2nd International Civil Engineering Conference (ICEC 2020)
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Development of Statistical Model to Predict the Shear Failure of Soil beneath Shallow Foundation

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ABSTRACT
A statistical model of shear failure of soil beneath modelled shallow foundations in A-7-5 and A-7-6 clay soils was developed in this study. From the compaction result, the MDD is between 1.60 kg/m^2 and 1.90 kg/m^2 and OMC is between 19% and 26%. The shear failure parameters (cohesion, C and angle of internal friction, ∅) were obtained from Mohr circle failure envelope using triaxial compression test results. The cohesion obtained ranged between 36.6 kN/m^2 and 59.6 kN/m^2, while the angle of internal friction ranged between 5.80 and 16.90. Shear failure models were obtained using MATLAB and SPSS software. A general model f(x, y) = x +b*tan(y), with b = - 0.214 (-1.548, 1.112), R^2 = – 1.011, standard error = 4535; and τ = 0.020 +1.540∅ +0.994C, with correlation coefficient, R^2 = 0.999 and standard error of 0.053, were obtained using MATLAB and SPSS softwares respectively

Keywords: *Bearing Capacity, Shallow foundation, Shear failure, Soil and Statistical model*

1 INTRODUCTION

Modelling is a simplification of real-world problems which is an integral part of all geotechnical engineering analysis and design process. Modelling could include making predictions of stresses induced by the interactions of civil engineering systems with the soil, displacements as a result of imposed loads, development of pore water pressures and their effects on the stability, analyzing the stability of slope and bearing capacity of shallow and deep foundation. Statistical model can be defined as a form of mathematical model, which embodies a set of assumptions concerning the generation of some sample data, and similar data from a large population. Complex problems may be analyzed using numerical techniques such as finite difference, finite element, and discrete element methods. Traditional methods used in geotechnical analysis and design make use of the behaviour and properties of soils such as strength, stiffness, and flow characteristics and its interactions with geotechnical systems (Pradeep, 2009).

Soil plays vital role to support different type of structures like foundations, buildings, roads, railway lines and pipelines. Accurate investigation of the geotechnical properties can enhance a good design of foundation to support the structure (Too, 2012). Therefore, the geotechnical properties of soil on which a superstructure is to be constructed must be well understood in order to avoid superstructure and foundation failures (Omotoso *et al.*, 2011).

A foundation or foundation footing is a part of the structure which is in direct contact with soil for safe transmission of the loads. Foundation engineering deals with both the ability of the soil to carry the applied load and the structural design of the foundation which transmits the load to the soil. Considering the depth and breadth of foundation, the depth of the foundation (D_f) which is the vertical distance between the ground surface and base of foundation. The width or breadth of the foundation (B_f) is the shortest dimension of the foundation in plan depending on the depth-width ratio, foundation is classified into shallow and deep foundation. There are different types of shallow foundations namely; Spread footing, isolated footing or individual footing to support a single column, Combined footing to support two or more columns in a row, Continuous footing or strip footing to support a wall and Mat or raft foundation to support all the columns and walls together (Sitharam, 2013). Generally, the depth of shallow foundation is less than or equal to its width ($D_f \leq B_f$) (Terzaghi, 1943) but in practice, it has been modified as $D_f \leq$2B_f for shallow foundations (Sitharam, 2013). Failure of shallow foundation is due to; excessive load on the foundation, that is, the application of load greater than the bearing capacity of the soil causing shear failure and excessive settlement of underlying soil.

There are three specific modes or patterns of soil failure associated with soil type, foundation size and depth. They are general (Terzaghi, 1943), local and punching shear failure (Vesic, 1973). General shear failure can be defined as a diagonal slip surface movement of a well-defined wedge beneath a foundation that initially forces the side edges of the footing downward into the soil surface, followed by an upwards movement to the ground surface. This causes the soil structure adjacent to the footing to hump above ground level. It is commonly encountered in stiff clays and dense sand underlying shallow foundation in which the ultimate strength of soil is associated with the entire surface of sliding before the structure underlying soil is affected by excessive movement. It is characterized by large bulging or eave around the foundation column (Arindam and Shreyoshi, 2014). General shear failure will typically occur within soils that possess a brittle-type of stress-strain relationship (Terzaghi, 1943) Figure 1 shows a foundation undergoing general shear failure and a load-settlement relationship of the failure.

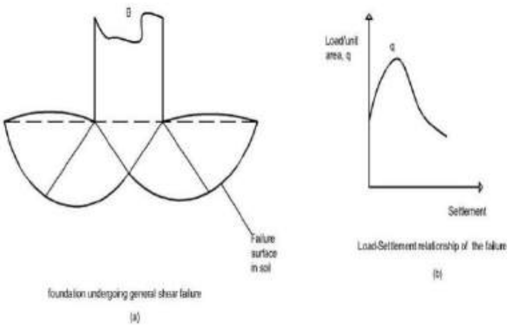

Figure 1: General shear failure (Das, 2007)

Local shear failure is encountered mostly in sandy soil or medium dense sand and medium stiff clay type of soils underlying shallow foundation. Local shear failure is characterized by absence of distinct peak in pressure against foundation settlement. Local shear failure is associated with progressive failure surface that extends to ground surface once bearing capacity has been reached. The bulging or eave around the foundation is less than in general shear failure (Das, 2007). Punching shear failure occurs in loose sands and soft clays types of soil underlying deep foundation. It involves failure of reinforced concrete slab that have been subjected to high local forces especially in flat slab structures and usually happens at column support points (Das, 1999).

Investigation into the frequent building collapse shows among other things that most of the structural members fail to bond due to stress, strain or shear. In Nigeria today, building failure has been categorized to be caused by factors including design fault (50%), faults on construction site (40%) and product failure (10%) (Oyewande, 1992; Ayininuola and Olalusi, 2004). Building collapse can also be traced to weak foundations, inefficient or sub-standard building materials, inexperience or lack of requisite expertise of builders or workers, excessive loads leading to intolerable settlement and inadequate bearing capacity of the underlying strata and lack of soil test. The focus of the study is to develop a statistical model for predicting the shear failure of soil beneath shallow foundation using soil collected from borrow pits in Lapai-Gwari, a suburb of Minna, Niger State.

METHODOLOGY

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1.1 SOIL

Disturbed samples were collected at depths of 0.5 m, 1.0 m and 1.5m at three selected points in 3 borrow pits in Lapai-Gwari, a suburb of Minna, Niger State were used for the experiments.

1.2 METHODS

Laboratory experiments were carried out to determine the geotechnical properties of soils. These properties include: specific gravity, sieve analysis, Atterberg limits, Soil compaction and Shear Strength or shear failure parameters; Cohesion (C) and Angle of internal friction (∅) of test soil. A statistical model to predict the shear failure of soil under axial load had been developed using MATLAB software and Statistical Package for the Social Science (SPSS) software. Comparison of the models obtained from the MATLAB and SPSS had been made.

Laboratory investigation

Preliminary and detailed investigations were carried out to obtain the geotechnical properties of the soil samples that were collected.

Moisture content test

Moisture content is the ratio of the weight of water to the weight of dry soil. It is measured in percentage and oven drying method had been applied in accordance with BS 812- 109: (1990).

Specific gravity test

It is the ratio of the weight in air of a given volume of dry soil to the weight of equal volume of distilled water at 40C. The particles that passed through 5mm BS sieve were used to obtain the specific gravity with the help of density bottle in accordance with BS 1377, (1990).

Sieve analysis

Sieve analysis to determine the gradation of the samples was carried out in accordance with ASTM D422-63 (2007); Raj, (1995).

Atterberg limit tests

The liquid limit is the moisture content that defines where the soil changes from a plastic to a viscous fluid state. The procedure had been carried out in accordance with BS 1377:2 (1990). The plastic limit is the water content in percent at which a soil can no longer be deformed by rolling into 3.2 mm diameter threads without crumbling. The plastic limit is the moisture content that defines where the soil changes from semi-solid to a plastic (flexible) state (Raj, 1995).

Plasticity Index is the numerical difference between liquid limit (LL) and plastic limit (PL). It indicates the degree of plasticity of the soil. The greater the difference between liquid and plastic limit, the greater is the plasticity of the soil. A cohesionless soil has zero plasticity index. Hence it is called non-plastic (Murthy, 2002).

Compaction Test (Standard Proctor)

Soil compaction test had been carried out to increase the density of the soil under the specification of ASTM D698 – 12.

Triaxial Shear Test

Triaxial shear test to determine the cohesion and angle of internal friction of samples were done according to the specification of BS 1377 Part 1-8 (1990).

Analytical Investigation

The shear failure parameters (C and φ) of soil sample were obtained using the triaxial test. The influence of the geotechnical properties on shear failure parameters was thereafter inferred. Consequently, the ultimate bearing capacity of the samples in relation to load-settlement was calculated.

The magnitude of settlement had been examined using the following Equations, for normal consolidated clay:

$$S_c = \frac{C_c H_0}{1+e_0}\log\frac{\sigma_{v0}+\Delta\sigma_v}{\sigma_{v0}} \qquad (1)$$

For over consolidated clay

Case I: $\sigma_{v0} + \Delta\sigma_v < \sigma_p$

$$S_c = \frac{C_r H_0}{1+e_0}\log\frac{\sigma_{v0}+\Delta\sigma_v}{\sigma_{v0}} \qquad (2)$$

Case II: $\sigma_{v0} + \Delta\sigma_v > \sigma_p$

$$S_c = \frac{C_r H_0}{1+e_0}\log\frac{\sigma_p}{\sigma_{v0}} + \frac{C_c H_0}{1+e_0}\log\frac{\sigma_{v0}+\Delta\sigma_v}{\sigma_p} \qquad (3)$$

Where

S_c–Consolidation settlement

e_o – void ratio

σ_{vo}–surcharge

C_r – recompression index

σ_p– pre-consolidation stress

C_c – compression index

H_0 – Thickness of the clay layer

Terzaghi derived Equation for ultimate bearing capacity of strip footing as:

$$q_{ult} = C^l N_c + D_f \gamma N_q + 0.5 B_f \gamma N_\gamma \qquad (4)$$

Where:

q_{ult} - soil bearing pressure (kN/m^2)

C^1 - effective cohesion of soil below the foundation (kN/m^2)

D_f - depth of footing (metres)

γ - unit weight of soil (kN/m^3)

B_f - width of footing (metres)

N_c,N_q,N_γ– Non-dimensional bearing capacity factors from chart (Vesic, 1973)

A statistical model to predict the shear failure of soil under axial load had been developed using MATLAB and Statistical Package for the Social Science (SPSS) software. The shear failure parameters (the cohesion and angle of internal friction) and the shear failure had been inputted into the workspace. The analysis had been done based on the data and result had been displayed. It showed the models and its level of accuracy had been checked. The correlation coefficient (R) and R2 should tend to unity (1.000) while the standard estimated error of tends approximately to zero (0).

2 RESULTS AND DISCUSSION

The natural moisture contents of the soil obtained ranged from 19.48% to 26.81%.The specific gravity of the soil ranged from 1.86 to 2.75. The tropical iron- rich laterite, as well as some lateritic soil has its specific gravity between 2.75 and 3.0 and could be higher, sand particles composed of quartz have ranged of 2.65 to 2.67, inorganic clays ranged from 2.70 to 2.80, soil with large amount of organic matter or porous particles have specific gravity below 2.60 and some low as 2.00. From the result obtained, the soil contained large amount of organic matter with specific gravity below 2.60. Increase in specific gravity can increase the shear strength parameters thereby increasing the shear strength of the soil (Roy and Dass, 2014).

For the sieve analysis, total weight of dry soil sample used was 300g. The percentage passing sieve 0.075 mm is greater than 50% for all the samples used. The plastic limit and liquid limit were determined to get the values of the plasticity index, PI which is useful in the classification of the soils. The soils are classified as A-5 and A-7-5 soil based on AASHTO. Observation showed that plasticity of a soil increases linearly with the percentage of the clay-sized fraction (Skempton, 1953). Plasticity and cohesion reflect soil consistency and workability of the soil (Ersoy et al., 2013). The grading curve and compaction of the sample from a test location are shown in Figures 2 and 3.

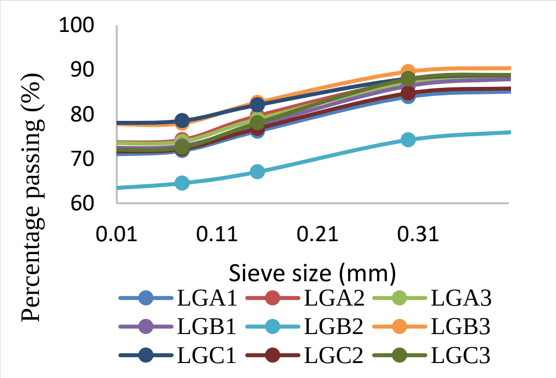

Figure 2: Grading curve of samples

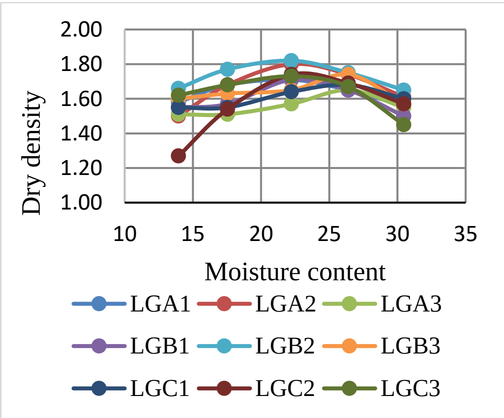

Figure 3: Sample compaction curve

Soil compaction increases shear strength, bearing capacity, density and stability of the soil thereby reducing the void ratio, porosity, permeability, compressibility and settlement of the soil (Prakash and Jain, 2002). The compaction energy applied is controlled by MDD which ranged from 1.60 to 1.90 kN/m^2 and the moisture content is controlled by the OMC which ranged from 19 to 26%. The optimum water content ranges for different soil types; for sand (6 to 10%), silty sand (8 to 12%), silt (12 to 16%) and clay (14 to 20%). The results of the triaxial tests for the samples are shown in Figures 4 – 6.

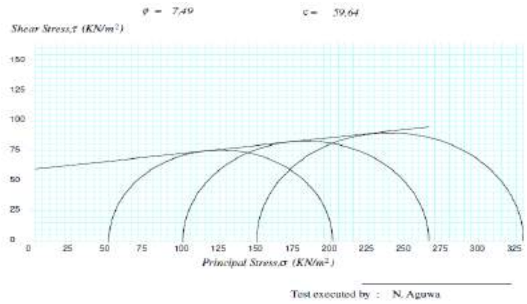

Figure 4: Mohr circle diagram for LGA samples

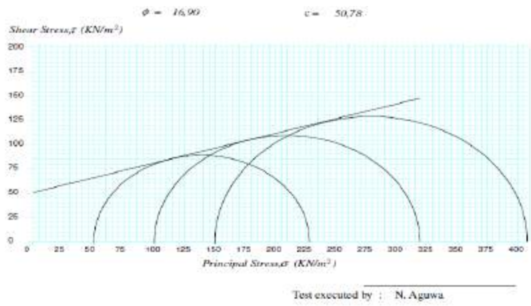

Figure 5: Mohr circle diagram for LGB samples

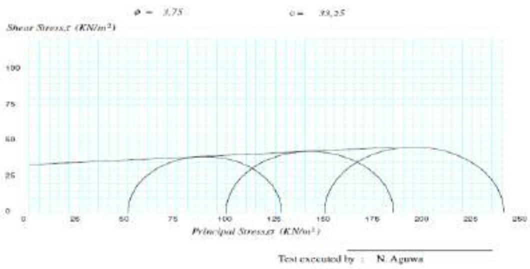

Figure 6: Mohr circle diagram for LGC samples

Cohesion value depends on whether the soil has moderate or high plasticity value. However, its value ranges from 10 – 100kPa for moderate plastic clay such as fire clay and Kaolinite and around 200 kPa for high plastic clay like bentonite. From the result obtained, the cohesion is within the moderate plastic value. The shear failure of samples and its parameters (cohesion and angle of internal friction) are shown in Figures 5-7.

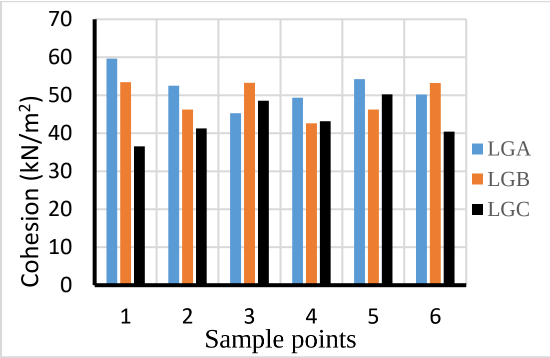

Figure 5: Cohesion of samples from clusters A, B and C

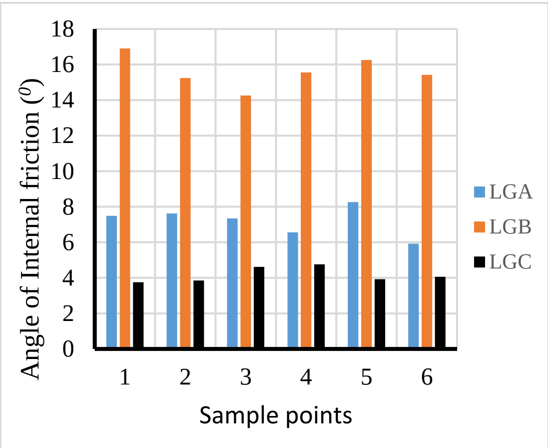

Figure 6: Ang. of Inter. friction of samples from clusters A, B and C

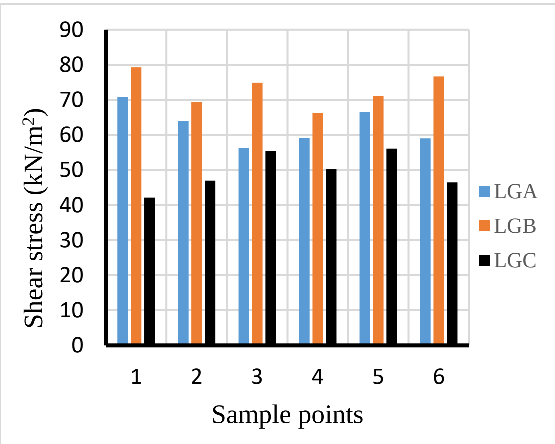

Figure 7: Shear stress of samples from clusters A, B and C

The set of data used for Figures 5-7, the cohesion (C) and angle of internal friction (Ø) obtained from the Mohr circle diagrams was used to determine the shear failure of the soil using the shear failure of the soils using a base/pivoter normal stress to the failure plane of 85 kN/m^2.

$$\tau = C + \sigma \tan \emptyset \qquad (5)$$

where;

τ – Shear failure of the soil along the failure plane (kN/m^2)

C - Cohesion of the soil (kN/m^2)

σ – Normal stress to the failure plane (kN/m^2)

The accuracy/suitability of the models were checked and the result shown in Table 6.

Table 6: Model summary

Model	Correlation coefficient R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0.862[a]	0.742	0.726	5.76640
2	0.999[b]	0.999	0.999	0.05324

a – Predictors: (Constant), Ø

b – Predictors: (Constant), C, Ø

c – Dependent Variable: τ

Ø - Angle of internal friction (°)

These data were inputted into statistical Package for the social science (SPSS) software. It was run through stepwise regression and two models were developed.

$$\text{Model 1: } \tau = 44.737 + 1.887\emptyset \qquad (6)$$

$$\text{Model 2: } \tau = 0.020 + 1.540\emptyset + 0.994C \qquad (7)$$

The accuracy/suitability of the models were checked and the result shown in Table 6. In order to determine the suitable model for the shear failure of soil beneath shallow foundation, correlation coefficient, R Square and Adjusted R Square should tend to “1” or approximately “1”, while the standard error of the estimate would tend to “0”. From Table 6, Model 2 is a superior model. Therefore, Model 2 ($\tau = 0.020 + 1.540\emptyset + 0.994C$) can be used to predict the shear failure of soil beneath shallow foundation.

Same data was inputted into MATLAB and the model obtained was less suitable for predicting the shear failure of soil beneath shallow foundation because the requirement was not met. Results obtained on MATLAB

General model: f(x, y) = x + b* tan(y); Coefficients (with 95% confidence bounds): b = - 0.214 (-1.548,1.12); Data: Z vs X,Y ; Goodness of fit: R Square: -1.0434; Adjusted R Square: -1.0434 ; Standard error (SSE): 4535

3 CONCLUSION

From the study of the development of statistical model to predict the shear failure of soil beneath shallow foundation that had been carried out, the following conclusions were drawn;

The index properties of the soils characterized and classified the samples as A-5 and A-7-5 corresponding to OL-CH-ML-OH according to AASHTO and USC system respectively. The specific gravity of the soil ranged from

1.86 to 2.75. Increase in specific gravity of the soil may increase the shear failure parameters (cohesion and angle of shearing resistance) relating to the strength of the soil beneath the foundation.

The work further revealed samples MDD ranged between 1.60 and 1.90 kg/m^2 with the OMC of 19 - 26%. The cohesion of the soil ranged from 36.56kN/m^2 to 59.64 kN/m^2 while the angle of internal friction ranged from 3.750to 16.900.

The statistical model developed can predict the shear failure of soil. SPSS software produced a superior model: $\tau = 0.020 + 1.540\emptyset + 0.994C$ with a more convergent correlation coefficient of $R = 0.999$ and the standard error of 0.053. MATLAB package produced a model" b = -0.214 (-1.548, 1.12) with a more divergent $R^2 = -1.043$, and standard error = 4535.

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