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Sub-Soil Geotechnical Investigation in Soft Soils for Foundation Type Selection

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Abstract: *Sub-soil geotechnical investigation for foundation selection of buildings is crucial for safe structural performance and operation. It is more critical with tropical climate especially in marshy areas with a history of sinking storey or collapsing buildings like in Barnawa Kaduna and Lagos in Nigeria respectively. The area under investigation is home to the popular Shagari housing estate in Barnawa, Kaduna. The housing estate involves many blocks of three-storey buildings which experiences sinking before it becomes operational. Several solutions were devised by local planning authorities and other stakeholders in Nigeria to address the recurring anomaly. Often time, unprofessional solutions were sought by private clients to evade professional design fees. The empirical and rule-of-the-thumb approach used by contractors or developers often results in overdesign. Therefore, engagement of geotechnical investigations and its judicious use as input for building foundation selection and design are the key issues to a lasting solution to building failures in Nigeria. Hence, this study adopts a laboratory geotechnical investigation of the soil for basic and engineering properties. In addition to Atterberg limits, the investigated engineering parameters includes shear strength, consolidation, grading, and bearing capacity. Results of the geotechnical investigation showed a safe bearing capacity range of 63 kN/m² in TP 5 to 95 kN/m² in TP 4 at 1.00 m depths respectively. The bearing capacity values increased at 2 m depth with a range from 128 kN/m² in TP 1 to 150 kN/m² in TP5 respectively, using a factor of safety of 2.50. Total settlement (Oedometer) values were moderate and ranged between 0.0004 – 0.0017 m. It follows therefore that the proposed structure could be supported on an isolated wide pad foundation which may be designed at 2.00 m depth below the practical ground level for columns, using a safe bearing pressure of 125 kN/m². Optional ground beams may be provided for enhanced stability and rigidity. Furthermore, based on the result of this study, the soil can support other types of foundations with adequate design consideration for safety and cost.*

Key words: *Foundation selection; geotechnical investigation; building collapse; Barnawa Kaduna; soil bearing capacity.*

1.Introduction

Foundation is the critical part of any civil and building structure upon which all other parts of the structure draw support. Therefore, a detailed geotechnical investigation of the soil upon which the foundation footing will be founded is crucial. The genesis of notable engineering disasters involving civil structures is a culmination of foundation distresses. Significant loss of lives results from building collapse in sub-Saharan Africa; the recent massive storey building collapse in Ikeja Lagos, Nigeria is one of many frequent occurrences. Even though, other factors like poor workmanship, use of inferior building materials, and quackery all contribute to structural failures, yet, foundation failures are critical. Usually, foundation soils are heterogeneous and non-isotropic, with significant possible variation in properties even within a short distance [1]. Critical and holistic sub-soil geotechnical investigation will yield valuable data in aiding informed decisions on foundation selection.

Many of the prevailing foundation design rules influenced by rule-of-the-thumb are often used for deciding foundation type suitable for buildings. Foundation designers used historical geotechnical data or previous designs within the same area to decide on a suitable foundation for a proposed structure. Moreover, in situations where a geotechnical investigation is used, peripheral sample acquisition is often conducted. Furthermore, the current state of practice for most construction in developing African countries involves analysis conducted on a few geotechnical parameters like consistency limits and shear strength parameters, but this approach is can be improved using more detailed tests. Moreover, a holistic geotechnical investigation is required to garner full information on the soil properties and possible performance under structural loading. As such, in addition to the standard geotechnical investigation, consolidation and bearing capacity/CBR testing are required for the settlement and strength capacity of undisturbed sub-soil samples taken at different depths.

Therefore, this study investigated the sub-soil in a site that was previously identified as soft soil by taking undisturbed soil samples at 1m and 2m depths from five (5) trial pits. The objective of this study is the laboratory geotechnical investigation of these sub-soil samples for informed decisions for the foundation selection of buildings.

2. Methodology and Experimental program

2.1. Methodology

The procedural approach of the study is subdivided into field investigation, soil sampling, and laboratory work. The field investigation entails all the activities involved in site reconnaissance, appraisal, environmental impact, and preliminary geological and geotechnical investigation.

2.1.1 Field investigation

The community where the site under investigation is situated has a geologic history of basement complexes. These basement complexes were observed to be of metamorphic origin which owes similar origins to garnet basements [2]. Developers often build two-storey buildings safely, but visible structural cracks appear under service after a long period. Nonetheless, the geology of the area was observed to have patchy rock outcrops, though generally flat terrain. It is made up of brownish lateritic sandy soil from ordinary ground level to 1.00 m depth and underlain by Brownish gravely lateritic soil up to the depth of 2.00 m as explored. The groundwater table is well below the surface of the soil, off typical foundation construction depths. The water table fluctuates in the vadose and recharge zones during rainy and dry weather. Importantly, the site is largely free from water logging as is the case with some silty soils. The site location is depicted by a drop pin in Fig. 1.

The site was subdivided into fifteen quadrants from which a total of five (5) trial pits were manually excavated to a maximum depth of 2.00 m depth from each quadrant. Both undisturbed and disturbed soil samples were collected using core cutter samplers and sample bags respectively at 1.00 m and 2.00 m depths and conveyed to the Kaduna polytechnic civil engineering, soil and geology laboratory for analysis.

Fig. 1. Position of the study location on a google map*
*Accuracy is approximated to a few metres

2.1.2 Soil sampling

Disturbed and undisturbed soil samples were obtained at 1.00 m and 2.00 m depths per ASTM D75 and BS 1377 part 1: 1990/2016 [3][4]. Undisturbed samples were taken for consolidation and shear box tests. Moisture content, Atterberg limits, sieve analysis, natural moisture content, and specific gravity tests use the disturbed soil samples. Both the disturbed and undisturbed samples were kept in air-tight containers up to the time of testing.

2.2 Experimental program

The laboratory testing program was grouped under short and long-term. In the first group, soil samples were pulverised and a representative portion was taken for NMC, specific gravity, grading and Atterberg limits testing. The second category is those tests conducted for the bearing capacity/shear strength and consolidation settlement evaluation of the soil. The samples for consolidation settlement and shear strength evaluation were kept in their pristine state. Soil samples from the core cutters are used for these tests, details for these tests are detailed in sections 2.2.1 to 2.2.5.

2.2.1 Natural moisture content test (NMC)

The test is a non-destructive test where pulveried soil samples taken from the site in air-tight bags are assessed for water content. The test was conducted following the BS 1377:1989/BS 812-109:1990 by taking the weight of representative samples (20 - 40 g) in spherical steel cans before and after oven drying at 110°C for 24 hours [5]. The statistical data accuracy is enhanced by testing three samples for each trial pit and averaging to arrive at the final result. The NMC is the ratio of the initial and final weight of the soil sample expressed in percentage. This parameter is important in computing some geotechnical parameters including porosity, and densities.

2.2.2 Specific gravity test

The specific gravity (Gs) test was conducted per BS 1377:1990 and ASTM C 128-2015 [6]. The gravimetric approach was used which entails soaking the sample in water for 24 hours for the pores to be fully saturated. Then, it was removed from the container and air-dried after which the mass was determined. Consequently, the sample (or a part of it) was placed in a graduated container and the volume of the sample is determined gravimetrically. Finally, the sample is oven-dried and reweighed again for mass determination. The determined mass values are inserted into equation 1 for relative density (specific gravity) computation and perhaps, absorption. The summary of the specific gravity of samples from the five (5) trial pits is presented in Table 1.

$$Specific\ gravity\ (apparent\ relaative\ density) = \frac{A}{B + A - C} \tag{1}$$

Where

A = mass of the oven-dried specimen, g

B = mass of pycnometer filled with water, to calibration mark, g

C = mass of pycnometer filled with specimen and water to calibration mark, g.

Table 1: Specific gravity result summary of the five (5) trial pits.

Samples	Depth (m)	M_1 (g)	M_2 (g)	M_3 (g)	M_4 (g)	Gs (g)
TP 1	1.00	22.20	50.20	90.80	75.40	2.22
TP 1	2.00	22.20	51.90	93.30	75.40	2.52
TP 2	1.00	22.20	52.20	93.40	75.40	2.50
TP 2	2.00	22.20	50.90	93.00	75.40	2.59
TP 3	1.00	22.20	51.50	92.00	75.40	2.31
TP 3	2.00	22.20	52.80	94.10	75.40	2.57
TP 4	1.00	22.20	51.90	91.60	75.40	2.20
TP 4	2.00	22.20	51.50	93.30	75.40	2.57
TP 5	1.00	22.20	51.20	91.30	75.40	2.21
TP 5	2.00	22.20	52.70	94.30	75.40	2.63

For this study, the specific gravity of the various samples from all the five (5) trial pits was determined and averaged. The averaged value is used for subsequent computations.

2.2.3 Grading test

Grading of the aggregate was conducted in two stages, firstly, the dried aggregate was sieved through stack of sieves with progressively reducing aperture sizes. Subsequently, the material finer than 75 µm was subjected to wet sieving to estimate the amount of clay and silt particles. Wet sieving following ASTM C117/136 was utilised in grading the soil from various trial pits [7][8]. The wet sieving ensures the estimation of the amount of clay and silt in any soil sample. Clay below the foundation of structures is dangerous due to variable swell and shrinkage potential. The grading result aid in soil classification and computation of other important geotechnical parameters like the D10.

2.2.4 Atterberg Consistency limits test

The pulverised soil samples from the various trial pits were sieved through the 425 µm sieve, the sieved sample is used for the tests. The tests were conducted following BS 1377:1990. For the liquid limit, a known amount of moisture as a percentage of the soil sample was added, mixed and placed in the Casagrande apparatus. A triplicate set of liquid limit (LL) tests were conducted and averaged.

For the plastic limit (PL), 3 mm diameter threads were cast and placed in steel containers for oven drying at 110°C for 24 hours. The difference in moisture content expressed as a percentage of the dry weight of the sample gives the PL of the soil. The plasticity index (PI) is computed mathematically from the difference between LL and PL. A shrinkage mould 12 cm in length was used for the shrinkage limit of the soil samples.

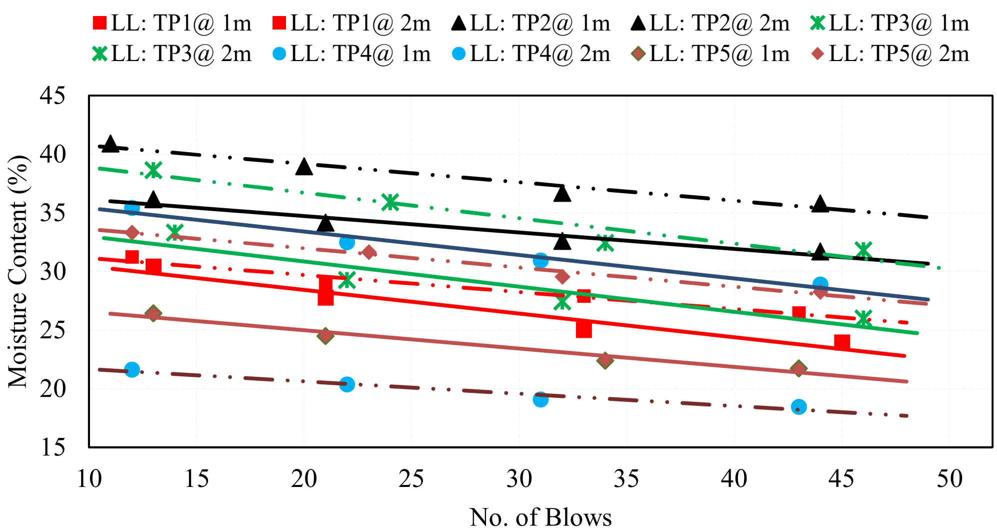
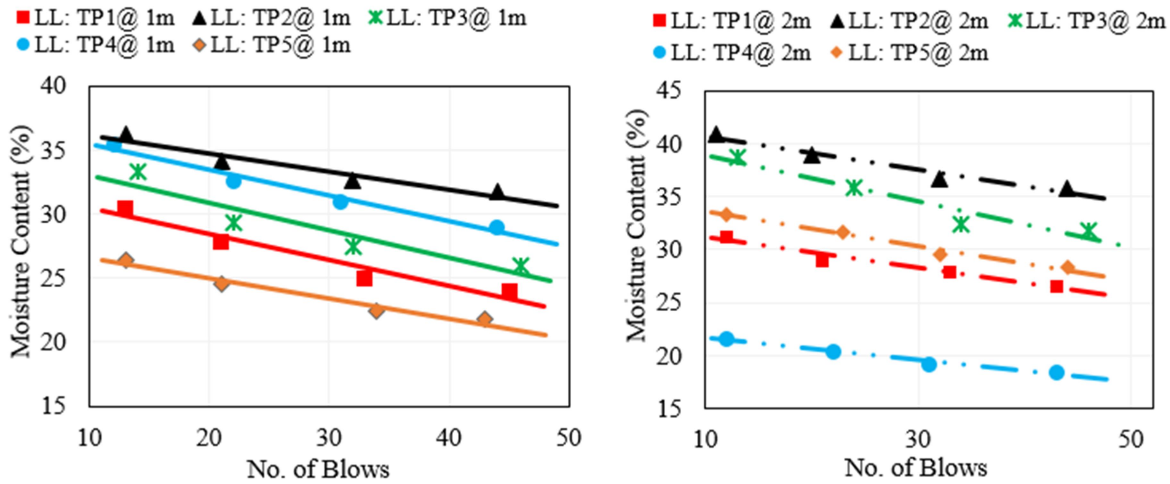


Fig. 2 . Combined Atterberg limit at 1m depth for trial pits 1-5



(a) (b)

Fig. 3. Atterberg limit plots for pits 1-5 at (a) 1 m depth, and (b) 2 m depth

2.2.5 Consolidation test

The test was conducted following BS 1377 part 6:1990 for partially saturated soils [9]. The temperature of the testing laboratory was maintained to within $\pm$ 2 ^{o}C by preventing test apparatus and equipment from the heat source and direct sunlight. The Laboratory data of the consolidation (Oedometer) test were used in estimating the primary consolidation settlement for the 5 No. trial pits at the two depths explored on the soil samples collected. These values were based on the increase in the effective pressure induced by loads from the structure. Since the soil from each location is deemed to be homogenous, thus, the coefficients of volume compressibility (Mv) are used in the analysis.

The total consolidation (Pc) in each of the trial pits is calculated thus,

$$\text{Pc (Oedometer)} = Mv \times \Delta\delta \times H \qquad (2)$$

Where

Pc = Total settlement (Oedometer).

Mv = Average Coefficient of volume compressibility obtained from the effective pressure increment in the particular layer under consideration.

$\Delta\delta$ = Average effective vertical stress imposed on the particular layer resulting from the foundation pressure.

H = Thickness of the particular layer under consideration.

2.2.6 Bearing capacity according to shear box test

The bearing pressure imposed by a foundation is a function of the characteristics of the shear strength of the soil as well as the depth and dimension of the foundation. The analytical approach adopted in estimating the bearing capacity is based on Terzaghi's Equation. The bearing capacity factors are also based on Terzaghi's bearing capacity coefficients, which are functions of the angle of shearing resistance or internal friction (Ø) of the soil samples as obtained from the direct shear box test and cohesion (C) of the soil. Terzaghi's bearing capacity equation was used assuming the worst wet site condition as no groundwater was encountered during excavation in any of the 5 trial pits explored.

$$Q\ (\text{ultimate}) = CN_C + \gamma_D\ (N_q - 1) + 1/2\ \gamma_B N_\gamma \qquad (3)$$

Where:
C = cohesion
Nc, Nq & N_γ = bearing capacity coefficients
γ_D & γ_B = unit weights

(a)

(b)

Fig. 4. (a) Driven Core-cutter at the required depth, (b) Sample in Core-cutter.

3. Results and discussion
3.1 Result summary
The sub-soil at the proposed site is underlain by deposits of brownish Lateritic sandy soil and brownish gravely lateritic soil to a depth of 2.00 m depth explored. The soils are of different ranges of strengths and geotechnical properties. The ground was relatively soft to the 2.00 m depth explored during the excavation of the trial pits and no groundwater was encountered in any of the five trial pits explored. The analytical bearing capacity computations revealed that the bearing pressures of the sub-soil at the site are generally satisfactory for foundations designs at 2.00 m depths with a 125 kN/m^2 average bearing pressure.

The detailed result summary for all the trial pits is presented in Table 2.

Table 2: Summary of results for the geotechnical investigation

TP NO.	Depth (m)	NMC Result	Gs	Consistency limits Result				Direct shear box Result			Sieve Analysis Test	Consolidation Test			Bearing capacity
		(%)	–	LL (%)	PL (%)	PI (%)	LS (%)	C (kN/m^2)	∅ (°)	γ (kN/m^3)	(Passing NO.200) (%)	Cv (m^2/Yr)	Mv (m^2/kN)	Pc (m)	Q(SAFE) (kN/m^2)
1	1.00	15.97	2.22	26	18.58	7.42	8.57	19	13	14.29	62.06	20.634	0.0129	0.0012	89.91
	2.00	10.52	2.52	29	19.96	9.04	9.29	20	15	15.46	47.54	77.790	0.0052	0.0005	127.58
2	1.00	16.02	2.50	33	18.08	14.92	10.00	18	12	14.51	86.04	5.606	0.0176	0.0017	80.31
	2.00	12.27	2.59	38	20.87	17.13	10.71	20	16	16.95	38.50	31.768	0.0044	0.0004	142.29
3	1.00	14.68	2.31	29	18.18	10.82	9.14	19	13	14.26	91.90	17.249	0.0154	0.0015	89.88
	2.00	13.93	2.57	34	21.64	12.36	10.00	20	15	16.12	47.98	19.732	0.0067	0.0006	129.27
4	1.00	14.71	2.20	31	18.19	12.81	9.07	20	13	15.20	85.26	16.983	0.0166	0.0016	94.82
	2.00	9.98	2.57	20	15.79	4.21	7.14	21		16.55	85.48	11.803	0.0080	0.0008	134.77
5	1.00	15.78	2.21	24	17.26	6.74	8.71	12	13	14.34	88.84	13.606	0.0098	0.0009	62.53
	2.00	9.24	2.63	30	21.29	8.71	10.00	21	16	17.92	28.32	29.100	0.0121	0.0011	149.77

3.1.1. Natural moisture content result

The result of the NMC from Table 2 indicated that the soil has a range of moisture content within 9 – 16 %. As evident, the site has its water table well of the foundation level, with average moisture of 13%.

Though the site exploration was done in the dry season, the NMC test revealed moderate moisture content in almost all the samples tested. This may mean that the underlying soil has a high water-holding capacity with minimum and maximum values of 9.24% to 16.02%. As the maximum average site, NMC is less than 20%, which means that the water table is well below the deepest typical standard building foundation. Furthermore, it is evident from Table 2 that NMC at a shallow depth of 1m is higher than that at 2 m for all the trial pits tested. Similarly, the NMC directly relates to all the Atterberg limits of liquid limit (LL), plastic limit (PL), and plasticity index (PI) so obtained with the except for samples at trial pit 4 at 2 m depth.

3.1.2. Specific gravity

The specific gravity (Gs) follows an indirect pattern as that of the NMC. The Gs at 1 m depth is lower than the Gs of samples at 2 m. The increase in the specific gravity with increasing depth signifies increased soil unit weight which in turn ensures better stability. The significance of higher Gs manifests in the computations of many geotechnical properties which assist in making informed decisions like the type and depth of foundation footing.

3.1.3. Atterberg limit result

The Atterberg limit values for all the sampled soil from the identified trial pits at 1 m and 2 m are presented in Table 3. The liquid limits obtained from the laboratory test vary from 20.00% to 38.00%. The Plastic limit ranged from 18.75% to 21.64%. The Plasticity index was determined within the range of 4.21% to 12.81%. These values indicate soils medium to high plasticity according to the Casagrande plasticity chart. The linear shrinkage ranged 7.14% to 10.71%, this range shows that the soils have potential for excessive shrinkage during the dry season and may swell appreciably in the rainy season. Therefore, the provision of a mat-type or continuous foundation like raft and strip may not respectively serve in this situation. Except for trial pit number 4, all the Atterberg limits of the other pits have higher values at 2 m depth than their corresponding 1 m sampled soils.

Table 3: Atterberg limit result for trial pits 1-5 at 1 m and 2 m

Trial Pit	Depth	LL	PL	PI	LS
TP 1	1.0 m	26.00	18.58	7.42	8.57
	2.0 m	29.00	19.96	9.04	9.29
TP 2	1.0 m	33.00	18.08	14.92	10.00
	2.0 m	38.00	20.87	17.13	10.71
TP 3	1.0 m	29.00	18.18	10.82	9.14
	2.0 m	34.00	21.64	12.36	10.00
TP 4	1.0 m	31.00	18.19	12.81	9.07
	2.0 m	20.00	15.79	4.21	7.14
TP 5	1.0 m	24.00	17.26	6.74	8.71
	2.0 m	30.00	21.29	8.71	10.00

3.1.4. Shear strength parameters

The result of the shear strength parameters as expressed in terms of cohesion, angle of internal friction and the unit weight of the soil is presented in Table 4. The soil is virtually a C-Æ soil with appreciable uniform unit weight.

Table 4: Shear strength result for trial pits 1-5 at 1 m and 2 m

Trial Pit	Depth	C (kN/m^2)	∅ (°)	γ (kN/m^3)
TP 1	1.0 m	19	13	14.29
	2.0 m	20	15	15.46
TP 2	1.0 m	18	12	14.51
	2.0 m	20	16	16.95
TP 3	1.0 m	19	13	14.26
	2.0 m	20	15	16.12
TP 4	1.0 m	20	13	15.20
	2.0 m	21		16.55
TP 5	1.0 m	12	13	14.34
	2.0 m	21	16	17.92

The soil is a cohesive soil with an average unit weight of 15 kN/m^3 thus, the soil exhibits sufficient ability to withstand shear stresses. The high angle of repose suggested that the soil can withstand high shear stresses which translates to a high bearing capacity. The aforesaid suggested that the soil can withstand significant shear pressures from footings and safely dissipate it to the underlying layers.

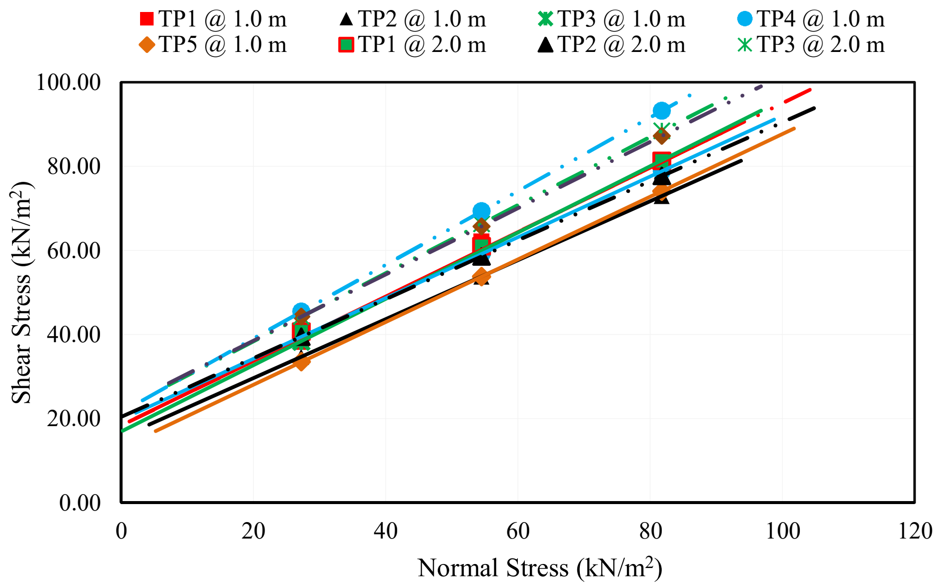


Fig. 5. Combined shear strength plot for trial pits 1-5

The combined shear stress against the normal stress plots for the trial pits 1-5 at both 1 m and 2 m depth is presented in fig. 5. As expected, it is evident from fig. 5 that a direct relationship exists between normal and shear stress. The trend is similar for all the samples at both 1 and 2 m depth.

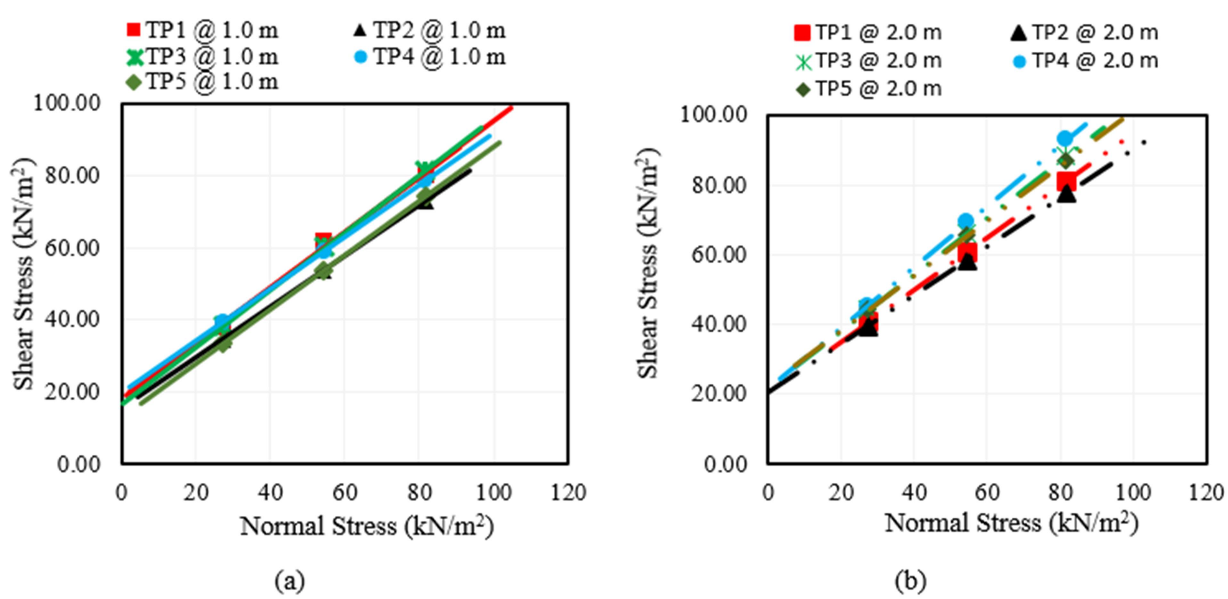


Fig. 6. Shear strength plot of trial pits 1-5 at (a) 1m depth, (b) 2 m depth

3.1.5. Consolidation result

Results of the one-dimensional consolidation test carried out on undisturbed soil samples as presented in Table 5 showed that the coefficient of volume compressibility (MV) varies from 0.0044 to 0.017 m^2/kN to 0.0294 m^2/kN. While the coefficient of consolidation (Cv) ranges from 5.606 to almost 78 m^2/year. The wide variability between TP 1 and the other trial pits could be due to relative soil heterogeneous nature even in proximate location, or perhaps laboratory setup variation. Total Oedometer settlement ranged from 0.0012 m to 0.0028 m. These values are indicative of soil material of moderate to high settlement in place.

Table 5: Consolidation parameter result for trial pits 1-5 at 1 m and 2 m

Trial Pit	Depth	Cv (m^2/Yr)	Mv (m^2/kN)	Pc (m)
TP 1	1.0 m	20.634	0.0129	0.0012
	2.0 m	77.790	0.0052	0.0005
TP 2	1.0 m	5.606	0.0176	0.0017
	2.0 m	31.768	0.0044	0.0004
TP 3	1.0 m	17.249	0.0154	0.0015
	2.0 m	19.732	0.0067	0.0006
TP 4	1.0 m	16.983	0.0166	0.0016
	2.0 m	11.803	0.0080	0.0008
TP 5	1.0 m	13.606	0.0098	0.0009
	2.0 m	29.100	0.0121	0.0011

The Mv result as presented in Table 5 is as low as a fraction of a thousand millimetres. Mv values from the various trial pits range from 4.40 x 10-3 to 17.6 10-3 m^2/kN. The recorded values suggest that no excessive settlement is expected throughout the service years of a structure built on this soil provided the safe or allowable bearing pressure of the soil is not exceeded.

3.1.6. Grading result

The wet sieve analysis conducted was quite revealing. Materials passing B.S. sieve No. 200 were moderate. This explains that the greater percentages of the soil constituents are fine to medium-sized grain materials. Values ranged from 62% to 92.04%. The resulting sieve analysis conducted on soil samples obtained at 1 m depth is presented in fig. 7. While the plot for samples obtained at 2 m depth is presented in fig. 8. The plot of the grading curve in fig. 7 suggests that most of the soils are fine-grained with a virtually high percentage of passing. On the other hand, the grading plot at 2 m depth for all soil samples except that of TP 4 indicated a coarser-grained soil. Therefore, with coarser fractions with increasing depth, the soil bearing pressure, shear strength and stiffness or incompressibility increase, hence, supporting more foundation load.

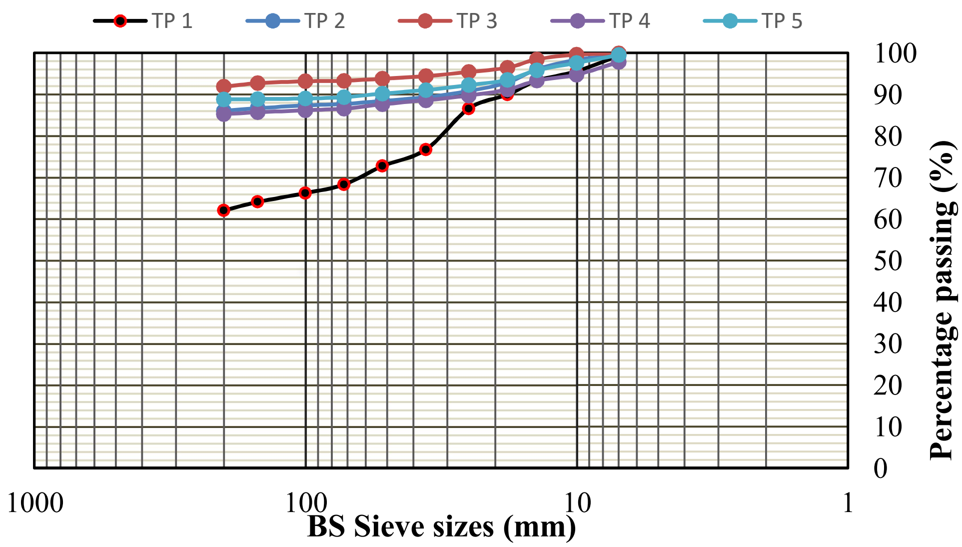


Fig. 1. Grading plot for trial pits 1-5 at 1 m depth

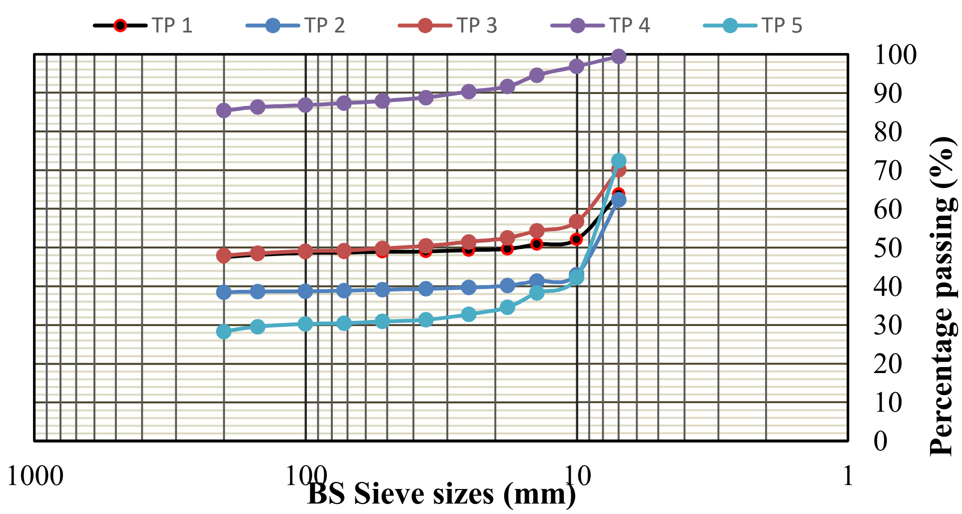


Figure. 2. Grading plot for trial pits 1-5 at 2 m depth

The result in Fig. 8 further highlighted that samples from TP 2 and 5 have the coarsest material with a percentage of 40% and less. On the other hand, TP 4 is a fine-grained soil with the larger soil proportions having a percentage passing of 80 - 90%. Overall, it can be deduced that the soil in the site is generally gravelly laterite with a high proportion of coarse material.

Conclusions and recommendation

The following conclusion are drawn based on the analysed results and careful correlation and interpretation of the field and laboratory data.

- Results of the geotechnical investigation revealed a safe bearing capacity in the range of 89.02 kN/m^2 in TP 5 to 155 kN/m^2 in TP4 at 1.00 m depths. The bearing values increased with depths ranging from 125 kN/m^2 in TP 6 to 210 kN/m^2 in TP4 at 2.00 m depths respectively, using a factor of safety of 2.50.

- No Static groundwater level was encountered in any of the five trial pits explored but adequate measures should be taken during construction to prevent ingress of moisture into the structure when in service by providing damp proof membrane and damp proof course linings.
- The excavated sides and hard-core level should be properly backfilled and well compacted with laterite to a maximum dry density of 2.00 gm/cm^3 at optimum moisture content to enhance the strength of the fill material.
- Supervision of all construction works should be carried out by qualified, experienced and certified registered civil engineers. All quality control measures and laboratory/field tests on all construction materials should be strictly carried out and documented as provided in the construction/ contract specifications.
- Total settlement (Oedometer) values ranged between 0.0012 m – 0.0028 m. It follows therefore that the proposed structure can be supported on an isolated wide pad foundation which may be designed at not less than 2.00 m depth below the ordinary ground level, using a safe bearing pressure of 120.00 kN/m^2, especially for the storey structures. However, the structural or foundation Engineer may design other footing types befitting for the proposed structure, considering the geotechnical laboratory data, financial implications and other relevant factors applicable.

Conflict of interest

The authors declare no conflict of interest concerning this paper's publication.

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