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Settlement Modelling of Raft Footing Founded on Oferekpe/Abakaliki Shale in South East Region of Nigeria

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ABSTRACT

In engineering practice, settlement of foundations is experimentally determined or numerically modeled based on conventional saturated soil mechanics principles. The study area, Oferekpe in Abakaliki LGA of Ebonyi State, South Eastern Region of Nigeria is characterized by sedimentary formations highly susceptible to compression under applied load. The study was aimed at evaluating raft footing settlement by both analytical and numerical modeling methods and determine the effect of raft thickness on the settlement. Standard penetration test (SPT) data was used to correlate soil properties that were used together with laboratory results to obtain the input parameters used for the prediction of settlement. Four footing embedment depths of 1.5, 3.0, 4.5 and 6.0 m with applied foundation pressures of 50, 100, 200, 300, 400 and 500 kN/m2 were considered using a raft footing dimension of 20 x 20 m2 at the varying thickness of 0.5, 0.75 and 1.0 m. The numerical modeling finite element application package used was Plaxis 3D. For applied pressure of 100 kN/m2 and at footing embedment depths of 1.5, 3.0, 4.5 and 6.0 m, settlement values of (21.89, 11.51, 9.04 and 6.52), (19.70, 8.60, 6.41 and 4.39), (25.62, 14.88, 12.05 and 9.27) and (25.20, 11.59, 5.57 and 2.58) were respectively predicted by the elastic, semi-empirical, empirical and finite element methods. It was observed that the elastic method of predicting foundation settlement proposed by Steinbrenner yielded a very close range results generally to those predicted by finite element method. It was generally observed that thickness of raft footing has no significant effect on the predicted settlement.

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1. Introduction

A raft foundation is mostly used where the site and load conditions could cause significant differential and/or total settlement between individual spread footings but where conditions are not so poor to warrant deep footing. For buildings with substantial overturning moments, which is common in regions of high seismicity or because of irregularities of the superstructure loading, a mat foundation is commonly used to distribute the bearing pressure over a large surface area and/or to resist substantial uplift forces that could develop. Another common use of mat footing is when individual pad footings would be large and close to each other. Likewise, in a situation where several grade beam ties among footings are required, it may not be economical to excavate and form individual spread footings as compared to constructing a single raft foundation [1]. It is also suitable for ground containing pockets of loose and soft soils [2]. Mats may be supported by piles, which help reduce the settlement of a structure built over highly compressible soil [3]. Where the water table is high, mats are often placed over piles to control buoyancy [2].

Numerical modeling is a powerful mathematical tool that makes it possible to solve complex engineering problems. The constitutive behavior of soils can be successfully modeled with numerical analyses using some basic soil properties as input data. The finite element method is a modeling code in which continuous media is divided into finite elements with different geometries. It makes it possible to idealize the material behavior of the soil, which is non-linear with plastic deformations and is stress-path dependent, in a more realistic manner [4]. There are several methods in use to predict foundations settlement in granular soils. One common assumption in these methods represent sand as possessing elastic strains only, and thereby plastic deformations are not directly taken into considerations [5,6]. In reality, the constitutive behavior of soils governs the response of the soil material under the foundation and therefore influences and seriously determines the prediction of bearing capacity and settlement [7].

The objective of all site exploration is to obtain data that will adequately quantify the variability of the geotechnical properties of the site. Site investigation and estimation of soil properties are essential parts of a geotechnical design process. Geotechnical engineers are tasked with the determination of the average values and variability of the site soil properties [8]. *In situ* testing is very important in geotechnical engineering, since simple laboratory tests may not be reliable while more sophisticated laboratory testing can be time-consuming and costly [9]. Standard Penetration Test (SPT), which was used in this study, is an *in situ* testing methods that is used to identify soil type and stratigraphy along with being a relative measure of strength. The results of the test can be indirectly used to estimate the bearing capacity and settlement characteristics of the soil and could be used to determine the type of foundation required to effectively carry the structural load without bearing capacity failure and/or excessive settlement.

Some Nigerian soils are problematic and create serious threats and adverse effects on foundations of structures and the structures themselves. These soil problems include excessive settlement, tilting, and collapse of structures [5]. Finite element technique that gives a better approximate values of footing settlement is needed for reliable prediction of foundation settlement. The prediction in this study was based on SPT results, being the most common and economical geotechnical *in-situ* test used in Nigeria. This study used SPT results as input data in foundation settlement estimation using analytical models and Plaxis 3D package. The specific objectives of this study were to predict raft settlement from measured penetration resistance in terms of the SPT N-value at varying depths and applied footing pressure, to evaluate analytical equations used settlement prediction that are based on different constitutive models, to model foundation settlement numerically using PLAXIS 3D software, compare the results of the analytical methods with those of numerical analysis and investigate the effect of raft thickness on settlement.

2. Location and geology of the study area

The study area is Oferekpe in Abakaliki Local Government Area of Ebonyi State, South Eastern Region of Nigeria. Nigeria is situated entirely within the tropical zone and has a total land mass of about 924,000km^2 [10]. The coastal areas are usually covered by soft rocks which are prominent along the Niger Delta, Niger Benue trough and Lake Chad Basin. The lowland areas are composed of sedimentary rock and cover the Sokoto plains, Chad Basin, Niger-Benue trough, western areas of Nigeria, south-eastern Nigeria and coastal margins and swamps [11]. Residual soils of shales are of a rather wide occurrence in the south-eastern region of Nigeria (the study area), and they are notorious as problematic soils in numerous civil or geotechnical engineering works. Engineering structures built on these shale soils have experienced problems such as slope and bearing capacity failures and ground settlement. In a detailed study on the soil deposites of southeastern Nigeria by Obasi et al. [12], it was concluded that the lithofacies identified are shales, which are dark grey and brown, siltstones, mudstones and limestones. The paleoenvironment of the rocks were interpreted as the low energy shallow marine environment. A geological map of the study area is shown in Figure 1.

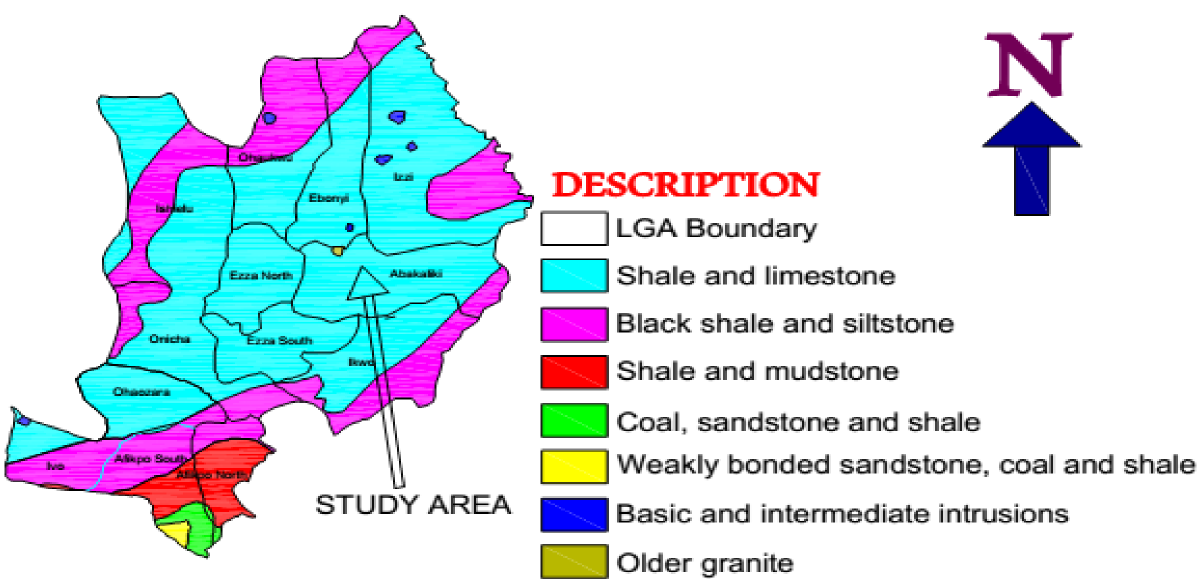

Fig. 1. Geological map of Ebonyi State is showing the soil groups.

3. Research methodology

This study made use of Standard Penetration Test (SPT) data conducted at four footing embedment depths of 1.5, 3.0. 4.5 and 6.0 m. Computation of foundation settlement were done at raft footing thickness of 0.5, 0.75 and 1.0 m which are a random choice and applied foundation pressures of 50, 100, 200, 300, 400 and 500kN/m^2 which represent the applied structural loads on the foundation. A raft footing with plan dimension of 20 m x 20 m was randomly considered for the study.

3.1. Analytical methods

Based on analytical methods, foundation settlement estimations were performed using three common settlement prediction models to compare with the results of the numerical analysis as shown in Table 1. The models are elastic, semi-empirical and empirical in nature which was proposed by Steinbrenner [13], Terzaghi *et al.* [14] and Schultze and Sherif [15] respectively. Various analytical methods available at the present time to calculate the elastic settlement can be summarised into three different categories [16]. The first category is the empirical methods which are methodologies based on *in situ* measured settlement of structures and full-scale prototypes. These methods are empirical in nature and are correlated with the results of the standard *in situ* tests such as the SPT. The second category is the semi-empirical methods which are based on a combination of field observations and some theoretical studies. Lastly, the elastic methods, which are based on theoretical relationships derived from the theory of elasticity.

Based on elastic theory, Steinbrenner [13] computed the settlements at any depth below the corner of a uniformly loaded rectangular footing located on the horizontal surface of a semi-infinite homogeneous isotropic elastic mass of constant elastic properties. He assumed that the settlement at the corner on a soil layer of depth H was equal to the settlement of the surface point minus the settlement of the point at depth H. Terzaghi *et al.* [14] made numerous comparisons between the results of settlement observations on actual footings and estimates based on other procedures using several hundred reliable records of settlements of structures on sand which were used in statistical studies resulting in more reliable semi-empirical methods for estimating the elastic settlements. Based on the results of a study of the observed settlements at 48 sites, Schultze and Sherif [15] developed an empirical method to estimate the settlement of shallow foundations on sand using SPT results. The analytical models used in this study were considered based on their recommendations in the literatures.

Table 1
Analytical models for settlement prediction.

Method category	Expression	Definitions	Reference
Corrected N-value (N_{60})	$N_{60} = \dfrac{N\eta_H\eta_B\eta_S\eta_R}{60}$	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	[17,18]

Elastic	$S = \frac{qB}{E}\lfloor(1-\mu^2)F_1 + (1-\mu-2\mu^2)F_2\rfloor$	S_e = Elastic settlement (mm) q = Applied foundation pressure (kN/m^2) B = Width of foundation (m) E=Elastic modulus of soil (kN/m^2) μ = Poisson's ratio of soil F1 and F2 are further expressions that depend on the length and depth factors	[13]
Semi-Empirical	$S_{e=} Z_1 \frac{1.7}{\acute{N}_{60}^{\;1.4}} q$	$Z_1 = B^{0.75}$ Z_1 = Represents the depth of influence below which the vertical strains under the foundation are negligible	[14]
Empirical	$S_{e=} \frac{fq\sqrt{B}}{N^{0.87}\left(1+\frac{0.4D_f}{B}\right)}$	f = influence factor depending upon the foundation geometry	[15]

3.2. Numerical modeling

On the other hand, numerical analysis of foundation settlement was performed using 3-D non-linear finite element analysis software, Plaxis, a finite element code. The input data in Plaxis are from the processed SPT results. The Soil properties and material properties of the raft footing and wall (to prevent the collapse of the excavated surface) used for numerical analysis and general computations are presented in Tables 2 and 3, respectively. The software portfolio includes simulation of soil and soil-structure interaction. Soil layers were defined by means of boreholes which is a method specific with Plaxis 3D. Structures were defined in horizontal work planes. Details on this topic can be found in Plaxis 3D Manual [19].

Table 2
Soil properties for numerical analysis and general computations.

Parameter	**Unit**	**Values according to depth of standard penetration test boring**			
		1.5 m	3.0 m	4.5 m	6.0 m
SPT N-value (N)	-	26	47	58	76
Corrected N-value (N_{60})	-	23.21	41.95	51.77	67.83
Bulk Unit Weight	kN/m^3	20.51	19.82	21.84	22.34
Friction angle	Degree	33.77	38.73	41.18	44.96
Dilatancy angle	Degree	0.0	0.0	0.0	0.0
Cohesion	kN/m^2	26.00	24.00	23.00	29.00
Young's modulus	kN/m^2	11603	20974	25883	33915
Poisson's ratio	-	0.232	0.306	0.343	0.399
Soil model	-	Mohr-Coulomb			
Soil behavior	-	Drained			

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

Parameter	Unit	Raft	Wall
Unit weight	kN/m^3	24	24
Thickness	m	Varied (0.5, 0.75, 1.0)	0.23
Young's modulus	kN/m^2	2.74×10^7	2.74×10^7
Poisson's ratio	-	0.2	0.2
Material behavior	-	Linear (Isotropic)	

3.3. Standard penetration test

The standard penetration test (SPT) was conducted in accordance with ASTM D-1586-99 [20] and [21]. The N-value was corrected to an average energy ratio of 60% (N_{60}) before used to correlate soil properties. SPT was conducted at four depth at intervals of 1.5 m. It should be noted that this study is focused on the use of SPT data to generate soil properties that are used for the settlement predictions. It is not an objective of this study to discuss the Pedogenesis of the soil type which is shale in this case. All soil properties are based on the SPT resistance of the soil. However, a detailed description of the geology of the study area is herein presented.

4. Results and discussion

4.1. Soil conditions

Standard penetration test (SPT) and laboratory tests were performed to determine the engineering properties of soil layers as presented in Table 2. The soil investigation revealed that loose silty clay up to 2 m depth followed by dense shale down to 6 m exists in the study area. The groundwater table was encountered at a depth of 1.5 m below ground level. The soil boring log and SPT results are presented in Figure 2. A sample of models used for the numerical modeling is shown in Figure 3. 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.

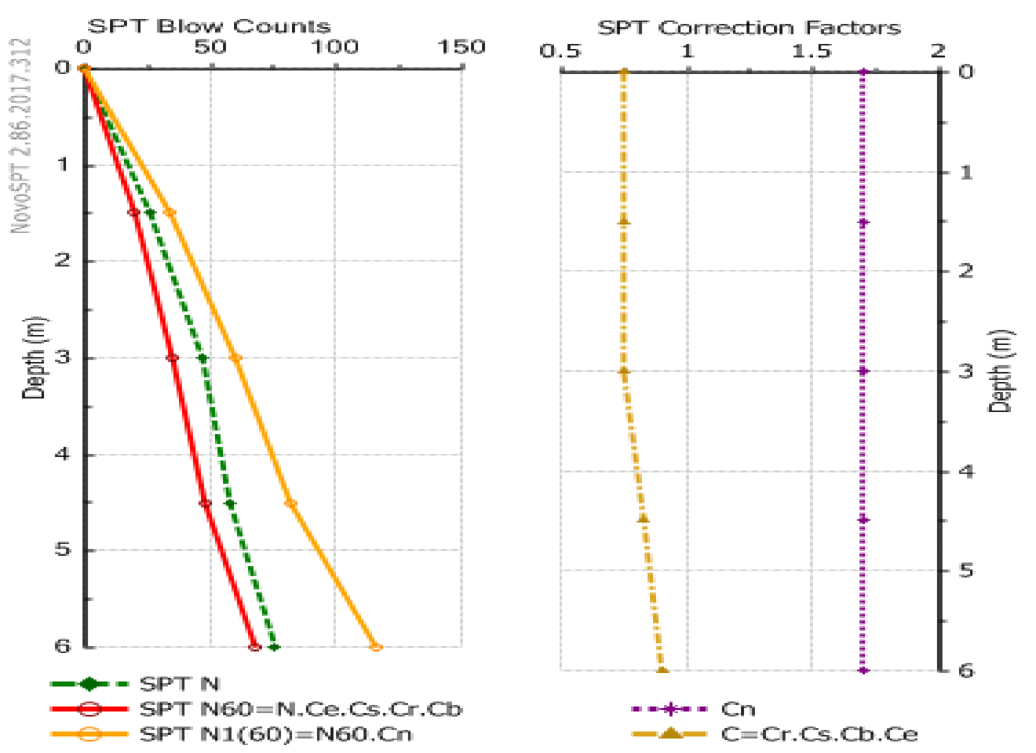

Fig. 2. Soil boring log layering and SPT results.

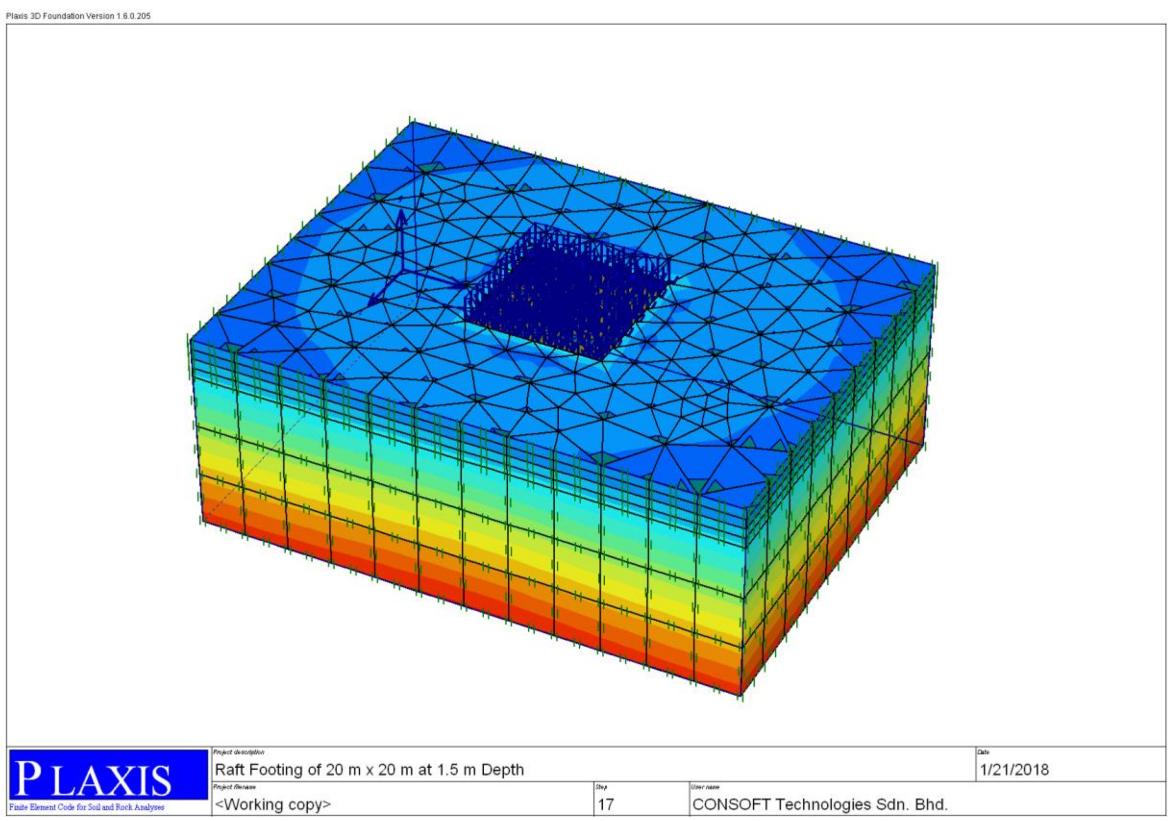

Fig. 3. 3D soil model used for numerical analysis.

4.2. Settlement of raft foundation

The elastic settlements of raft versus boring depths are shown in Figures 4 – 9 for applied pressures of 50, 100, 200, 300, 400 and 500 kN/m^2 respectively at a constant raft thickness of 0.5 m. The figures show three analytical models (one for each of empirical, semi-empirical and elastic methods) commonly used in computing elastic settlement of foundations and results of the finite element in numerical modeling using Plaxis 3D Foundation software which was used as a yardstick to measure the performance of the analytical methods. It should be noted that numerical modeling has been confirmed to give an acceptable prediction of footing settlement in the literatures. For applied pressure of 100 kN/m2 and at footing embedment depths of 1.5, 3.0, 4.5 and 6.0 m, settlement values of (21.89, 11.51, 9.04 and 6.52), (19.70, 8.60, 6.41 and 4.39), (25.62, 14.88, 12.05 and 9.27) and (25.20, 11.59, 5.57 and 2.58) were respectively predicted by the elastic, semi-empirical, empirical and finite element methods. From the observed trends, it is obvious that the elastic method of predicting foundation settlement proposed by Steinbrenner [13] yielded a very close range results generally to those predicted by finite element method followed by the empirical method proposed by Schultze and Sherif ([14] and lastly by the semi-empirical method proposed by Terzaghi *et al.* [15]. It can also be observed that it is difficult to reach a conclusion on the actual settlement values based on the maximum allowable limiting values recommended by codes of practices due to the wide range of results produced by different analytical methods. This is exactly why numerical modeling, as emerging technology is very vital and useful for predicting the actual and exact value of foundation settlement in sites were physical measurement is not viable owing to the consideration of the actual soil constitutive model in numerical analysis.

The observed trend is in line with observations of Rasin [22]. A comparison carried out by Shahin et al. [23] based on field measurement, and artificial neural networks (ANN) results of three settlement prediction methods rated the Schltze and Sherif [15] method as the best for estimating shallow foundation settlements. Ahmed [24] rated the semi-empirical method proposed by Schmertmann et al. [25] as best among others. In a study carried out by Salahudeen et al. [6] in the South-East region of Nigeria based on 425 case history and 3825 database, a comparison of fifteen empirical/analytical methods was made and methods proposed by Schmertmann *et al*. [25], Burland and Burbidge [26], Terzaghi *et al.* [14], Mayne and Poulos [27] as well as Canadian Foundation engineering Manual (CFEM) [28] were considered to give good estimations of foundation settlement. This could be due to consideration of several conditions that applied in all types of soils in the development of these models. In a detailed study by Raymond [29], Salahudeen and Sadeeq [30,31] and Salahudeen [10] comparing several elastic methods of predicting foundation settlement rated the method proposed by Steinbrenner [13] as best of all elastic methods. This could be due to the fact that Steinbrenner's method considered all the footing dimensions in addition to several other considerations which is rarely done in most other methods.

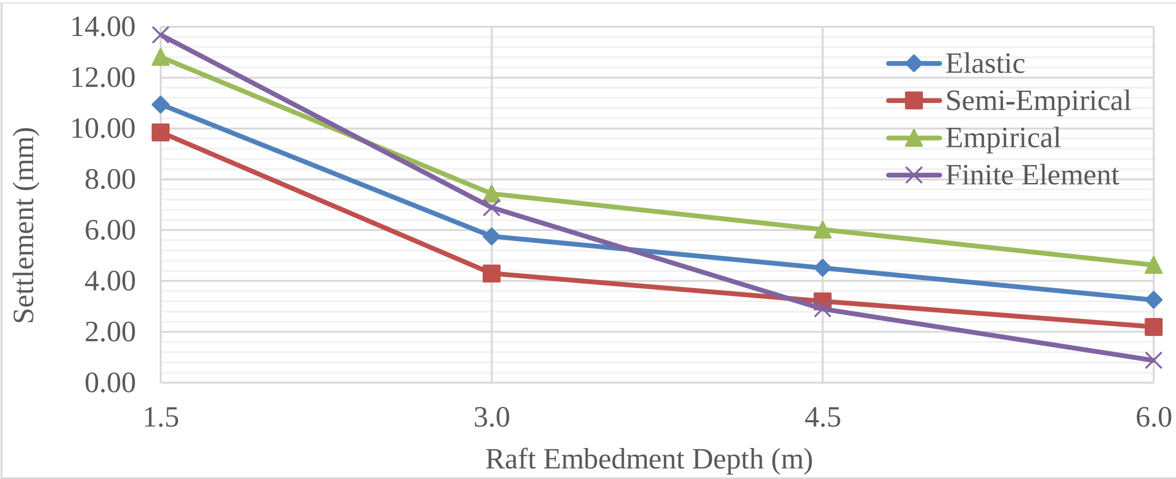

Fig. 4. Settlement versus embedment depth for 50 kN/m^2 applied pressure.

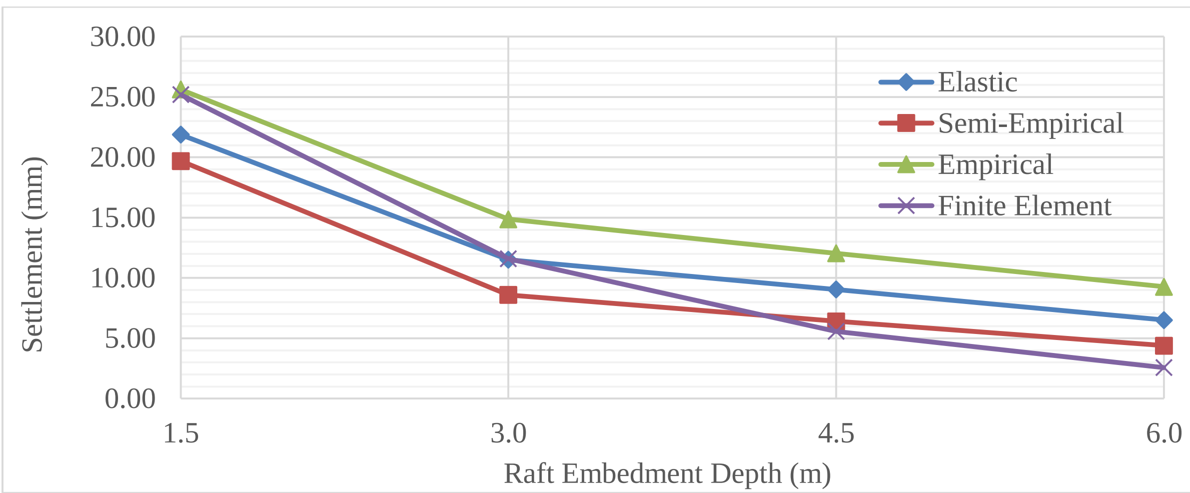

Fig. 5. Settlement versus embedment depth for 100 kN/m^2 applied pressure.

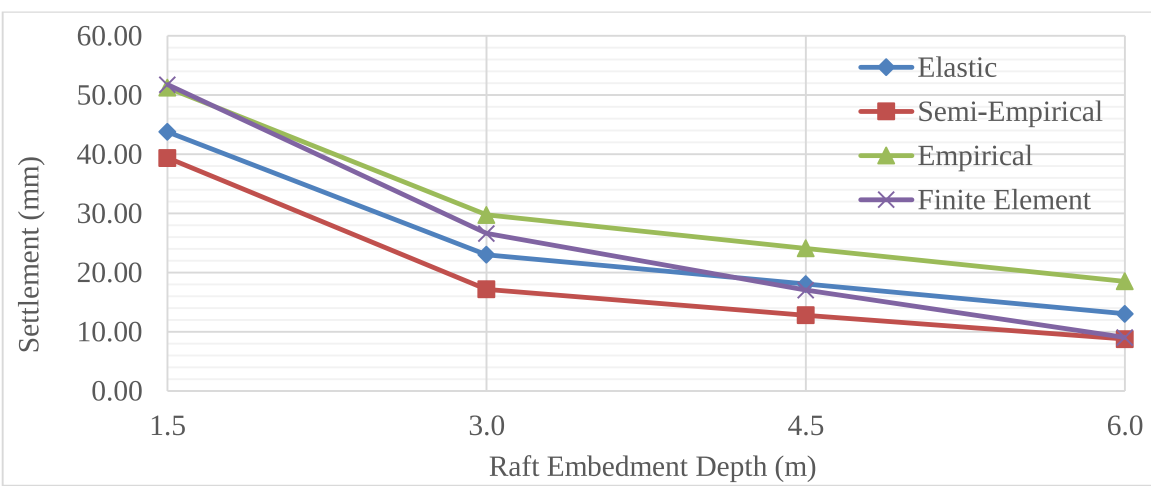

Fig. 6. Settlement versus embedment depth for 200 kN/m^2 applied pressure.

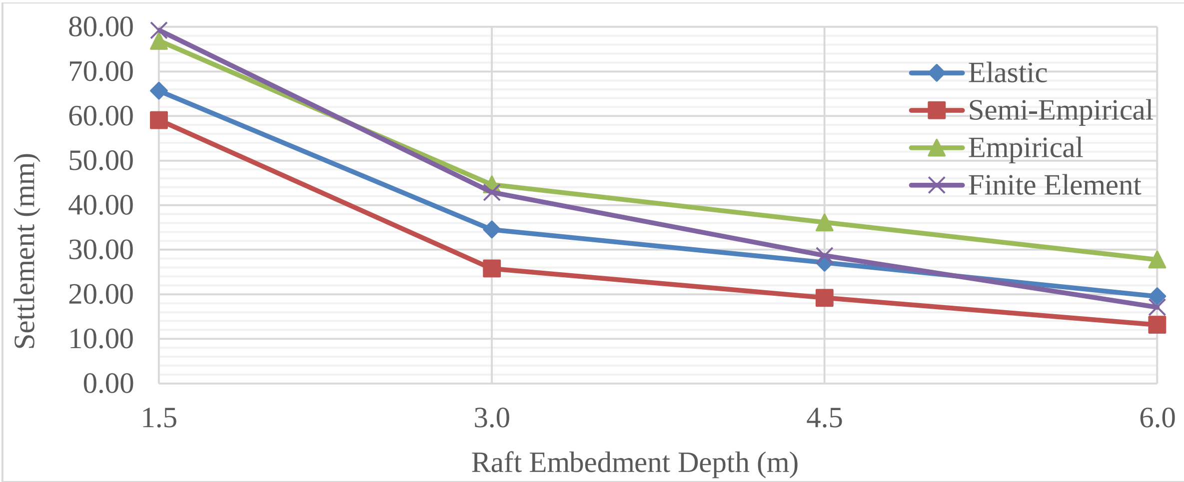

Fig. 7. Settlement versus embedment depth for 300 kN/m^2 applied pressure.

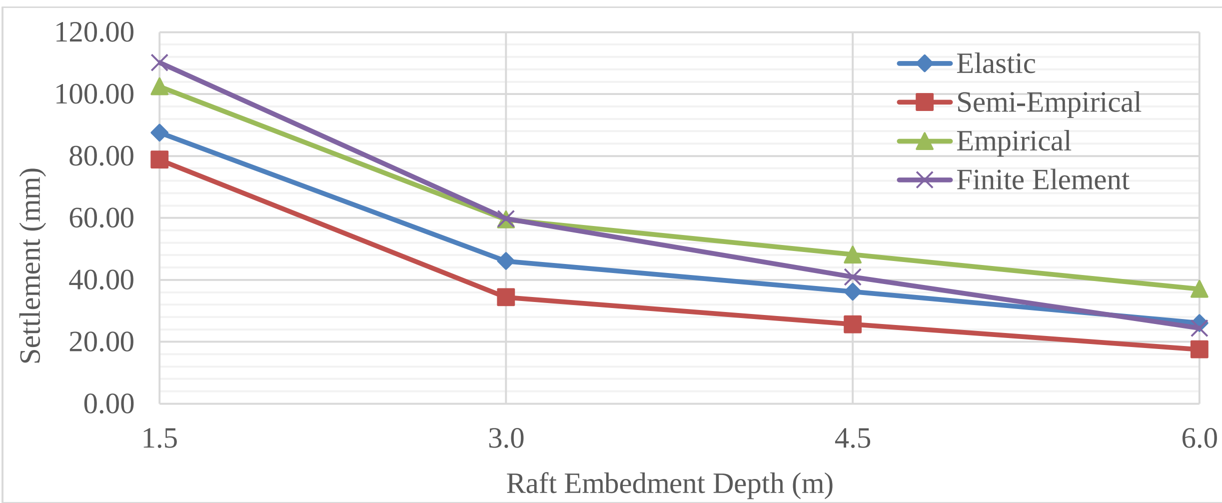

Fig. 8. Settlement versus embedment depth for 400 kN/m^2 applied pressure.

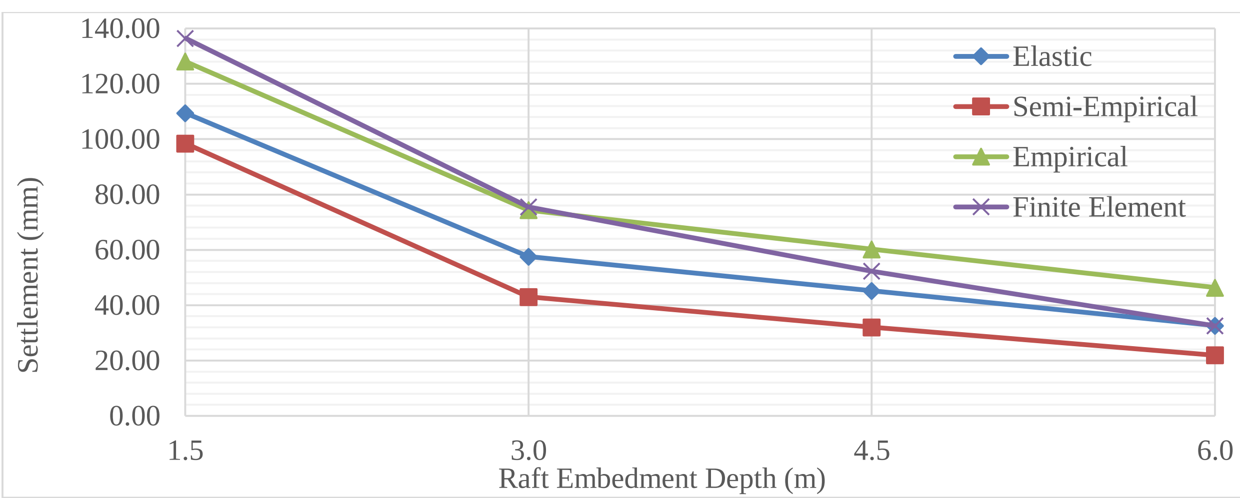

Fig. 9. Settlement versus embedment depth for 500 kN/m^2 applied pressure.

5. Effect of raft thickness on settlement

The effect of thickness of raft footing on the predicted settlement was assessed. Footing thicknesses of 0.5, 0.75 and 1.0 m were considered. Only the Finite Element and Elastic methods were employed in the footing thickness assessment due to their consideration of all footing dimensions which are limitations in other methods. For the applied pressure of 100 kN/m^2 and raft thickness of 0.5, 0.75 and 1.0 m, settlement values of (21.89, 22.32 and 22.75 mm) and (25.20, 26.67 and 24.17) were observed respectively for Elastic and Finite Element methods at 1.5 m footing embedment depth. However, footing settlement values of (6.52, 6.58 and 6.65 mm) and (2.58, 2.52 and 2.58) were observed respectively for Elastic and Finite Element methods at 6.0 m footing embedment depth for raft thickness of 0.5, 0.75 and 1.0 m. It was generally observed that thickness of the raft footing has no significant effect on the predicted settlement. Variations of the settlement with depth showing the effect of raft thickness for the six applied foundation pressures considered in this study are shown in Figures 10 – 15.

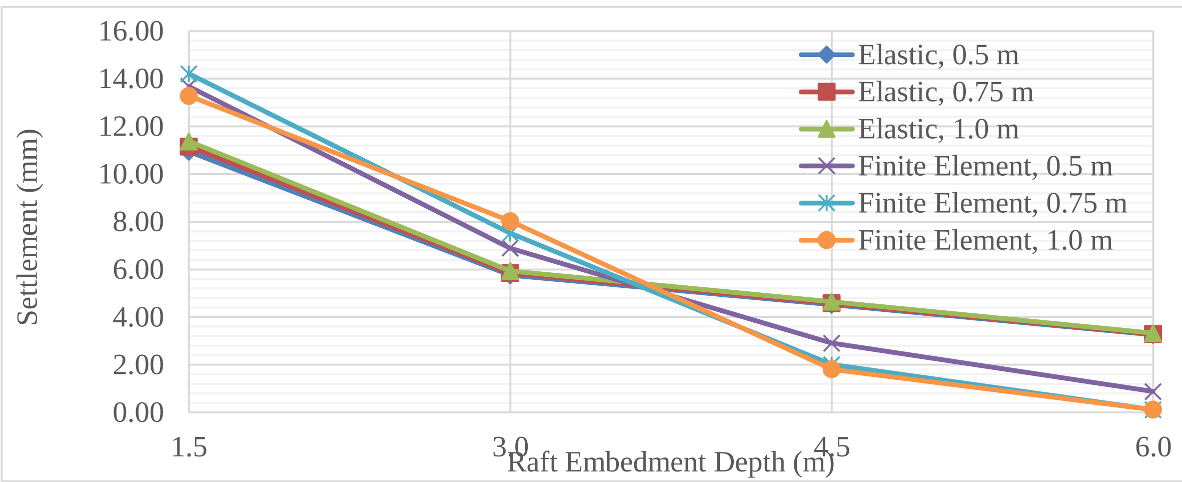

Fig. 10. Settlement versus depth showing the effect of raft thickness for 50 kN/m^2.

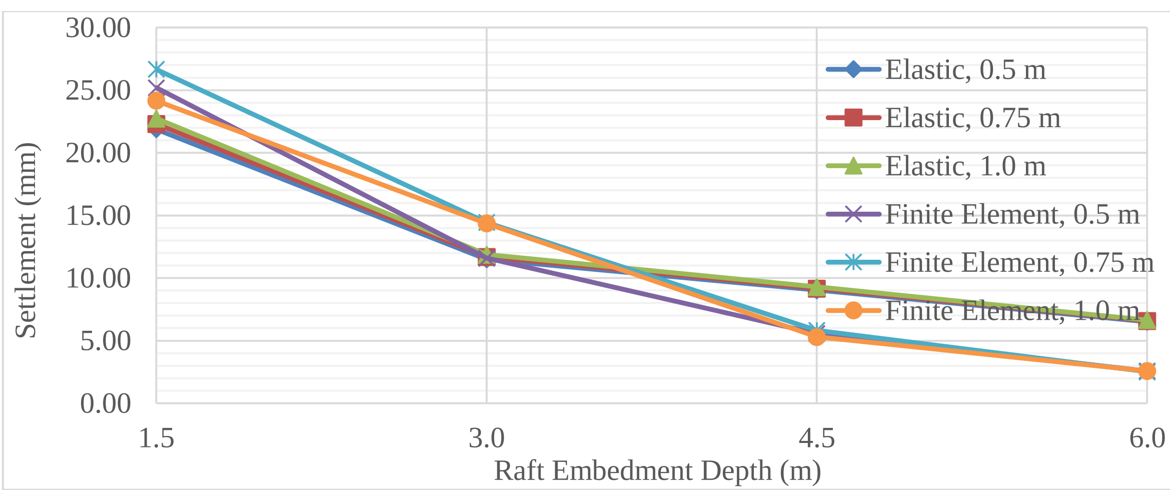

Fig. 11. Settlement versus depth showing the effect of raft thickness for 100 kN/m^2.

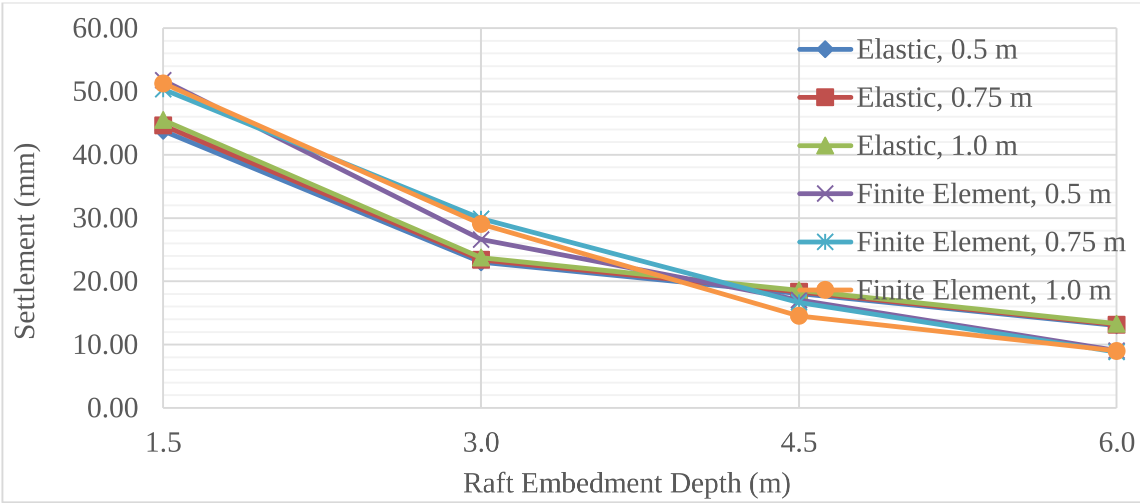

Fig. 12. Settlement versus depth showing the effect of raft thickness for 200 kN/m^2.

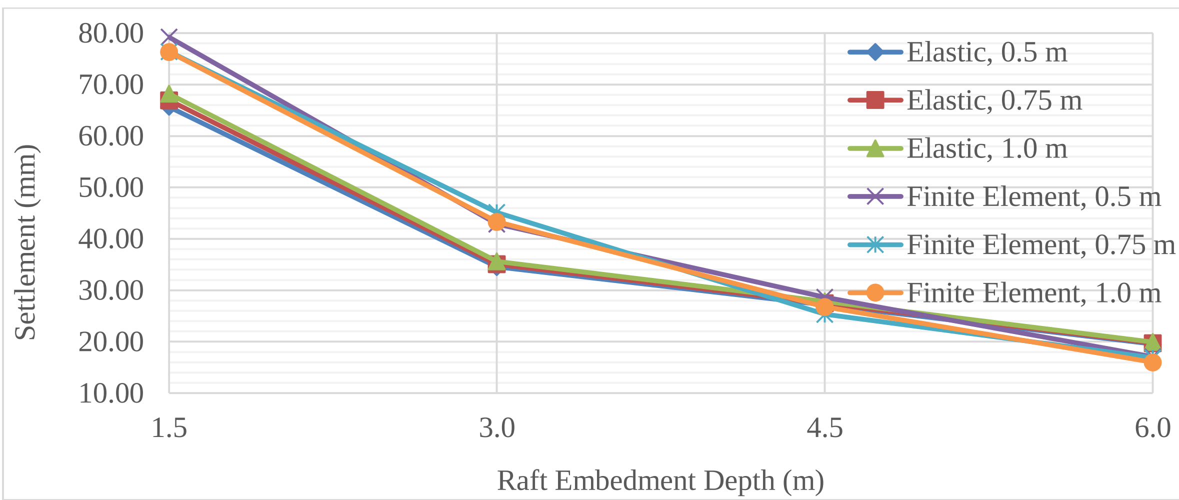

Fig. 13. Settlement versus depth showing the effect of raft thickness for 300 kN/m^2.

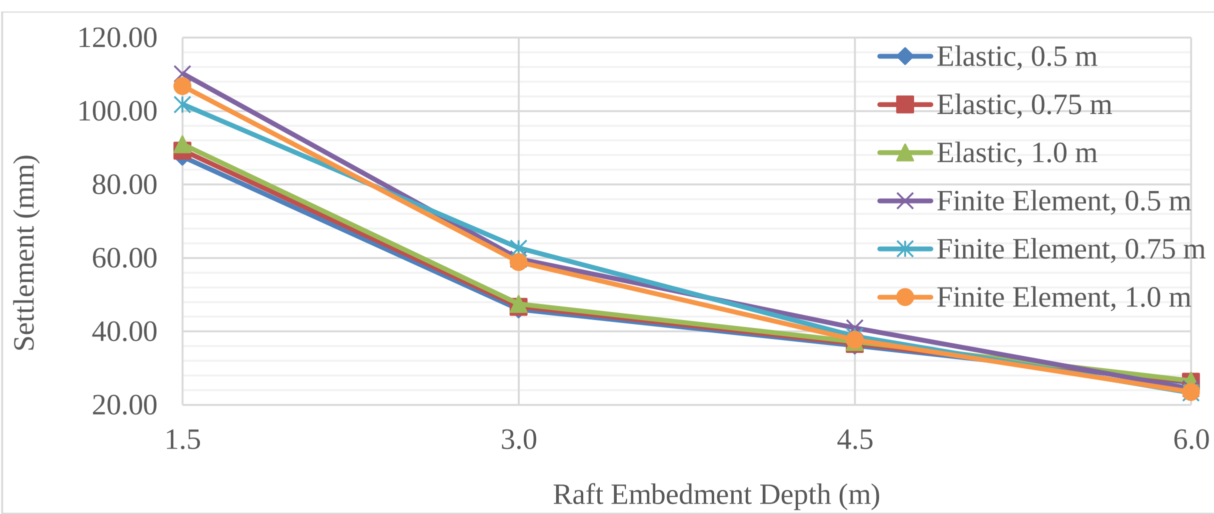

Fig. 14. Settlement versus depth showing the effect of raft thickness for 400 kN/m^2.

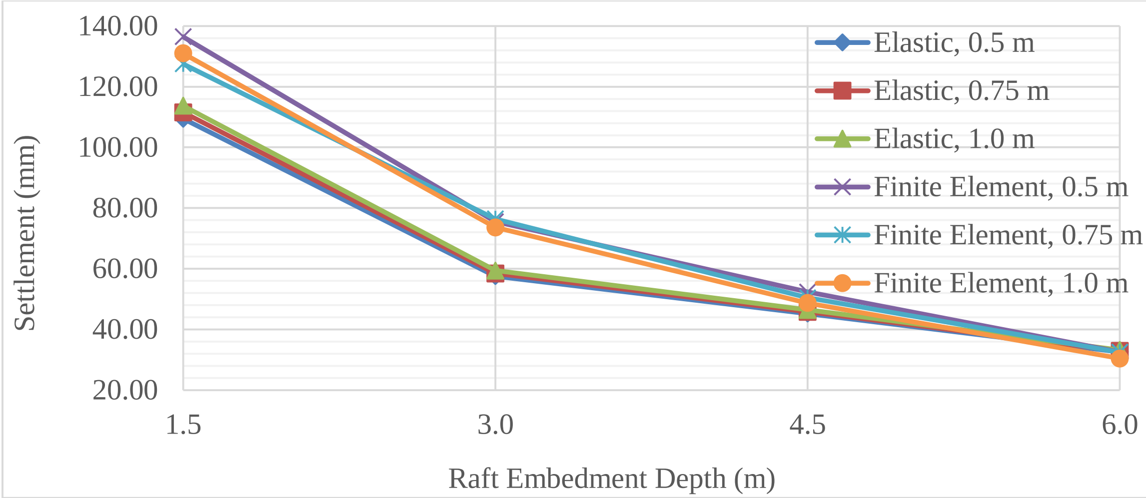

Fig. 15. Settlement versus depth showing the effect of raft thickness for 500 kN/m^2.

6. Conclusion

The study carried out made use of SPT N-values and laboratory results as input data in analytical and numerical models for the prediction of foundation settlement at Oferekpe in Abakaliki Local Government of Ebonyi State, Federal Republic of Nigeria. Raft footing plan of 20 m x 20 m at varied thickness of 0.5, 0.75 and 1.0 m and applied pressures of 50, 100, 200, 300, 400 and 500kN/m^2 at foundation embedment depths of 1.5, 3.0, 4.5 and 6.0 m were adopted. Foundation settlement estimations were performed using three very common settlement prediction models to compare with the results of numerical analysis based on finite element method. The models are elastic, semi-empirical and empirical in nature which were proposed Steinbrenner, Terzaghi *et al.* and Schultze and Sherif respectively based on the results obtained, the following conclusions can be made.

1. From the observed trends, it is obvious that the elastic method of predicting foundation settlement proposed by Steinbrenner gave a very close range results generally to those predicted by finite element method followed by the empirical method proposed by Schultze and Sherif and lastly by the semi-empirical method proposed by Terzaghi *et al*.
2. It was also observed that it is difficult to reach a conclusion on the actual settlement values based on the maximum allowable limiting values recommended by codes of practices due to the wide range of results produced by different analytical methods.
3. It was generally observed that thickness of the raft footing has no significant effect on the predicted settlement.

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