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Prediction of Force Displacement Behavior of Pad Foundation on Lagoon Clay Soil

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Abstract
The determination of bearing-capacity is more challenging when complicated cases are encountered. This research aim to build a numerical (FE) model of an axi-symmetric (square) shallow foundation under vertical load to determine its load-deformation behavior, using appropriate constitutive models and soil properties derived from laboratory and/or in-situ test data. To achieve this aim, the soil parameter were calibrated, then un-drained response model was developed using both total and effective stress-based analyses, then the effects of meshing and mesh refinement on the results was done and the simulation results were validated against measured load-test data. From the results it was observed that the mesh refinement has a significant effect on the Plaxis calculation time period, the output results and number of iteration it takes to achieve a specified result. Thereafter, it was observed that the total stress path analysis using Mohr-coulomb model predictions were very conservative and below the real field results. Finally, it was observed that both effective and total stress path analysis experienced general shear failure. It can thus be concluded that effective stress path analysis using Modified cam clay model predictions were closed to real field results compared to total stress path analysis.

INTRODUCTION
The stress distribution in soil underneath a foundation is significant in geotechnical engineering (Zeybek, Madabhushi

and Pelecanos, 2020; Waruwu, Hardiyatmo and Rifa'I, 2019; Saeed, 2022). The additional stress caused by the external load in soil may depend on factors such as value of the applied load, properties of the soil, and dimensions of the loaded area (Kurhan and Fischer, 2022; Zhai and Horn, 2019). The bearing-capacity problem has been one of the earliest subjects in geotechnical engineering, for which various methods have been extensively applied (Ghazavi and Eghbali, 2008). These methods may be performed either analytically or experimentally. The analytical methods involve the slip line approach (Liu and Wang, 2008; Peng and Chen, 2013), limit equilibrium approach(Ghazavi and Eghbali, 2008) , limit analysis (Michalowski, 1997; Mofidi Rouchi, Farzaneh and Askari, 2014), numerical approaches (Benmebarek, Saifi and Benmebarek, 2017) and limit analysis in combination with numerical approaches(Hjiaj, Lyamin and Sloan, 2005). Experimental work includes laboratory or in situ full-scale and centrifuge tests. The bearing-capacity topic is more challenging when complicated cases are encountered, for example, when the foundation width becomes large in comparison with the soil thickness or when the soil profile is non-homogeneous (Chen, 2013; Kardani, Zhou, Nazem and Shen, 2020; Moayedi, et al., 2020). Most geotechnical analyses in general practice are treated as deterministic. These involve analyses using representative values of design parameters, usually an average or the lowest value obtained from field and/or laboratory test results and application of a suitable factor of safety to arrive at an allowable loading condition. However, in nature, soil parameters such as physical, strength and hydraulic properties generally vary spatially in both the horizontal and vertical directions. The distribution of these soil properties at a site depends on the heterogeneity of constituent materials forming the soil matrix, the geological history of soil formation and its continuous modification by nature. A uniform soil condition is rarely encountered in practical problems. In most site conditions, soil properties show a significant variation over space.

Geotechnical analyses are generally carried out by treating the soil as a single homogeneous layer with uniform soil properties or as a multilayered medium with each layer having a uniform property. Numerical techniques such as finite difference or finite element methods have facilitated modeling the layer wise uniform material variation of soil properties in the horizontal direction is generally ignored. Since the variation in the horizontal direction is not so significant in many situations and a greater number of boreholes is required to establish this horizontal variation, which is impractical due to economic considerations.

This work aim to simulate load – settlement behavior of pad foundation resting on soil mediums of soft clay with uniform loads using PLAXIS 2D, a FEM based geotechnical software.

STUDY AREA

The site under study is located at Eti-Osa, along the Lagoon, Lagos, Nigeria as shown in Figure 1. Due to ground investigation, the sub-soil of the site has been found to range from a lightly over-consolidated to normally consolidated soft silty clay extending to 15m below ground level (BGL). Also, the founding plane and water table are at 0.8 m below ground level (BGL). A foundation of 2.2 m square in plan and 0.8m deep has been casted on the site, of which it was load-tested to failure over a period of 90 hours.

Figure1: Showing Site Location on Map of Lagos. Source: https://d-maps.com

EFFECTIVE STRESS PATH ANALSYSIS

MODIFIED CAM CLAY KEY PARAMETERS

To perform the effective stress path analysis, the modified cam clay model analysis under un-drained condition A was chosen. To use the modified cam clay model, three major parameter are necessary, the lambda, λ, Kappa, κ, and M. lambda, λ is the slope of the normal compression (virgin consolidation) on Specific volume versus pressure (v-InP) plane, Kappa, κ is the slope of swelling line and M is the slope of the C-S-L in p-q space. The lambda, λ and κ can be obtained from both the oedometer test and Consolidated isotropic test while the M is obtained from the Consolidated isotropic test and their values are as shown in Table 1. It was observed that the valued obtained from both test were too different, so a soil test using plaxis was conducted to simulate the laboratory test and to optimize the input parameter to be used.

Table 1: Range of Values of λ, κ, M as obtained from the oedometer tests and CIU test.

Test	λ	κ	M
Oedometer Test	0.087-0.098	0.00765-0.0145	-
CIU test	.054-0.057	0.004-0.006	0.88

A simulation of the oedometer test was conducted on Plaxis using the values obtained from both the oedometer test and CIU test. The best simulation close to the original laboratory test is as shown in Figure 2 and Figure 3. From the Plaxis oedometer test, the optimized value of ,, M for both laboratory test is as shown in Table 2.

Table2: Optimized Values of λ, κ, M as obtained from the oedometer tests and CIU test.

Test	λ	κ	M	Preconsolidation Pressure
Oedometer Test	0.091	0.0076	-	100
CIU test	0.054	0.004	0.88	55

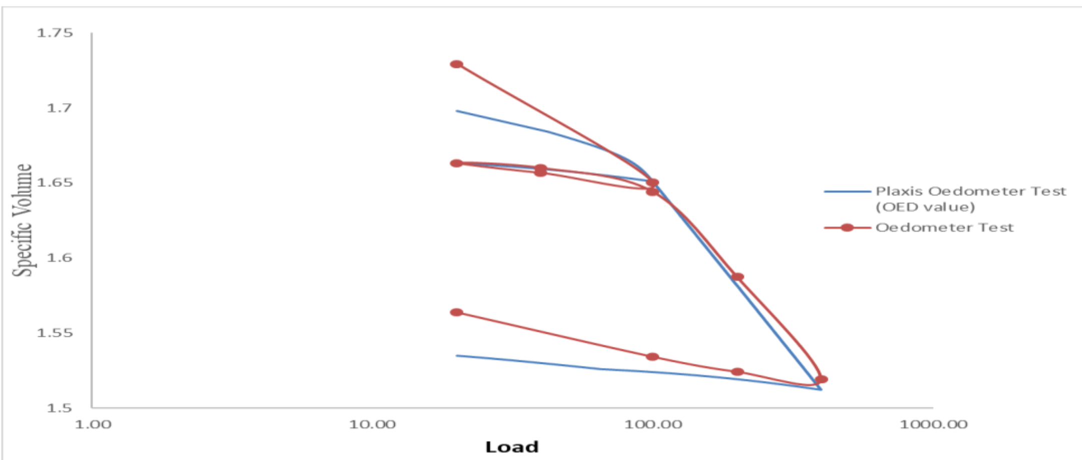

Figure 2: Plot of plaxis oedometer test using calibrated Oedometer test value Vs the actual Oedometer test values.

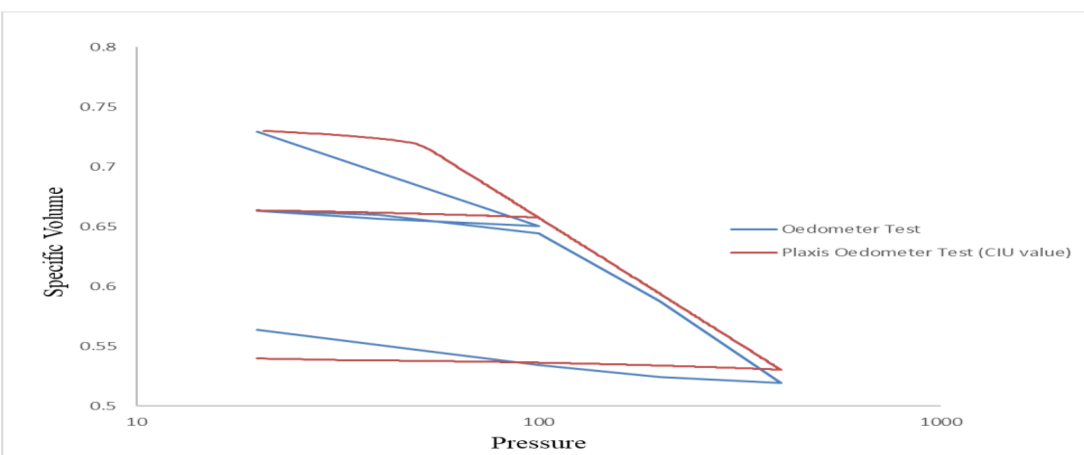

Figure 3: Plot of plaxis oedometer test using calibrated CIU test value Vs the actual Oedometer test values.

Also, a simulation of the CIU test was conducted, the optimized CIU values gives a closer prediction as shown in Figure – in appendix compare to the optimized oedometer values. Thus, the optimized CIU values of ,, M was used to conduct the effective stress path analysis.

MODEL SIZE AND BOUNDARY CONDITIONS

The soil is considered as a semi-infinite layer. Thus, the model has a depth of 17.6m (8 X Total breadths of the footings) and length of 12m (> 5 X Total breadth of the footings) as shown in Figure 3. The half of the footing is considered for the model and it is considered as a rigid footing as shown in Figure 3. The soil profile was done using soil polygon to give a real field situation. This method of approach was adopted instead of creating a rectangle soil profile with surcharge because the surcharge applied only represent the weight of the soil, it does not take into consideration the other soil parameters which might affect the behavior of the soil.

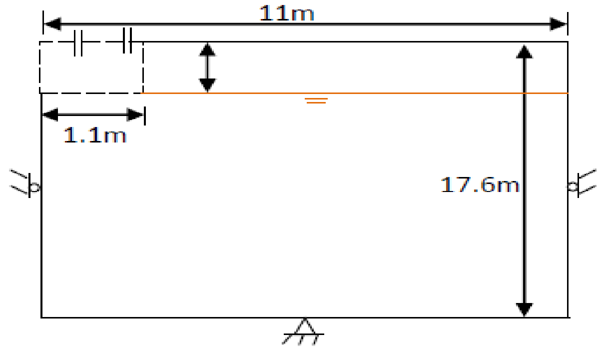

Figure 4: Model size and boundary conditions.

A total number of 13 layers of soil was created, to have a good representation of some depth in the soil where there are drastic changes in the soil parameters as shown in Figure 4.

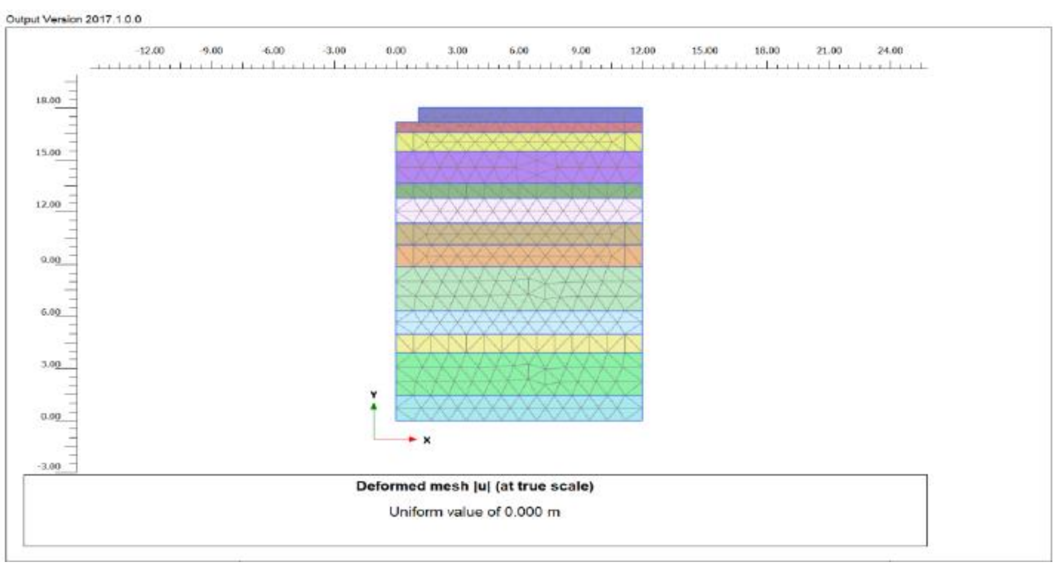

Figure 5: The soil layers and mesh

To obtain the other soil parameter for each soil layer from the in-situ data, an average line was first drawn through each soil parameter and then to obtain value for each specific layer, an interpolation between points was done. The other soil parameter inputted in the effective stress analysis using modified cam clay model is as shown in Table 3.

Table 3: Other input soil parameter for effective stress path analysis using modified cam clay

Soil Layers	e_0	$\gamma_{dry}(kN/m^3)$	$\gamma_{sat}(kN/m^3)$	v	POP	Frictional Angle, φ
0-0.8	1	12.82	17.68	0.25	80.00	23°
0.8-1.12	1	11.49	16.95	0.25	80.00	23°
1.12-2.51	1.44	10.48	16.57	0.25	48.83	23°
2.51-4.35	1.7	9.78	15.89	0.25	60.02	23°
4.35-5.21	1.614	9.70	15.92	0.25	68.07	23°
5.21-6.64	1.66	10.11	15.87	0.25	81.45	23°
6.64-7.89	1.81	9.71	15.82	0.25	93.15	23°
7.89-9.16	1.67	9.8	16.09	0.25	105.15	23°
9.16-11.68	1.58	9.93	16.16	0.25	129.87	23°
11.68-13.03	1.58	9.93	16.16	0.25	143.11	23°
13.03-14.09	1.37	9.93	16.16	0.25	153.50	23°
14.09-16.56	1.145	9.93	16.16	0.25	177.73	23°
16.56-17.60	1.145	9.93	16.16	0.25	187.93	23°

TOTAL STRESS PATH ANALYSIS

The same soil layers and boundary conditions used for the effective stress path was used for the total stress analysis. To perform the Total stress path analysis, the Mohr-Coulomb model analysis at Non-Porous Drainage type was used. The Input parameters for each soil layer are as shown in Table 4. The highest constrained modulus from the oedometer test was assumed as the constrained modulus for the first soil layer, the subsequent layer constrained modulus was obtained analytically from the expression between specific volume and constrained modulus.

Table 4: Input parameters for total stress path analysis.

Soil Layers	e_0	$\gamma_{dry}(kN/m^3)$	$E'\ (MPa)$	υ	Cohesion
0-0.8	1	12.82	64.00	0.45	10.4
0.8-1.12	1	11.49	64.00	0.45	10.4
1.12-2.51	1.44	10.48	77.20	0.45	11.26
2.51-4.35	1.7	9.78	85.00	0.45	17.66
4.35-5.21	1.614	9.70	82.42	0.45	20.01
5.21-6.64	1.66	10.11	83.80	0.45	21.87
6.64-7.89	1.81	9.71	87.30	0.45	22.42
7.89-9.16	1.67	9.8	84.10	0.45	26.06
9.16-11.68	1.58	9.93	81.40	0.45	35.51
11.68-13.03	1.58	9.93	81.40	0.45	30.4
13.03-14.09	1.37	9.93	75.10	0.45	35.43
14.09-16.56	1.145	9.93	68.35	0.45	38.1
16.56-17.60	1.145	9.93	68.35	0.45	38.1

RESULTS AND DISCUSSION

MESH REFINEMENT FOR EFFECTIVE STRESS PATH ANALYSIS

It was observed that as the mesh is being refined from Very coarse to Very Fine for effective stress analysis, the duration required completing the whole calculation increases as shown in Table 5. Also, it was observed that number of iteration increases with refinement of mesh except at moving from very coarse to coarse that it reduces. Also, it was observed that the prediction value decreases with the refinement of the mesh.

Table 5: Type of mesh refinement and effect on effective stress path analysis

Mesh	Effective stress analysis duration	Number of iteration/Step	Prediction Value
Very Coarse	8 secs	68	Highest Value
Coarse	9 secs	63	Higher Value
Medium	11 secs	74	High Value
Fine	18 secs	79	Low Value
Very Fine	26 secs	92	Lowest Value

MESH REFINEMENT FOR TOTAL STRESS PATH ANALYSIS

It was observed that as the mesh is being refined from Very coarse to Very Fine for total stress path analysis, the duration required to complete the whole calculation also increases as shown in Table 6. Also, it was observed that number of iteration initially reduces, then increases, then remain constant and later reduces again as shown in Table

6. Also, it was observed that the prediction value decreases with the refinement of the mesh as shown in Table 6.

Table 6: Type of mesh refinement and effect on total stress analysis

Mesh	Effective stress analysis duration	Number of iteration/Step	Prediction Value
Very Coarse	36 secs	348	Highest Value
Coarse	38 secs	265	Higher Value
Medium	114 secs	1001	High Value
Fine	178 secs	1001	Low Value
Very Fine	185 secs	614	Lowest Value

PREDICTED FORCE DISPLACEMENT FOR EFFECTIVE STRESS ANALYSIS VS LOAD TEST DATA

The predicted force-displacement for effective stress path analysis using modified cam clay model for each mesh refinement and the field load test is as shown in Figure 6. It was observed from Figure 6 that the predicted force at about up to 80mm displacement from plaxis for all mesh refinement was initially greater than the actual load test data but at above 80mm displacement the predicted force from the plaxis for all mesh refinement was lower than the actual field load test except for coarse mesh predicted value which was above the actual field load test. It was observed that the plaxis predicted force to achieve a settlement of 200mm is around 85%-102% of the actual force from the field test analysis. This suggested that the effective stress path analysis using modified cam clay soil model is conservative to some extent but can over predict if not properly checked.

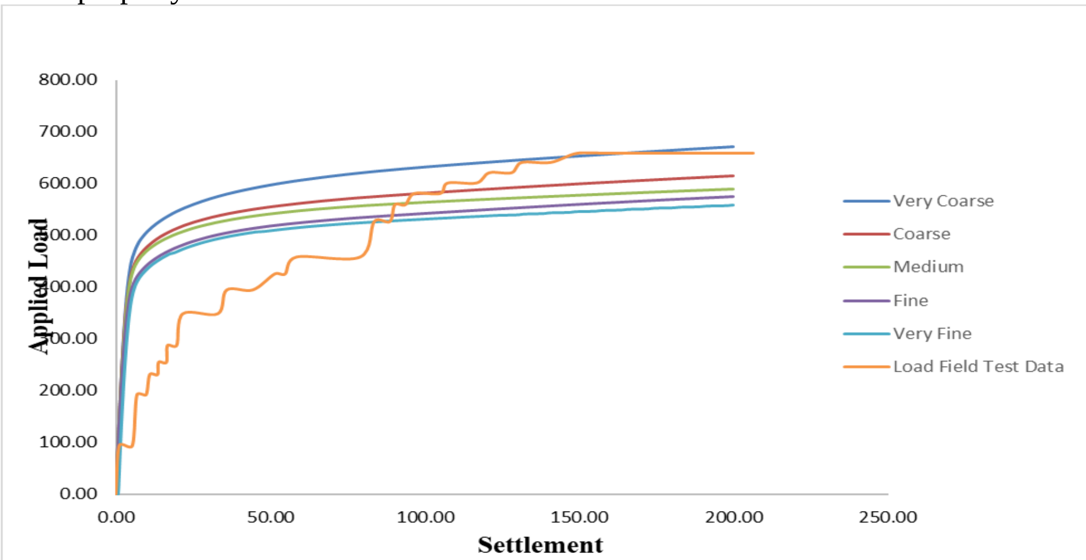

Figure 6: Plot of force- displacement behavior for effective stress path against load test data

PREDICTED FORCE DISPLACEMENT FOR TOTAL STRESS PATH ANALYSIS VS LOAD TEST DATA

The predicted force-displacement for total stress path analysis using Mohr-Coulomb model for each mesh refinement and the field load test is as shown in Figure 7. Also, it was observed from Figure that the predicted force at about 30mm displacement from plaxis was initially greater than the actual load test data but at above 30mm displacement the predicted force from the plaxis was lower than the actual field load test. It was observed that the plaxis predicted force to achieve a settlement of 200mm is around 59%-62% of the actual force from the field test analysis. This suggested that the Total stress analysis using Mohr-coulomb soil model is very conservative compared to the effective stress path analysis using modified cam clay model.

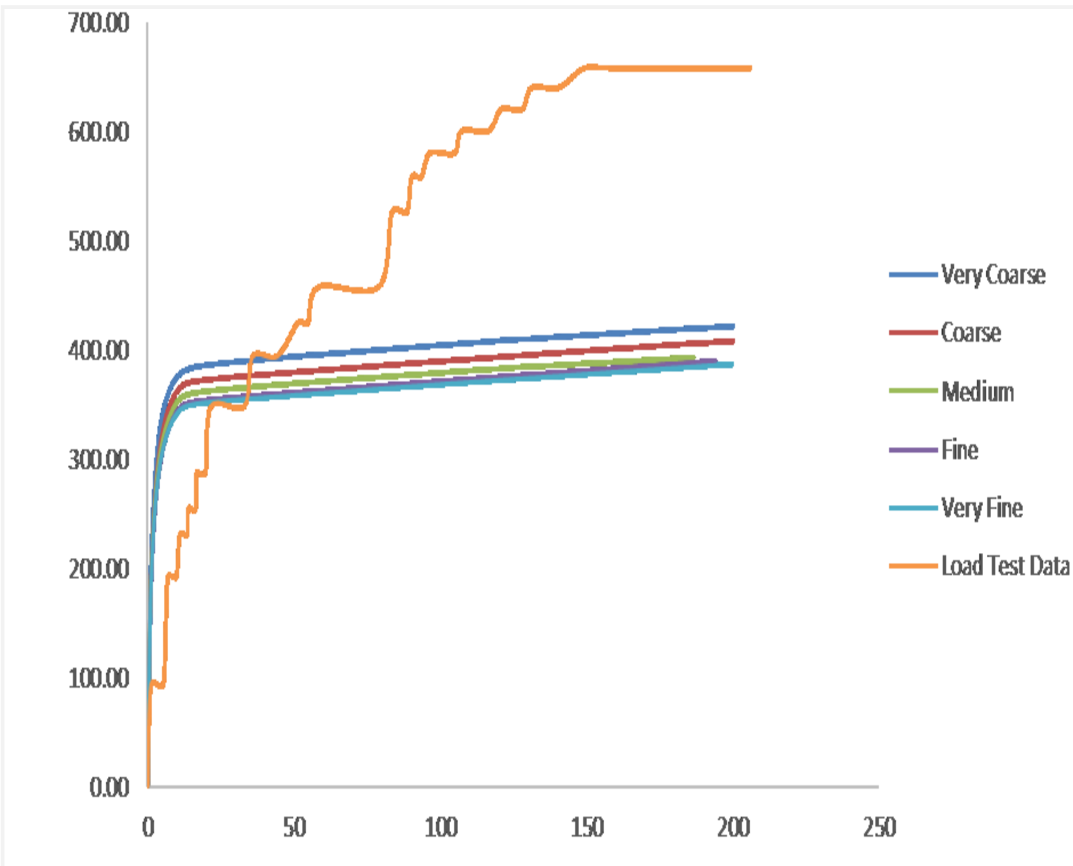

Figure 7: Plot of force- displacement behavior for total stress path against load test data

SHEAR FAILURE AND STRESS DISTRIBUTION

The shear failure and stress distribution of both effective stress path analysis and total stress path analysis is as shown in Figure 8 and 9.

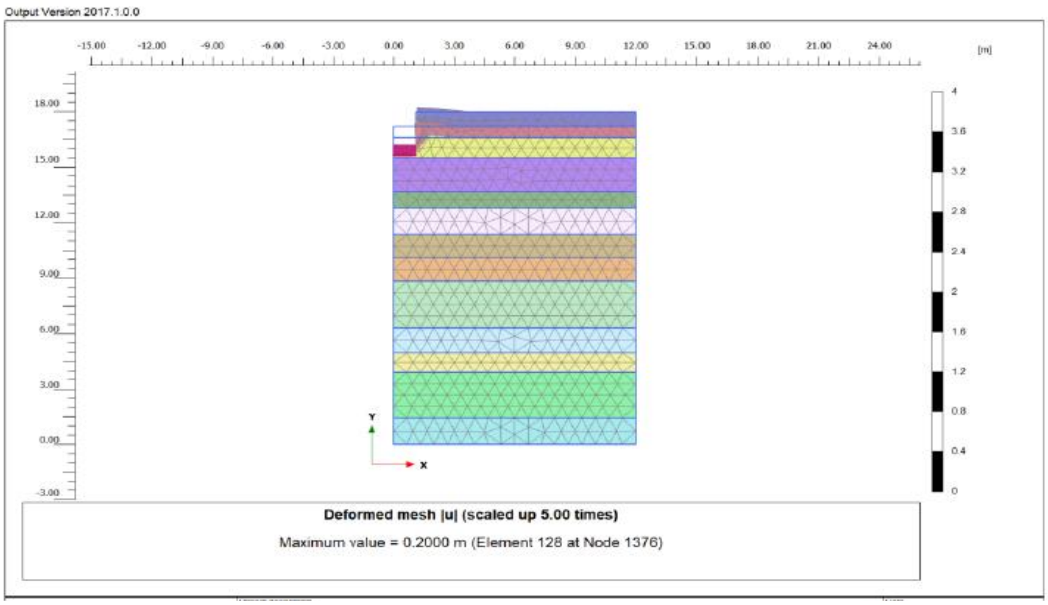

Figure 9: Shear failure and stress distribution of effective stress path analysis.

SUMMARY AND CONCLUSION

This work aims to simulate load – settlement behavior of pad foundation resting on soil mediums of soft clay with uniformly distributed loads using PLAXIS 2D, a FEM based geotechnical software. The Modified cam clay model, Un-drained A condition was used for the effective stress path analysis, while the Mohr-coulomb model, Non-porous condition was used for the total stress path analysis. A total of 13 layers of the soil were created to have a good representation of some depth in the soil where there are drastic changes in the soil parameters. From results and observations, the following conclusions were made;

1. The mesh refinement has a significant effect on the Plaxis calculation time period, the output results and number of iteration it takes to achieve a specified results.
2. The effective stress path analysis using Modified cam clay model predictions were closed to real field results.
3. The total stress path analysis using Mohr-coulomb model predictions were very conservative and below the real field results.
4. Both the effective stress path analysis and total stress path analysis experienced general shear failure.

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