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Conceptual Model on the Effect of Axial Load on Shallow Isolated Footings Resting on Clay Soil

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Abstract: This study investigates the geotechnical behavior and bearing capacity of clay soils at the Polo Ground in Maiduguri, Nigeria, with a focus on their suitability for building and shallow structural foundation design. Laboratory tests were conducted on soil samples collected at a depth of 2.0 meters to determine key index properties such as moisture content, specific gravity, Atterberg limits, grain size distribution and shear strength parameters. The results indicated high plasticity indices (PI > 17), classifying the soils as highly plastic clays (CL and CH) under the Unified Soil Classification System (USCS). Specific gravity values ranged from 1.32 to 2.60, suggesting the presence of organic material and further raising concerns regarding the soil's load-bearing capability. The computed safe bearing capacities for the soil samples ranged from 136.9 to 166.4 kN/m², with an average design value of 152 kN/m². These results reflect moderate bearing strength, typical of soft clay soils, which necessitate careful foundation design. The settlement analysis conducted for samples A, B, and C revealed settlement values of 196 mm, 291 mm, and 186 mm, respectively. These values are considered significantly high and may pose serious risks to the structural integrity of buildings supported by isolated footings. Excessive settlement of this magnitude can lead to differential movement, cracking, and potential failure of foundation elements, particularly in structures with limited load redistribution capacity. To validate the structural performance on such soils, STAAD Pro Connect software was used to model and analyze isolated footing system under various load conditions. The analysis confirmed that the footing design complies with BS 8110-97 standards, offering adequate load distribution and structural stability under the evaluated geotechnical conditions. This integrated geotechnical and structural analysis approach provides a reliable framework for safe and optimized foundation design in clay-rich soils.

Keywords: *Clay Soils, Shear Strength, Bearing Capacity, Footing Design, Settlement.*

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I. INTRODUCTION

Soft clay soils are well-documented in geotechnical engineering for their poor shear strength, high compressibility, and excessive settlement characteristics, which can pose significant challenges in construction (Terzaghi et al., 1996; Das, 2010). These problematic soils are particularly prevalent in Maiduguri, Nigeria, where certain areas, such as the Polo region, are known for their challenging geotechnical conditions.

The Polo area, including the Polo Ground, is predominantly covered with clayey soils, which can lead to foundation stability issues, differential settlement, and reduced bearing capacity, particularly under heavy structural loads. Due to its high moisture retention and susceptibility to swelling and shrinkage, the clayey soil in this area can significantly impact the design and construction of buildings and infrastructure (Coduto et al., 2011).

To ensure the effective design, safety, and stability of foundations in clayey soils, it is essential to conduct comprehensive geotechnical modeling and analysis. This involves utilizing real soil data, including parameters such as shear strength, compressibility, permeability, and consolidation characteristics, alongside the actual geometry of the structural elements. By integrating these factors into numerical and analytical models, engineers can develop optimized foundation designs that accurately reflect the physical behavior of the soil-structure interaction.

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Advanced geotechnical modeling techniques, such as finite element analysis (FEA) and limit equilibrium methods, allow for the simulation of soil response under various loading conditions. These models help predict potential settlement, bearing capacity, and lateral deformations, thereby enabling engineers to make informed design decisions that enhance structural performance and mitigate risks associated with soft clay foundations (Muhammad et al., 2022). Additionally, incorporating soil-structure interaction analysis ensures that the foundation system is designed to accommodate real-world geotechnical conditions, leading to improved stability and long-term performance (Coduto et al., 2011).

In this research, structural analysis was performed using STAAD Pro Connect, a widely recognized software for structural and geotechnical engineering applications. The analysis was conducted by generating a frame model within the software, which served as a digital representation of the structural system under investigation.

The STAAD Pro Connect software was utilized to simulate the structural behavior under various loading conditions, incorporating real soil-structure interaction parameters to ensure accuracy and reliability. By employing this modeling approach, the study was able to assess critical factors such as load distribution, deflection, stress-strain response, and stability of the structure when supported by clayey soil.

The use of STAAD Pro Connect for analysis provides significant advantages, including its ability to handle complex geometries, multiple load cases, and advanced finite element modeling techniques. This approach enhances the precision of the study by allowing for the evaluation of structural integrity under real-world conditions, ultimately leading to more efficient and resilient foundation design solutions for construction on clayey soils (Muhammad et al., 2023).

II. MATERIAL AND METHODS

A. Materials

The soil sample used in this work was collected from Polo ground Maiduguri at a depth of 2m. The samples were collected by manually digging pits using digger and shovels and stored in polythene bags and transported to the Department of Civil and Water Resources Engineering, University of Maiduguri for laboratory analysis. Other equipment used in the laboratory include weighing balance, oven, Casagrande apparatus, spatula and direct shear machine. Polo ground is located within Maiduguri Borno State Nigeria. The site lies at 1°48’15” N, and 13° 08’55” E, covering a land area of 87,404,38m^2 and a total distance of 1.3km.

B. Methods

➢ *Index Properties*

The soil was classified in accordance with the method outlined by the Unified Soil Classification System (USCS) (ASTM, 1992). Index tests such as sieve analysis, specific gravity, moisture contents, liquid limit, plastic limit, plasticity index and compaction characteristics of both natural and treated soil were determined in accordance with BS 1337 (1990).

➢ *Moisture Content*

Moisture content determination, a clean and dry container was weighed to the nearest 0.l g (M_1). Representative sample was crumbled and placed in the container, weighed (M_2). The container with sample was oven dried under a temperature of 105°C to 110°C and weighed (M_3). The value was calculated using the following relation:

$$W = \frac{M_2 - M_3}{M_3 - M_1} \times 100\% \quad (1)$$

Where

W = moisture content

M_1= mass of empty container (g)

M_2= mass of container with wet sample (g)

M_3= mass of container with oven dried sample (g)

➢ *Specific Gravity*

Soil sample (oven dried) passing a 2 mm sieve was used in determining the soil particle density. A density bottle (50 ml) with stopper was dried and weighed to the nearest 0.01g (M_1). 10 g of soil sample was introduced into the density bottle, the weight of density bottle with soil and stopper was taken (M_2). Air-free water was added to the soil until the water covered the soil, then the water was added again until the bottle is filled. The stoppered bottle with soil and water was weighed (M_3). Finally, the bottle was emptied and filled with water and weighed (M_4). The particle density was calculated using the relation:

$$\mathbf{Gs} = \frac{M_2 - M_1}{\{(M_4 - M_1) - (M_3 - M_2)\}} \quad (2)$$

Where

G_s= specific gravity of soil

M_1= mass of empty bottle (g)

M_2= mass of bottle with soil (g)

M_3= mass of bottle with soil and water (g)

M_4= mass of bottle with water only (g)

➢ *Particle Size Analysis*

The particle size distribution analysis was conducted in accordance with the specification given in BS 1377 of 1990. Dried sample weighing 200g was prepared and introduced into a BS set of sieve and shaken using a mechanical shaker after which the mass of material retained on each sieve was

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weighed using a digital weighing balance sensitive to 0.001g.

- *Liquid Limit*

Air dried soil sample for the liquid limit test were crushed. About 3000g of the sample passing through the 425µm sieve aperture was placed on a glass plate and thoroughly mixed with water into a paste. The paste was then placed in the brazen cup of the Casagrande apparatus and a standard groove was cut from the back of the cup to the front. The spinning wheel is then rotated 38 at an approximate rate of two drops per second and the number of drops required for the groove was counted, recorded and repeated for number of varying blows.

The results were plotted on a semi-logarithm chart with the moisture content as ordinate and number of blows as abscissa. The moisture content corresponding to the 25 blows was taken as the liquid limit.

- *Plastic Limit*

The plastic limit test was conducted in accordance with BS 1377 (1990). A portion of the soil taken form the samples used for the liquid limit was rolled into ball shape between the palms of the hand so that the warmth of the hand slowly dried it. The samples were divided three to four part and each rolled out between the hand and the glass into about 3mm thick thread until it began to crumble when slight crack began to appear. At this stage, section of the thread was removed for moisture content determination which is the plastic limit and same procedure was conducted for the varying water content.

- *Plasticity Index*

The plasticity index is the difference between the liquid limit and plastic limit, mathematically expressed in equation 3.

Plasticity Index (PI) = Liquid Limit (LL) – Plastic Limit (PL) …(3)

- *Settlement Analysis*

The settlement analysis was carried out using existing model equations tailored to key factors such as sensitivity, plasticity, remolded condition, softness, and the normally consolidated nature of the clay soil. Settlement was determined based on the compression index (C_c) using the following equations:

$C_c = 0.007(LL- 10)$ ……………………………………..(4)

For the coefficient of consolidation (C_v), the model equation based on multiple regression by (Kok et al., 2018) was adopted.

$C_v = 0.451 + 0.011LL – 0.0367PI$ ……………………….(5)

- *Settlement was Computed using the Equation:*

$\Delta H = C_c H_o/1+e_o \log_{10} P_o + \Delta P/P_o$ ………………………..(6)

Where ΔH = settlement of the clay, H_o = thickness of clay layer, e = void ratio of clay, P_o = effective pressure due to overlaying strata and ΔP = incremental pressure caused by footing.

- *Laboratory Direct Shear Test*

The direct shear test was conducted to determine the effective shear strength parameters of the soil, c and ϕ, the values are used in this study to calculate the bearing capacity of soil. The whole test was carried out using the procedure outlined in British Standard (BS 1377, 1990). The square prism of soil was laterally restrained and sheared along a mechanically induced horizontal plane while subjected to a pressure applied normal to that plane. The shearing resistance offered by the soil as one portion was made to slide on the other was recorded at regular intervals of displacement. Failure occurs when the shearing resistance reaches the maximum value that the soil can sustain.

- *Bearing Capacity Computation*

The bearing capacity of the soils were calculated using Terzaghi's general formulae for ultimate bearing capacity which states that:

$q_u = CN_c + qN_q + 0.5B\gamma N_\gamma$ ………………………………….(4)

Where q_u = ultimate bearing capacity of the soil which is usually divided by a suitable factor of safety to get the allowable bearing capacity.

c = cohesion,

q = surcharge,

B = foundation width,

γ = unit weight of soil and N_c, N_q and N_γ are dimensionless coefficients that depend on the angle of internal friction of soil.

- *Software Modelling*

The structural modeling was carried out using STAAD Pro Connect Edition V22. This involved the detailed framing and profiling of structural elements, assignment of relevant soil parameters, application of design loads, and execution of model analysis—all in compliance with the British Standard BS 8110-97. The model focused on an isolated footing system, as illustrated in Figure 1, comprising a total of 36 individual footings. The overall foundation layout spans a length of 32 meters and a width of 16 meters, with footings spaced uniformly at 4-meter intervals in both longitudinal and transverse directions. Within the modeling environment, appropriate cross-sectional properties and dimensions were assigned to key structural elements including columns, beams, and slabs. The entire system was analyzed using the finite element method (FEM) integrated within STAAD Pro, which facilitated accurate assessment of structural behavior under applied loads and ensured that design requirements were adequately met.

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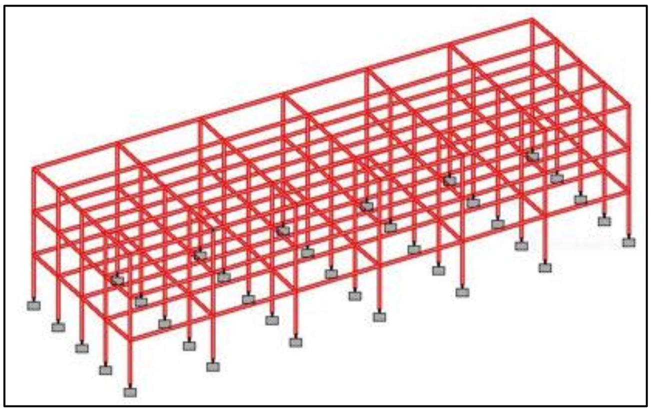

Fig 1 Foundation model adopted for the analysis

III. RESULTS AND DISCUSSION

A. Index Properties of Soil

The Value of the physical properties of the soil samples is given in the table 4.1 below. The percentage passing sieve no.200 for samples A, B and C are 85, 73 and 89% respectively. Their corresponding liquid limits, plastic limits and plasticity indices are 33, 46 and 50%; 13,16 and 18%; and 20,30 and 32% respectively.

Table 1 Physical Properties of the Soil

Properties	Value		
	Sample A	**Sample B**	**Sample C**
Natural moisture content (%)	13.0	12.2	19.0
Liquid limit %	33	46	50
Plastic limit %	13	16	18
Plasticity index %	20	30	32
Specific gravity	1.32	2.50	2.60
Bulk density (Mg/m^3)	1.75	1.50	1.75
Percentage clay (%) Percentage sand (%)	52.20 10.30	67.20 5.30	62.20 12.80
Percentage silt (%)	37.50	27.50	25.0
% passing BS NO 200sieve size	89.7	94.7	87.2
UCS	Lean clay (CL)	Lean clay (CL)	Fat clay (CH)

These values of plasticity index showed that all the samples are highly plastic (PI>17) (Surendra, 2017). Based on the USCS standard, the samples A, B and C are classified as CL, CL and CH respectively. The specific gravity of the samples ranges between 1.32 and 2.60 which fall within the range of 1.00-2.60 that are regarded as organic soil and not suitable for construction purposes (Bowles, 2012).

B. Footing Settlement Analysis

The settlement analysis conducted for samples A, B, and C revealed settlement values of 196 mm, 291 mm, and 186 mm, respectively. These values are considered significantly high and may pose serious risks to the structural integrity of buildings supported by isolated footings. Excessive settlement of this magnitude can lead to differential movement, cracking, and potential failure of foundation elements, particularly in structures with limited load redistribution capacity (Garg, 2013).

C. Soil Bearing Capacity Computation

The bearing capacities of the soil samples computed using excel is presented in Table 4.2 below. The ultimate bearing capacity values for samples A, B and C are 305.2, 273.8 and 332.6 KN/m^2 respectively. Using factor of safety, FS= 2, their corresponding safe bearing capacities becomes 152.6,136.9 and 166.4 KN/m^2. Therefore, the average safe bearing capacity for foundation design across Polo ground soil can be taken as **152 KN/m^2.**

Table 2 Soil Bearing Capacity Result at 2.0m Depth

Parameter/sample	SA	SB	SC
Depth (m)	2.0	2.0	2.0
unit weight (KN/m^3)	17.6	14.6	17.6
angle of friction (^{0})	6	7	5
Cohesion (KN/m^2)	33	28	38
Ultimate bearing capacity (kn/m^2)	305.2	273.8	332.7
Safe bearing capacity (kn/m^2)	152.6	136.9	166.4

D. Foundation Footing Modelling

The analysis confirms that the isolated footing designed in accordance with BS 8110-97 is structurally sound and meets all safety regulations under the assessed loading conditions. The detailed assessment of load distribution, stability checks, shear forces, and development lengths all indicates that the footing is prepared to effectively distribute loads while providing stability in soft clay conditions.

➢ *General Footing and Reinforcement Details*

Table 3 Footing Geometry

Footing No.	Length (m)	Width (m)	Thickness (m)
1	1.11	1.11	0.70

Table 4 Reinforcement Details

Footing No.	Bottom Reinforcement (Mz)	Bottom Reinforcement (Mx)	Top Reinforcement (Mz)	Top Reinforcement (Mx)	Main Steel
1	T16@ 120 mm c/c	T16 @ 120 mm c/c	N/A	N/A	N/A

➢ *Input and Design Parameters*

- Design Type: Calculate dimensions with user-specified minimums.
- Footing Minimum Dimensions: 610 mm (Length & Width)
- Footing Thickness: 700 mm
- Column Shape: square, diameter: 0.4 m
- Concrete Strength: 20 N/mm², Rebar Yield Strength: 350 N/mm²
- Soil Bearing Capacity: 150.24 kPa × 1.70 (for ultimate loads)
- Concrete Unit Weight: 24 kN/m³, Soil Unit Weight: 17.6 kN/m³
- Clear Cover (Footing & Pedestal): 50 mm

➢ *Load Combinations*

Table 4 Load Combinations

Load Combination/s- Service Stress Level					
Load Combination Number	**Load Combination Title**	**Load Case Multiplier (a)**	**Soil Bearing Factor (b)**	**Self Weight Factor (c)**	**Code**
a - Value specified in the Load Multiplier table b - Value specified in the Pile/Soil Bearing Capacity Factors table c - Value specified in the Apply Self Weight and Dead Weight Factor table					
1	LOAD CASE 1	1.00	1.00	1.00	-
2	LOAD CASE 2	1.00	1.00	1.00	-
3	COMBINATION LOAD CASE 3 ULS	1.00	1.00	1.00	-
Load Combination/s- Strength Level					
Load Combination Number	**Load Combination Title**	**Load Case Multiplier (a)**	**Soil Bearing Factor (b)**	**Self Weight Factor (c)**	**Code**
a - Value specified in the Load Multiplier table b - Value specified in the Pile/Soil Bearing Capacity Factors table c - Value specified in the Apply Self Weight and Dead Weight Factor table					
1	LOAD CASE 1	1.00	1.00	1.00	-
2	LOAD CASE 2	1.00	1.00	1.00	-
3	COMBINATION LOAD CASE 3 ULS	1.00	1.00	1.00	-

➢ *Final Footing Dimensions and Calculations*

- Final Dimensions: 1.11 m x 1.11 m x 0.70 m (Governing Load Case: #3)
- Area: 1.23 m², Soil Height: 0.50 m
- Self-weight of footing: 20.70 kN, Soil above footing: 9.74 kN
- Required Area: 0.86 m² (initial), Provided: 1.23 m²

➢ *Load Summary and Stability Checks*

- Critical Load Case: #3
- Safety Against Sliding (X/Z): > 39, Required: 1.5
- Safety Against Overturning (X/Z): > 25, Required: 1.5
- No uplift (Area in contact = 1.23 m²)
- Max Gross Pressure at Corner: 105.22 kN/m² < Allowable 110.24 kN/m²

➢ *Structural Checks (Moments and Shear)*

- *Moment Check (X & Z axis):*

✓ Mu = 4.79 kNm, Effective Depth = 0.63 m
✓ K = 0.0005 < 0.156 ⇒ Safe (BS 8110-97)

- *Shear Check (XY & YZ):*

✓ Vu = 0.00 kN, V < Vc = 664.24 kN/m² ⇒ Safe

IV. CONCLUSION

The study has provided a comprehensive evaluation of the geotechnical properties and bearing capacity of clay soils in the Polo Ground area of Maiduguri, Nigeria. Laboratory tests revealed that the soils are highly plastic with low specific gravity values, indicating poor engineering properties and potential organic content. The classification

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of the soils as CL and CH under the USCS system, along with high plasticity indices, confirms their soft and compressible nature, which poses challenges for conventional foundation construction. Despite these limitations, the computed safe bearing capacities ranging from 136.9 to 166.4 kN/m² indicate that, with proper foundation design, stable structures can still be achieved. The use of STAAD Pro Connect software for modeling isolated footings demonstrated that compliant designs based on BS 8110-97 standards can effectively accommodate the weak soil conditions while maintaining structural integrity. Therefore, this study concludes that while the Polo Ground soil presents geotechnical challenges, appropriate investigation, soil characterization, and structural modeling can lead to safe and optimized foundation solutions suitable for construction in the area. Further improvement techniques such as soil stabilization may be explored in future work to enhance bearing performance.

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