Modelling of Typical Square Footing for Sustainable Infrastructure

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Abstract: *This study investigated the empirical modelling of a typical square footing with a focus on predicting bearing capacity. To achieve the aim of the study, soil samples were collected from identified construction sites withjn Obafemi Awolowo University, Ile-Ife, Osun state, Southwestern Nigeria. The samples were subjected to preliminary and geotechnical engineering tests, using standard procedure. The values of bearing capacity (square footing) of the soils were also computed using Terzaghi;s bearing capacity equation. Subsequently, Microsoft Excel tool was used to develop multilinear regression bearing capacity model models by relating computed bearing capacity values and experimental values of selected soil properties. Validation of the models showed moderate predictive capability, confirming the practicality of simplified approaches for preliminary design. The results demonstrate that soil gradation and plasticity significantly affect load-bearing behaviour. The findings highlight the importance of combining experimental data with numerical tools to improve accuracy in geotechnical design. The study contributes to sustainable infrastructure development by providing cost-effective and reliable methods for foundation analysis. Ultimately, the integration of statistical modelling offers a robust framework for optimising shallow foundation performance in heterogeneous soil conditions.*

Keywords: Bearing capacity, footing, foundation, modelling, sustainable development

INTRODUCTION

The design and analysis of shallow foundations have evolved significantly with advancements in geotechnical engineering and computational modelling. Classical theories such as Terzaghi's bearing capacity theory (Terzaghi *et al*., 2010) laid the foundation for understanding soil–foundation interaction. However, these methods often rely on simplifying assumptions that may not adequately capture soil heterogeneity. Recent studies emphasise the use of numerical methods such as the Finite Element Method (FEM) for more accurate predictions (Brinkgreve *et al*., 2012). FEM allows for modelling complex soil behavior, including nonlinearity and stress-dependent properties. According to Das (2013), integrating laboratory test results into numerical models enhances predictive reliability. Soil index properties such as Atterberg limits and grain size distribution play a critical role in determining engineering behaviour (Budhu, 2015). Mitchell and Soga (2014) noted that plasticity significantly influences compressibility and shear strength. Similarly, Lambe and Whitman (2011) established relationships between soil structure and mechanical response.

Several researchers have explored regression-based models for predicting bearing capacity of soil (Adunoye & Agbede, 2013; Adunoye & Agbede, 2014; Adunoye & Agbede, 2017). Recently, some researchers explore the option of statistical modelling the bearing capacity of shallow foundations for timely and cost-effective determination of bearing capacity. In most of these attempts, index properties were explored as possible predictors of bearing capacity of soil (Adunoye & Agbede, 2013; Adunoye & Agbede, 2014; Adunoye & Agbede, 2017).. Bowles (2011) demonstrated that empirical correlations can provide quick estimates when detailed testing is unavailable. Studies by Phoon and Kulhawy (2016) highlighted the importance of probabilistic approaches in accounting for soil variability.Compaction characteristics are also crucial in foundation performance. According to Holtz *et al*. (2011), optimum moisture content and maximum dry density directly affect soil stiffness and load-bearing capacity. Studies by Head (2014) further confirm that well-graded soils exhibit improved engineering performance due to better particle interlocking.

Advancements in constitutive modelling, such as the Hardening Soil Model, have improved simulation accuracy (Schanz *et al*., 2019). These models account for stress history and nonlinear stiffness, making them suitable for realistic geotechnical problems. Additionally, machine learning techniques are emerging as powerful tools for predicting soil behaviour (Zhang *et al*., 2020).In tropical regions, soil variability poses significant challenges. Research by Oyediran and Kalejaiye (2011) highlights the influence of climatic conditions on soil properties. Furthermore, Akinmusuru (2018) emphasised the need for localised studies to improve foundation design in Nigerian soils.Recent works on modelling of bearing capacity of soil increasingly advocate for integrated approaches combining laboratory testing, numerical modelling, and statistical analysis. This holistic approach improves accuracy, reduces uncertainty, and supports sustainable infrastructure development.

MATERIALS AND METHODDS

Materials and Equipment

The main material used for the study is soil samples which were collected from identified construction sites. The tools and equipment used are those for sample collection and laboratory analysis (moisture content determination, particle size analysis, specific gravity test, Atterberg limits determination, compaction test, direct shear test). All equipment was available at the Geotechnical Engineering Laboratory (referred to as the Laboratory) of the Department of Civil Engineering, Obafemi Awolowo University (OAU), Ile-Ife, Osun state, Southwestern Nigeria.

Methods

A total of twenty (20) soil samples were collected from 20 locations (see Table 1) across five different construction sites on OAU campus. The method of sampling adopted was disturbed sampling, and the depth of sampling ranged between 0.5 m and 1.0 m. About 25 kg of each sample was collected using a hand auger, kept in waterproof bags, sealed, properly labelled and immediately transported to the Laboratory. At the Laboratory, representative samples were taken for the determination of natural moisture content, while the remaining soils were air-dried for subsequent laboratory analysis.The following preliminary and geotechnical tests were conducted on the soil samples, using standard procedure as outlined in BS 1377 (1990): particle size distribution, specific gravity, Atterberg limits, compaction, and direct shear.

The shear strength parameters (cohesion, *c* and angle of internal friction, ϕ) obtained from the direct shear tests were employed in Terzaghi's bearing capacity equation (1) for square footing (Terzaghi *et al*., 2010) to compute the bearing capacity of the soil samples for square footing. The values of bearing capacity factors were obtained from Das (2016) using the corresponding values of angle of internal friction obtained from the direct shear tests. According to Das (2015), the factor of safety should be at least 3 in all cases. Therefore, a factor of safety value of 3 was adopted. Unit width and unit depth were also adopted.

Table 1 : Description of sampling points

Sample ID	GPS Location	
	Latitude	Longitude
Sample 1	7.520313	4.526961
Sample 2	7.520606	4.526984
Sample 3	7.520353	4.527216
Sample 4	7.520581	4.527261
Sample 5	7.51066	4.518028
Sample 6	7.510689	4.517968
Sample 7	7.510296	4.518022
Sample 8	7.510168	4.518014
Sample 9	7.509398	4.518783
Sample 10	7.509263	4.519017
Sample 11	7.509494	4.518926
Sample 12	7.509437	4.519325
Sample 13	7.51327	4.526631
Sample 14	7.51332	4.526752
Sample 15	7.513296	4.526933
Sample 16	7.513701	4.527133
Sample 17	7.511679	4.526109
Sample 18	7.51199	4.526087
Sample 19	7.511802	4.526216
Sample 20	7.511846	4.526463

$Q_u = 1.3N_c + \gamma D N_q + 0.4\gamma B N_\gamma$ (1)

Where,

Q_u = ultimate bearing capacity (kN/m^2);

c = cohesion (kN/m^2);

γ = effective unit Weight of soil (kN/m^3);

D = depth of footing (m);
B = width of footing (m);

Nc, Nq and Nγ are bearing capacity factors,which depend on the values of angle of internal friction.
A model was developed by using Microsoft Excel to predict the bearing capacity of typical square footing. The model was based on multiple regression analysis that related measured (computed) bearing capacity values to selected soil index properties. The predictor variables considered included liquid limit (LL), plastic limit (PL), plasticity index (PI), particle size parameters (D_{10}, D_{30}, D_{60}, C_c, C_u), and specific gravity (Gs). These properties were chosen because they capture the fundamental aspects of soil behaviour, including plasticity, gradation and mineralogical composition, all of which have a direct bearing on strength and compressibility (Bowles, 1997; Das, 2010).
A key consideration in developing the regression models was the need to avoid multicollinearity, that is, to avoid the use of two or more properties that are interrelated (either empirically or mathematically) in the development of models (Mitchell & Soga, 2005).

The regression models were evaluated using the coefficient of determination (R^2), adjusted R^2, root mean square error (RMSE), and 5-fold cross-validation root mean square error (CV RMSE). This ensured that model performance was assessed not only on fit to the training data but also on predictive robustness.

RESULTS AND DISCUSSION

Results of Preliminary and Geotechnical Tests

The natural moisture content of the tested soil samples ranged between 2.31 % (Sample 4) and 7.28 % (Sample 19), with an overall mean value of 4.5 %. These relatively low values indicate that the soils within the study area are generally in a dry to slightly moist state at the time of sampling.From a geotechnical standpoint, the natural moisture content plays a critical role in determining the in-situ condition of the soil. Soils with low natural moisture content are typically unsaturated, leading to strength and stability, low compressibility and settlement.From the particle size distribution tests and resulting curves, the following data range was obtained: effective size, D_{10} = 0.17 mm – 0.37 mm; intermediate size, D_{30} = 0.24 mm – 1.01 mm; characteristic size, D_{60} = 1.34 mm – 3.65 mm; coefficient of uniformity, C_u = 5.84 – 16.79; coefficient of curvature, C_g = 0.22 – 1.40

These results suggest that most samples exhibit well-graded behaviour since the majority have $C_u > 4$, especially for sandy soils (Head, 1986). However, some samples show $C_c<1$, indicating localised gap-graded soils where intermediate-sized particles are less represented.Well-graded soils typically offer higher interparticle interlock, resulting in increased friction angle (ϕ) and consequently higher ultimate bearing capacity for shallow foundations (Terzaghi *et al.*, 1996). Conversely, poorly graded or gap-graded soils may exhibit slightly lower shear strength and require higher compaction for stability.
Soils with higher proportions of coarse fractions (larger D_{10} and D_{60}) and low fines content are generally highly permeable, allowing rapid dissipation of pore-water pressures under footing loads. This is advantageous for drained foundation conditions, which simplify numerical modelling.

The specific gravity of the soil samples ranged from 2.38 to 2.65, with a mean value of 2.50. These values fall within the expected range for siliceous sandy soils dominated by quartz minerals, confirming that the soil lacks significant organic content or heavy mineral inclusions (Das, 2013).The descriptive statistics of the Atterberg limits are presented in able 2. The Atterberg limits of the tested samples indicate the following ranges: Liquid Limit, LL = 18.40 % – 45.64 %; Plastic Limit, PL = 13.47 % – 32.05 %; Plasticity Index, PI = 3.09 % – 31.06 %. These values classified the soils primarily as low- to medium-plastic silts (ML) and clays (CL) under the Unified Soil Classification System (USCS).

Compaction results showed that optimum moisture content (OMC) values ranged between 11.76 % and 22.00 %, with a mean value of 16.2 %. The maximum dry density (MDD) values varied between 1531.4 kg/m³ and 1877.4 kg/m³, with an average of 1763.6 kg/m³. These values fall within the expected range for fine-grained soils with a moderate amount of silt and clay fractions. The OMC values suggest that the soils require a moderate level of water addition to achieve maximum dry density under standard compactive effort. This is typical of silty-sand to clayey-sand soils, where water facilitates lubrication of particles and reduces inter-particle friction up to an optimum level (Das, 2013).

From a design perspective, the relatively consistent OMC and MDD values indicate that the soils within the study area are reasonably uniform in their compaction behaviour.

Table 2 Descriptive statistics for Atterberg limits

Statistics	LL (%)	PL (%)	PI (%)
Min	18.39	13.47	3.09
Max	45.64	32.05	31.06
Mean	30.8	19.96	10.84
Median	30.74	19.35	10.83
Mode	36.63	13.94	5.22
Std	9.38	5.81	7.24
Skewness	0.12	0.68	0.12
Kurtosis	1.66	-0.71	1.68
N	20	20	20

Results of Direct Shear Test and Modelling

The angle of internal friction values ranged from 28°–38° which is typical of medium-dense silty to sandy soils. Also, cohesion values ranged between 10 kPa and 30 kPa, supporting the fact that the samples are low plastic clays (Das, 2011).

The bearing capacity result shows that, for many of the tested samples, the soils are suitable for supporting shallow square footings under typical light to moderate loadings, provided that appropriate compaction and moisture control are achieved in the field.

From the results, the model 1 which combined LL, D_{10}, C_u, and Gs achieved the highest R^2 (0.546) and the lowest cross-validation RMSE (715.08), indicating that it provided the best balance between accuracy and generalizability. The adjusted R^2 values (0.407–0.425) confirm that although the models explain a moderate portion of the variability in bearing capacity, their predictive performance is meaningful in the context of preliminary design.The moderate R^2 values also highlight that soil index properties alone cannot fully capture the complexity of bearing capacity, as other factors such as soil fabric, density state, stress history, and degree of saturation contribute to variability but were not included in this regression framework. Nonetheless, the model 1 demonstrates the feasibility of using independent index parameters to estimate bearing capacity with reasonable accuracy, thereby providing a quick and practical tool for geotechnical foundation design.The Excel-based model is for the study area, and thus valid and can therefore serve as a valuable aid in practice, as it allows fast estimation of bearing capacity once soil index tests are performed.

CONCLUSION

This study demonstrates that numerical modelling, when combined with experimental soil data, provides a reliable approach for evaluating the performance of shallow foundations. The integration of soil index properties and regression-based models enables moderate prediction of bearing capacity. The results confirm that soil properties such as plasticity and gradation significantly influence foundation performance.The developed models, although moderately predictive, offer practical tools for preliminary design and decision-making. The study supports the adoption of integrated geotechnical approaches to enhance safety, efficiency, and sustainability in foundation engineering.

Table 3: Model description

Model ID	Model	R^2	Adjusted R^2	Sample RMSE	5-Fold CV RMSE
1	BC= -3010.047 - 58.177LL + 2921.115G_s -2904.398D_{10} - 25.769Cu	0.546	0.425	610.271	715.08
2	BC = -3091.572 - 58.428LL + 2882.308G_s -2128.892D_{10} - 109.147D_{60}	0.546	0.424	610.547	
3	BC= -10208.244 - 73.057PI + 5572.407G_s -2616.180D_{10} - 88.530C_u	0.532	0.407	620.026	763.71

4	BC= -10656.914 - 74.202PI + 5398.044G_s - 61.418C_u	0.502	0.408	639.546	833.26
5	BC= -5826.2 - 57.511LL + 3849.337G_s - 238.923C_u	0.529	0.44	622.004	

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