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Stochastic Application on the Variability of Soil Deformation Models

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Abstract

This study conducted a probabilistic evaluation of immediate settlement with foundation depths at the centre of raft foundation in Borokiri and Nwokekoro close, Old GRA, Port Harcourt, Rivers State, Nigeria. It utilized deterministic methods for immediate settlement analysis, specifically those developed by Meyerhof, Peck and Bazaraa, Steinbrenner and Fox, Mayne and Poulos, and Burland and Burbidge. The geotechnical and elastic parameters necessary for reliability estimation were derived from the geotechnical investigation of soil samples collected from the sites. Serviceability limit state functions were formulated based on the immediate settlement equations mentioned earlier. The uncertainties associated with the random variables for each limit state function were sourced from existing literature. Reliability estimates were performed using computer programs developed in MATLAB based on the First Order Reliability Method (FORM). The findings indicated that in the Borokiri area, the Steinbrenner and Fox method produced reliability index values ranging from 2.4 to 2.7, which are within the recommended target reliability index range (2.5 – 4.0) for geotechnical structures. In contrast, the Mayne and Poulos method yielded a higher reliability index (6.1 to 6.5). The other methods, such as Burland and Burbidge (-0.07 to 1.6), Meyerhof (-1.4 to 0.8), and Peck and Bazaraa (-2.5 to - 0.6), underestimated the target reliability index. For the Nwokekoro close, Old GRA area, Steinbrenner and Fox again provided reliability index values between 3.4 and 4.0, aligning with the recommended target reliability index, while Mayne and Poulos (6.3 to 7.2) overestimated. The other methods, such as Burland and Burbidge (-2.3 to 1.9), Meyerhof (-2.4 to 1.7), and Peck and Bazaraa (-3.3 to 0.5), underestimated the target reliability index. Consequently, the Steinbrenner and Fox method emerged as the most reliable for predicting the immediate settlement of raft foundations in both Borokiri and Nwokekoro close, Old GRA. These results corroborate the findings from deterministic methods, suggesting that as estimated settlement exceeds the maximum allowable limit, the reliability index is expected to decrease, and vice versa. The MATLAB program developed in this research is user-friendly and suitable for geotechnical applications.

Keywords: ***Immediate settlement; Reliability index; Deterministic analysis; Probabilistic analysis; Target reliability index.***

1.0 Introduction

Soil settlement (deformation) occurs when the weight of structures or other loads is placed on the soil, leading to a rearrangement of soil particles and a reduction in the voids between them. This settlement can happen immediately after the load is applied, referred to as immediate (elastic) settlement, or it can occur over an extended period, known as consolidation settlement (Awarri & Akpila, 2025). In granular soils, three key factors influence settlement: the applied pressure, the stiffness of the soil, and the width, depth, and shape of the foundation. For foundations resting on granular soil, only the immediate settlement needs to be calculated (Das & Sivakugan, 2007).

Calculating soil settlement is a significant aspect of geotechnical engineering where deterministic analysis is frequently used. In this type of analysis, engineers apply established principles and empirical relationships to predict soil settlement under specific loading conditions. However, it's important to recognize that deterministic settlement analysis treats soil properties and loading conditions as fixed values, overlooking the uncertainties and variability associated with these elements (Arel & Mert, 2021; Nour et al., 2002; Shahin et al., 2005). Changes in soil properties or loading conditions can significantly impact settlement behavior (Fenton et al., 1996). As a result, probabilistic or risk-based methods are often used to account for uncertainties in soil properties and loading conditions, offering a more thorough and realistic evaluation of settlement (Cheng et al., 2022; Wang et al., 2017; Wu et al., 2011).

The use of stochastic methods in geotechnical engineering dates back several decades. Probability theory and stochastic analysis began to be applied in the 1960s, with early researchers focusing on probabilistic modeling of soil properties such as strength and stiffness. Significant contributions from this period include the work of Ditlevsen and Madsen (1996) on reliability analysis and the introduction of Monte Carlo simulation to assess uncertainty in geotechnical design.
As the century turned, advancements in stochastic techniques continued in geotechnical engineering. Researchers began to tackle more complex issues, including reliability-based design optimization and the integration of uncertainties into numerical modeling techniques like finite element analysis and boundary element analysis. Moreover, efforts were made to create more precise probabilistic models for various geotechnical phenomena, including liquefaction, settlement, and slope stability (Abdellah, 2015; Sudret & Berveiller, 2008).

Previous studies on the immediate settlement of soil using the first-order reliability method have primarily concentrated on strip foundations, applying stochastic analysis exclusively to the method developed by Burland and Burbidge (1985) for predicting foundation settlement. However, there is insufficient information regarding the assessment of stochastic immediate settlement of soil for raft foundations using the first-order reliability method. Furthermore, there is a necessity to apply this method to evaluate immediate soil settlement in relation to other well-established foundation settlement prediction methods, such as those proposed by Meyerhof (1956), Peck & Bazaraa (1969), Burland & Burbidge (1985), and Mayne & Poulos (1999).

2.0 Materials and Methods

2.1 Materials

The research utilized existing materials and data from previous studies on granular soils, obtained through standard laboratory and field testing.

2.2 Methods

This study used data from the works of notable geotechnical engineers and researchers, which provided insights into the subsurface conditions of Borokiri and Nwokekoro close, Old GRA, Port Harcourt, in Rivers State. The data included information from ground borings conducted to shallow depths ranging from 1.0 to 5.0 m, using a light cable percussion boring rig to collect both disturbed and undisturbed soil samples for visual inspection, laboratory testing, and classification. Additionally, Standard Penetration Tests (SPT) were carried out to evaluate the penetration resistance of cohesionless layers at specific depths during the boring process. Essential laboratory tests such as moisture content, specific gravity and particle size distribution on soil samples were performed to derive input parameters for analyzing bearing capacity and immediate settlement.

2.2.1 Determination of Immediate Settlement and Performance Function

This study discusses five established methods for calculating immediate settlement:

2.2.1.1 Meyerhof's Method

Meyerhof (1956) introduced formulas for determining the immediate settlement of foundations on granular soil, as indicated in Equation (3.1), while Equation (3.2) presents the limit state or performance function equation.

$$S_e = C_w C_D \ \text{x} \ \frac{1.25_q}{N_{60}} \ (\text{for B} \leq 1.22\text{m}) \quad (3.1)$$

Where C_w = ground water table correction

C_D = correction for depth of embedment = 1 - $\left(\frac{D_f}{4B}\right)$

q = bearing pressure (kN/m^2)

B = width of foundation (m)

N_{60} = SPT number at 60% energy level

The limit state or performance function is

$$G(X) = S_p - C_w C_D \ \text{x} \ \frac{1.25_q}{N_{60}} \quad (3.2)$$

S_p = permissible value of settlement (mm)

2.2.1.2 Peck and Bazaraa Method

Peck and Bazaraa (1969) proposed method is shown in equation (3.3)

$$S_e = C_w C_D \ \text{x} \ \frac{2_q}{(N_1)_{60}} \left(\frac{B}{B + 0.3}\right)^2 \quad (3.3)$$

The limit state or performance function is given by;

$$G(X) = S_p - C_w C_D \ \text{x} \ \frac{2_q}{(N_1)_{60}} \left(\frac{B}{B + 0.3}\right)^2 \quad (3.4)$$

2.2.1.3 Burland and Burbidge Method

Burland and Burbidge (1985) proposed a method that can be summarized as shown in equation (3.5)

$$S_e = \frac{q_n B^{0.7}}{3} \left(\frac{1.71}{N^{1.4}}\right) \quad (3.5)$$

The limit state or performance function is given by;

$$G(X) = S_p - \frac{q_n B^{0.7}}{3} \left(\frac{1.71}{N^{1.4}}\right) \quad (3.6)$$

2.2.1.4 Mayne and Poulos Theory

Mayne and Poulos (1999) method is shown in Equation (3.7)

$$S_e = \frac{q B_e I_G I_R I_E}{E_0} (1 - \mu_s^2 (3.7)$$

The limit state or performance function is given by;

$$G(X) = S_p - \frac{q B_e I_G I_R I_E}{E_0} (1 - \mu_s^2 (3.8)$$

Where I_G = influence factor for the variation of E_s with depth = $f\left(\beta - \frac{E_0}{kB_e}, \frac{H}{B_e}\right)$

I_R = foundation rigidity correction factor

I_E = foundation embedment correction factor

μ_s = Poisson ratio

B_e = equivalent diameter (m)

2.2.1.5 Steinbrenner and Fox's Theory

Steinbrenner and Fox's Theory is shown in Equation (3.9)

$$S_e = q(\alpha' B')\, \frac{1-\mu_s^2}{E_s}\, I_s I_f \quad (3.9)$$

The limit state or performance function is given by;

$$G(X) = S_p - q(\alpha' B')\, \frac{1-\mu_s^2}{E_s}\, I_s I_f \quad (3.10)$$

2.2.2 Immediate Settlement Determination using Stochastic Method

The stochastic method used is the First Order Reliability Method (FORM), which is implemented in a MATLAB program. In FORM, the limit state function g(x) is linearized using Taylor series, and the reliability index is determined as the shortest distance from the origin to the failure surface. Hasofer and Lind (1974) introduced a consistent definition for the reliability index, which is the basis of the FORM approach. The process begins with defining the performance function g(x), where x represents the vector of fundamental random variables.

The limit state or performance function is characterized as a function of capacity and demand, as indicated in Equation (3.11).

$$g(x) = R - Q \quad (3.11)$$

Where;

R = structural resistance or capacity of the structural component

Q = load effect or demand of the structural component with the same units as the resistance.

When

$$g(x)\begin{cases} > 0 \; safe\ state \\ = 0 \; limit\ state \\ < 0 \; failure\ state \end{cases}$$

The primary goal of stochastic analysis is to ensure that the probability of failure remains below an acceptable threshold. If the joint probability density function of all random variables F_X(X) is known, the probability of failure P_f can be expressed as:

$$P_f = \int_L^1 F_X(X)dX$$

Where L represents the domain of X, where G(X) < 0.

Generally, this integral cannot be solved analytically. In the FORM approximation, the vector of random variables X is transformed into standard normal space U, where U consists of independent Gaussian variables with a mean of zero and a standard deviation of one, and G(U) is a linear function. The probability of failure P_f is then given by:

$$P_f = P\,[G(U) < 0] \approx P\left[\sum_{i=1}^{n} \alpha_i U_i - \beta < 0\right] = \varphi\,(-\beta)$$

Here, α_i is the direction cosine of the random variable, U_i, β is the reliability index representing the distance from the origin to the hyperplane G(U) = 0, n is the number of basic random variables X, and φ is the standard normal distribution function. A more convenient measure of the probability of failure is the reliability index (β), defined as:

$$\beta = -\,\varphi^{-1}\,(P_f)$$

The coded MATLAB computer program is shown below.

Subfunction for Rackwitz-Fiessler Transformation of Lognormal Distribution to Equivalent Normal Distribution

```
function [mean,std]= logn(rfmu,rmfx)
xo = rmfx/rfmu;
om = sqrt(log(1.0 + (xo)^2));
x = log(rfmu)-0.5*om^2;
std = om*rfmu;
mean = rfmu*(1-log(rfmu)+x);
fprintf('std = %.3f\nmean = %.3f\n',std,mean);
end
```

Subfunction for Rackwitz-Fiessler Transformation of Gumbel Distribution to Equivalent Normal Distribution

```
y=?;stan=?;
a = 1.282/stan;u=y-0.577/a;
pdf=a*exp(-a*(y-u)-exp(-a*(y-u)))/(1-exp(-exp(a*u)));
cdf=exp(-exp(-a*(y-u)));
z=norminv(cdf);
pdfz=exp((-z^2)/2.0D0)/sqrt(6.2833185307D0);
std=pdfz/pdf
mean=y-norminv(cdf)*stan
```

3.0 Results and Discussion

3.1 Immediate Settlement with Depth using Deterministic Methods

3.1.1 Results from Nwokekoro Close-Old GRA.

Peck and Bazaraa recorded the highest immediate settlement values in relation to foundation depths at boreholes 1, 2, and 3, followed by the methods of Burland and Burbidge, Meyerhof, Mayne and Poulos, and finally Steinbrenner and Fox, as illustrated in Figures 3.1 (a) to 3.1 (c).

At boreholes 1 and 2, there was a decrease in immediate settlement as the foundation depth increased from 1.0 to 5.0 meters for all methods, except for the Steinbrenner and Fox method at borehole 2, where immediate settlement increased with greater foundation depth. Conversely, borehole 3 exhibited an increase in immediate settlement as the foundation depth rose from 1.0 to 3.0 meters. However, all methods indicated a reduction in immediate settlement when the foundation depth was further increased from 3.0 to 5.0 meters.

The rise in immediate settlement with increased foundation depth was attributed to a high water table, which contributed to greater immediate settlement. Additionally, the lateral confinement from the surrounding soil decreased, allowing for more soil compression and thus higher immediate settlement. On the other hand, the reduction in immediate settlement with greater foundation depth was due to the increase in vertical stress (overburden pressure), which helps mitigate immediate settlement. Increased confining pressure also enables soil particles to interlock more effectively, further reducing the likelihood of immediate settlement.

The immediate settlement values obtained using various methods at different foundation depths and boreholes ranged from 15.93 to 165.99 mm. The methods of Peck and Bazaraa, Meyerhof, and Burland and Burbidge yielded results that exceeded the maximum allowable settlement. In contrast, the Mayne and Poulos method produced immediate settlement values that fell within the maximum permissible limit for raft foundations, which is 65 mm (Skempton & MacDonald, 1956).

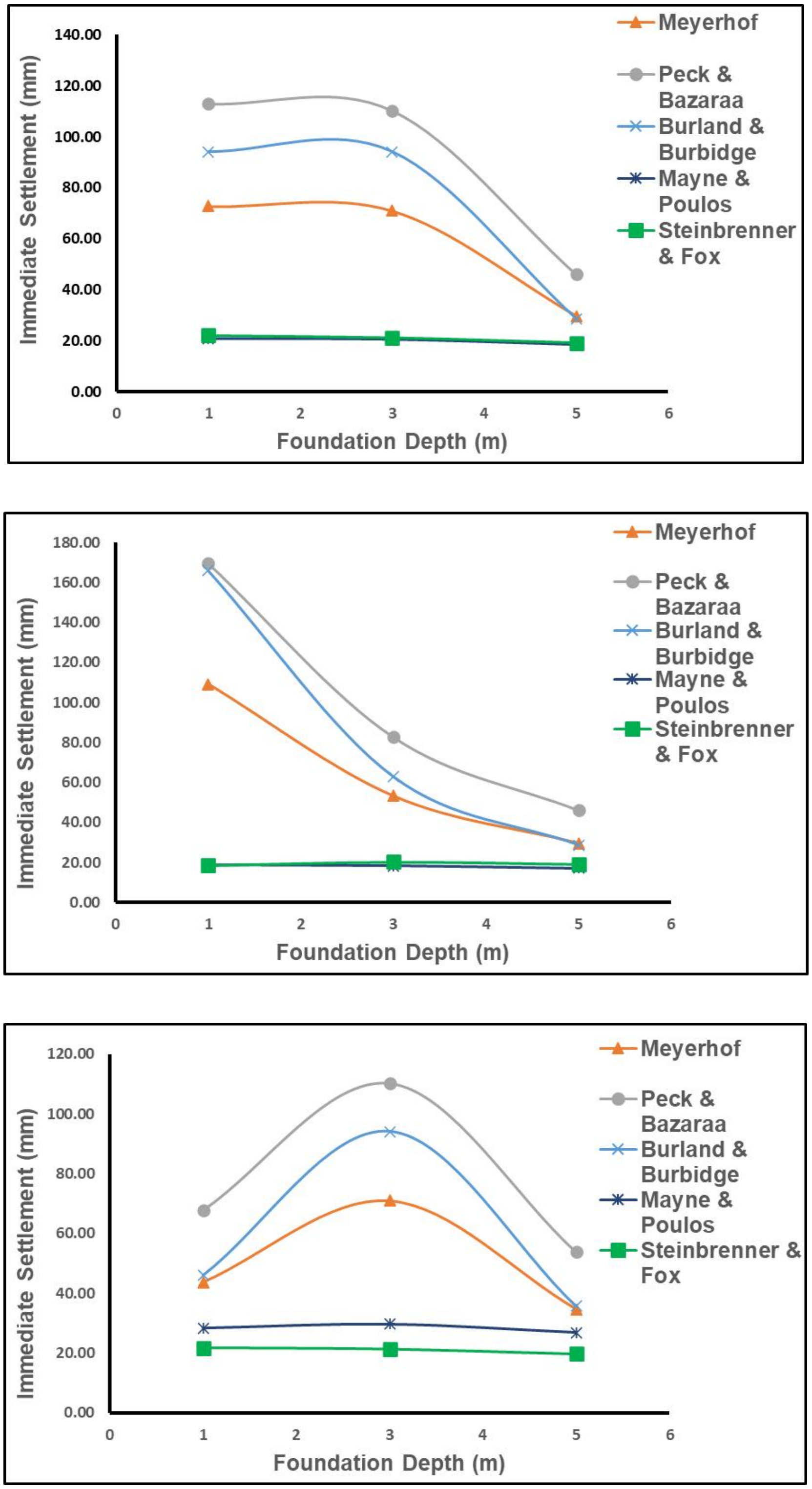


Figure 3.1: Immediate Settlement of Soil against Foundation Depth at Nwokekoro Close-Old GRA for (a) Borehole 1, (b) Borehole 2, (c) Borehole 3

3.1.2 Results from Borokiri

Figures 3.2 (a) to 3.2 (c) indicate that among the various deterministic methods, the Peck and Bazaraa method yielded the highest immediate settlement values in relation to foundation depths, followed by the Meyerhof, Burland and Burbidge. Mayne and Poulos, and finally the Steinbrenner and Fox methods. Overall, boreholes 1 to 3 showed a reduction in immediate settlement as the foundation depth increased from 1.5 m to 4.5 m. This decrease in immediate settlement with greater foundation depth can be attributed to the same factors mentioned for the Nwokekoro-Old GRA area. The immediate settlement results obtained from the different deterministic methods across various foundation depths and boreholes ranged from 26.15 to 126.94 mm. The Peck and Bazaraa, Meyerhof, and Burland and Burbidge methods produced immediate settlement values that exceeded the maximum allowable settlement for raft foundations, whereas the Mayne and Poulos, and Steinbrenner and Fox methods yielded immediate settlement values that fell within the permissible limits for raft foundations.

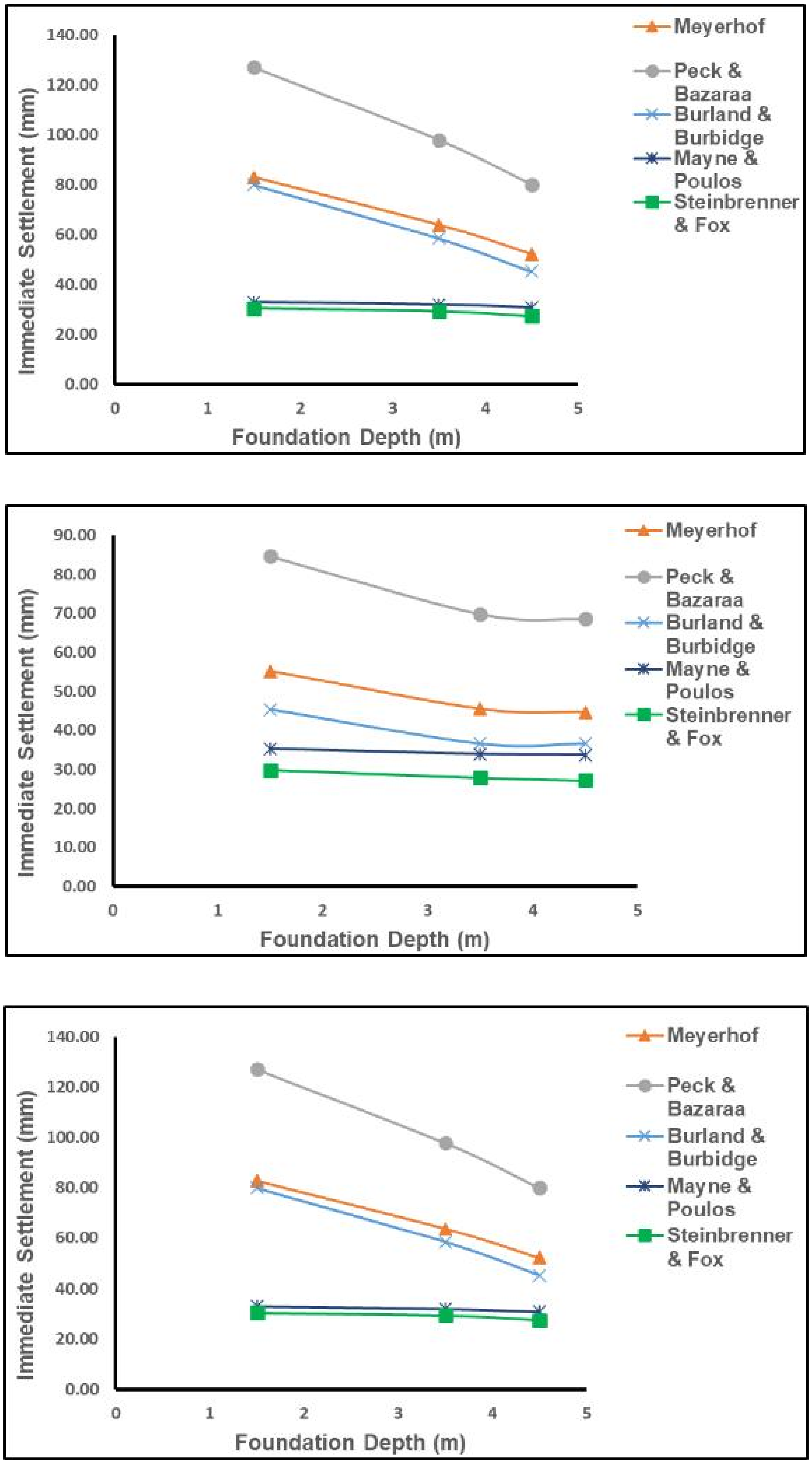


Figure 3.2: Immediate Settlement of Soil against Foundation Depth at Borokiri for (a) Borehole 1, (b) Borehole 2, (c) Borehole 3

3.2 Immediate Settlement with Depth Using a Probabilistic Approach

3.2.1 Results from Nwokekoro Close-Old GRA.

Results from Nwokekoro Close-Old GRA indicate the following: Figures 3.3 (a) to 3.3 (c) demonstrate that among the various methods evaluated, the Mayne and Poulos method yielded the highest reliability indices in relation to foundation depths, followed by the Steinbrenner and Fox, Burland and Burbidge, Meyerhof, and finally the Peck and Bazaraa methods.

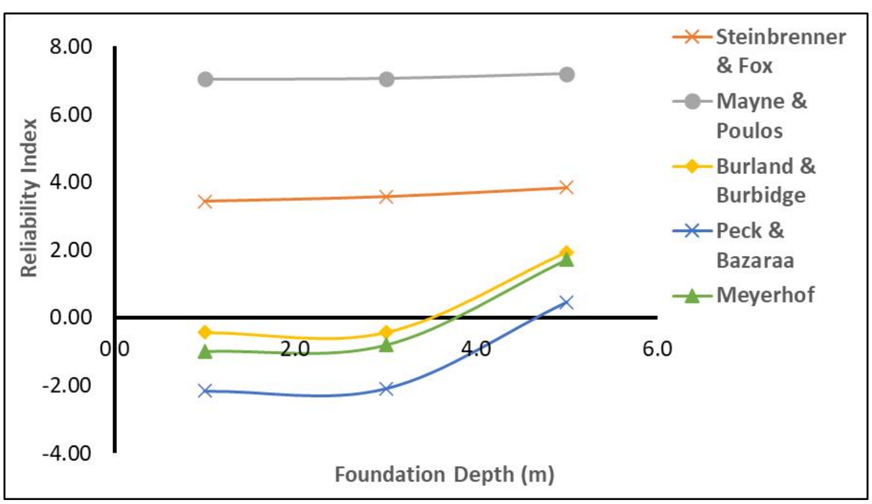
For borehole 1, the reliability index of the granular soil increased with greater foundation depth across all methods. This trend is attributed to deeper foundations typically encountering stiffer soil layers, which are less prone to excessive settlement, leading to higher reliability indices.

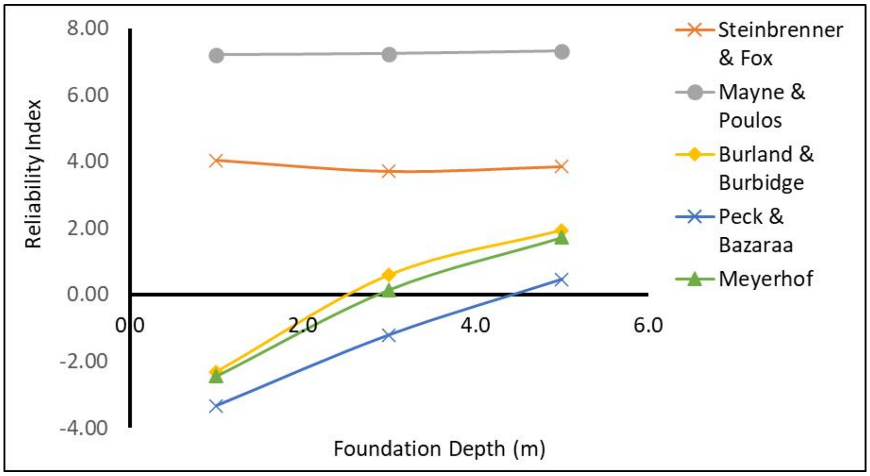
In borehole 2, the reliability index of the granular soil also increased with foundation depth for all methods, except for the Steinbrenner and Fox method, which showed a decrease in reliability index when the foundation depth increased from 1.0 to 3.0 m. However, further increasing the foundation depth from 3.0 to 5.0 m resulted in an increased reliability index.

For borehole 3, both the Mayne and Poulos and Steinbrenner and Fox methods indicated that increasing the foundation depth from 1.0 to 5.0 m led to higher reliability indices. Conversely, the Burland and Burbidge, Meyerhof, and Peck and Bazaraa methods showed a decrease in reliability indices when the foundation depth increased from 1.0 to 3.0 m, but an increase was observed when the depth was further increased from 3.0 to 5.0 m.

The rise in reliability indices with greater foundation depth is due to deeper foundations encountering stiffer soil layers, which are less likely to undergo excessive settlement. The observed decrease in reliability indices is a result of the variability in soil properties with depth, caused by layering and compaction, which leads to greater variability in predicted settlements and a reduced reliability index.

Ultimately, the results from the Mayne and Poulos method overestimated the reliability indices, exceeding the target range of 2.5 to 4.0 for the raft foundation considered (Baecher & Christian, 2003; Phoon, 2008). In contrast, the results from the Burland and Burbidge, Meyerhof, and Peck and Bazaraa methods underestimated the reliability indices, falling below the target range. The Steinbrenner and Fox method, however, met the target reliability indices of 2.5 to 4.0.
When the target reliability indices are greater than 0, the settlement is within acceptable limits (safe region), indicating satisfactory foundation performance. Conversely, when the target reliability indices are less than 0, the settlement exceeds acceptable limits (failure region), resulting in unsatisfactory foundation performance.





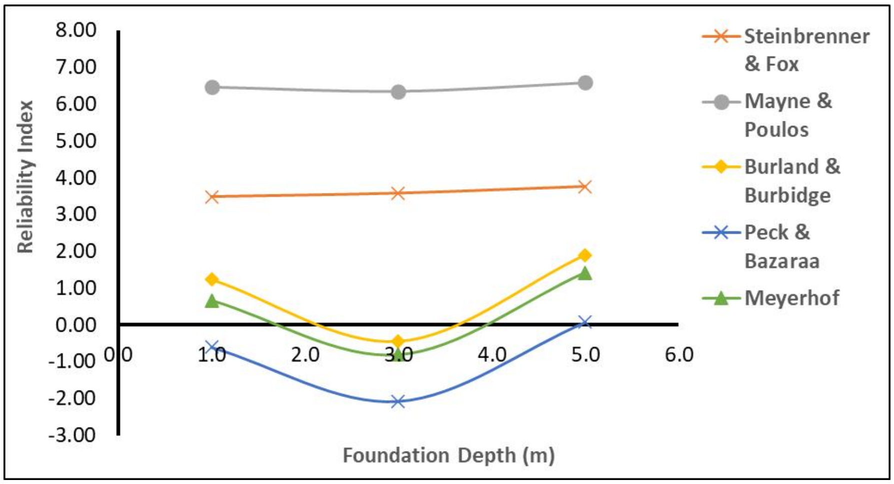


Figure 3.3: Reliability Index of Soil against Foundation Depth at Nwokekoro Close-Old GRA for (a) Borehole 1, (b) Borehole 2, (c) Borehole 3

3.2.2 Results from Borokiri

Results from Borokiri indicate that, as shown in Figures 3.4 (a) to 3.4 (c), the Mayne and Poulos method achieved the highest reliability indices in relation to foundation depths, followed by the Steinbrenner and Fox method, then Burland and Burbidge, Meyerhof, and finally Peck and Bazaraa methods.

It was generally observed that an increase in foundation depth led to a rise in the reliability index of the granular soil across all methods for boreholes 1, 2, and 3. This is attributed to deeper foundations typically encountering firmer soil layers, which are less prone to excessive settlement, thereby resulting in higher reliability indices. Additionally, deeper soils may possess enhanced characteristics, such as greater density or cementation, which further improve reliability.

Ultimately, the results from the Mayne and Poulos method overestimated the reliability indices, exceeding the target range of 2.5 to 4.0 for the raft foundation examined (Baecher & Christian, 2003; Phoon, 2008). In contrast, the results from Burland and Burbidge, Meyerhof, and Peck and Bazaraa methods underestimated the reliability indices, falling below the target range of 2.5 to 4.0. However, the Steinbrenner and Fox method met the target reliability indices of 2.5 to 4.0.

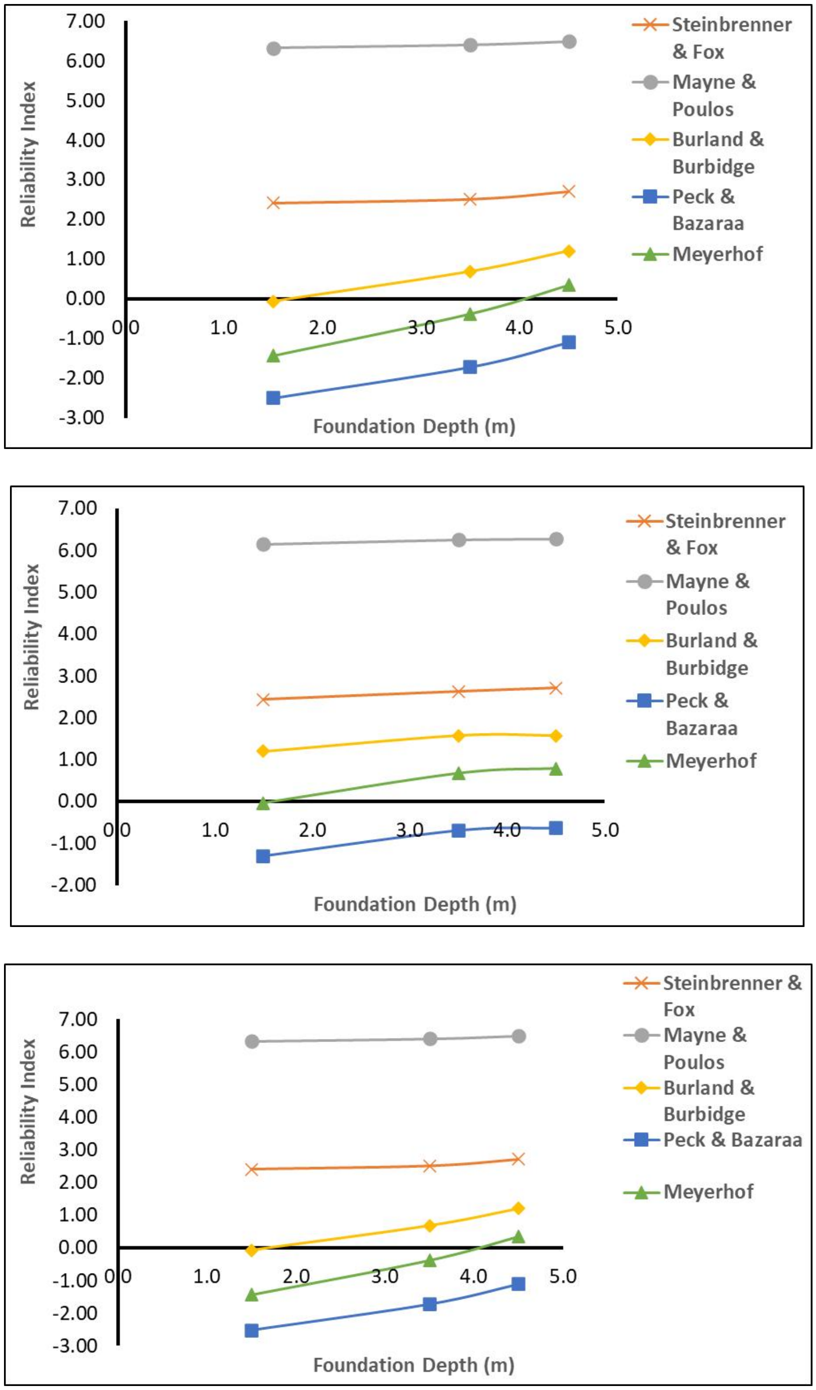


Figure 3.4: Reliability Index of Soil against Foundation Depth at Borokiri for (a) Borehole 1, (b) Borehole 2, (c) Borehole 3

3.3 Comparison of the Results of Deterministic Based Settlement with the Results of the Reliability-Based Method.

The reliability indices and the deterministic immediate settlement are compared with respect to the target reliability index for the granular soil as shown in Tables 3.1 and 3.2.

The findings showed that Peck and Bazaraa failed to meet the target reliability indices (2.5 to 4.0) for raft foundation in the research locations, as well as the allowable maximum settlement (65 mm) of soil deterministically. Additionally, Meyerhof, Burland and Burbidge did not meet the target reliability indices, although they did partially satisfy the allowable maximum settlement of soil deterministically. Mayne and Poulos overestimated the target reliability indices while deterministically satisfying the allowable maximum settlement of soil. Nonetheless, Steinbrenner and Fox met the target reliability indices as well as the permissible maximum settlement of soil deterministically. In general, it was also found that the reliability index increased with decreasing deterministic immediate settlement and vice versa.

Table 3.1: Deterministic-based Immediate Settlement and its Reliability Indices in Terms of Reliability Index for Borokiri

Method	Deterministic Immediate settlement (Permissible settlement value = 65 mm)	Reliability Index (Target reliability index = 2.5 - 4.0)
Steinbrenner and Fox	28.5 - 31.3	2.4 - 2.7
Mayne and Poulos	33.2 - 37.7	6.1 - 6.5
Burland and Burbidge	48.4 - 106.1	-0.07 - 1.6
Peck and Bazaraa	83.9 - 156.8	-2.5 - (-0.6)
Meyerhof	54.7 - 102.3	-1.4 - 0.8

Table 3.2: Deterministic-based Immediate Settlement and its Reliability Indices in Terms of Reliability Index for Nwokekoro Close, Old G.R.A.

Method	Deterministic Immediate settlement (Permissible settlement value = 65 mm)	Reliability Index (Target reliability index = 2.5 - 4.0)
Steinbrenner and Fox	18.8-22.8	3.4 - 4.0
Mayne and Poulos	19.1-31.3	6.3 - 7.2
Burland and Burbidge	38.1-220.4	-2.3 - 1.9
Peck and Bazaraa	56.4-207.6	-3.3 - 0.5
Meyerhof	36.3-133.7	-2.4 - 1.7

4.0 Conclusion

The results of the study suggest the following conclusions:

i. The study demonstrates the applicability of stochastic methods in capturing the variability of soil deformation models. The results provide a more comprehensive understanding of the uncertainty associated with soil behaviour, highlighting the importance of considering stochastic approaches in geotechnical engineering practice for optimal and safer foundation designs.
ii. The Steinbrenner and Fox method should be utilized for the probabilistic analysis of granular soils in raft foundations within the studied areas.
iii. Additional research should be conducted using probabilistic methods on other immediate settlement techniques.

Declarations

Credit authorship contribution statement

A.A.W: S.B.A and T.K.S: Conceptualization. Wrote the original draft, Methodology, Validation, Resources, project administration, and review of the manuscript.

Declaration of competing interest
The authors declare no conflict of interest.

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Consent for publication
Not applicable

Ethics and Consent to Participate
Not applicable

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