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ORIGINAL RESEARCH ARTICLE

AN INVESTIGATION OF SOIL BEARING CAPACITY FOR BUILDING AND STRUCTURAL FOUNDATION DESIGN: A CASE STUDY OF POLO AREA, MAIDUGURI, NIGERIA

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ABSTRACT

The foundation of any structure is the back born of its stability against all kinds of deformation and this depends on the geotechnical behavior of the supporting soil. Clay soils usually posed serious threats to buildings due to shrink-swell behavior, settlements and low strength which is associated with their minerals. In this research, the safe bearing capacity of Polo soil have been investigated using direct shear laboratory analysis on twenty representative soil samples across virgin area where future development is approaching. Most of the soils were classified as lean clay with sand (CL) according to Unified Soil Classification System (USCS) although some were otherwise. The average natural moisture content of the soils at 1m depth is 8.38% with liquid limit and plasticity index of 30.2% and 15.7% respectively while that of 1.5m were 9.14%, 29.4% and 14.6% respectively. Results also revealed an average friction angle and cohesion of 21° and 18 kN/m^2 at 1m and 22o and 19 kN/m^2 at 1.5m depths respectively. Safe bearing capacity values ranges from 44.95 to 411.11 kN/m^2 and 75.27 to 397.31 kN/m^2 for 1m and 1.5m respectively using foundation widths of 0.5m, 1m and 2m. Foundation design carried out using the different safe bearing capacities and load combinations revealed that the pad footings analyzed with 1500 kN indicated that the minimum footing size that could be used is 1800mm×1800mm using 400kN/m^2 safe bearing capacity. It also revealed that for a 100kN/m2 safe bearing capacity, the footing size is as much as 3500mm×3500mm which is very high and raft foundations were recommended for such situations.

1.0 Introduction

The determination of soils shear strength parameters is very crucial to geotechnical and structural engineers as it forms the essential data required for estimating foundation bearing capacity, factor of safety for slope stability and pressures on earth retaining structures for effective and economical design. The stability and integrity of engineering structures erected on any soil depends on the shearing resistance offered by the foundation soil (Alkali et al., 2018). The shear strength of soils is generally depicted by the Mohr-Coulomb theory which says that the shear strength of soils varies linearly with the applied stress through two components known as the cohesion intercept and angle of shearing resistance (Garg, 2013). The tangent to the Mohr–Coulomb failure envelopes is represented by its slope and intercept. The slope expressed in degrees is the angle of shearing resistance and the intercept is the cohesion (Pravin and Karim 2016). The angle of shearing resistance represents the interlocking between the soil particles whereas cohesion is mainly due to the intermolecular bond between the adsorbed water surrounding each grain, especially in fine grained soils (Odeyemi et al., 2012).

The attempt to investigate the bearing capacity of soils in this area through shear strength values came from the fact that most private, government, contractors and compromising engineers are reluctant toward soil investigation for structural design. On the contrary, they based their designs on arbitrary safe bearing value which may sometimes lead to unsatisfactory or uneconomical design causing serious infrastructural damage. Lack of data for proper foundation design has led to continuous distress in buildings erected on Polo soils due its clayey nature. Presently, there is no published material covering this subject in the study area. This study, therefore, aimed toward investigating the type and bearing capacity of Polo soil, Maiduguri, for structural/foundation design purposes. With the results from this work, an engineer can easily compare and locate the category of soil type and possible safe bearing value based on knowledge and experience. However, this will be after obtaining preliminary laboratory results of soil index properties such as soil particles size distribution, moisture contents, Atterberg limits, and bulk and dry densities of a given sample which are by far cheaper and non-cumbersome compared to shear strength parameters which require equipment such as direct shear or triaxial machine.

Otuaga, 2015, investigated the shear strength parameters of soils across zones of Owo Local Government Area of Ondo State, Nigeria, using triaxial and direct shear box methods. The study recommends a safe bearing capacity of 139.01 kN/m^2 be adopted for foundation design. Similar investigations were carried out by Egbe et al., 2011, Oluwapelumi 2013 and Surendra and Gurcharan, 2014. These investigations address soils from Calabar south, Nigeria; lateritic soil in Akure, Nigeria and soils from Sirsa, India, respectively. Researchers have developed model equations using soil index properties and recommended its usage following the soil type. This work will, however, concentrate on soils from Polo area of Maiduguri by computing their safe bearing capacities. This is due to increasing number of defective houses in the area resulting from swelling and shrinking behavior of the clay soil which is predominant. This will be sound and more useful in computing new bearing capacities of samples collected across the area since they lie within same formation rather than model equations which do not always give good correlation. Using similarities in index properties and classification of soils in the location, one can use the information provided in this study to compute new bearing capacities based on knowledge and experience.

2. Materials and Methods

2.1 Materials

The tools used for collecting the disturbed samples include sterilized digger and shovel, measuring tape, digital weighing balance, mobile phone with google map application and polythene bags.

2.1.1 Soil Samples

The soil samples used in this study were collected from Polo area of Maiduguri, Borno State, Nigeria. Soil samples were dug at a depth of 1m and 1.5m respectively. Virgin area where development is rapidly approaching was used to collect the samples. The area is located at latitude 11^{0}46' 41" N and longitude 13^0 08' 29" E. The samples are collected at the interval of 200m from the last cluster of buildings in the area to the west where future development is expected. A total of twenty (20) samples were obtained from ten (10) different pits. Soil samples were then taken into polythene bags to avoid loss of moisture and further subjected to laboratory analysis.

Figure 1. Google map of the study area

2.2 Methods

2.2.1 Index Properties

All tests were carried out on the twenty (20) soil samples in accordance with specifications outlined in British Standard (BS) 1377 (1990).

Bulk and dry densities were determined using the following relations:

$$\text{Bulk density } (\rho) = \frac{M_2 - M_1}{V} \quad (1)$$

where: M_1 is the mass of mold and base plate, M_2 is the mass of mold, baseplate and compacted soil, V is the volume of the mold (cm^3)

$$\text{Dry density } (\rho d) = \frac{100\rho}{100+w} \quad (2)$$

where: w is the moisture content of the soil (%)

2.2.2 Direct Shear Test

Direct shear test was carried out using shear box with the specimens (60mm x 60mm). Specimen with plain grid plate at the bottom of the specimen and plain grid plate at the top of the specimen was fitted into position in the shear box housing and assembly placed on the load frame. The serrations of the grid plates were kept at right angle to the direction of shear. The loading pad was kept on the top grid plate. The required normal stress was applied, and the rate of longitudinal displacement/shear stress application adjusted so that no drainage can occur in the sample during the test (1.25 mm/min). The upper part of the shear box was raised such that a gap of about 1mm was left between the two parts of the box. The test was conducted by applying horizontal shear load to failure or to 20 percent longitudinal displacement whichever occurs first. The test was repeated on identical specimens.

2.2.3 Computation of Soil Bearing Capacity

The bearing capacity of the various samples were computed using the formula proposed by Terzaghi.

$$q_{ult} = c.N_c + \gamma D_f N_q + 0.5B\gamma N_\gamma \quad (3)$$

where: γ = Unit weight of foundation soil in KN/m³, D_f = depth of the foundation (m), c,φ = Strength parameters of the soil below foundation level in KN/m² and degrees respectively,

B = Width of foundation in (m), N_c N_γ N_q

= Bearing capacity coefficients dependent on the angle of internal friction.

Safe bearing capacity of the soils, q_{safe}, was determined using:

$$q_{safe} = Q_{ult} / FS \quad (4)$$

where: FS is the factor of safety

3. Results and Discussion

Geotechnical properties like particles size distribution, bulk and dry densities, Atterberg limits and natural moisture content of soils collected in Polo were determined. Shear strength parameters of the soils mainly friction angle and cohesion were also assessed. Most of the soils were classified as clay. Tables 1 and 2 below represents the data obtained for different soils from laboratory analysis.

3.1 Index properties and classification

The index properties of Polo soils at 1m and 1.5m depths are presented in Tables1 and 2. The average natural moisture content of the soils at 1m depth is 8.38% with liquid limit and plasticity index of 30.2% and 15.7% respectively. All the soils at this depth are classified according to Unified Soil Classification System (USCS) as Lean Clays with sand (CL) with the exception of samples SD, SF and SG which falls within the class of Sandy Clay (SC), Sandy Clay (SC) and Silty Sand (SM) respectively. The index properties at 1.5m revealed that samples SA and SG were Silty Clay (ML) and SC while the remaining belongs to CL as well. The average natural moisture content, liquid limit and plasticity index are 9.14%, 29.4% and 14.6% respectively. The low Atterberg limits values also indicate low compressive strength which is as reported elsewhere (Ezenwaka et al., 2014).

Table 1: Index properties of Polo soils at 1m depth

Parameters/Sample	SA	SB	SC	SD	SE	SF	SG	SH	SI	SJ
Natural moisture content (%)	23.0	13.2	15.0	3.9	3.5	2.9	2.9	9.9	6.9	2.6
Liquid limit (%)	34	36	34	22	33	29	29	37	26	22
Plastic limit (%)	18	20	15	11	10	13	24	15	09	10
Plasticity index (%)	16	16	19	11	23	16	05	22	17	12
% Fine	77	75	68	67.7	76	48	35	79	56	68
% Coarse	23	25	32	32.3	24	52	65	21	44	32
USCS	CL	CL	CL	SC	CL	SC	SM	CL	CL	CL
Bulk unit weight (KN/m³)	11.7	16.9	17.8	15.4	15.7	15.4	15.5	14.6	14.5	15.8
Dry unit weight (KN/m³)	15.6	14.9	15.4	14.9	14.6	14.9	14.9	13.3	13.6	14.6

USCS (ASTM, 1992)

Table 2: Index properties of Polo soils at 1.5m depth

Parameter/Sample	SA	SB	SC	SD	SE	SF	SG	SH	SI	SJ
Natural moisture content (%)	17.3	13.9	17.3	5.1	5.9	8.9	3.1	9.1	3.3	7.5
Liquid limit (%)	25.0	38.0	28.0	26.0	48.0	27.0	24.0	24.0	21.0	33.0
Plastic limit (%)	21	16.0	13.0	10.0	18.0	14.0	8.0	15.0	10.0	23.0
Plasticity index (%)	4.0	22.0	15.0	16.0	30.0	13.0	16.0	9.0	11.0	10.0
% Fine	74.0	80.0	78.0	73.5	59.0	63.0	47.0	60.0	60.0	71.0
% Coarse	26.0	20.0	22.0	26.5	41.0	37.0	53.0	40.0	40.0	29.0
USCS	ML	CL	CL	CL	CL	CL	SC	CL	CL	CL
Bulk unit weight (KN/m^3)	17.5	15.6	18.5	16.0	15.7	15.3	15.4	14.6	14.6	15.5
Dry unit weight (KN/m^3)	14.9	13.7	15.8	14.5	14.42	13.9	14.8	13.4	13.5	15.0

USCS (ASTM, 1992)

3.2 Computation of Soil Bearing Capacities

The bearing capacities (Tables 3 and 4) were computed using foundation widths of 0.5m, 1.0m and 2.0m for all the soils. The average friction angle and cohesion of soils at 1m depth were 21° and 18 kN/m^2 while that of 1.5m were 22° and 19 kN/m^2 respectively. The safe bearing capacities at 1m depth ranges between 44.95 – 90.32 kN/m^2 for samples SA to SC and this is due to low friction angles of 6°,13° and 5° respectively. The value increases between 135.18 – 411.11 kN/m^2 for samples SD – SJ for the various widths investigated as a result of increase in angle of shearing resistance value. The same values at 1.5m depth revealed an increasing trend with the exception of sample SF which has a value little below that of 1m depth following the decline in friction angle value observed. This occurred as a result of additional increase in cohesion value of the soil when compared to that of SF at 1m depth.

Table 3: Bearing capacities for shallow foundations at 1m depth

Parameter/Sample	SA	SB	SC	SD	SE	SF	SG	SH	SI	SJ
Depth (m)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Width (m)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
ThUnit weight (KN/m^3)	11.7	16.9	17.8	15.4	15.7	15.4	15.5	14.6	14.5	15.8
Angle of friction (°)	6.0	13	5.0	29	24	29	33	18	25	25
Cohesion (kN/m^2)	18	20	16	14	22	17	9.0	24	18	22
Ultimate bearing capacity (kN/m^2)	145.87	258.80	134.84	715.25	612.32	800.22	883.69	405.53	565.87	666.75
	146.28	262.85	135.25	775.95	639.95	860.93	1000.23	414.75	595.91	699.46
	147.09	270.95	136.07	897.36	695.20	982.34	1233.32	433.18	655.96	764.88
Safe bearing capacity (kN/m^2)	48.62	86.27	44.95	238.41	204.11	266.74	294.56	135.18	188.62	222.25
	48.76	87.62	45.08	258.65	213.32	286.98	333.41	138.25	198.64	233.15
	49.03	90.32	45.36	299.12	231.73	327.45	411.11	144.38	218.65	254.96

Table 4: Bearing capacities for shallow foundations at 1.5m depth

Parameter/Sample	SA	SB	SC	SD	SE	SF	SG	SH	SI	SJ
Depth (m)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Width (m)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Unit weight (KN/m^3)	17.5	15.6	18.5	16.0	15.7	15.3	15.4	14.6	14.6	15.5
Angle of friction (°)	29.0	12.0	9.0	29.0	27.0	21.0	29.0	21.0	22.0	19.0
Cohesion (kN/m^2)	4.0	22.0	20.0	19.0	19	20.0	17.0	25.0	24.0	23.0
Ultimate bearing	620.87	280.69	225.83	1002.98	823.27	501.85	928.93	573.82	603.45	473.47
capacity (kN/m^2)	689.70	283.70	227.57	1066.00	868.15	518.22	989.59	589.44	621.93	485.22
	827.35	289.71	230.89	1192.05	957.92	550.95	1110.93	620.68	658.88	508.73
Safe bearing capacity	206.96	93.56	75.27	334.32	274.42	200.74	309.64	191.27	201.15	157.82
(kN/m^2)	229.90	94.56	75.86	355.33	289.38	207.29	329.86	196.48	207.31	161.74
	275.78	96.57	76.96	397.35	319.31	220.38	370.31	206.89	219.63	169.58

3.3 Foundation Design

The foundation design based on different safe bearings capacities and column load combinations has been analyzed using Prota Structure software and the results is presented in Table 5. The analysis was carried out using average bearing capacities of 100, 150, 200, 250, 300, 350 and 400 kN/m^2 respectively. For each safe bearing capacity, a column loads of 200, 500 and 1500 kN were used to analyzed its punching shear capacity and settlement using different pad footing sizes. The results show that for all the safe bearing capacities, footings subjected to 200 and 500 kN column loads can be constructed as singly reinforced section with sizes between 700 mm × 700 mm to 2000 mm × 2000 mm depending on the safe bearing capacity used. This is due to the low load intensity acting on the footing as well as the fair average safe bearing capacity of the soils.

Furthermore, the pad footings analyzed with 1500 kN indicated that the minimum footing size that could be used is 1800 mm × 1800 mm using 400 kN/m^2 safe bearing capacity. It was also observed that for a 100 kN/m^2 safe bearing capacity, the footing size is as much as 3500 mm × 3500 mm, which is very high. As a result, raft foundations were recommended for such situations in order to accommodate the high load intensity of the structure under single footing (raft) instead of larger footings covering almost the entire foundation area.

Table 5: Foundation analysis and design using different safe bearing capacities, column loads and footing sizes

Foundation Type	Column Load (KN)	Safe Bearing Capacity (KN/m^2)	Foundation Size (m)	Punching Shear Capacity (N/mm^2)		Settlement (mm)	Rebar (mm^2)	Factor of Safety	Remark/Comment
				PSS	USS				
Pad Footing	200	100	1300×1300	0.11	0.36	19	380.64	2	Singly Reinforced Section
	500		2000×2000	0.29	0.36	22	1035.90	2	Singly Reinforced Section
	1500		3500×3500	0.3	0.36	34	3355.09	2	Raft Foundation Recommended
Pad Footing	200	150	1000×1000	0.06	0.36	16	319.44	2	Singly Reinforced Section
	500		1700×1700	0.23	0.36	24	824.18	2	Singly Reinforced Section
	1500		2900×2900	0.31	0.36	32	2927.91	2	Raft Foundation Recommended

Pad Footing	200	200	900×900	0.03	0.36	24	261.36	2	Singly Reinforced Section
	500		1500×1500	0.33	0.36	23	838.30	2	Singly Reinforced Section
	1500		2400×2400	0.33	0.36	32	2550.24	2	Raft Foundation Recommended
Pad Footing	200	250	800×800	0.09	0.36	24	232.40	2	Singly Reinforced Section
	500		1300×1300	0.25	0.36	25	679.34	2	Singly Reinforced Section
	1500		2400×2400	0.28	0.36	36	2273.98	2	Raft Foundation Recommended
Pad Footing	200	300	800×800	0.09	0.36	23	232.30	2	Singly Reinforced Section
	500		1200×1200	0.20	0.36	25	601.70	2	Singly Reinforced Section
	1500		2000×2000	0.35	0.36	38	2279.20	2	Raft Foundation Recommended
Pad Footing	200	350	750×750	0.14	0.36	24	217.80	2	Singly Reinforced Section
	500		1100×1100	0.13	0.36	23	525.40	2	Singly Reinforced Section
	1500		1900×1900	0.32	0.36	35	525.40	2	Raft Foundation Recommended
Pad Footing	200	400	700×700	0.19	0.36	22	203.30	2	Singly Reinforced Section
	500		1000×1000	0.05	0.36	24	450.40	2	Singly Reinforced Section
	1500		1800×1800	0.27	0.36	33	1978.0	2	Raft Foundation Recommended

3.4 Conclusion and Recommendation

The index properties and shearing strength parameters of Polo soil for bearing capacity values was investigated. The results indicated that most of the soils are classified as lean clay with sand (CL) according to USCS although there exist sandy clay (SC), silty clay (ML) and Silty sand (SM). The average natural moisture contents of the soils at 1m and 1.5m were 8.38% and 9.14% respectively. The average liquid limit and plasticity index values ranges from 30.2% to 15.75% and 29.4% to 14.6% respectively which is an indicative of low compressive strength.

The minimum and maximum safe bearing capacities observed for 1m and 1.5m depths were 44.95 to 411.11 kN/m^2 and 75.27 to 397.31 kN/m^2 respectively. Sample SA, SD and SF were also observed to have possessed heterogeneity between the depths investigated. Due to different safe bearing capacities and load combinations, the foundation design conducted revealed that certain foundations will be singly reinforced section while other will call for raft.

It is, therefore, recommended that a minimum of index properties test of soil in the study area be carried out to compare e the possible corresponding shear strength parameters based on the information provided above before foundation design in the study area. This could be achieved by comparing parameters such as % fines and coarse, plasticity index, bulk density and soil type obtained in the laboratory with the ones provided here, this will however require knowledge and experience. It is also our conviction that this will mitigate blind assumption of bearing values during design as some soils misbehave within short spans, a typical example being some samples with safe bearing capacity less than 50 kN/m^2.

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