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Quality Assessment of Relationships Between Soil Bearing Capacity and California Bearing Ratio of Soil

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Abstract

This study investigates the relationship between selected geotechnical soil properties and the California Bearing Ratio value (CBRv), with the aim of enhancing foundation design and stability analysis in civil and structural engineering applications. Geotechnical and foundation engineering play a pivotal role in mitigating structural settlement and collapse, especially in infrastructure projects. In this work, twenty disturbed soil samples were systematically collected from four designated sites within Elizade University, Ilara-Mokin, Ondo State, Nigeria. Key geotechnical index and engineering properties—namely Atterberg limits (liquid and plastic limits), particle size distribution, moisture content, consolidation characteristics, and CBR (soaked and unsoaked) values—were determined in accordance with established ASTM and BS standard procedures. Regression models were developed using Microsoft Excel to evaluate the statistical relationship between the selected soil parameters and CBRv. Results showed that the natural moisture content ranged between 9.24% and 29.04%. The liquid limit exhibited a standard deviation of 6.457, while the plastic limit had a skewness value of 0.913. The plasticity index revealed a kurtosis of 2.908, indicating moderately peaked distribution. The calculated ultimate bearing capacities for square and circular footings ranged from 125.0 to 668.2 kN/m^2 and 109.0 to 553.0 kN/m^2, respectively. Regression analysis yielded correlation coefficients (R) of 2.137 for linear models without intercept and 1.180 for those with an intercept of 25.075, indicating moderate to strong relationships depending on the model applied. A positive linear relationship was established between CBRv and soil bearing capacity, with a coefficient of determination (R^2) of 0.7798 and a Pearson correlation coefficient (R) of 0.8831, suggesting a strong and statistically significant correlation. The findings confirm that CBRv is directly proportional to the bearing capacity of soils in the studied region, and that geotechnical properties such as moisture content, Atterberg limits, and particle size distribution are reliable predictors of CBR performance. These insights are valuable for preliminary site assessments and for optimizing shallow foundation design in similar tropical soil environments.

Keywords
California Bearing Ratio,
Bearing capacity,
Compaction Properties,
Subgrade,
Soaked
Unsoaked Situations

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INTRODUCTION

Soil is an essential ingredient to both plants and man in several ways, specifically for the ecosystem, food, agriculture, clothing, transportation, shelter, and medicine services (Olusola et al., 2023; Orimoloye et al., 2024; Oyebiyi et al., 2024; Oke et al., 2024). Furthermost civil engineering constructions (highways, tunnels, earth dams, roads, airport runways, bridges, curvets, and pavements) require utilisation of soil and earthwork (Olusola, 2021; Díaz and Spagnoli, 2024).

These structures classically need to establish a suitable soil-bearing capacity and sub-base layer (subgrade). Subgrade soils (S_{bgs}) are a dynamic part of the long-term efficiency of pavements (Adunoye et al., 2019; Adebisi et al., 2024). S_{bgs} give these civil engineering-structures crucial foundational sustenance (Ali et al., 2012; Khatti and Grover, 2024). The lack of essential foundational sustenance results in the collapse of these civil engineering-structures (Mokhar, 2023; Oke et al., 2024). Figure 1 shows information and data on collapsed buildings. These S_{bgs} must satisfy specific geotechnical engineering criteria (Ter-Martirosyan et al., 2024; Ti et al., 2009).

The specific geotechnical engineering criteria which must be met include soil-bearing capacity, engineering index, settlement, and swelling properties. The California bearing ratio (CBR) is one of the most frequently utilised examinations to evaluate the rigorousness and bearing capacity of S_{bgs} (Varol et al., 2021; Ukah et al., 2022). The CBR_v of any S_{bgs} sample can be evaluated in unsoaked and soaked situations (Orimoloye et al., 2024; Oyebiyi et al., 2024). However, the CBR_v attained for soaked S_{se} is classically lower in magnitude than the value accomplished for unsoaked S_{se} (Bayamack et al., 2019; Bello and Adegoke, 2010).

It has been established that the CBR_v for soaked S_{se} is regularly considered a conventional estimate for engineering design resolutions. On the other hand, the soaked CBR examination is time-consuming and labour-intensive (Abdella et al., 2017; Bello, 2012). The soaked CBR examinations involve soaking the S_{bgs} samples in water for 96 hours to put on the worst-case scenario (the pavement is submerged in water). In addition, the soaked CBR examinations demand a substantial quantity of materials and greater efforts in the preparation of the specimen to be examined (Bharath et al., 2021; Bherde et al., 2023). Also, it is important to communicate that the S_{bgs}'s properties can show significant differences even over brief distances, principally due to the heterogeneous nature of subgrade soil. This inconsistency of S_{bgs} can make it interesting to establish dependable models of engineering design parameters.

In building, an earth dam or a new road, CBR becomes necessary to accumulate several S_{se} and then estimate the CBR_v for each of these S_{bgs} samples utilising the CBR examination. This procedure naturally takes at least 4 or more days per S_{bgs} sample (Farooq and Mujtaba, 2017; Jaleel, 2011). This procedure can principally cause a setback in obtaining quality examination results (Janjua et al., 2016). These setbacks may not be encouraging for making rapid decisions in relation to pavement and civil engineering structural design, possibly resulting in a substantial rise in operational and construction costs (Joseph and Vipulanandan, 2011). Moreover, these examinations and techniques involve costs in relation to materials, storage of materials and transportation and evaluation fees. In addition, subgrade soil evaluation results can sporadically be unreliable due to S_{bgs} sample disturbance and problems with the quality and accuracy of the laboratory situations. Therefore, it can be challenging to guarantee that the subgrade soil sample utilized for the CBR test accurately replicates the in-situ situations. Considering the problem of time and complexity of soaked CBR value determination, numerous works, and research studies such as Mallikarijunappa et al. (2022); Nazir et al. (2022); Osouli et al. (2017); Razouki et al. (2005); Taha et al. (2015; 2019); Teklehaymanot and Alene (2021) have tried to create correlations between the CBR_v and readily available determinable index properties of subgrade soils. These correlations are limited to Liquid Limit, Plastic Index, Maximum Dried Density and Optimum Moisture Content, with little or no correlations between CBR (soaked and unsoaked) and soil-bearing capacity. The main contributions of this study are as follows: propose a reliable relationship model between soaked and unsoaked CBR and soil-bearing capacity, and evaluate statistically the model for predicting the soaked and unsoaked CBR_v

Figure 1a: Front View of Collapsed Structure (Source: Oke et al 2024)

Figure 1b: Aerial View of Collapsed Structure (Source: Oke et al 2024; Akinyemi et al 2019)

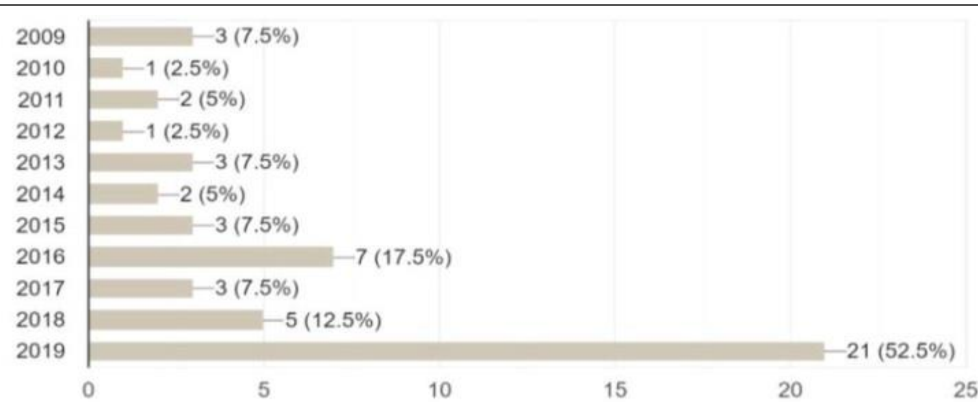

Figure 1c: Sum of collapsed structures between 2009 and 2019 (Source: Oke et al., 2024; Awoyera et al., 2020)

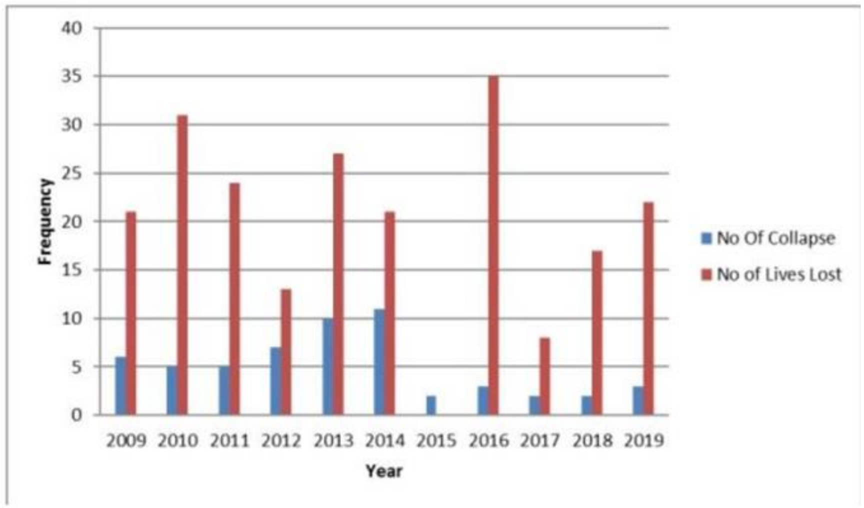

Figure 1d: Figure of collapsed structures and lives lost (Source: Oke et al., 2024; Odeyemi et al., 2019)

Materials and Methods

Soil samples (S_{se}) were collected at four major construction sites (Faculty of Engineering Building, Faculty of Law Building, golf course, and New Hostel Building) in Elizade University, Ilara–Mokin. The boreholes were drilled to a depth of 1.5 m each below the existing ground level. Twenty S_{se} (disturbed and undisturbed) suitable for identification, geotechnical engineering characteristics, and engineering index properties examination purposes were collected at 1.5 m depths with the aid of core cutters. Samples were transported to the laboratory for laboratory examinations.

Figure 2 presents the location of the sampling points and sites in the University. The standard procedures stated in BS 1377 (1990) were used in the collection of S_{se} from all the locations. Soil samples collected were subjected to selected tests as stated in BS 1377 (1990). Selected geotechnical engineering examinations were conducted on the collected S_{se}. The examinations conducted include moisture content, specific gravity, sieve analysis, consolidation and triaxial examinations. Computations of these geotechnical engineering parameters were conducted as follows:

a) **Moisture Contents (Mc):** The normal moisture contents of the collected S_{se} were scrutinised utilizing procedures and techniques stated in the American Society for Testing and Materials (ASTM) D- 2216 (2019). Full explanations of the procedures are shown in Oke et al. (2024).

b) **Particle Size Distribution (Sieve Analysis, Particle Size Analysis):** This evaluation was conducted utilizing methods and techniques stated in BS 1377 (1990) and the soil categorisation into groups and sub-groups was based on similar engineering properties and engineering index utilising Unified Soil Classification System (USCS) technique as stated in ASTM-D 2487-93 (2017). Full explanations of the procedures and steps are shown in Oke et al. (2024).

c) **Determination of Atterberg limits** (Plastic and Liquid limits): The determinations of Atterberg limits, which are Plastic and Liquid limits of the S_{se} were conducted utilising procedures highlighted in ASTM D-4318 (2017). Oke et al. (2024) provide a full explanation of the procedure and technique.

d) **Evaluation of Consolidation Properties:** Consolidation examinations were conducted utilising standard techniques and procedures stated in the previous studies such as Chuantao et al. (2020); ASTM D5321 / D5321M-20 (2020). Full explanations of the procedures and computations are shown in Oke et al. (2024).

e) **Determination and Computation of CBR:** CBR examinations and computations were conducted utilising standard techniques and procedures stated in studies such as Hight and Stevens (1982); Roy et al. (2010); ASTM D1883 (2007).

f) **Calibration of Equipment and Accuracy of the Materials Utilised:** All reagents and chemicals utilised in this study had a chemical purity of 95% or above. Distilled water was utilised in the preparations of primary, secondary and tertiary standard solutions. All equipment and facilities utilised in the laboratory experiments were calibrated utilizing standard procedures, techniques, and methods. The coefficient of determination (R^2) of these calibrations (relationship between experimental and attained values of the results) was 0.96 or above. Full explanations of the procedures and techniques are shown in Oke et al. (2024).

g) **Determination of Ultimate Bearing Capacity of Soil:** The bearing capacities of soils are a direct quantity of the resistance of the soil to sidewise or lateral settlement or displacement (Razouki et al., 2005). The soil's bearing capacity expression for circular footing under centrical loading can be expressed as follows (Terzaghi, 1967; Bowles, 1988; Razouki et al., 2005):

$$q_u = 1.3c\,N_C + p_o N_q + 0.3\,\gamma B N_\gamma \tag{1}$$

Where; q_u is the Terzaghi's ultimate bearing capacity of the soil, c is the soil cohesion property, γ is the unit weight of the soil (in the case the water table is higher than the underside of the structural footing the submerged unit weight γ' has to be utilized instead of γ), p_o is the overburden load or pressure at the base of the structural footing, B is the diameter of the structural footing, N_c, N_γ and N_q are the Terzaghi's soil bearing capacity factors (Razouki et al., 2005). A well-known Terzaghi equation with correction terms suggested by Schultze was utilised to calculate the bearing capacity of a rectangular foundation of any side ratio breadth to length The bearing capacity was computed using the Terzaghi method (analytical method) as follows:

$$q_u = nN_c s_c + \gamma_0 D N_q s_q + 0.5\gamma_1 B N_y s_y \tag{2}$$

where: γ_o is the Unit weight of soil above the foundation level (KN/m³), γ_1 is the Unit weight of soil below the foundation level (KN/m³) , c, φ_f are the Strength parameters of the soil below the foundation level in KN/m² and degrees respectively. B is the Width of the foundation (m). L is the length of the foundation (m). N_c, N_q, N_γ are the bearing capacity coefficients dependent on the angle of internal friction of the soil below the foundation level. D is the depth of the foundation (m). s_c, s_q and s_γ are shape factors for the footing.

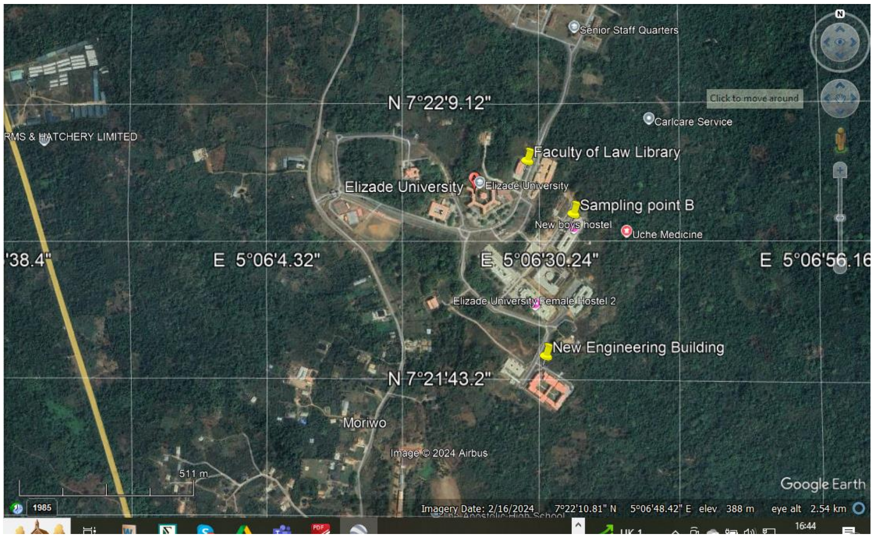

Figure 2a: Three soil sampling sites (Law, New Hostel and Engineering building) (Source: Goggle map 2024)

Figure 2b: The fourth soil sampling site (Smoki Hill) (Source: Goggle map 2024

h) Determination Correlation Between CBR and Ultimate Bearing Capacity of Soil (Computation of Models): Models examinations and computations were conducted utilising standard techniques and procedures stated in literature such as Wilches et al. (2020); Rashed et al. (2021); Bardhan et al. (2021); Rehman et al. (2017); Ramasubbarao and Sankar (2013); Araujo and Ruiz (2016); Prasanna et al. (2017); Ratnam and Prasad (2019); Roy (2016); Wroth and Wood (1978); Rakaraddi and Gomarsi (2015); Pule and Yendaw (2024). Since the CBR examination was intended to quantify the ultimate bearing capacity of the soil, it has been reported that there must be some degree of correlation between these geotechnical and foundation engineering parameters (Black, 1962).The basic model equations utilised are shown in Equations 3 to 5 as follows:

Linear without intercept: $CBR_v = \beta_1 X_i$ (3)

Linear with intercept: $CBR_v = \beta_0 + \beta_1 X_i$ (4)

Non-Linear with intercept: $CBR_v = \beta_0 + \beta_1 X_i + \beta_2 X_i^2$ (5)

Where, CBR_v is the California Bearing Ratio value, β_0, β_1 and β_2 are coefficients of the variables such as Liquid Limit and soil bearing capacity. The determinations of these coefficients were conducted utilising Data Analysis in Microsoft Excel. The procedures for utilising Data Analysis in Microsoft Excel are shown in Figure 3 as a flow chart.

i) **Statistical Computation of Parameters:** The choice of these statistical measures as the quality characteristic was selected and analysed based on the need to express both the mean level of the properties and the variation around the mean. The mean, standard deviation, and skewness were calculated using equations (6 to 8) respectively.

The mean: $\overline{X} = \frac{\sum_{i=1}^{N} X_i}{N}$ (6)

The standard deviation $\sigma = \sqrt{\frac{\sum_{i=1}^{N}\left(X_i - \overline{X}\right)}{N}}$ (7)

The skewness $\mu = \frac{\sum_{I=1}^{N}\left(X_i - \overline{X}\right)^3}{\left(N-1\right)\sigma^3}$ (8)

RESULTS AND DISCUSSION

Results from the study are discussed as follows:

a) **Properties and classifications of the selected S_{se} :** Table 1 provides a statistical breakdown and properties of the selected S_{se} from the selected sites measured. The table revealed that moisture content was between 9.24 and 29.04 %, liquid limit had a standard deviation of 6.457, Skewness of plastic limits was 0.913, Kurtosis of plastic index was 2.908, bearing capacity for square and circular footings was between 125.0 and 668.20; and 109.00 and 553.00 KNm^{-2}, respectively. Figure 4 presents the particle size distribution. The figure revealed that there is a similarity within the S_{se}. Based on these findings the S_{se} can be classified as GW (well-graded gravel, gravel sand mixtures), SW (well-graded sand, gravel sand – gravel mixtures) and GC (clayed gravel, gravel sand-clay mixtures) using Unified Soil Classification System or can be classified as CL, or CI using Unified Soil classification system and A_{2-4} to $A_{.2-6}$ soil using Classification According to AASHTO. The details of these results (engineering index and properties, soil classification and effective sizes) are shown in Oke et al. (2024). Table 2 shows the effects of locations on the properties and engineering index of the soil. The Table revealed no significant differences between the engineering index and engineering properties of the soil at a 95 % confidence level ($F_{19, 140}$ = 0.677 and p = 0.837, which indicates that $F_{19, 140} < 1.661$ and $p > 0.05$).

b) **Correlation between Soaked and Unsoaked CBR:** Table 3a presents data and information on the relationship between soaked and unsoaked CBR_v. The Table provides information on the coefficients for both linear expressions with and without intercept as well as the statistical significance of the parameters. From the Table, the coefficient of the relationships is 2.137 with a standard error of 0.012, a t-statistics of 172.545and p-value of 7.968×10^{-32} for a linear relationship without intercept, but for the linear relationship with an intercept, the coefficient is 1.180, with a standard error of 0.005, a t-statistics of 254.151 and p-value of 1.88×10^{-33}. These results show that unsoaked CBR_v are higher than soaked CBR_v

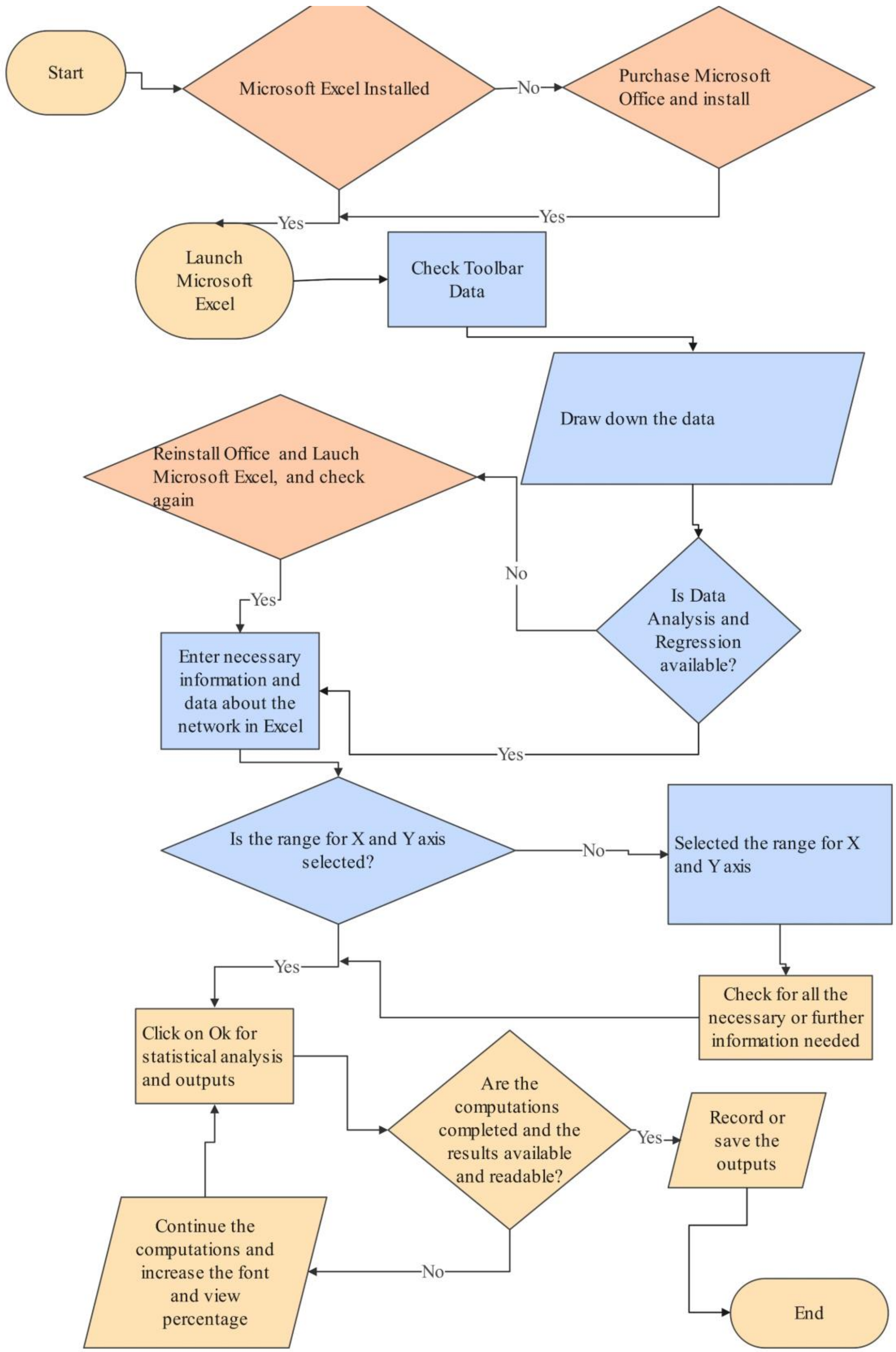

Figure 3 Flow chart of the procedures for utilising Data Analysis in Microsoft Excel

Table 1 A statistical breakdown and properties of the selected S_{se}.

Samples	Mc	LL(%)	PL (%)	PI (%)	Bcf	Bsf	C (KNm^{-2})	φ
1	18.62	38	22	16	147	158	55	10.2
2	13.49	45	27	18	138	155	30	19.3
3	17.67	41	22	19	125	135	40	19.3
4	12.38	39	22	17	120	150	45	21.8
5	12.38	40	22	18	127	143	56	22.8
6	18.9	58.5	34	24.5	216.5	269.4	41.1	23
7	11.6	42	24.8	17.2	270.8	318.7	29.1	22.5
8	18	52.5	32.5	20	329.5	394.2	56	16
9	12.1	38.5	24	14.5	433.7	519.6	43.2	17.5
10	12.7	39	25	14	553	668.2	67	15
11	19.05	45	29	16	127	143	37.8	11.1
12	21.28	48	42	6	112	135	23.2	14.5
13	13.64	52	20	32	130	145	28.7	16.1
14	20.5	38	34	4	109	125	32.4	14.9
15	29.04	57	35	22	125	154	29.7	18.1
16	12.06	42.7	24.9	17.8	223	280	52	12.41
17	10.22	44.6	26.97	17.63	253	312	42	16.7
18	9.24	46	28.2	17.8	261	325	48	15.64
19	10.31	43.2	25.63	17.57	259	320	42	17.22
20	11.02	35.5	18.38	17.12	211	260	36	16.17
Maximum	29.040	58.500	42.000	32.000	553.000	668.200	67.000	23.000
Minimum	9.240	35.500	18.380	4.000	109.000	125.000	23.200	10.200
SD	4.986	6.457	5.939	5.752	117.914	145.264	11.410	3.672
Skewness	1.176	0.918	0.913	-0.058	1.598	1.495	0.425	0.060
Kurtosis	1.448	0.104	0.609	2.908	2.616	2.287	-0.315	-0.440

Where; SD is the standard deviation, φ is the Angle of Internal Friction (°), *C* (KNm^{-2}) is the Soil Cohesion (KNm^{-2}) B_{sf} is the Bearing Capacity (KNm^{-2}) for Square footing, B_{cf} is the Bearing Capacity (KNm^{-2}) for Circular footing; PI (%) is the *Plasticity index (LL–PL = PI)*, PL (%) is the *Plastic limit;* LL(%) is the *Liquid limit* and M_c is the Natural moisture contents.

Table 2: the effects of locations on the properties and engineering index of the soil.

Source of Variation	*Sum of Squares*	*Degree of freedom*	*Mean Sum of square*	*F-value*	*P-value*	*F crit*
Between S_{se}	167874.6	19	8835.504	0.677	0.837	1.661
Within S_{se}	1827965	140	13056.9			
Total	1995840	159				

Table 3a: Information on the coefficients for both linear expressions with and without intercept

	Linear with no intercept				Linear with intercept			
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Coefficients*	*Standard Error*	*t Stat*	*P-value*
Intercept	0	0	0	0	25.075	0.121	206.660	7.75×10^{-32}
Soaked	2.137	0.012	172.545	7.968×10^{-32}	1.180	0.005	254.151	1.88×10^{-33}

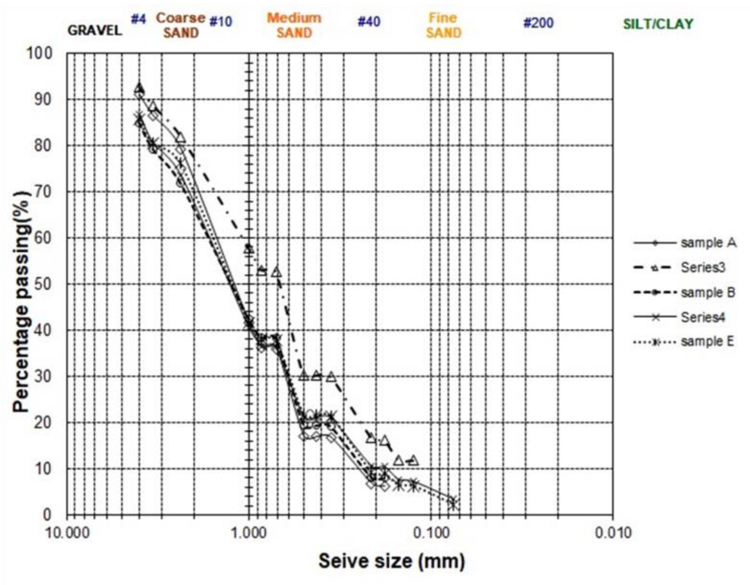

Figure 4a Particle size distribution of the Engineering Building site.

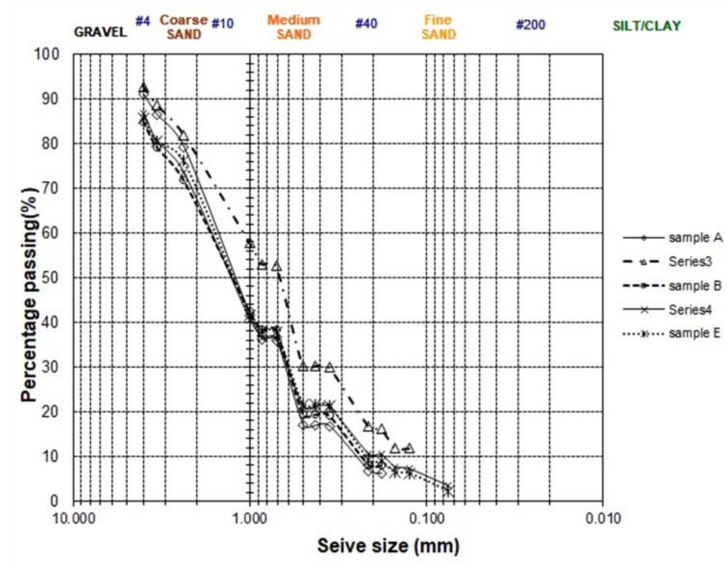

Figure 4b Particle size distribution of the Smoki Hill site.

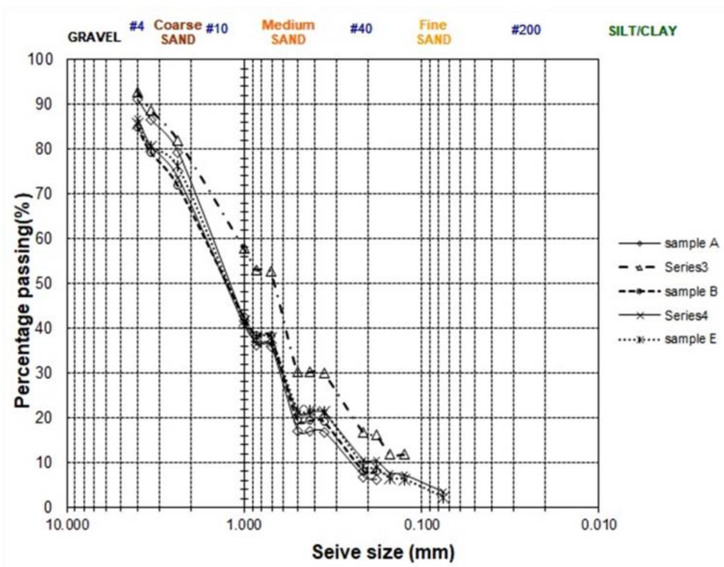

Figure 4c Particle size distribution of the Faculty Law Building site.

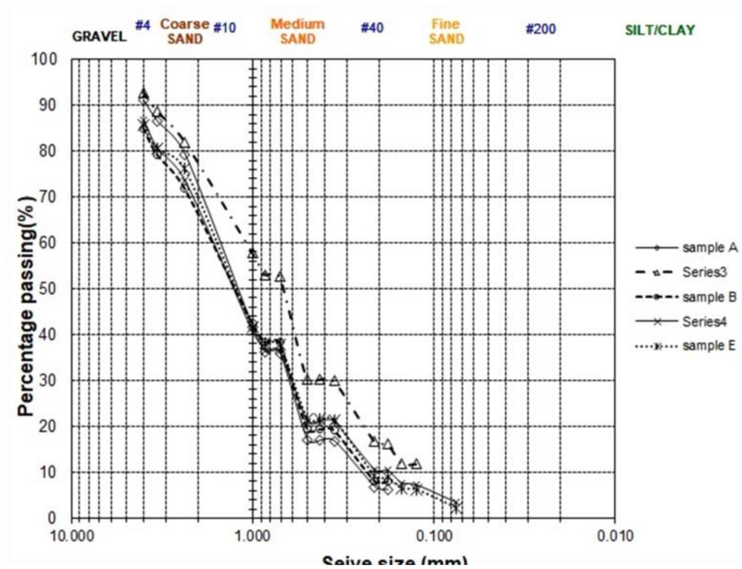

Figure 4d Particle size distribution of the New Hostel site.

Table 3b : Result of ANOVA for linear regression without *intercept*

Source of Variation	Sum of Squares	Degree of freedom	Mean Sum of square	F-value	P-value
Regression	62435.670	1	62435.670	29771.751	1.99×10^{-30}
Residual	39.846	19	2.097		
Total	62475.516	20			

Table 3c : Result of ANOVA for linear regression with *intercept*

Source of Variation	*Sum of Squares*	*Degree of freedom*	*Mean Sum of square*	*F-value*	*P-value*
Regression	60.238	1	60.238	64592.897	1.875×10^{-33}
Residual	0.017	18	0.001		
Total	60.255	19			

In addition, the p-values revealed that the relationships are directly proportional and significant at a 95 % confidence level (p= 1.88×10^{-33} and 7.968×10^{-32} which are less than 0.05). These proportional relationships statement agrees with studies (Kormu et al., 2022; Lakshmi et al., 2016; Othman and Abdelwahab, 2023; Palomino Ojeda et al., 2023; Kassa et al., 2024), which reported that

$$CBR_V\,(soaked) = \alpha \times CBR_V\,(unsoaked) \qquad where \quad \alpha = 30 - 70\% \tag{9}$$

$$CBR_V\,(unsoaked) = \beta \times CBR_V\,(soaked) \qquad where \quad \beta = 1.4286 - 3.3333 \tag{10}$$

The large values of the coefficients (greater than 1.000) indicate that the soils are cohesive soils such as clays and silts, and it is an indication of a poor drainage property of the soil if used it requires mitigation actions. Table 3b revealed that equations 11a and b are significant ($F_{1,19}$ = 29771.751; p = 1.99×10^{-30}) based on result of ANOVA

Linear without intercept: $CBR_{vun} = \beta_1 CBR_{vsoaked}$ (11a)

Linear without intercept: $CBR_{vun} = 2.137 \times CBR_{vsoaked}$ (11b)

Where; CBR_{vun} is the unsoaked CBR_v ; β is the directly proportional constant and CBRvsoaked is the soaked CBR_v. Table 3c revealed that equations 12a and b are significant ($F_{1,18}$ = 64592.897; p = 1.875×10^{-33}) based on result of ANOVA

Linear with intercept: $CBR_{vun} = \beta_0 + \beta_1 CBR_{vsoaked}$ (12a)

Linear with intercept: $CBR_{vun} = 25.075 + 1.180 \times CBR_{vsoaked}$ (12b)

Where; CBR_{vun} is the unsoaked CBR_v, β is the directly proportional constant, β_0 is the constant (intercept) and CBRvsoaked is the soaked CBR_v. Table 3d presents regression statistic of equations 11b and 12 b. The Table revealed the correlation coefficient (multiple R) and coefficient of determination (CD) for linear with and without intercept for soaked and unsoaked CBR_v as 0.9997 and 0.9994, and 0.9999 and 0.9997. Although, these relationships were excellent, but relationship linear without intercept performed better than linear with intercepts, which agreed with previous studies such as Razouki and Kuttah (2006); Razouki et al. (2005); Kudur et al.(2022); Mallikarijunappa et al. (2022).

c) **Correlation between CBR_v and Liquid Limit(LL) of the Soil:** Table 4a provides information between LL and CBR_v linear without an intercept. The Table revealed the coefficients for both linear expressions for both soaked and unsoaked as well as the statistical significance of the parameters. From the Table, the coefficient of the relationships is 57.94151 with a standard error of 1.77422, a t-statistics of 32.657 and a p-value of 3.71×10^{-18} for soaked CBR_v, but for unsoaked CBR_v, the coefficient is 123.873, with a standard error of 3.807, a t-statistics of 32.537 and a p-value of 3.98×10^{-18}. These results established that unsoaked CBR_v are higher than soaked CBR_v

In addition, the p-values revealed that the relationships are directly proportional and significant at a 95 % confidence level (p= 3.98×10^{-18} and 3.71×10^{-18} which are less than 0.05), which were confirmed in the analysis of variation (ANOVA) of the results as presented in Tables 4b (p = 1.79×10^{-17}) and 4c (p = 1.91×10^{-17}). Table 4d presents regression statistics for the linear without an intercept for both soaked and unsoaked CBR_v. The Table revealed that the correlation coefficients (multiple R) and Coefficients of determination (R Square) were 0.99121 and 0.9825, and 0.991146 and 0.98237 for soaked and unsoaked CBR_v , respectively.

Table 3d: Regression Statistics of Linear with Intercept and Linear without Intercept

Regression Statistics	*Linear With Intercept*	Linear Without Intercept
Multiple R	0.9997	0.9999
R Square	0.9994	0.9997

Table 4a: Relationship between CBR_v (soaked and unsoaked) and LL without *intercept*

Linear without Intercept	Soaked				Unsoaked			
	Coefficients	Standard Error	t Stat	P-value	Coefficients	Standard Error	t Stat	P-value
Intercept	0	0	0	0	0	0	0	0
LL	57.94	1.77	32.66	3.71×10^{-18}	123.8725	3.81	32.53727	3.98×10^{-18}

Table 4b: Result of ANOVA for relationship between soaked CBR_v and LL without *intercept*

Source of Variation	Sum of Squares	Degree of freedom	Mean Sum of square	F-value	P-value
Regression	13428.1	1	13428.10	1066.511	1.79×10^{-17}
Residual	239.223	19	12.59		
Total	13667.32	20			

Table 4c: Result of ANOVA for relationship between unsoaked CBR_v and LL without *intercept*

Source of Variation	Sum of Squares	Degree of freedom	Mean Sum of square	F-value	P-value
Regression	61374.04	1	61374.04	1058.674	1.91×10^{-17}
Residual	1101.48	19	57.97		
Total	62475.52	20			

Table 4d: Regression Statistics of relationship between CBR_v and LL with Intercept and Linear without Intercept

Linear Regression without intercept			Linear Regression with intercept		
Regression Statistics	*Soaked*	Unsoaked	*Regression Statistics*	Unsoaked	Soaked
Multiple R	0.99121	0.991146	Multiple R	0.065	0.049
R Square	0.982497	0.982369	R Square	0.004	0.002

Table 5a: Relationship between CBR_v (soaked and unsoaked) and LL with *intercept*

Linear with Intercept	UnSoaked				Soaked			
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Coefficients*	*Standard Error*	*t Stat*	*P-value*
Intercept	56.499	3.277	17.240	1.23×10^{-12}	26.82711	2.795	9.5972	1.68×10^{-8}
LL	2.020	7.3283	0.276	0.785939	1.304856	6.251	0.209	0.836984

Table 5b: Result of ANOVA for relationship between soaked CBR_v and LL with *intercept*

Source of Variation	Sum of Squares	Degree of freedom	Mean Sum of square	F-value	P-value
Regression	0.13488	1	0.13488	0.043578	0.836984
Residual	55.712	18	3.095111		
Total	55.84688	19			

Table 5c: Result of ANOVA for relationship between unsoaked CBR_v and LL with *intercept*

Source of Variation	Sum of Squares	Degree of freedom	Mean Sum of square	F-value	P-value
Regression	0.323317	1	0.323317	0.075996	0.7859
Residual	76.57915	18	4.254397		
Total	76.90247	19			

The results indicate a very good relationship, which agreed with previous studies such as Raza et al. (2018); Sarsam (2020); Shirur and Hiremath (2014), Taha et al. (2015; 2019) and Tables.

Table 5a provides information between LL and CBR_v linear with an intercept. The Table revealed the coefficients for both linear expressions for both soaked and unsoaked as well as the statistical significance of the parameters. From the Table, the coefficient of the relationships is 2.020 with an intercept of 56.499, standard errors of 3.277 and 7.3283, t-statistics of 17.240 and 0.276 and p-values of 1.23×10^{-12} and 0.78594 for unsoaked CBR_v, but for soaked CBR_v, the coefficient is 1.3049, with an intercept of 26.8271, standard errors of 2.795 and 6.251, t-statistics of 9.5972 and 0.209 and p-values of 1.68×10^{-8} and 0.8370, which indicate that coefficients are not significant compared to the intercept.

These results established that the relationships are directly proportional and significant at a 95 % confidence level and the coefficients are not significant factors, which are confirmed in the analysis of variation (ANOVA) of the results as presented in Tables 5b (p = 0.8370) and 5c (p = 0.7859). Table 5d presents regression statistics for the linear without an intercept for both soaked and unsoaked CBR_v. The Table revealed the correlation coefficients of 0.065 and 0.0049 for unsoaked and soaked CBR_v , respectively.

The results indicate a very weak relationship, which agrees with previous studies such as Ali et al. (2012); Shirur and Hiremath (2014); Sarsam (2020); Oyebiyi et al. (2024); Khatti and Grover (2024) and selected Tables in this study. Table 6 compares this study with previous studies on the relationship between CBR_v, LL and their correlation coefficients. The Table provides information and data on the relationship between LL and CBR_v and the correlation coefficients, which indicate that the relationships are similar and agree with previous documents, but different in magnitude.

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c) **Correlation between CBR and Ultimate Bearing Capacities of the Soil:** Tables 7 and 8 provide information and data on the empirical relationship between CBR_V and the bearing capacity of the soil. Previous studies tried to establish empirical relations between CBR_V and the bearing capacity of soil from its CBR_v, but these values gave approximate values and the values varied with soil type and conditions. One of the frequently cited relationships is expressed as follows:

$$q_u = K_{es} \times CBR_v \quad or \quad CBR_v = K_{escbr} \times q_u \tag{13}$$

Where; q_u is the ultimate bearing capacity of the soil (kNm^{-2}), CBR_v is the California Bearing Ratio value (percentage) and K_{es} or K_{escbr} are empirical constants, that depend on the soil type and conditions. Typical ranges of K_{es} are between 10 and 30 for cohesive soils and between 30 and 75 for granular soils. Table 7a presents the relationship between the ultimate bearing capacity of the soil for circular footing and soaked CBR_v. From Table 7a the value of the coefficients for both linear with and without intercept are 0.002088 and 0.099984 with an intercept of 26.95893, standard errors of 0.0122, 0.003392 and

0.822413, t-statistics of 8.203, 0.616 and 32.780, p-values of 1.15×10^{-7}, 0.54577 and 1.67×10^{-17}, respectively. The Table established that linear regression with intercept is insignificant (Table 7b, p = 0.54577) and linear regression without intercept is significant (Table 7c, p = 1.71×10^{-7}). Table 7d shows the R and CD for both linear regression with intercept and linear regression without intercept. The values are 0.143628, and 0.020629, and 0.883063 and 0.7798, respectively. These results indicate that linear regression without intercept is more reliable than linear regression with intercept. These equations can be expressed as follows:

$$CBR_{vsoaked} = 0.099984B_{cf} \tag{14}$$

Table 6: a comparison of this study with previous studies on the relationship between CBR_v, LL and their correlation coefficients

Equations	Source/Reference	Correlation coefficient	Coefficient of Determination
CBR_{vun} = 83.19+0.031(LL) CBRvsoaked = 28.87+0.22 (LL	Bello (2012); Pule and Yendaw (2024)		

Table 7a Relationship between CBR_v and Ultimate Bearing Capacity for Circular footing

Soaked	Coefficients	Standard Error	t Stat	P-value	Coefficients	Standard Error	t Stat	P-value
Intercept	26.95893	0.822413	32.780	1.67×10^{-17}	0	0	0	0
B_{cf}	0.002088	0.003392	0.616	0.54577	0.099984	0.0122	8.203	1.15×10^{-7}

Table 7b: Result of ANOVA of the regression with intercept

Source of Variation	Sum of Squares	Degree of freedom	Mean Sum of square	F-value	P-value
Regression	1.152065	1	1.152065	0.379143	0.54577
Residual	54.69481	18	3.038601		
Total	55.84688	19			

Table 7c: Result of ANOVA of the regression without intercept

Source of Variation	Sum of Squares	Degree of freedom	Mean Sum of square	F-value	P-value
Regression	11756.54	1	11756.54	67.28521	1.71×10^{-7}
Residual	3319.812	19	174.727		
Total	15076.35	20			

Table 7d: Regression Statistics for both linear with intercept and without intercept

Regression Statistics	*With intercept*	*Without*	*Regression Statistics*	*Non-Linear*
Multiple R	0.143628	0.883063	Multiple R	0.339228
R Square	0.020629	0.7798	R Square	0.115076

Table 7e : Non-Linear Relationship between CBR_v and Ultimate Bearing Capacity for Circular footing

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	24.81132	1.785809	13.89361	1.04×10^{-10}
B_{cf}	0.020767	0.014258	1.456491	0.163479
$(B_{cf})^2$	-3.1×10^{-5}	2.32×10^{-5}	-1.34699	0.195666

CBRvsoaked=0.045LL	Ramasubbarao and Sankar [2013]; Pule and Yendaw (2024)	0.82	
CBRvsoaked = -1.588LL + 73.734	Araujo and Ruiz (2016); Pule and Yendaw (2024)	0.60	
CBRvsoaked = -0.070LL + 17.49	Pule and Yendaw(2024)	0.25	
CBRvsoaked = -0.0813LL + 7.2087	Reddy et al . (2019); Pule and Yendaw(2024)	0.93	
CBR_{vun} = 24.377 + 0.151LL	Katte et al. (2019); Pule and Yendaw(2024)	0.19	
CBRvsoaked = -0.4829LL + 24.018	Rashed et al. (2021) ; Pule and Yendaw (2024)	0.77	
CBR_{vun} = 123.8725 LL	This study	0.9912	0.9824
CBRvsoaked = 57.9415 LL	This study	0.9912	0.9825
CBR_{vun} = 2.020 LL + 56.4990	This study	0.065	0.0040
CBRvsoaked = 1.3048LL + 26.8271	This study	0.049	0.0020

$$CBR_{vsoaked} = 0.002088B_{cf} + 26.95893 \tag{15}$$

These equations are similar to equations obtained in previous studies such as which are expressed as follows for granular, cohesive and general approximate expression):

Granular Soils: $CBR_{vsoaked} = 0.02B_{cf}$ (16)

Cohesive Soils: $CBR_{vsoaked} = 0.067B_{cf}$ (17)

General Approximation $CBR_{vsoaked} = 0.033B_{cf}$ (18)

Table 7e presents the non-linear relationship between the ultimate bearing capacity of the soil for circular footing and soaked CBR_v. From Table 7e the value of the coefficients for non-linear regression with intercept are 0.020767 for B_{cf} and -3.1×10^{-5} for $(B_{cf})^2$ with an intercept of 24.81132, standard errors of 2.32×10^{-5}, 0.014258 and 1.785809, t-statistics of -1.34699, 1.456491 and 13.89361, and p-values of 0.195666, 0.163479 and 1.04×10^{-10}, respectively. The result established that these regression coefficients with $p > 0.05$ are insignificant and the intercept of $p < 0.05$ is significant. Table 8a presents the relationship between the ultimate bearing capacity of the soil for square footing and soaked CBR_v. From Table 8a the value of the coefficients for both linear with and without intercept are 0.002491 and 0.172442 with an intercept of 56.75745, standard errors of 0.003211, 0.021659 and 0.938016, t-statistics of 7.961767, 0.775578 and 60.50797, p-values of 1.80×10^{-7}, 0.448069 and 2.98×10^{-22}, respectively.

The Table established that linear regression with intercept is insignificant (Table 8b, F-value = 0.601521; p = 0.448069) and linear regression without intercept is significant (Table 8c, F-value= 63.38974; $p = 2.62 \times 10^{-7}$). Table 8d shows the R and CD for both linear regression with intercept and linear regression without intercept. The values are 0.179826, and 0.032337, and 0.877148 and 0.769389, respectively. These results indicate that linear regression without intercept is more reliable than linear regression with intercept. These equations can be expressed as follows:

$$CBR_{vunsoaked} = 0.172442B_{sf} \tag{19}$$

$$CBR_{vunsoaked} = 0.002491B_{sf} + 56.75745 \tag{20}$$

Table 8e presents the non-linear relationship between the ultimate bearing capacity of the soil for circular footing and soaked CBR_v. From Table 8e the value of the coefficients for non-linear regression with intercept are 0.021536 for B_{sf} and -2.7×10^{-5} for $(B_{sf})^2$ with an intercept of 56.19177, standard errors of 0.012731, 1.75×10^{-5} and 1.893412, t-statistics of -1.54221, 1.691568 and 2662123, and p-values of 0.141432, 0.108976 and 8.01×10^{-16}, respectively. The result established that these regression coefficients with $p > 0.05$ are insignificant and the intercept of $p < 0.05$ is significant. Table 9 compares this study with previous studies on the relationship between CBR_v, B_{sf} , B_{cf} and their correlation coefficients. The Table provides information and data on the relationship between CBR_v, B_{sf} , and B_{cf} and the correlation coefficients, which indicate that the relationships are similar and agree with previous documents, but different in magnitude.

Table 8a Relationship between CBR_v and Ultimate Bearing Capacity for Square footing

Unsoaked	*Coefficients*	*Standard Error*	*t Stat*	*P-value*	*Coefficients*	*Standard Error*	*t Stat*	*P-value*
Intercept	56.75745	0.938016	60.50797	2.98E-22	0	0	0	0
Bsf	0.002491	0.003211	0.775578	0.448069	0.172442	0.021659	7.961767	1.8E-07

Table 8b: Result of ANOVA of the regression with intercept

Source of Variation	Sum of Squares	Degree of freedom	Mean Sum of square	F-value	P-value
Regression	2.486812	1	2.486812	0.601521	0.448069
Residual	74.41566	18	4.134203		
Total	76.90247	19			

Table 8c: Result of ANOVA of the regression without intercept

Source of Variation	Sum of Squares	Degree of freedom	Mean Sum of square	F-value	P-value
Regression	50747.23	1	50747.23	63.38974	2.62×10^{-07}
Residual	15210.62	19	800.559		
Total	65957.85	20			

Table 8d: Regression Statistics for both linear with intercept and without intercept

Regression Statistics		Without	Non-Linear	
Multiple R	0.179826	0.877148	Multiple R	0.38872
R Square	0.032337	0.769389	R Square	0.151103

Table 8e: Non-Linear Relationship between CBR_v and Ultimate Bearing Capacity for Square Footing

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	54.19177	1.893412	28.62123	8.01×10^{-16}
B_{sf}	0.021536	0.012731	1.691568	0.108976
$(B_{sf})^2$	-2.7×10^{-5}	1.75×10^{-5}	-1.54221	0.141432

Table 8f: Result of ANOVA of non-linear regression

Source of Variation	Sum of Squares	Degree of freedom	Mean Sum of square	F-value	P-value
Regression	11.6202	2	5.810101	1.512995	0.248466
Residual	65.28227	17	3.840133		
Total	76.90247	19			

Table 9 A comparison of this with previous studies on the relationship between CBR_v , Ultimate Bearing Capacity for Square footing and Ultimate Bearing Capacity for Circular footing

Equations	Source/Reference	Correlation coefficient	Coefficient of Determination	Condition and type
$q_u = 172.6\ CBR_v - 601$	Razouki et al.(2005)	0.944		
q_u (kPa)= 68.89 CBR_v or $CBR_v = 0.01452q_u$	Razouki et al. (2005)			
$CBR_v = 0.09998\ q_u$	This study	0.883063	0.7798	Soaked and Circular footing
$CBR_v = 0.002088q_u + 26.95893$	This study	0.143628	0.020629	Soaked and Circular footing
$CBR_v = 0.020767q_u - 3.3 \times 10^{-5}q_u^2 + 24.81132$	This study	0.339228	0.115076	Soaked and Circular footing
$CBR_v = 0.021659\ q_u$	This study	0.877148	0.769389	Unsoaked and Square footing
$CBR_v = 0.002491q_u + 56.75745$	This study	0.179826	0.032337	Unsoaked and Square footing
$CBR_v = 0.021536q_u - 2.7 \times 10^{-5}q_u^2 + 54.19177$	This study	0.38872	1.51103	Unsoaked and Square footing

CONCLUSIONS

Based on the study and the findings, the following key conclusions can be drawn as follows:

a) no significant differences between the engineering index and engineering properties of the S_{se} at a 95 % confidence level ($F_{19, 140} = 0.677$ and $p = 0.837$, which indicates that $F_{19, 140} < 1.661$ and $p > 0.05$).
b) The relationship between soaked and unsoaked CBR_v revealed that unsoaked CBR_v are higher than soaked CBR_v
c) the relationships between soaked and unsoaked CBR_v are directly proportional and significant at a 95 % confidence level ($p = 1.88 \times 10^{-33}$ and 7.968×10^{-32} which are less than 0.05).
d) the correlation coefficients and Coefficients of determination between LL and CBR_v were 0.99121 and 0.9825, and 0.991146 and 0.98237 for soaked and unsoaked CBR_v , respectively, which indicate a very good relationship
e) the relationship between the ultimate bearing capacity of the soil for circular footing and soaked CBR_v revealed that linear regression without intercept is more reliable than linear regression with intercept;
f) non-linear relationship between the ultimate bearing capacity of the soil for circular footing and soaked CBR_v established that the regression coefficients are with $p > 0.05$, which indicates that non-linear regression coefficients are insignificant, but the intercept of $p< 0.05$ is significant

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