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Original Research Article

Reliability Based Design of Pad Foundation in Abuloma Community, Rivers State, Nigeria

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Abstract

This paper presents the results of the reliability-based design of pad foundation based on the results of the geotechnical investigation of the soil sample collected at 1m to 5m depth in Abuloma Community, Rivers State. Three boreholes, namely BH1, BH2 and BH3 were excavated utilizing a manual auger to depths of 1m, 2m, 3m, 4m, and 5m respectively. Laboratory investigations were conducted on the soil samples in the laboratory to determine the geotechnical properties of the soil such as soil cohesion, Poisson's ratio, unit weight, angle of internal friction, and modulus of elasticity of the soil respectively. The bearing capacity of the soil at each selected location was obtained using Terzaghi's bearing capacity formula. The results of the laboratory investigations on the soil properties such as cohesion, Poisson's ratio, specific weight, internal friction angle, and elasticity modulus of the soil were used to conduct the reliability assessment and reliability-based design of the pad foundation at Abuloma using the method of response surface. The descriptive statistics of the geotechnical parameters were obtained utilizing a statistical tool called Minitab 17.0. The Full Factorial method of design of Experimental Design was used to obtain the design points. The types of probability distribution of the basic random variables were established using Anderson Darling Statistics. The performance functions were developed were developed considering bearing capacity and immediate settlement failure of the pad foundation at the four selected locations. The First Order Reliability technique implemented in MATLAB was used in the reliability estimates. The findings revealed that the Abuloma soil is safe only for a foundation pressure of 50KPa and for foundation pressures of 50KPa, 100KPa and 150KPa respectively when considering settlement criterion. The reliability indices generally decreased with increase in values of variation coefficient of soil cohesion, internal friction angle and soil density respectively. The MATLAB code developed is very easy for application geotechnical and coastal applications.

Keywords: Reliability-based design, Pad foundation, Geotechnical parameters, Full Factorial method, Bearing capacity, immediate settlement.

1. INTRODUCTION

All structural foundation must be properly designed in order to support structural loads (Das Braza, 2011). The interest of the engineering community is that all structural foundations when designed and built should serve the intended purpose, safe and economical with respect to both construction and maintenance cost (Mosley and Bungay, 1989). The loads that act on structures or structural members vary with time and they exhibit variability. This neglect has been discovered as one of the major causes of structural failure in Nigeria. Most foundation failure can be traced to underestimation of uncertainties of foundation design parameters. The conventional design of structural foundations is based on limit state principle which applies partial safety factors which cannot guarantee absolute safety of structural foundations. According to Duncan (2000), the use of partial safety factors in the design of geotechnical systems does not cater for uncertainties that are inherent in the geotechnical design parameters. Most loads and material properties are stochastic in character. The application of partial safety factor in the existing structural design codes and standards may result to inadequate or uneconomical design of structures (Melchers 2000; Sule and Benu, 2019; Ranganathan, 1999; Abejide, 2014; Nowak and Collins, 2013; Abubakar, 2006). There is therefore a need to use probabilistic approach in the design of geotechnical structures (Duncan, 2000; Phoon, 2008). Structural reliability provides a rational framework that quantifies the uncertain parameters that are associated with both the structural resistance and load effects (El-Reedy, 2012; Abubakar, 2015). Soil properties exhibit variability. Consequently, their responses to applied loads are not the same. The probabilistic design of geotechnical structures requires the knowledge of structural capacity and load effects. The structural capacity is a function of the geometric properties of the materials. Load effects are due to the applied loads and the condition of the environmental to which a particular geotechnical structure is exposed (Phoon, 2008; Phoon *et al.,* 2003; Phoon and Kulhawy, 1999). The results of the deterministic design of geotechnical structures are just mere approximations due to the presence of uncertainties inherent in the design parameters and therefore must be quantified using a probabilistic framework. Reliability is the ability of a structural system to serve the intended purpose for some specified period of time (Afolayan, 2005; Melchers, 2000; Ranganatan, I999). Sub-soil geotechnical data are required to properly design and construct structural foundations to prevent structural failure (Bowles, 1997; Das Brajah, 2011; Afolayan *et al.,* 2014).

This paper therefore used the results of the geotechnical properties of soil in Abuloma Community, Rivers State to carry out the reliability-based design of a pad foundation using First Order Reliability method coded in MATLAB language considering bearing capacity and immediate settlement failure criterion respectively.

2. MATERIALS AND METHODS

Three boreholes were drilled at depth 1m, 2m, 3m, 4m and 5m respectively at Abuloma using hand auger to collect disturbed and undisturbed soil samples for laboratory investigation and classification. The geotechnical properties of the soil such unit weight, soil cohesion, angle of internal friction, Poisson's ratio and modulus of elasticity respectively were determined. All the tests followed standard procedures of testing soils for civil engineering purposes (BSI 377, 1990). The shear strength properties of the soil were determined based on unconfined compression test. The descriptive statistics of the geotechnical and elastic properties of the soil obtained from the four locations was carried out using statistical software called Minitab 17.0. The set of design variables and their corresponding outputs are used to develop linear regression model for bearing capacity and settlement respectively. A general Factorial Design of Experiment was used to develop the response surface models for bearing capacity and immediate settlement of the pad foundation at Abuloma, Rivers State. The probability distributions of the geotechnical and elastic properties of the soil at Abuloma were obtained using Anderson Darling statistics. The probabilistic assessment of shallow foundation was then carried out based on First Order Reliability method coded in MATLAB language.

2.1 Development of the Performance Functions

The model of a shallow foundation for the probabilistic study is shown in Figure 1.

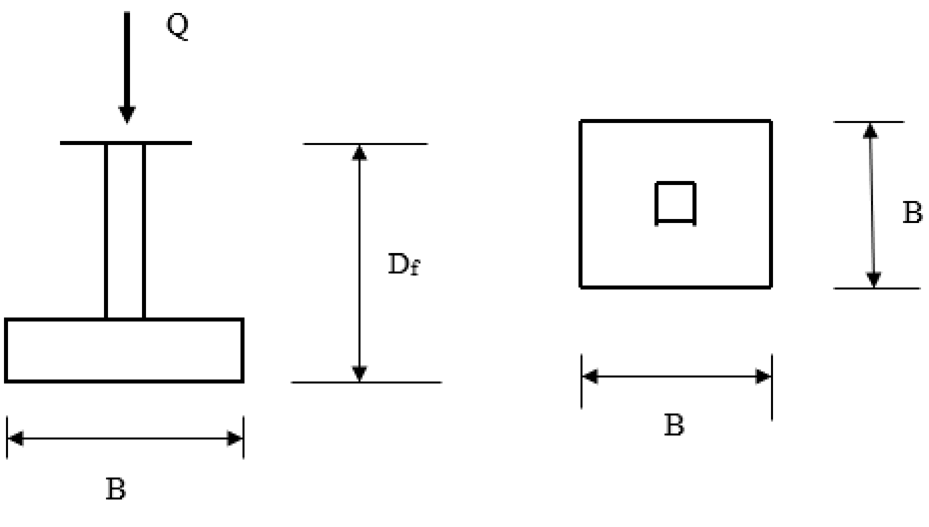

Figure 1: Model of a Shallow Foundation for the Probabilistic Study

2.2 Bearing Capacity Failure Criterion

According to Terzaghi et al. (1996), the equation for the ultimate bearing capacity of the soil supporting a square footing is given by:

$$Q_u = 1.3CN_c + \gamma D_f N_q + 0.4\gamma BN_\gamma \quad (1)$$

Where N_c, N_q, N_γ represent bearing capacity factors respectively and are dependent on angle of internal friction of the soil

$$G(X) = 1.3CN_c + \gamma D_f N_q + 0.4\gamma BN_\gamma - q \quad (2)$$

Where C = soil cohesion, D_f, B = Depth and width of foundation respectively, Q = Axial load on foundation, $\frac{Q}{B^2} = q$ = applied foundation pressure, γ = unit weight of soil

2.3 Immediate Settlement Failure Criterion

According to Terzaghi *et al.,* (1996), the immediate settlement of shallow foundation is given by:

$$S_i = \frac{q * B * (1 - \mu^2) * I_f}{E_s} \quad (3)$$

Where E_s = Design value of soil modulus, ν = Soil Poisson's ratio = 0.30, I_f = Influence factor of square footing = 0.82 (Bowels, 1996)

Therefore, the limit state function for immediate settlement of shallow foundation based on Terzagi *et al.,* (1996) is given by:

$$G(X) = S_i - \frac{q * B * (1 - \nu^2) * I_f}{E_s} \quad (4)$$

2.4 Response Surface Methodology

Let the response surface be represented by equation (5).

$$y = \alpha_0 + \alpha_1 X_1 + \alpha_2 X_2 + \alpha_3 X_3 + e \quad (5)$$

Where α_0, α_1, α_2, α_3 represent the regression coefficients, e = statistical error term

The model coefficients are obtained by least squares method.

2^n Factorial was used to fit equation (5) for the three number of input or natural variables, ϕ, c, γ (angle of internal friction, soil cohesion and unit weight) respectively.

The natural variables are changed into coded variables by using Equation (6).

$$\rho_i = \frac{X_i - [\max(X_i) + \min(X_i)]/2}{[\max(X_i) + \min(X_i)]/2} \quad (6)$$

The 2n+1 samples of x are generated using equation (7) and (8).

$$Max(X_i) = X_i + k\sigma_i \quad (7)$$

$$Min(X_i) = X_i - k\sigma_i \quad (8)$$

Where k = 1.645 for 5% level of significance and $\sigma_i s$ is standard deviations of the input parameters

Sample points are obtained using general full factorial design of experiment found in Minitab 17.0.

2.5 Test of Adequacy of the Regression Model

The fitted bearing capacity and immediate settlement models corresponding to the four selected study locations were tested for adequacy using the coefficient of multiple determination, R^2 and adjusted R^2 with the aid of a statistical tool called Minitab 17.0.

R^2 is calculated using Equation (9).

$$R^2 = \frac{\sum_{i=1}^{n}(y_i' - \bar{y})^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2} \quad (9)$$

Where y_i', $\bar{y}$, y_i = predicted mean, estimated mean and actual value of output variable respectively

$R^2 (R^2_{adj})$ is determined using equation (10).

$$R^2_{adj} = 1 - \frac{k-1}{k-p}(1 - R^2) \quad (10)$$

Where k, p represents the total number of observations and total number of regression coefficients respectively

The geotechnical parameters determined are all assumed to follow normal distribution. Therefore, the variance is given by:

$$S_x^2 = \sum_{k=1}^{k}\left(\frac{\partial z}{\partial x}\right)^2 \sigma \quad (11)$$

The corresponding standard deviation o is given by:

$$S_x = \left(\sum_{k=1}^{k}\left(\frac{\partial z}{\partial x}\right)^2 \sigma_x^2\right)^{0.5} \quad (12)$$

3. Method of Reliability Analysis

The First order method of structural reliability analysis was used to carry out the reliability-based design.

Let the limit state function in the space of input variables $x_1, x_2, ..., x_n$ be given by: $g(x_1, x_2, ..., x_n) = 0$ (13)

For a nonlinear limit state, the performance function is given by:

$$g(X) = g(x_1, x_2, x_3, ..., x_n) = R(x) - S(x) \quad (14)$$

According to Melchers (2000), $g(x) = 0$ represents the limit state surface and it represents the demarcation between the safe and failure region of the structure, $g(x) > 0$ represents the safe condition of a structure while $g(x) < 0$ represents the unsafe state of a structure.

The reduced form of n- dimensional random variables X_i is given by:

$$z = \frac{x_i - \mu_{xi}}{\sigma_{xi}}, \ (i = 1, 2, ..., n) \quad (15)$$

Making xi the subject and substituting for xi in equation (15) yields the performance function for n transformed variates as:

$$g(\sigma_{x1} * z_1 + \mu_{x1}, \sigma_{x2} * z_2 + \mu_{x2}, \sigma_{x3} * z_3 + \mu_{x3}, ..., \sigma_{xn} * z_n + \mu_{xn}) = 0 \quad (16)$$

Where μ and σ represents the mean and standard deviation of the basic variables respectively.

Equation (16) is solved by optimization to yield the design points on the failure surface as:

$$z^* = \left(z_1^*,\ z_2^*,\ z_3^*,\ z_n^*\right) \quad (17)$$

The reliability index β corresponding to the vector of the design points is given by:

$$\beta = \sqrt{\left(z_1^2 + z_2^2 + ... + z_n^2\right)} \quad (18)$$

The statistics of the basic random variables are presented in Table 1.

Table 1: Statistics of the Soil Properties and other Random Variables at Abuloma

Variable	Probability Distribution	Mean	Standard Deviation	Coefficient of Variation
Unit weight of Soil, γ (KN/m^3)	Normal	18.4	0.909	0.05
Poisson's Ratio	Normal	0.387	0.031	0.08
Angle of Internal Friction $(^0)$	Normal	21.55	4.77	0.22
Modulus of Elasticity of Soil, E (N/mm^2)	Normal	8655	1240	0.14
Soil Cohesion, C (KN/m^2)	Normal	17.01	2.436	0.143
Width of Foundation, B (m)	Normal	1.5	0.015	0.01
Allowable Bearing Capacity, q_{all} (KN/m^2)	Normal	225.95	6.7784	0.03
Depth of foundation (m)	Normal	1.2	0.012	0.01

4. RESULTS AND DISCUSSIONS

The maximum and minimum values of the design variables and the combination of natural variables and corresponding ultimate bearing capacity at Abuloma are shown in Tables 2 and 3 respectively.

Table 2: Maximum and Minimum Values of the Design Variables at Abuloma

Variables	Mean	Standard Deviation	Lower Value $(\mu - 1.645*\sigma)$	Higher Value $(\mu + 1.645*\sigma)$
$\gamma\ (KN/m^3)$	18.4	0.909	16.91	19.90
$Cohesion\,(KN/m^2)$	17.01	2.44	13.00	21.02
$\phi\,(Degree)$	21.55	4.766	13.71	29.39

Table 3: Combination of Natural Variables and Corresponding Ultimate Bearing Capacity at Abuloma

$Cohesion\,(KN/m^2)$	$\phi\,(Degree)$	$\gamma\ (KN/m^3)$	$q_u\ (KN/m^2)$
13	13.71	16.91	307.43
13	13.71	19.9	326.65
13	29.39	16.91	1325.47
13	29.39	19.9	1453.17
21.02	13.71	16.91	430.04
21.02	13.71	19.9	449.26
21.02	29.39	16.91	1697.65
21.02	29.39	19.9	1825.35

Using values in Table 3 and a statistical tool Minitab 17.0, the regression equation for ultimate bearing capacity equation of pad foundation at Abuloma is given by:

$$q_u = -1645 + 30.85C + 76.34\phi + 24.6\gamma \quad (19)$$

Model Coefficient of Determination of equation (19) is 0.975. This value is close to 1. The model is therefore adequate to predict the ultimate bearing capacity of pad foundation at Abuloma, Rivers State.

Using equation (1), the mean value of the bearing capacity of the soil at Abuloma is obtained as:

$$\mu_{qu} = 977.77 KN/m^2$$

The standard deviation of the ultimate bearing capacity of the foundation soil using equation (12) is obtained as:

$$\sigma_{qu} = \left(30.85^2 * \sigma_C^{\ 2} + 76.34^2 * \sigma_\phi^{\ 2} + 24.6^2 * \sigma_\gamma^{\ 2}\right)^{0.5}$$

$$\sigma_{qu} = \left(30.85^2 * 2.44^2 + 76.34^2 * 4.766^2 + 24.6^2 * 0.909^2\right)^{0.5} = 372.21 KN/m^2$$

Performance functions are developed for reliability-based design of pad foundation at Abuloma, considering the failure of pad foundation considering the foundation failure in immediate settlement and bearing capacity using equations (3) and 19.

4.1 Bearing Capacity Criterion

$$G = -1645 + 30.85C + 76.34\phi + 24.6\gamma - q \qquad (20)$$

4.2 DISCUSSION OF RESULTS

The response surface models for predicting the bearing capacity of the pad foundation at Abuloma was tested for adequacy using the coefficient of determination and Minitab 17.0. The coefficient of determination value for the response surfaces model developed 0.975 which is very close to 1 showing that the model is very reliable. The expected value of the ultimate bearing capacity of the foundation soil of the foundation soil at Abuloma is 977.77KPa. The corresponding standard deviation is 372.21KPa.

The results of reliability-based design of pad foundation at Abuloma are presented in Figures 1and 2 respectively.

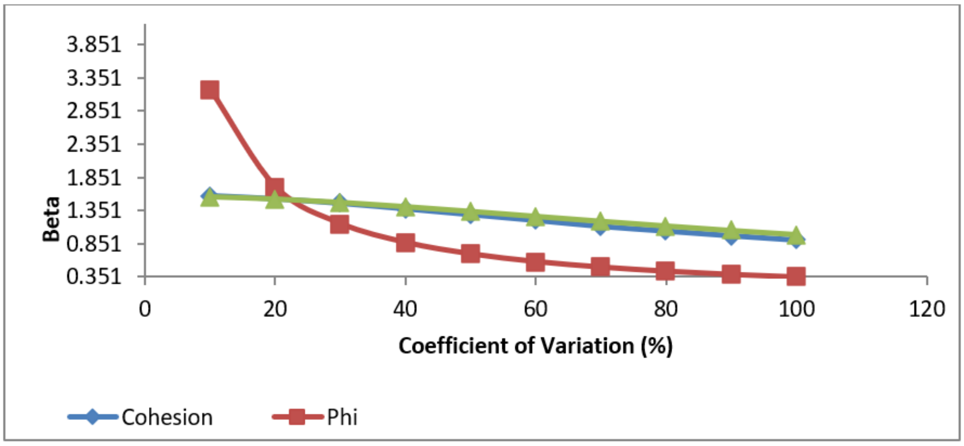

Figure 1: Relationship between Index Reliability and Coefficient of Variation of Soil Properties

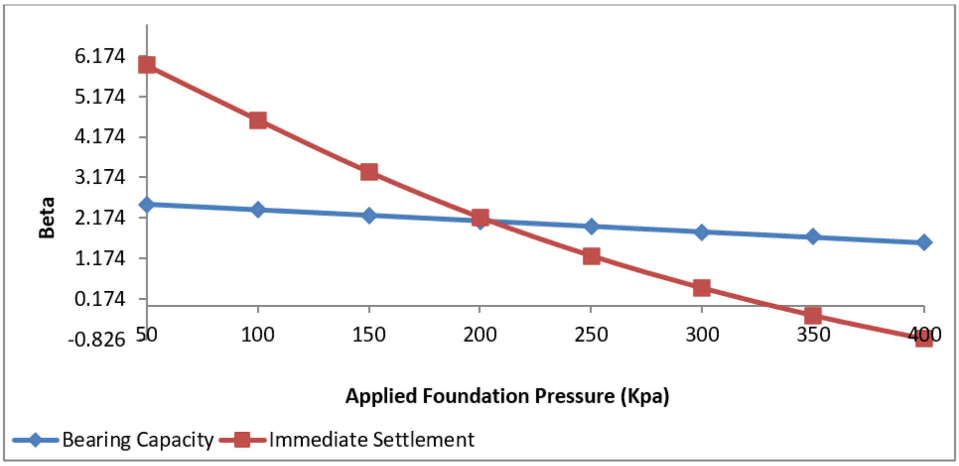

Figure 2: Relationship between Reliability Index and Applied Foundation Pressure

The results of the variation of reliability index at varying values of coefficient of variation in the range of 10% to 100% for soil cohesion, angle of internal friction and unit weight of soil at Abuloma considering bearing capacity failure mode are presented in Figures 1 and 2 respectively. It can be seen Figures 1 and 2 that the reliability index decreases with increase in values of the coefficient of variation. This is because the increase in coefficient of variation causes a corresponding increase in the uncertainties of the soil cohesion, angle of internal friction and unit weight of soil respectively. However, it can be seen from Figures 1 and 2 that the unit weight of soil Abuloma appear to be more sensitive to increase in coefficient of variation. The performance of the pad foundation at Abuloma was evaluated for applied foundation pressure at 50KPa interval to ascertain the maximum pressure that the structural foundation at Abuloma can support without failure as can be seen in Figure 2. At Abuloma, it can be observed that the pad foundation is safe only for an applied foundation pressure of 50Kpa as the implied reliability index is 2.505. This is because; the performance level of the structural foundation is above average as recommended by the US Army Corps of Engineers (1997). For applied foundation pressure of 100KPa and 150KPa, the corresponding reliability indices are 2.369 and 2.235 respectively. The obtained values of the reliability indices corresponding to the applied foundation pressures of 100KPa and 150KPa show that the performance of the pad foundation corresponding to the aforementioned loads is below average as recommended by the US Army Corps of Engineers (1997). For an applied foundation pressure of 200KPa, 250KPa, 300KPa, 350KPa and 400KPa, the pad foundation performance level is poor as recommended by the US Army Corps of Engineers (1997). This is because the corresponding implied reliability indices are 1.965, 1.829, 1.695 and 1.560 respectively. It can also be seen from Figure 3 that the pad foundation is safe for applied foundation pressure of 50KPa, 100Kpa and 150KPa respectively as their corresponding probability of exceeding the 40mm allowable pad foundation settlement are 5.942, 4.597 and 3.308 respectively. This is in agreement with the recommendation of the US Army Corps of Engineers (1997). For applied foundation pressure of 200KPa, 250Kpa and 300KPa, the pad foundation performance levels are below average, satisfactory and hazardous respectively as their corresponding probability of exceeding the 40mm allowable pad foundation settlement are 2.185, 4.597 and 0.435 respectively. This is in agreement with the recommendation of the US Army Corps of Engineers (1997). For applied foundation pressure of 350KPa and 400KPa, the pad foundation is not safe at all as their corresponding probability of exceeding the 40mm allowable pad foundation settlement are -0.245 and -0.826 respectively. This is in agreement with Abejide (2014) that for negative value of implied reliability index, the structure is not safe at all.

CONCLUSIONS

Based on the results obtained from the study, the following conclusions are hereby made:

1. Abuloma soil is safe only for an applied foundation pressure of 50KPa and performed below average for applied foundation pressure of 100KPa and 150KPa respectively, considering foundation failure in bearing capacity.
2. The pad foundation is safe for applied foundation pressure of 50KPa, 100Kpa and 150KPa respectively considering settlement criterion.
3. The reliability index increased with increase in the value of the coefficient of variation of soil cohesion, angle of internal friction and unit weight of soil respectively.

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