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Finite Element Analysis of Raft Foundation on Expansive Soils

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ABSTRACT

Load-bearing response of Raft or mat footing is affected by symmetry, load concentration and textural composition of the underlying or surrounding soil. Raft or mat foundation is a combined footing that covers the entire area beneath a structure and supports all walls and columns. This work presents Finite Element Analysis of raft foundation on expansive clay. Plaxis 3D computer software was used for the analysis. The result was compared with the classical Mohr-Coulomb analysis. The free swell index (*FSI*) of test clay samples collected from 0 – 1.5 metres depth ranged from 105.95 to 118.18%, which classified it under highly expansive clay. The deformation of model raft foundations were estimated at three stages namely; the initial stage, the excavation stage and the loading stage. The results revealed that the deformation of raft footing was higher at the excavation stage with a value of $4.55*10^{-3}$m, when compared with $615.15*10^{-6}$m recorded at the initial stage under the same load. With the introduction of model raft, the total deformation of the footing at this critical stage (excavation) reduced to $606.95*10^{-6}$m. Under the same threshold pressure and load-factor difference, the deformation obtained using the classical Mohr-Coulomb model is $18.442*10^{-3}$m, which is higher than the $601.01*10^{-6}$m obtained using the finite element analysis. Finally, the loading rate efficiency of modelled raft foundation using Finite Element Analysis is 10.3% higher than that of Classical Mohr-Coulomb model. Raft foundation analyzed using Finite Element Analysis is therefore recommended especially where the underlying strata is or has similar properties as that of expansive clay.

Keywords: *Expansive Clay soil; Finite element analysis, Load-bearing response; PLaxis 3D, Raft foundation,*

1 INTRODUCTION

Clays, according to Johnson (1969) are the finest grained soils. The upper limit on grain size is 0.002mm, but most of the clay particles will even be smaller. Clay soil pose a great hazard in regions with pronounced wet and dry season. The cycle of wetting and drying annually causes clay soil to shrink and swell each year (Yenes *et al*., 2012)

Raft foundations are sometimes referred to as raft footings (Jawad, 1998). They are formed by reinforced concrete slabs of uniform thickness that cover a wide area, often the entire footprint of the building (Jawad, 1998). Raft foundations are widely used in supporting structures for many reasons such as weak soil conditions or heavy column loads (Pusadkar and Bhatkar, 2013).

The use of Finite element procedures has gained wide application in engineering analysis (Kraskiewicz *et al.,* 2015). With its effectiveness, its use or that of the advanced version of it, is expected to increase significantly in years to come. The procedures are employed extensively in the analysis of solid structures. It is also used in the analysis of heat transfer and fluids and in virtually in every field of engineering analysis (De-Weck and Kim, 2004).

Many studies have been conducted on the analysis of deep and shallow foundation. Conte *et al*. (2013) worked on the Progressive failure analysis of shallow foundations on soils with strain-softening behaviour. In the said work, the authors discovered that a finite element approach in which a non-local elasto-visco-plastic constitutive model in conjunction with the Mohr–Coulomb yield function is incorporated, can be used to predict the response of strip footings resting on soils with strain-softening behaviour. This behaviour is simulated by reducing the strength parameters by increasing the accumulated deviatoric plastic strain produced through the repeated loads.

Al-Zaidee *et al*. (2015) used finite element to modify Winkler model for raft foundation supported on dry granular soils and in an attempt to modify traditional Winkler model to consider the shear forces between adjacent soil prisms into account in computing subgrade reactions and bending moments in raft foundations. Two finite element soil simulations were considered in their study; Winkler simulation was adopted in the first model, while soil mass was simulated with brick finite element in the second model.

According to SaadEldin and El-Helloty (2014), opening and type of soil have important effect on settlement of soil and deformation of raft foundation, especially when the raft is analysed using PLAXIS 3D analyser.

With the recent increase in building collapse in many part of Nigeria, which has led to loss of lives and properties, which among other thing has been traced to structural, construction or member failure including foundation. The foundation failure on expansive clay soil properly analyzed using Plaxis 3D analyzer and compared with Mohr-Coulomb model, a more resourceful approach of raft foundation analysis would be evolved (Vardoulakis, 1998; Shield, 1955; Mogi, 1971; Mogi, 1974; Labuz and Zang, 2012; Colmenares and Zobach, 2002; Labuz and Bridell, 1993).

2 MATERIALS AND METTHOD

2.1 MATERIALS

Soil: The soil used in this investigation was collected using the disturbed sampling technique at depths of 0 meter, 1 meter and 1.5 meter from borrow pits around Birgi Village, a suburb of Minna, Niger State, Nigeria. The soil samples were carefully packaged and transported to soil Mechanics /Geotechnics Laboratory, Federal University of Technology, Minna for detailed investigation.

Plaxis 3D software: The Finite element analysis of model raft foundation in clay was done by using PLAXIS 3D 2018 software depending with correlated compatibility with Mohr-Coulomb model. All the data necessary for the Mohr-Coulomb model were explored. These parameters with their standard units are listed as: E: Modulus of elasticity [kN/m^2], ϕ: Angle of internal friction [°], υ: Poisson's ratio [-], c: Cohesion [kN/m^2], ψ: Angle of dilatancy [°], γ_{sat}, γ_{unsat}: Saturated and Unsaturated unit weight respectively [kN/m^3] **(**Plaxis 3D 2018).

2.2 METHODS

Index properties: Natural moisture content, specific gravities, sieve analysis and Atterberg limits tests were conducted on the samples collected from borrow pits around Birgi Village, a suburb of Minna, Niger State in accordance with tests procedures specified in BS 1377: 1990.

Compaction characteristics: Compaction of clay specimens was conducted in accordance with the guidelines specified in BS 1377 (1990) to compute the required parameters. The reduced British Standard light (RBSL) compactive effort was used. The RBSL compaction is the energy resulting from 2.5 kg rammer falling through a height of 30 cm onto three layers of soil, each receiving 25 blows.

Free Swell Index of soil: this test was done to determine the free swell index of the soil samples and it has helped in identifying the swelling potential of the soil samples. This was done in accordance with guidelines specified in (BS 1377:1990; IS 2720: 1977).
It was calculated using equation 2.1.

$$FSI = \frac{V_d - V_k}{V_k} \times 100 \qquad (2.1)$$

Where:

FSI = Free swell index

V_d = The volume of soil specimen read from the graduated cylinder containing distilled water

V_k = The volume of soil specimen read from the graduated cylinder containing Kerosene.

Sridharan and Prakash (2000) classification for expansive soil chart was used to obtain the swelling potential or the rate of expansion of the soil at different depth. The kerosene absorbent test method was used to examine the free swell index of samples.

Consolidated Undrained Triaxial test (CU)

The CU test was conducted in accordance with the procedure specified in BS, 1377: (1990). The treated specimens were prepared relative to OMC and compacted with RBSL compactive energy. The CU test was done using all round pressure of 50, 100 and 150 kN/m^2 different soil sample specimens each of which was consolidated in three layers cycles.

Plate 1: Consolidated undrained test on samples

Model Raft Foundation Analysis

The analysis was conducted on a raft foundation of 40 meters long, 20 metres wide and 1.5 meters deep. Six loads of 5000 kN were applied on the foundation in two symmetrical gridlines. Figure 1 shows the dimensions of the foundation and the position where the loads were applied.

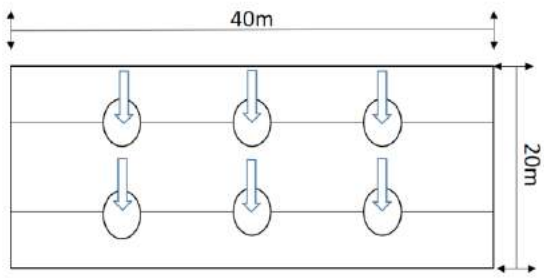

Figure 1: Loading points of modelled raft footing

3 CONSTITUTIVE MODEL

Mohr-Coulomb model

Coulomb proposed the first plasticity model in soil mechanics. It is composed of two symmetrical lines in Mohr's plane (σ, τ), having an angle ϕ with the normal stresses axis, σ and having as equation.

$$F(\sigma_{ij}) = \sigma_1 - \sigma_3 - (\sigma_1 + \sigma_3)\sin\emptyset - 2c\cos\emptyset \leq 0 \quad (2.2)$$

Where:

σ_1 and σ_3 are the extreme main stresses

Parameter c represents the soil cohesion, while ϕ is the internal friction angle.

In the space of main stresses (σ_1, σ_2, σ_3) the surface defined by function F is a pyramid with hexagonal section having line $\sigma_1 = \sigma_2 = \sigma_3$ as the x-axis.

The plastic potential defined as a function of the extreme main stresses is:

$$G(\sigma_{ij}) = \sigma_1 - \sigma_3 + (\sigma_1 + \sigma_3)\sin\varphi + \text{const} \quad (2.3)$$

Where:

φ is the dilatancy angle (φ = ϕ if it is an associated criterion)

The elasticity associated to the Mohr – Coulomb criterion is a linear Isotropic-Hooke type one. The criterion contains 5 mechanical parameters:

i. E – elasticity modulus,
ii. ν – Poisson's coefficient: elastic parameters;
iii. c, ϕ, ψ: plastic parameters.

4 RESULTS AND DISCUSSION

Index properties of the soil different depths:

The results of index properties of the soils are shown in Table 1. The fraction passing through No 200 sieve for depth 0m, 1m and 1.5m are 68.57%, 70.73% and 71.27% respectively. The soils are classified A-7-5 (CL), A-7-5 (CH) and A-7-6 (CH) at 0m, 1.0m and 1.5m depths respectively according to AASHTO and USC soil classification systems respectively (AASHTO, 1986; ASTM, 1992).

Table 1: Summary of properties of test clay

Properties (Average)	**Layer A (0m)**	**Layer B (1.0m)**	**Layer C (1.5m)**
Specific gravity (Gs)	2.73	2.57	2.77
Natural moisture content (%)	18.94	17.55	28.10
Atterberg Limits			
Liquid limit (%)	54.5	47.0	43.2
Plastic limit (%)	38.19	32.92	29.63
Shrinkage limit (%)	9.64	9.21	10.00
Plasticity index	16.31	14.08	13.57
% Passing BS No. 200 sieve	51.90	52.70	54.70
Classification			
USCS	CL	CH	CH
AASHTO	A-7-5	A-7-5	A-7-6

Free Swell Index of test samples

The results of free swelling index of samples collected from 0 metre depth are shown in Table 2.

Table 2: Free swell index of samples at 0m depth

Trial	Vd(ml)	Vk(ml)	FSI (%)	Average FSI (%)
1	22.50	11.00	104.55	
2	24.00	11.50	108.70	105.93
3	22.50	11.00	104.55	

From Table 2, the average free swell index of the soil at 0 metre depth is 105.93%. Therefore the soil, having a FSI of 105.93% (which falls between 95 – 120%) is highly expansive according to (Sridharan and Prakash, 2000).

The results of swelling index of samples collected from 1.0 metre depth are shown in Table 3.

Table 3: Free swell index of sample at 1.0m depth

Trial	Vd(ml)	Vk(ml)	FSI (%)	Average FSI (%)
1	22.50	10.50	114.29	
2	23.00	11.00	109.09	110.82
3	23.00	11.00	109.09	

The average free swell index of the soil at 1.0m depth is 110.82%. Therefore the soil at this depth, having a FSI of 110.82% (which falls between 95 – 120%) is highly expansive according to (Sridharan and Prakash, 2000).

Table 4: Free swell index of sample at 1.5m depth

Trial	Vd(ml)	Vk(ml)	FSI (%)	Average FSI (%)
1	22.00	10.00	120.00	
2	22.00	10.50	109.52	118.17
3	22.50	10.00	125.00	

The average free swell index for the soil at depth 1.5m is 118.17%. Therefore the soil at this depth, having a FSI of 118.17% (which falls between 95 – 120%) is highly expansive according to (Sridharan and Prakash, 2000).

Consolidated undrained triaxial test (CU)

The following are the results obtained from the test and computation of the results of triaxial test of sample moulded using the MDD and OMC from British Standard Light compaction test according to BS 1377: 1990). The test was repeated for other samples collected from 0, 1.0 and 1.5m depth respectively. The results are shown in Tables 5 – 10 and Figures 2 – 4.

Table 5: Triaxial test results of samples at depth of 0m

Item	Quantity		
All round Pressure (kN/m^2)	50	100	150
Axial Deformation (mm)	400	600	525
Loading (N)	12	19	32

Table 6: Principal stresses of test samples at 0m

σ_3(kN/m^2)	σ_2(kN/m^2)	σ_1(kN/m^2)
50	72	122
100	110	210
150	191	341

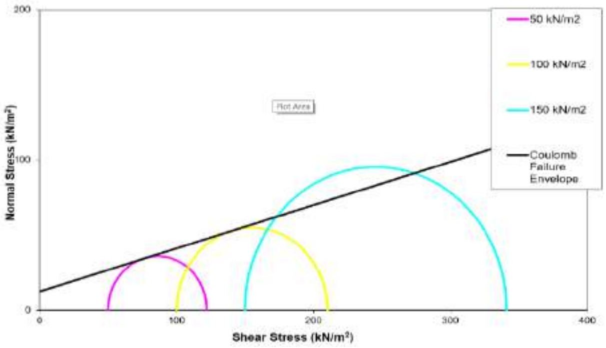

Figure 2: Mohr circle diagram of sample at 0 m

Table 7: Triaxial test results of sample at 1.0m

Item	Quantity		
All round Pressure(kN/m^2)	50	100	150
Axial Deformation (mm)	400	525	425
Loading (N)	11.2	17	19.8

Table 8: Principal stresses for sample at 1.0m depth

$\sigma_3(kN/m^2)$	$\sigma_2(kN/m^2)$	$\sigma_1(kN/m^2)$
50	67	117
100	100	200
150	115	265

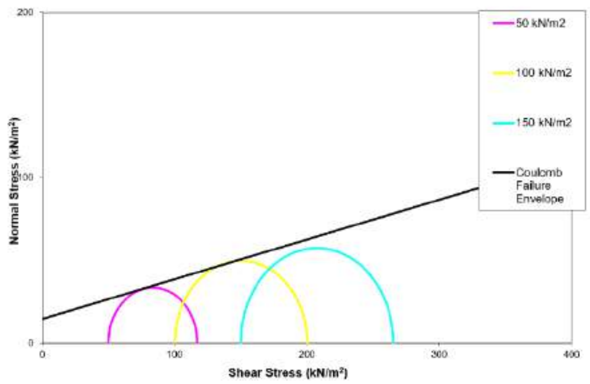

Figure 3: Mohr circle diagram of sample at 1.0m depth

At the depth of 1.5m

Table 9: Triaxial test results of sample at 1.5m depth

Item	Quantity		
All round Pressure (kN/m^2)	50	100	150
Axial Deformation (mm)	475	525	625
Loading (N)	13.2	20.1	30

Table 10: Table from computation of the results

$\sigma_3(kN/m^2)$	$\sigma_2(kN/m^2)$	$\sigma_1(kN/m^2)$
50	78	128
100	118	218
150	173	323

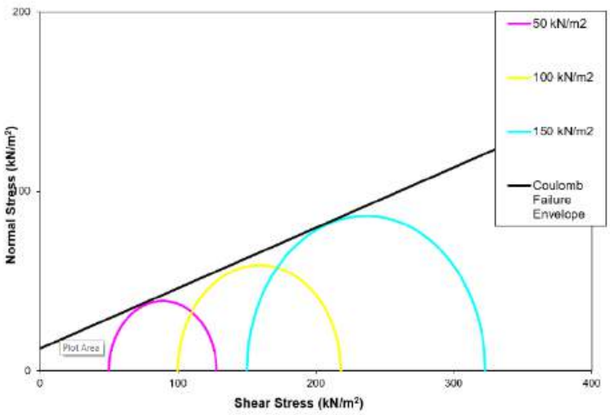

Figure 4: Mohr circle diagram of sample at 1.5m depth

The summary of geotechnical properties of the critical test samples used for both Mohr-Coulomb model and Finite Element Analysis is shown in Table 11, while the discussion is presented thereafter.

Table 11: Summary of the soil properties inputs for FEA

Layer 1 (0 meter)	$\Upsilon_{sat} = 17.8kN/m^3$ $\Upsilon = 15.6kN/m^3$ $c = 12.5\ kN/m^2$ $\phi = 23^0$ $v = 0.25$ $E = 3000\ kN/m^2$ $\psi = 0$
Layer 2 (1.0m)	$\Upsilon_{sat} = 17.4\ kN/m^3$ $\Upsilon = 16.4\ kN/m^3$ $c = 14.7\ kN/m^2$ $\phi = 23^0$ $v = 0.23$ $E = 3000\ kN/m^2$ $\psi = 0$
Layer 3 (1.5m)	$\Upsilon_{sat} = 16.9\ kN/m^3$ $\Upsilon = 15.6\ kN/m^3$ $c = 12.7\ kN/m^2$ $\phi = 26^0$ $v = 0.23$ $E = 3000\ kN/m^2$ $\psi = 0$

Table 11: Concrete parameter of modelled raft foundation

Parameter	Value
Raft Length	40 metres
Raft Width	20 metres
Raft Thickness	0.5 metre
Modulus of Elasticity (E)	1.0e10^7 kN/m^2
Poisson's ratio	0.3
Unit Weight	24 kN/m^3

Deformation of samples

Initial Stage Deformation

An increase deformation at the initial stage is shown in the interphase mesh in Plate II. The extreme deformation at this stage is 615.15*10-6m, which is lower than those of excavation and final stages. The load here is gradual and the soil around the foundation is stll within the elastic state, with little or minimum distortion of soil particles.

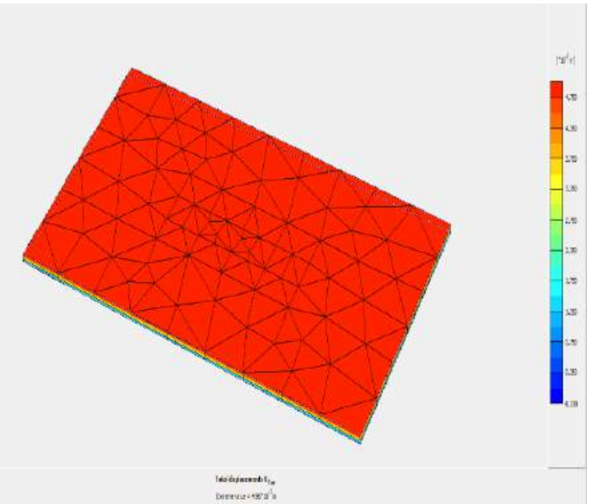

Plate II: Initial stage deformation of the soil

Excavation Stage Deformation

Due to the forces invloved in foundation excavation, the deformation at this stage increased due structural imbalance and particles phase distortion. Another factor, which contributed to the increase deformation is soil grain distabilization resulting from displacement, remoulding and other disturbnaces during soil during excavation. The increase deformation caused be the threshold load at this stage is 4.55*10^{-3}m.

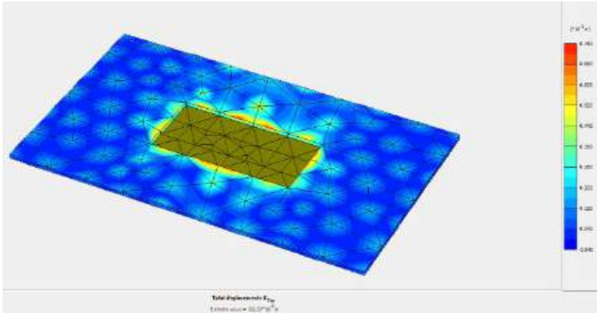

Plate III: Excavation stage deformation of the soil

Final Stage Deformation

A higher deformation of 18.442*10^{-3}m. occurred at the final loading stage. However, with the introduction of model raft, the total deformation at this stage reduced to 606.95*10^{-6}m. The raft served as both stiffner and brace, thereby reducing the effect on surroundig soil. Also, the loading rate efficiency of raft foundation analyzed by Finite Element Model is 10.3% higher than that of Classical Mohr-Coulomb model. The load or bearing capacity efficiency using Mohr-Coulomb model and Finite Element Analysis are 82.1% and 92.4% respectively

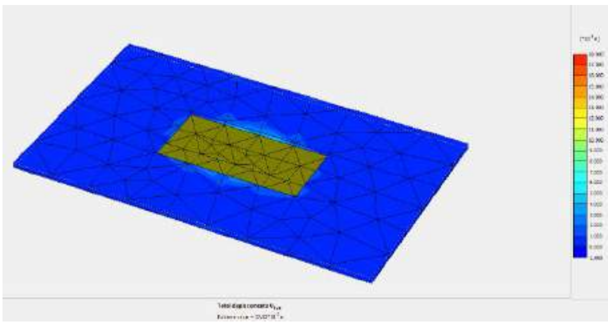

Plate IV: Final stage deformation of the soil

Comparison of Mohr-Coulomb model and Finite Element Method

A comparative study of load bearing response of modelled raft foundation in expansive clay analyzed using Finite Element method classical Mohr-Coulomb model revealed that, under the same threshold pressure, the deformation obtained using the classical Mohr-Coulomb model is higher than the one obtained using the finite element analysis. Under a threshold pressure of σ = 310 kN/m^2, the former produced a maximum deformation of 18.442*10^{-3}m, while the latter produced a deformation 601.01*10^{-6}m respectively.

5 CONCLUSION

From the results of Finite Element Analysis of raft foundation load-bearing response in expansive clay, the following conclusions were drawn;

I. The free swell index (*FSI*) of test clay samples collected from 0 – 1.5 metres depth raged from 105.95 to 118.18%, which classified it under highly expansive clay.

II. Higher deformation of the soil, which was due to disturbance and distortion was recorded at the excavation stage than the one recorded at initial stage with values of 4.55*10^{-3}m and 615.15*10^{-6}m respectively.

III. With the introduction of model raft, the total deformation at excavation stage reduced to 602.01*10^{-6}m, with the raft serving as both stiffner and brace, while the deformation obtained using the classical Mohr-Coulomb stood at 18.442*10^{-3}m.

IV. Also, the loading rate efficiency of raft foundation analyzed by Finite Element Model is 10.3% higher than that of Classical Mohr-Coulomb model

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