represent soil constitutive behaviour are required to develop an improved approximation of immediate settlement. As part of this effort, an extensive investigation to determine a reliable and more effective model for foundation settlement prediction using results of *in-situ* tests was conducted in this study.

One of the most significant components of any structure is its foundation. Foundations are integral to overall structural performance. They help in bearing and transmitting the structural loads to the soil, reduce settlements, prevent possible movement of structures due to periodic shrinkage and swelling of sub-soils, allow building over water-logged grounds, resist uplifting or overturning forces due to wind, resist lateral forces due to soil movement and control water penetration and dampness (Salahudeen, 2017). To perform satisfactorily, foundations must have two main characteristics: they have to be safe against overall shear failure in the soil that supports them and they must not undergo excessive settlement (Das, 2011). The design of shallow foundations is generally controlled by settlement rather than bearing capacity (Shahin et al., 2002). As a consequence, settlement prediction is a major concern and is an essential criterion in the design process of foundations. Consistent and accurate prediction of settlement is yet to be achieved by the use of a variety of methods ranging from purely empirical to complex nonlinear finite elements (Poulos, 1999).

Numerical modelling is a powerful mathematical tool that makes it possible to solve complex engineering problems. A model is a structure or framework designed to symbolize a physical concept or phenomenon (Salahudeen and Sadeeq, 2016). The finite element method (FEM) is a well- established numerical analysis technique used widely in many civil engineering applications both for research and the design of real engineering problems (Ornek et al., 2012). The constitutive behaviour of soils can be successfully modelled with numerical analyses. The finite element method is one of the mathematical methods in which continuous media is divided into finite elements with different geometries (Salahudeen and Sadeeq, 2017). It provides the advantage of idealizing the material behaviour of the soil, which is non-linear with plastic deformations and is stress-path dependent, in a more rational manner (Ornek et al., 2012).

The finite element method can also be particularly useful for identifying the patterns of deformations and stress distribution during deformation and at the ultimate state. Because of these capabilities of the finite element method, it is possible to model the construction method and investigate the behaviour of shallow footings and the surrounding soil throughout the construction process, not just at the limit equilibrium conditions (Laman and Yildiz, 2007). The finite element method (FEM) allows modelling complicated non linear soil behaviour through constitutive model, various geometrics with different boundary conditions and interfaces. It can predict the stresses, deformations and pore pressures of a specified soil profile (Subramaniam, 2011).

In this study, standard penetration test (SPT) results were used because the test is the most common field test in Nigeria. Bowles (1996) 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 (Kulhawy and Mayne, 1990). The specific objectives of this study were to estimate the settlement of foundation soils from measured penetration resistance in terms of the SPT N-value at varying depths, to evaluate some highly rated, recommended and applied design equations that are widely accepted for foundation settlements using different constitutive models and to model foundation settlement numerically using geotechnical dedicated modelling software and compare the results of the analytical methods with those of numerical analysis.

2. METHODOLOGY

2.1. Location and Geology of the Study Area

Nigeria lies between latitude 4° and 14° N and longitudes 2° and 15° E. It is bounded by the Gulf of Guinea in the South and the southern edge of the Sahara Desert in the north. The country has a surface area of over 90 million km^2 (Ola, 1983). The geology of Nigeria is dominated by crystalline and sedimentary rocks which occur in about equal proportions. The crystalline rocks are largely distributed around three main areas: (i) A roughly circular area in the North Central part of the country (ii) A triangular area in the South-western part of the country and (iii) A third area in the eastern and north-eastern parts where crystalline rocks occur in three main units. All the areas of crystalline rocks are bounded by sedimentary basins in Nigeria (Ola, 1983). The sedimentary rocks are distributed within seven sedimentary basins namely: Dahomey basin, Niger delta basin, Anambra basin, Benue trough, Chad basin, Bida basin and Iullemeden basin. The basement complex, which characteristically yields radiometric ages in excess of 500 million years occupies about forty percent of the total surface area of Nigeria (Grant, 1971). A proper evaluation of foundation settlements in the study areas will enhance a far better insight of the soil type characterization. A map of soil groups in Nigeria is shown in Figure 1.

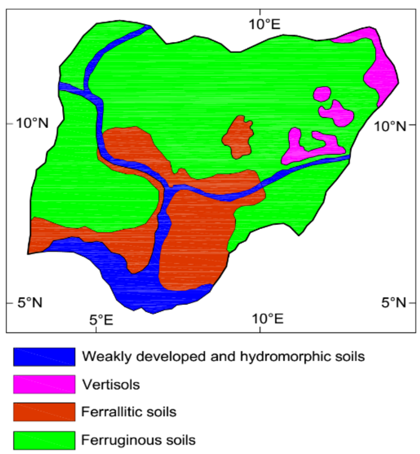

Figure 1: Map of Nigeria showing the soil groups (Adapted from Ola, 1983)

2.2. Data Collection

This study made use of standard penetration test (SPT) data obtained from 4,181 test holes (i.e., 37,629 data sets) distributed over the study area (the six geo-political zones of the Federal Republic of Nigeria) using Donut hammer equipment. Foundation settlements were determined at embedment depths 0.6, 2.1, 3.6, 5.1, 6.6, 8.1, 9.6, 11.1 and 12.6 m for applied foundation pressure 200 kN/m^2 using three analytical methods and three non-linear finite element codes. Computation of foundation settlement was done at pad footing of 2 m x 2 m x 0.4 m for length, width and thickness respectively.

2.3. Analytical Methods

Based on analytical methods, foundation settlement estimations were performed using three common settlement prediction models to compare with the results of numerical analysis as shown in Table 1.

Table 1: Analytical models for settlement prediction

Method category	Expression	Definitions	Reference
Corrected N-value (N_{60})	$N_{60} = \frac{N\eta_H\eta_B\eta_S\eta_R}{60}$	N_{60}=Corrected standard penetration number for field conditions 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	Seed et al. (1985) and Skempton (1986).
Empirical	$S_e = 0.14\alpha B_R\left(\frac{1.71}{(N_{60(a)})^{1.4}}\right)\left(\frac{1.25(L/B)}{0.25+(L/B)}\right)^2\left(\frac{B}{B_R}\right)^{0.7}\left(\frac{q}{P_a}\right)$ $N_{60(a)} \approx 15 + 0.5(N_{60} - 15)$ $\alpha = \frac{H}{Z'}\left(2 - \frac{H}{Z'}\right) \le 1$ $\frac{Z'}{B_R} = 1.4\left(\frac{B}{B_R}\right)^{0.75}$	S_e = Elastic settlement (mm) q = Applied foundation pressure (kN/m^2) $N_{60(a)}$ = Adjusted N_{60} value B = Width of foundation (m) L = Length of foundation (m) B_R = Reference width = 0.3 m α = Depth of stress influence correction factor H = Thickness of the compressible layer (m) Z'= Factor correlated with B and B_R	Burland and Burbidge (1985)
Semi-Empirical	$S_e = qC_1C_2\sum_0^{Z_1}\frac{I_z}{E_s}Z_1$ $Z_1 = 2B\left[1 + \log\left(\frac{L}{B}\right)\right]$ $E_s = 2.5q_c$ $I_z = 0.5 + 0.1\left(\frac{q}{\sigma_0'}\right)^{0.5}$ $C_1 = 1 - 0.5\frac{q_o}{q} \ge 0.5$ $C_2 = 1 + 0.2\log\left(\frac{t}{0.1}\right)$	C_1= Correction factor for embedment of foundation C_2= Correction factor to account for creep in soil I_z = Strain influence factor Z_1 = Represents the depth of influence below which the vertical strains under the foundation are negligible q = Net effective pressure applied at the level of the foundation (kN/m^2) q_o = Effective overburden pressure at the level of the foundation (kN/m^2) t= Time (in years) q_c = Cone penetration resistance (kN/m^2) $q_c = 400N_{60}$	Schmertmann et al. (1978)
Elastic	$S_e = \frac{q_0 B i_c}{E_s}$	E=Elastic modulus of soil (kN/m^2) μ = Poisson's ratio of soil i_c=Influence factors which takes into account the layer thickness and foundation geometry	CFEM (2006)

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The three analytical methods considered in this study were chosen based on their recommendations, acceptance and wide application by foundation engineers and researchers in the literatures. The models are empirical, semi-empirical and elastic in nature which were proposed by Burland and Burbidge (1985), Schmertmann et al. (1978) and Canadian Foundation Engineering Manual (2006) respectively. Burland and Burbidge (1985) proposed an empirical method for calculating the elastic settlement of sandy soil using the standard penetration number (N_{60}). Schmertmann *et al.* (1978) modified the strain influence factor variation (2B – 0.6Iz) proposed by Schmertmann (1970). The revised theoretical and experimental distribution of vertical strain influence factor below the centre of a circular loaded area are given as shown in Table 1. The Canadian Foundation Engineering Manual (CFEM) suggests that settlement estimates of footings may be made by dividing the soil into layers, calculating the value of the applied stress at the midpoint of each layer and using an apparent modulus of elasticity of the soil layer to determine the settlement of each layer. This elastic method is based on the method reported by Janbu *et al.* (1956).

2.4. Numerical Modelling

In modelling foundation settlements numerically, the actual soil properties and conditions are considered together with the actual construction method, process and stages. In this study, the SPT was conducted in nine different layers per test hole and foundation settlement values were evaluated in each of these layers. The applied boundary conditions used in numerical analysis are conditions in which the soil model bottom is restricted from movement in all directions (fixed in all of x, y and z-axes), the two sides are horizontally fixed and restrained from movement but vertically freed to move (fixed in x, and z axes but free in y-axis) while the soil surface is totally unrestrained.

2.4.1. Plaxis 2D

Plaxis 2D is an axisymmetric finite element package 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. Plaxis 2D portfolio models the structure, the soil and the interaction between the structure and the soil. Soil layers and foundation structure parameters are inputted into Plaxis and the construction stages, loads and boundary conditions are defined in an already defined geometry cross-section containing the soil model then Plaxis automatically 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 input data in numerical modelling are index, elastic and strength parameters obtained from the processed SPT results. The soil properties and material properties of the pad footing and wall used for numerical analysis and general computations are presented in Tables 2 (for North Central zone only) and 3 respectively.

2.4.2. Plaxis 3D

Plaxis 3D Foundation is a three-dimensional Plaxis programme and advanced of the 2D version, developed for the analysis of foundation constructions including raft foundations and offshore structures. A project's geometry is modelled using a top view approach. The input of soil data, structures, construction stages, loads and boundary conditions was based on convenient computer aided design (CAD) drawing procedures, which allows for a detailed and accurate modelling of the major geometry. From this geometry a 3D finite element mesh is generated. Soil layers are defined by means of boreholes. Structures were defined in horizontal work planes. The Plaxis 3D Foundation program allows for an automatic generation of unstructured 2D finite element meshes based on the top view. There are options for global and local mesh refinement. From this 2D mesh, a 3D mesh is automatically generated, taking into account the soil stratigraphy and structure levels as defined in the bore holes and work planes. The Plaxis postprocessor has enhanced 3D graphical features for displaying computational results. Exact values of displacements, stresses, strains and structural forces

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can be obtained from the output tables. A special tool is available for drawing load-displacement curves, stress paths and stress-strain diagrams. Particularly the visualization of stress paths provides a valuable insight into local soil behaviour and enables a detailed analysis of the results of a Plaxis 3D Foundation calculation.

2.4.3. GeoStudio

GeoStudio is a 2D geotechnical engineering modelling software packages that consist of several programs. Since this study is concerned with modelling of foundation settlement, the SIGMA/W package in GeoStudio for stress and deformation modeling (load-displacement) was used. SIGMA/W is a two-dimensional axisymmetric finite element software product that can be used to perform stress and deformation analyses of earth structures. Its comprehensive formulation makes it possible to analyse both simple and highly complex problems like a simple linear elastic deformation analysis or a highly sophisticated nonlinear elastic-plastic effective stress analysis.

Table 2: Soil properties for numerical analysis and general computations (North Central Zone)

Parameter	Values according to depth of standard penetration test boring								
	0.6 m	2.1 m	3.6 m	5.1 m	6.6 m	8.1 m	9.6 m	11.1 m	12.6 m
SPT N-value (-)	12	24	34	51	65	76	84	98	100
Corrected N-value (N_{60})	10.71	21.42	30.35	45.52	58.01	67.83	74.97	87.47	89.25
Bulk unit weight (kN/m^3)	17.85	18.35	17.98	18.23	21.32	18.99	22.02	19.54	22.45
Friction angle (^{o})	30.25	33.28	35.71	39.64	40.00	40.00	40.00	40.00	40.00
Dilatancy angle (^{o})	0.00	0.00	0.00	0.00	2.69	4.96	6.56	9.21	9.57
Cohesion (kN/m^2)	2.36	8.25	14.14	11.03	28.92	31.81	37.70	33.54	32.48
Young's modulus	5355	10710	15173	22759	29006	33915	37485	43733	44625
Poisson's ratio (-)	0.179	0.224	0.261	0.320	0.365	0.399	0.423	0.463	0.469
Soil model (-)	Mohr-Coulomb								
Soil behaviour (-)	Drained								

Table 3: Material properties for raft and wall above raft footing in numerical analysis

Parameter	Unit	Pad footing	Wall
Unit weight	kN/m^3	24	24
Thickness	m	0.4	0.23
Young's modulus	kN/m^2	2.74 x 10^7	2.74 x 10^7
Poisson's ratio	-	0.2	0.2
Material behaviour	-	Linear (Isotropic)	

2.5. Standard Penetration Test

The standard penetration test SPT was conducted in accordance with ASTM D-1586-99 (2001). The number of blows required for the last two 150 mm intervals were added to give the standard penetration number, N, which is generally referred to as the N-value. The N-value was corrected to an average energy ratio of 60% (N_{60}). SPT was conducted at depth intervals of 1.5 m. The correction factors are used to standardize the field penetration number as a function of the input driving energy and its dissipation around the sampler into the surrounding soil.

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3. RESULTS AND DISCUSSION

3.1. Soil Conditions

Standard penetration test and laboratory tests were performed to determine the engineering properties of soil layers. The soil investigation revealed that the soils are averagely silty sands up to about 1.5 m depth followed by dense sand down to the 12.6 m of the test. The ground water table was encountered at varying depths below the ground level. The average SPT results obtained from each of the six geo-political zones of Nigeria; North Central (NC), North East (NE), North West (NW), South East (SE), South South (SS) and South West (SW) are presented in Figures 2 – 7. Samples of soil models used for the numerical modelling are shown in Figures 8 - 10. The results presented in this study were computed based on the average SPT values obtained from the available field information at the time of the study. It is pertinent to state that the input data approximately represent soil conditions in each of the six geo-political zones of Nigeria. Factors responsible for the trend observed in the SPT results presented in Figures 2 – 7 have been discussed in the geology of the study area presented in Section 2.1.

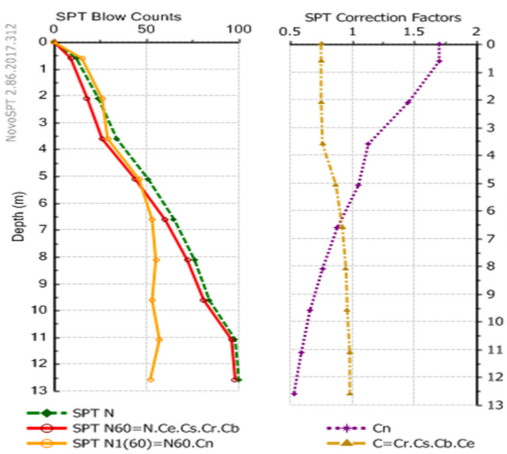

Figure 2: Soil layering and SPT results NC

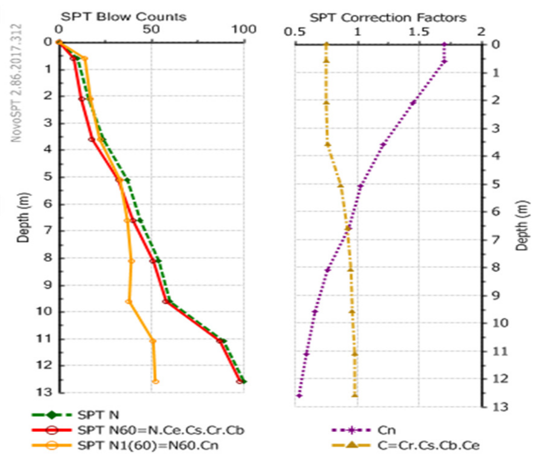

Figure 3: Soil layering and SPT results NE

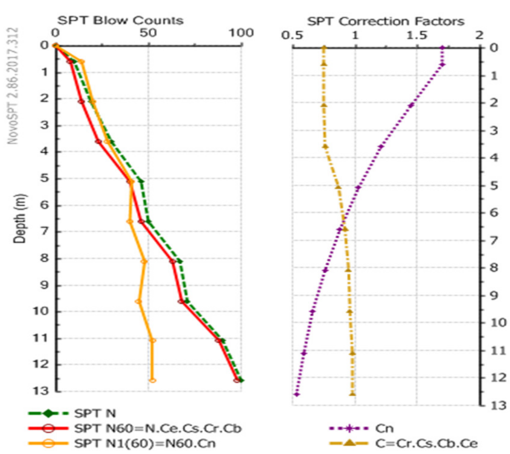

Figure 4: Soil layering and SPT results NW

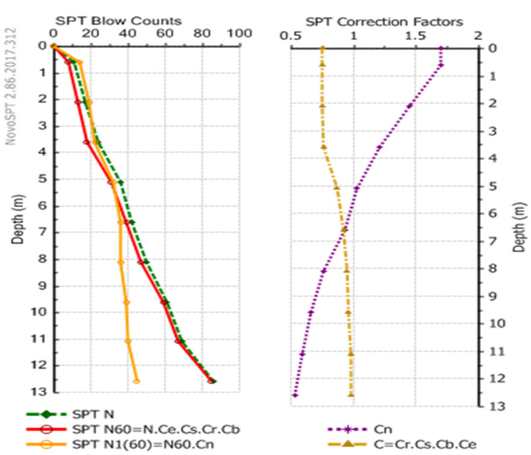

Figure 5: Soil layering and SPT results SE

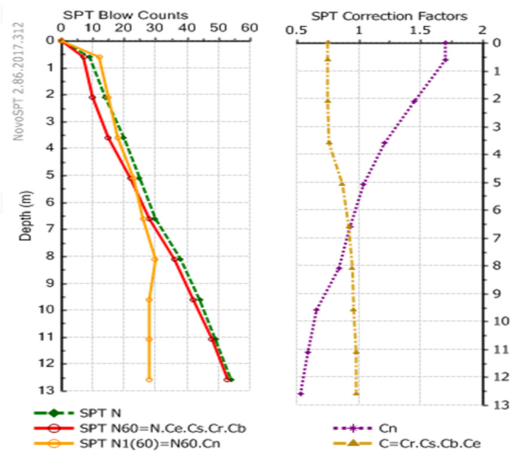

Figure 6: Soil layering and SPT results SS

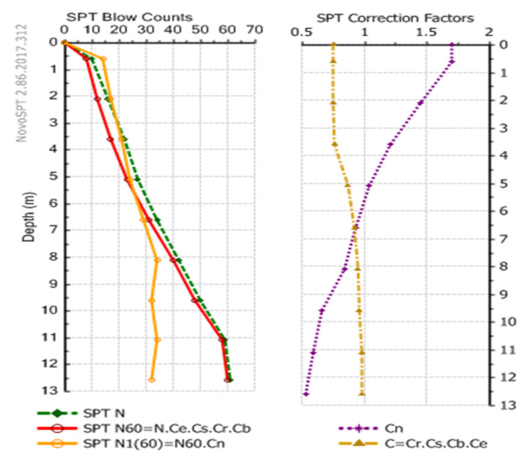

Figure 7: Soil layering and SPT results SW

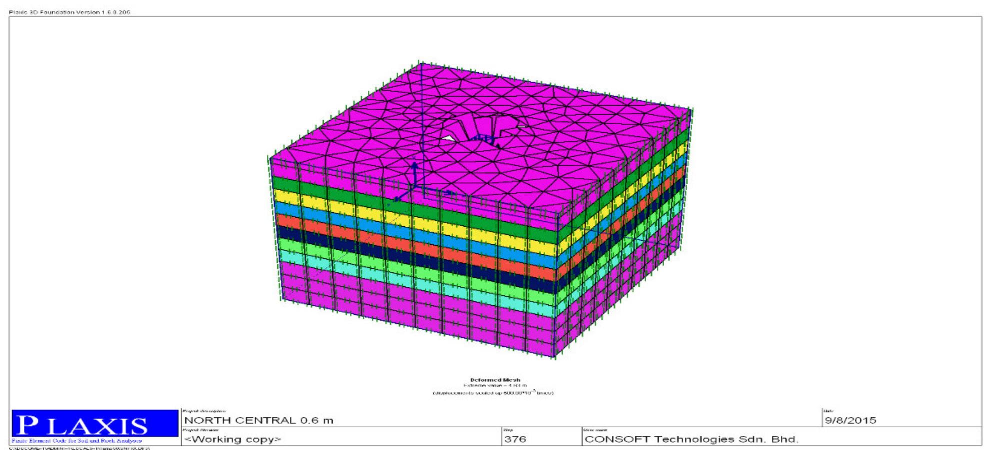

Figure 8: Plaxis 3D soil model used for numerical analysis

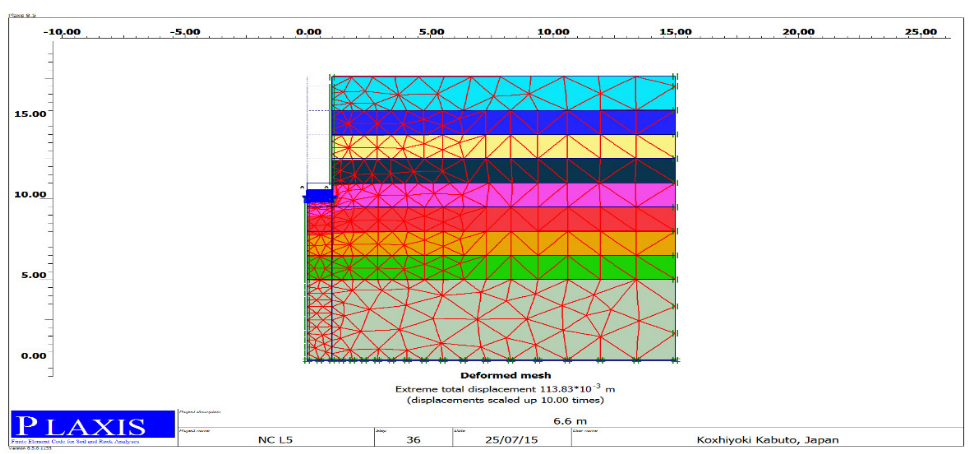

Figure 9: Plaxis 2D soil model used for numerical analysis

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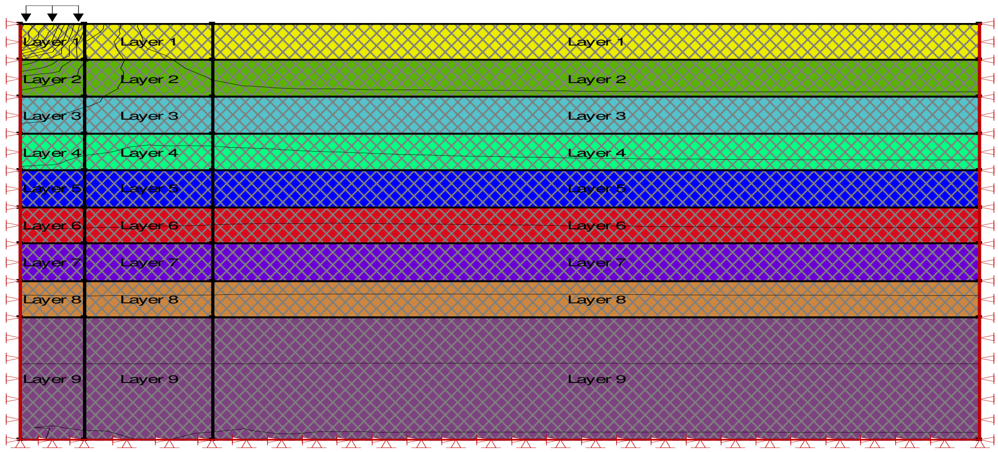

Figure 10: Sigma/W in GeoStudio soil model used for numerical analysis

3.2. Numerical Modelling of Foundation Settlement

The relation between settlement and foundation embedment depths for the 200 kN/m^2 applied foundation pressure on a 2 x 2 m^2 pad footing and 0.4 m depth are presented in Figures 11 - 16. The results of numerical analysis using the three numerical modelling software (Plaxis 3D, Plaxis 2D and Geo-Studio) considered in this study for the six geo-political zones were compared with three analytical methods, viz: empirical, semi-empirical and elastic methods proposed by Burland and Burbidge (1985), Schmertmann et al. (1978) and Canadian Foundation Engineering Manual (2006), respectively. Footing settlement values of 30.48, 27.27, 24.28, 25.46, 31.85 and 56.26 mm were obtained for the North Central at 2.1 m footing embedment depth for the empirical, semi-empirical, elastic, Plaxis 3D, Plaxis 2D and Geo-Studio respectively. Footing settlement values predicted for North East (NE), North West (NW), South East (SE), South South (SS) and South West (SW) are (41.37, 40.90, 36.42, 37.50, 50.61 and 98.38 mm), (36.60, 34.45, 30.67, 27.91, 47.58 and 74.94 mm), (39.66, 38.50, 34.28, 33.99, 47.58 and 102.83 mm), (45.17, 46.75, 41.62, 56.20, 61.88 and 157.84 mm) and (41.37, 40.90, 36.42, 41.87, 52.57 and 131.68 mm) respectively at 2.1 m footing embedment depth. It was observed that while Plaxis 2D and 3D results are in very close range with the analytical methods considered, Geo-Studio numerical modelling software overestimates the foundation settlement most especially at shallow depths (in the range 0.6 to 3.6 m). Similar trends were reported by Shahin et al. (2000), Ahmed (2013), and Salahudeen et al. (2017) in their comparison of foundation settlement obtained using analytical and numerical methods. The numerical modelling results showed that soils in the geo-political zones are susceptible to settlement in a decreasing order of South South (SS), South West (SW), South East (SE), North East (NE), North West (NW) and North Central (NC). The results are consistent with the findings reported by Osinubi et al. (2013) in a similar study. In a detailed study by Salahudeen (2017) comparing fifteen analytical methods with three different numerical techniques, it was observed that Burland and Burbidge (1985) foundation settlement prediction method performed best among several empirical, semi-empirical and elastic methods. This observation was explained by the fact that Burland and Burbidge method considered all footing dimensions and several soil parameters and it was also concluded that Geo-Studio numerical modelling software overestimates footing settlement. However, in this study, comparing the analytical methods using results of Plaxis 2D and 3D as yardstick, best performance at shallow depths was observed in the semi-empirical, elastic and lastly empirical methods considered. The best performance observed in the semi-empirical method proposed by Schmertmann et al. (1978) could be largely due to the strain influence factor variation consideration. In foundation engineering, footing settlement is a direct factor of vertical strain. The deformation of a soil layer is the strain times the thickness of the soil layer and the settlement of the foundation is the sum of the deformations of the soil layers below the foundation. The possible reasons responsible for the disparities in the results of the three methods considered may be due to the peculiarities in their approaches as presented in Section 2.3.

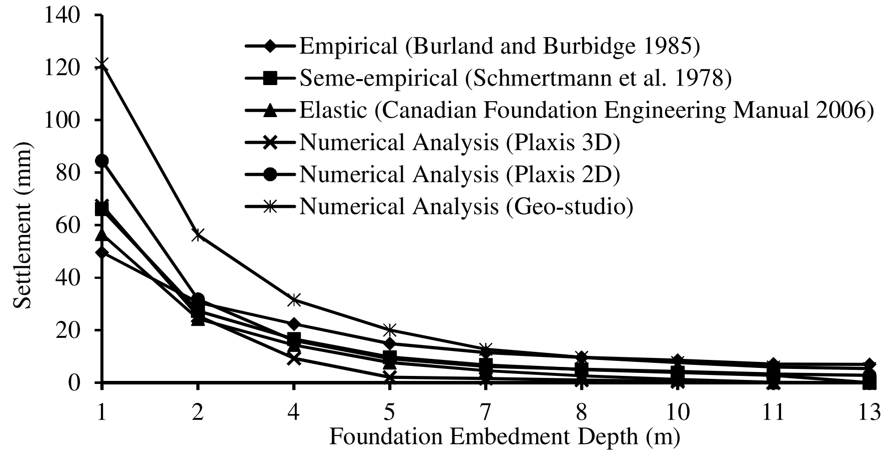

Figure 11: Variation of settlement with foundation embedment depth (North-Central zone)

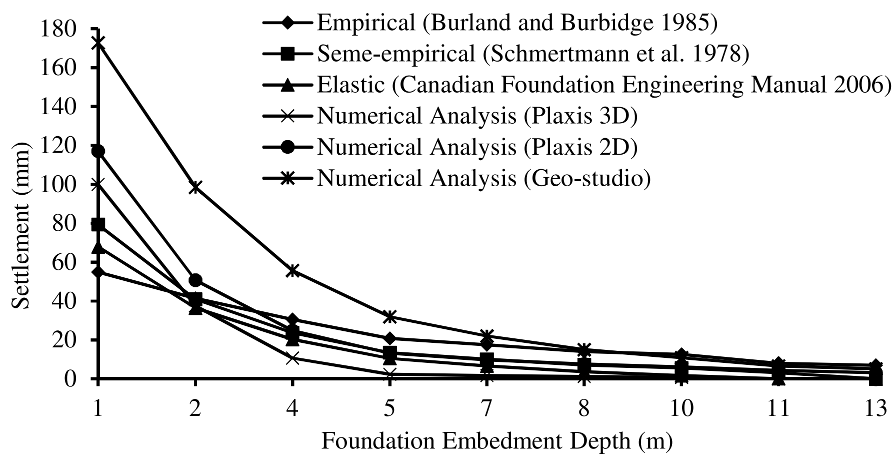

Figure 12: Variation of settlement with foundation embedment depth (North-East zone)

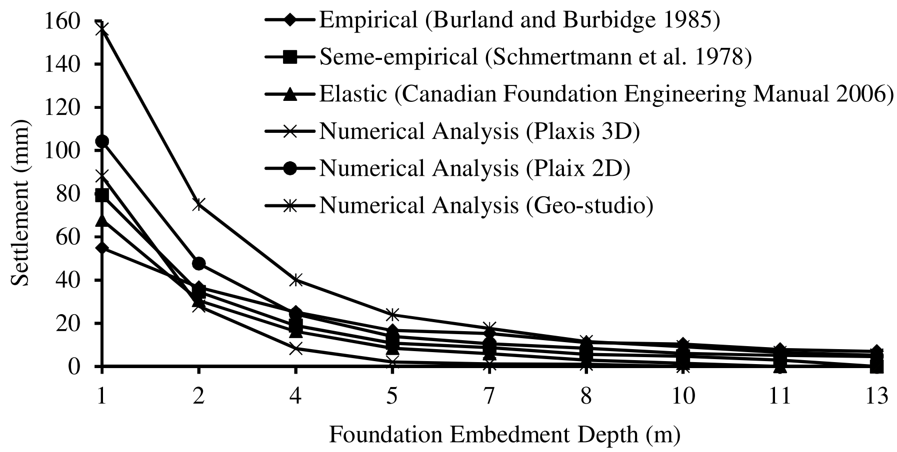

Figure 13: Variation of settlement with foundation embedment depth (North-West zone)

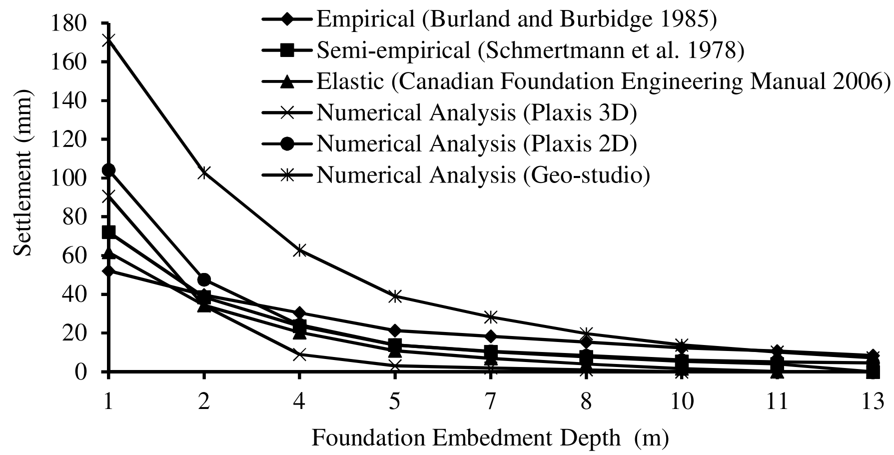

Figure 14: Variation of settlement with foundation embedment depth (South-East zone)

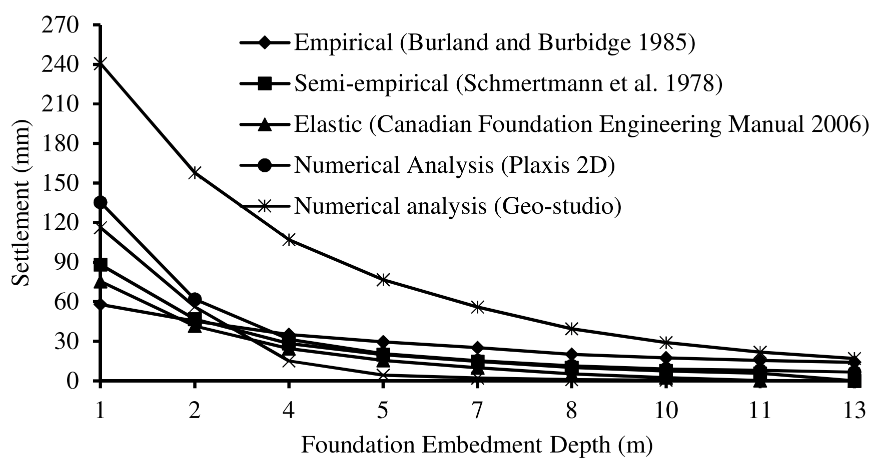

Figure 15: Variation of settlement with foundation embedment depth (South-South zone)

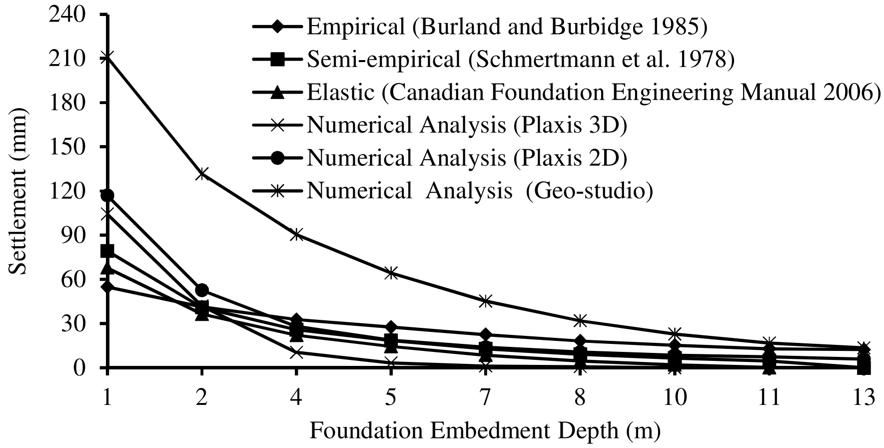

Figure 16: Variation of settlement with foundation embedment depth (South West zone)

It was gathered from the literatures that the predicted settlement values are higher than the actual measured ones (Das and Sivakugan, 2007). Seycek (1991) concluded that predicted settlements are usually considerably higher than real settlements because the true stresses measured in the soil near the footing edge are finite and significantly less than the singular stresses predicted by theory. According to Gordon et al. (2005), the finite elements truncate the singular stresses that occur along the edge of a rigid footing, leading to smaller settlements than predicted by theory.

4. CONCLUSION

Based on the results of this study, the following conclusions were drawn:

1. Footing settlement values of 30.48, 27.27, 24.28, 25.46, 31.85 and 56.26 mm were obtained for the North Central at 2.1 m footing embedment depth for the empirical, semi-empirical, elastic, Plaxis 3D, Plaxis 2D and Geo-Studio respectively. These results show that the soils considered from the six geo-political zones are susceptible to settlements in the following decreasing order South South (SS), South West (SW), South East (SE), North East (NE), North West (NW) and North Central (NC).

2. Comparison of numerical analysis results with those using empirical, semi-empirical and elastic methods proposed by Burland and Burbidge (1985), Schmertmann et al. (1978) and Canadian Foundation Engineering Manual (2006) respectively showed that Plaxis 2D and 3D results are in very close range with the analytical methods considered while Geo-Studio numerical modelling software overestimated the foundation settlement most especially at depths in the range 0.6 – 3.6 m.

5. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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