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Bearing Capacity of Shallow Foundations in Homogeneous and Layered Soils under Varying Ground Water Table Conditions by using PLAXIS 2D

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Abstract: This present study focuses on the numerical analysis of the UBC of shallow foundations subjected to different soil layers and GWT case. A finite element-based analysis was examined by PLAXIS 2D to study the response of foundations placed on both homogeneous and layered soil profiles. The investigation considered foundation width, soil-layer thickness, clay cohesion, friction angle of sand, and groundwater table depth as the principal variables. Homogeneous sand and clay profiles were first analyzed by considering different groundwater levels and foundation widths of 1 m and 2 m. The influence of clay strength was examined by adopting different cohesion values. In addition, layered profiles comprising sand over clay and clay over sand were modeled with different layer thicknesses and groundwater conditions to evaluate the effect of soil stratification on foundation bearing capacity. The numerical results show that changes in groundwater position, foundation width, soil strength, and layer arrangement can significantly alter the UBC. The interaction between the upper and underlying soil layers also plays a significant role in the bearing response of layered foundations. This study demonstrates the usefulness of finite element analysis for evaluating shallow foundation behavior under complex soil and groundwater conditions and provides a systematic understanding of the parameters governing ultimate bearing capacity.

Keywords: Shallow foundation, Bearing capacity, Strip foundation, Homogeneous and Layered soils, Ground water table condition, PLAXIS 2D.

I. INTRODUCTION

Shallow foundations are used to transfer structural loads to the underlying soil below the foundation. Their bearing capacity is influenced by soil strength, foundation width, soil layering, and groundwater conditions. In general soil deposits commonly consist of different layers or profiles with varying engineering properties, making the assessment of foundation behaviour more complex than that of a homogeneous soil.

The position of the groundwater table can affect the effective stress of soil and also strength parameters of soil, which in turn influences the bearing capacity of a foundation. The extent of this influence depends on the soil type, foundation dimensions, and groundwater depth. In layered soils, the thickness and arrangement of the individual layers can further modify the foundation response. The finite element method provides a useful approach for studying the interaction between foundations, soil layers, and groundwater conditions. The study uses PLAXIS 2D to examine the UBC of shallow foundations for homogeneous and stratified soil profiles. The analysis considers homogeneous sand, homogeneous clay, sand-over-clay, and clay-over-sand profiles, with foundation widths of 1 m and 2 m. Different clay cohesion values, upper-layer thicknesses, and groundwater-table depths are considered to examine the resulting changes in foundation bearing behaviour.

II. OBJECTIVES

The study is undertaken to:

1) Examine the bearing response ofstrip foundations placed on uniform soil profile and heterogeneous soil profiles through PLAXIS 2D.
2) Assess the influence of groundwater-table position on the ultimate bearing capacity under different soil conditions.
3) Evaluate the effect of foundation width by considering 1 m and 2 m strip footings.

4) Investigate the role of clay cohesion on the bearing capacity of homogeneous clay deposits.
5) Examine the effect of upper-layer thickness on the bearing behaviour of sand-over-clay and clay-over-sand profiles.
6) Identify the changes in UBC associated with variations in soil type, layer configuration, foundation width, and groundwater depth.

III. LITERATURE REVIEW

1) Mandeel et al. [2020]: Investigated the bearing capacity of full-scale shallow foundations on homogeneous and stratified soil profiles through PLAXIS 3D. The study considered different combinations of sand and clay profiles and analyzed the effects of footing width, upper-layer thickness, cohesion, and friction angle on UBC. The findings indicated that the bearing capacity of layered foundation is strongly impacted by the thickness and strength of the upper soil profile and the footing width. The study provides a useful numerical basis for assessing shallow foundations on layered soils.
2) Eshkevari et al.[2019] : The behaviour of strip footings on sand over clay has been investigated extensively using numerical and limit-analysis techniques. He studied about the rigid type of strip footing resting on a finite-thickness sand profile over clay using finite-element limit analysis. Their study examined the influence of the layered-soil geometry and failure mechanism and demonstrated that simplified empirical approaches may have limitations outside the range of conditions for which they were developed.
3) Yamamoto and Hira [2005]: They used finite-element analysis to investigate rigid strip footings on sand overlying clay and compared the numerical limit loads with existing analytical and limit-equilibrium approaches. Their results demonstrated the usefulness of numerical analysis for examining stress distributions and failure mechanisms in layered soil profiles.
4) Cascone et al. [2021]: He investigated the influence of groundwater on the bearing capacity of shallow strip footings under plane-strain conditions and developed groundwater-dependent bearing-capacity relationships. Their results were also checked against finite-element analyses, showing the importance of incorporating groundwater effects when evaluating foundation capacity. The position of the GWT changes the effective stresses and the effective unit weight of soil, thereby affecting the available shear resistance beneath the foundation.
5) Bhardwaj and Sharma [2023]: They have examined the BC behaviour of foundations supported by uniform- and hetrogeneous soil profiles using both laboratory model tests and numerical simulations. The study considered square and rectangular footing configurations with aspect ratios (L/B) of 1 and 2. The layered profiles consisted of an upper stabilized clay profile placed over an dense typeof sand, with the relative soil thickness of the uppermost layer represented by H/B values of 0.8, 1.2, 1.6 and 2.0.

IV. NUMERICAL MODELLING

The numerical investigation was implemented through PLAXIS 2D to understand the UBC of strip foundations under various soils profiles and also various GWT conditions. The analysis was planned to examine the effects of footing width, groundwater-table depth, soil cohesion, and soil layering. Both homogeneous sand and clay also layered soil profiles were considered and the numerical results were subsequently compared with analytical bearing-capacity methods.

A. Finite Element Model

A 2D plane-strain model was used to represent the behaviour of the strip footing. This idealization is appropriate for a continuous footing where the variation in the longitudinal direction is assumed to be negligible. The soil domain was modelled with a width of 20 m and a depth of 10 m. Footing widths, 1 m and 2 m, were considered in the study.

The numerical models comprised four main soil configurations: homogeneous sand and clay profile, sand overlying clay, and clay overlying sand. For homogeneous clay, three cohesion values of 25, 40, and 80 kPa were used to study the effect of clay on the foundation response. In the layered models, the thickness of the upper soil layer was varied to examine its influence on the ultimate bearing capacity.

B. Soil Behaviour and Material Properties

The stress-strain behaviour of the soil profile is modelled with Mohr- coulomb model. The required material parameters, including unit weight, stiffness, Poisson's ratio, cohesion, friction angle, and drainage condition, were assigned according to the soil type considered in each model..

Table-1: Properties of material

Parameters	Units	Sand	clay
Unit weight , γ_{unsat}	(kN/m³)	17.5	18
Unit weight , γ_{sat}	(kN/m³)	19	19
Young's modulus, E	(kN/m^2)	20,000	18,000
Angle of internal friction, φ	(°)	35	0
cohesion	(kN/m^2)	0	25, 40, 80

C. Foundation and Loading

The strip footing was represented by a plate element in PLAXIS 2D. The footing widths considered were 1 m and 2 m, while the corresponding structural properties were defined using the required axial stiffness and flexural rigidity.

A line load was applied along the footing to simulate foundation loading. The load was increased progressively during the calculation so that the variation of settlement with applied load could be obtained.

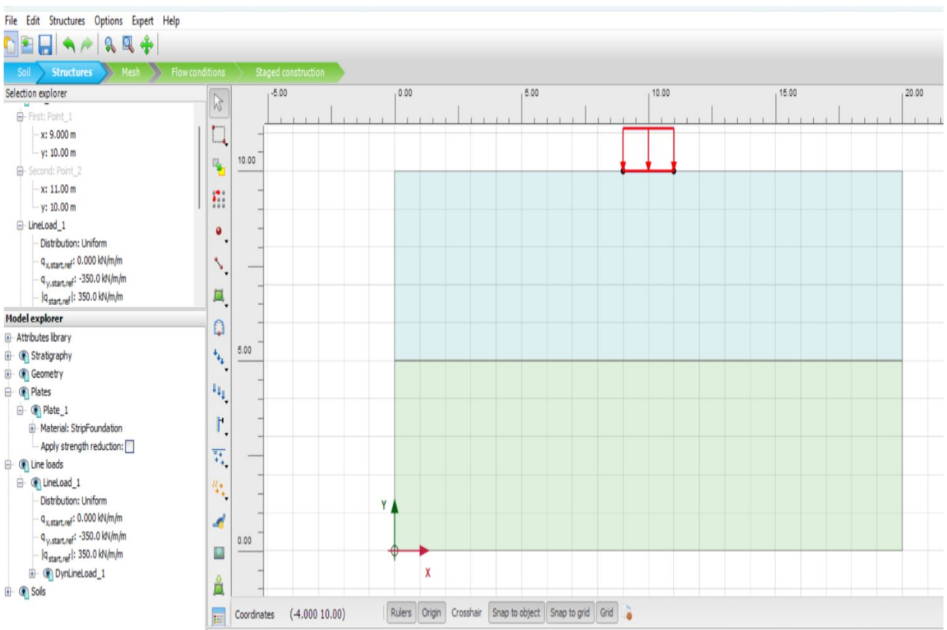


Fig 1: Creation of footing and line load in structure phase

D. Mesh Generation

A medium finite-element mesh was used for the analyses. The generated mesh provided adequate discretization of the soil domain and the region surrounding the footing, where significant changes in stress and deformation occur during loading.

E. Groundwater Conditions

The GWT was varied systematically and investigate its impact on the UBC of the Shallow foundation. Depth of the groundwater table below the ground level is represented by D_w.

The analyses included groundwater conditions at the GL and at different or various depths below the ground surface. A no-GWT condition was also considered as a reference case. The specified groundwater levels were introduced through the flow conditions before the foundation loading stage.

F. Modelling of Layered Soils

The effect of soil stratification was investigated using two layered configurations: sand overlying clay and clay overlying sand. In each case, the depth of the upper layer of soil was varied while the parameters of the underlying layer were kept unchanged.

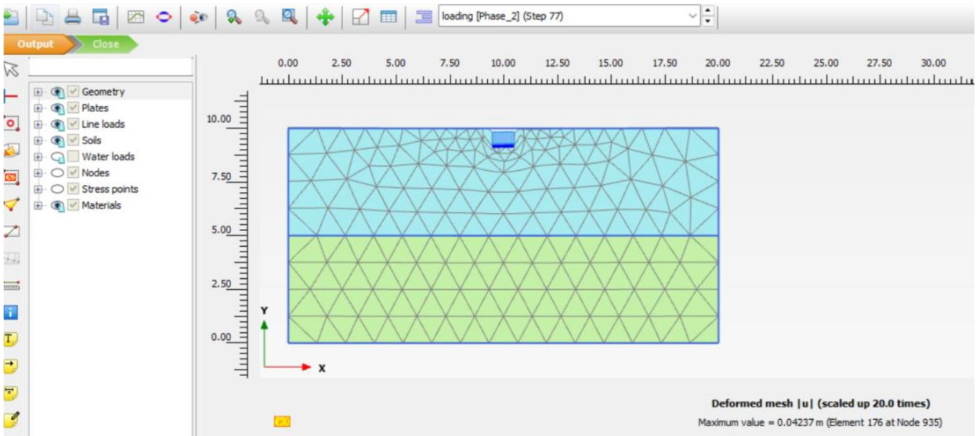


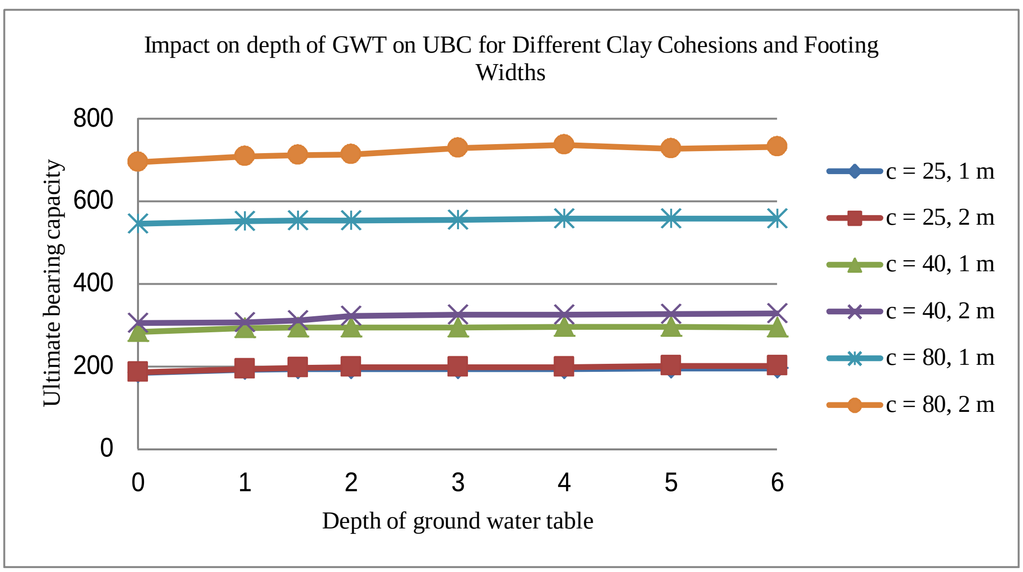
Fig 2: Deformed mesh in output window

V. RESULTS

The results acquired from the Finite Element Method (FEM) analysis through PLAXIS 2D are discussed in this section. The study examines the variation in UBC of shallow strip footings under different soil profile conditions and groundwater-table (GWT) depths. Effects of footing width, soil cohesion, soil profiles, and GWT position are considered. The numerical results are first discussed for homogeneous soils, followed by layered soil profiles

A. PLAXIS 2D – Ultimate bearing capacity

1) Homogeneous Clay



Graph 1: Variation of UBC of uniform clay with groundwater-table depth for different cohesion values and footing widths.

The impact of GWT depth on the UBC of uniform clay profile was examined for undrained cohesion values of 25, 40, and 80 kPa, considering footing widths of 1m and 2m. The GWT was varied from GL to 6 m below the GL.

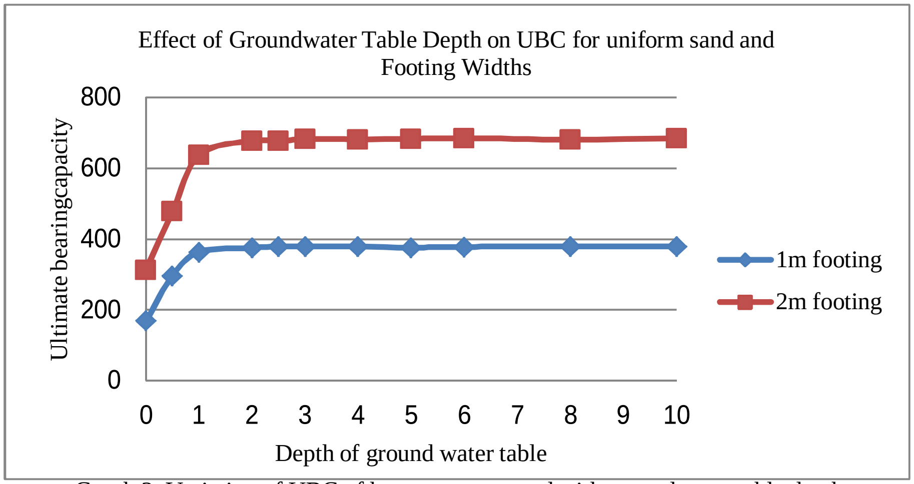
The observations give a clear increase in UBC with an increase in clay cohesion. At the ground-level groundwater condition, the values for the 1 m footing were 183.46, 284.03, and 546.65 kPa for c=25, 40, and 80 kPa, respectively. For the 2 m footing, the corresponding values were 185.56, 305.54, and 694.78 kPa**.**

For each cohesion value, lowering the groundwater table generally increased the ultimate bearing capacity. However, beyond the shallow groundwater depths, the change in became relatively small.

The 2 m footing consistently provided higher bearing-capacity values than the 1 m footing, with the difference being more noticeable for the higher cohesion soil. These observations shows that soil cohesion and footing width impact the bearing capacity of homogeneous clay, while the effect of groundwater depth becomes less pronounced as the water table moves deeper below the ground surface

2) Homogeneous Sand

The impact of GWT depth on the UBC of homogeneous sand was studied for 1 m and 2 m wide strip footings**.** The PLAXIS 2D results are presented in Graph 2.



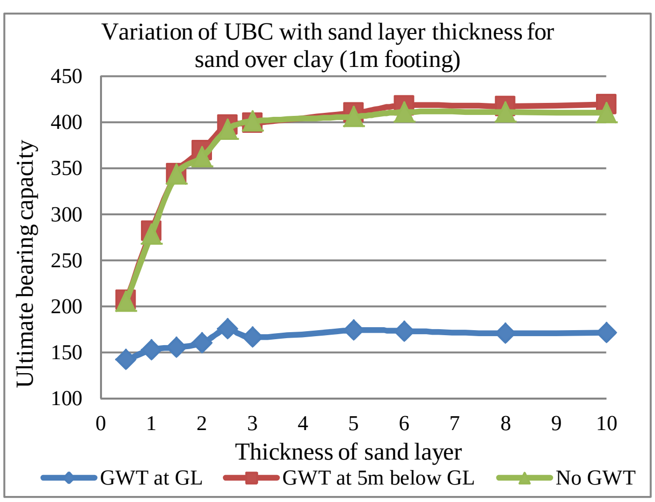
Graph 2: Variation of UBC of homogeneous sand with groundwater-table depth**.**

The results show that UBC increases with groundwater table moves below the ground surface. For 1m footing, increased from 169.40 kPa at GWT at GL to about 379.5 kPa at greater depths. For the 2 m footing, it increased from 313.60 kPa to a maximum of 717.65 kPa at 2.5 m depth. Beyond this depth, only small variations were observed. The 2 m footing generally showed higher bearing capacity than the 1 m footing.

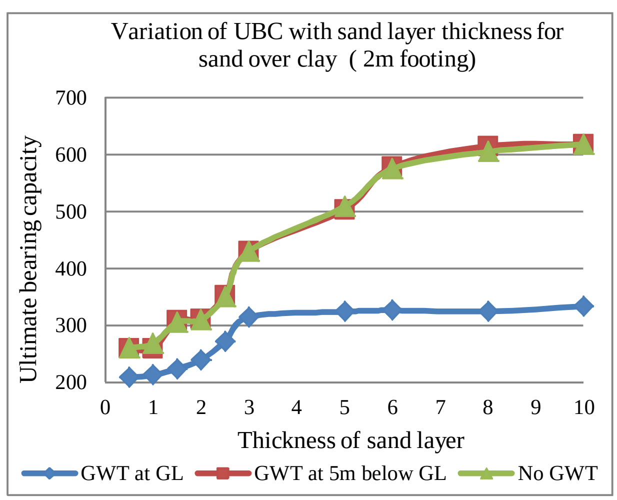
3) Sand over clay

a) Sand over clay – 1m and 2m footing

The variation in ultimate bearing capacity of strip footings resting on sand overlying clay was examined for different sand layer thicknesses and groundwater table conditions. The results obtained for 1 m and 2 m footing widths are presented together in Graph 3 and Graph4, respectively.



Graph 3: Variation of UBC for sand over clay under different groundwater conditions (1 m footing)



Graph 4: Variation of UBC for sand over clay under different groundwater conditions (2 m footing)

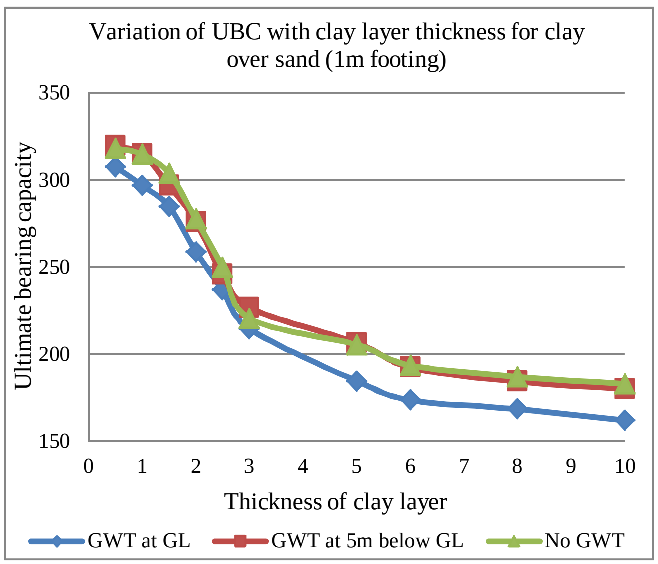
From the results, it is observed that the ultimate bearing capacity generally increases with an increase in the thickness of the upper sand layer for both 1 m and 2 m footing widths. The increase is more noticeable at smaller sand-layer thicknesses, as the stronger sand layer progressively contributes to the bearing resistance of the foundation. With further increase in the sand-layer thickness, the influence of the underlying clay layer becomes less significant, and the bearing capacity tends to approach the behaviour of a predominantly sand layer. Similar trends are observed for both footing widths, although the 2 m footing exhibits higher ultimate bearing capacity values than the 1 m footing under the corresponding conditions.

The groundwater table also has an impact on the UBC. When the GWT is located at the ground level, lower ultimate bearing capacity values are generally obtained due to the reduction in the effective unit weight of the soil. As the groundwater table is lowered to 5 m below GL, the bearing capacity increases considerably and approaches the values obtained for the no-groundwater condition. Thus, the effect of groundwater is more pronounced when the GWT is near to the foundation, while its influence becomes comparatively small when it is located sufficiently below the foundation level.

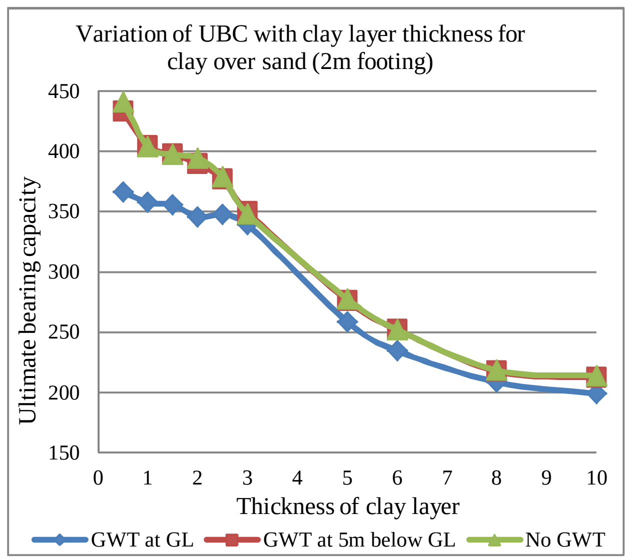
4) Clay over sand

a) Clay over sand – 1m and 2m footing

*T*he impact of groundwater conditions on the UBC of the 1m and 2 m strip footing was investigated for the clay-over-sand profile. The results are presented in graph 5 and graph 6 respectively.



Graph 5: Variation of UBC for clay over sand under different groundwater conditions (1 m footing)



Graph 6: Variation of UBC for clay over sand under different groundwater conditions (2 m footing)

From the results, it is observed that the UBC generally decreases with an increment in the thickness of the uppermost clay layer for both 1 m and 2 m footing widths. The reduction is more noticeable at smaller clay-layer thicknesses, indicating that the influence of the under sand layer is significant when the clay profile layer is relatively thin. As the thickness of the clay layer increases, the influence of the underlying sand layer gradually decreases, and the bearing capacity tends to be governed predominantly by the properties of the upper clay layer. Beyond a certain clay-layer thickness, further increase in the thickness of the clay layer produces only a relatively small change in ultimate bearing capacity. Similar trends are observed for both footing widths, with the 2 m footing generally showing higher ultimate bearing capacity than the 1 m footing under corresponding conditions.

The groundwater table also affects the UBC of the clay-over-sand system. The lowest bearing values are generally observed when the groundwater table is at ground level, whereas lowering the GWT to 5m below GL results in an increase in bearing capacity. The results for a groundwater table at 5 m depth are generally closer to those obtained under the no-groundwater condition, indicating that the influence of groundwater becomes less significant when the water table is sufficiently deep. Overall, the results indicate that both the thickness of the upper clay layer and the position of the groundwater table influence the ultimate bearing capacity of clay-over-sand foundations.

B. Analytical – Ultimate bearing capacity

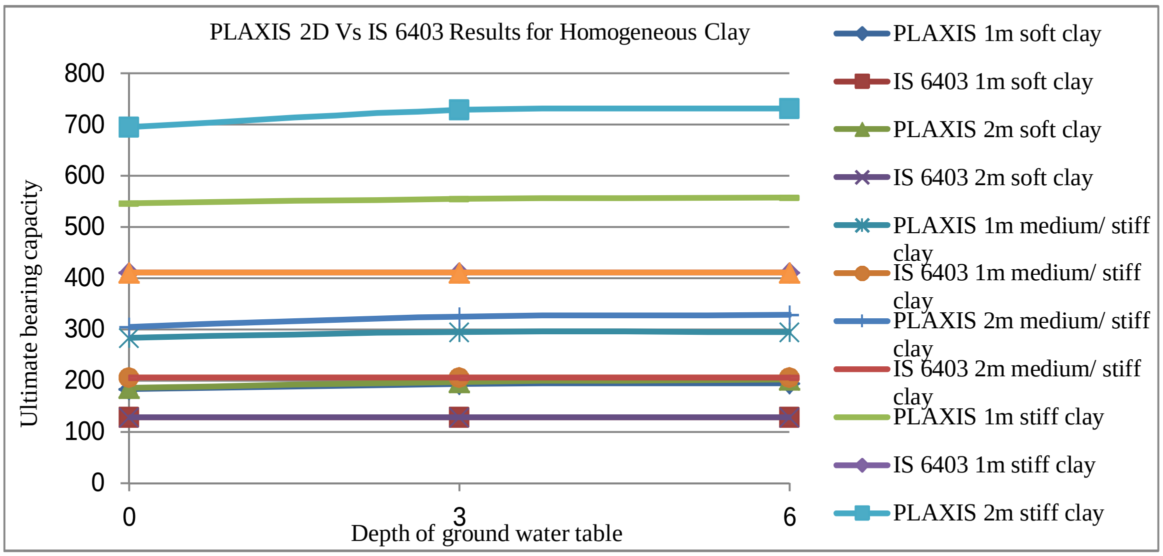
1) Homogeneous Clay

The influence of GWT depth on the ultimate bearing capacity of homogeneous clay was studied for 1 m and 2 m wide strip footings**.** The PLAXIS 2D Vs IS 6403 observations and results are shown in Graph 7.

The UBC of homogeneous clay was compared using IS 6403 and PLAXIS 2D for soft clay (C=25 kPa), medium/stiff clay (C=40 kPa), and stiff clay (C=80 kPa). Footing widths of 1 m and 2 m were considered under groundwater conditions at GL, 3 m below GL, and 6m below GWT.

The results show that the PLAXIS 2D values are higher than the IS 6403 valu**es** for all the cases considered. Bearing capacity increases with increasing clay cohesion and footing width. A gradual increase in PLAXIS results is also observed as the groundwater table is lowered.

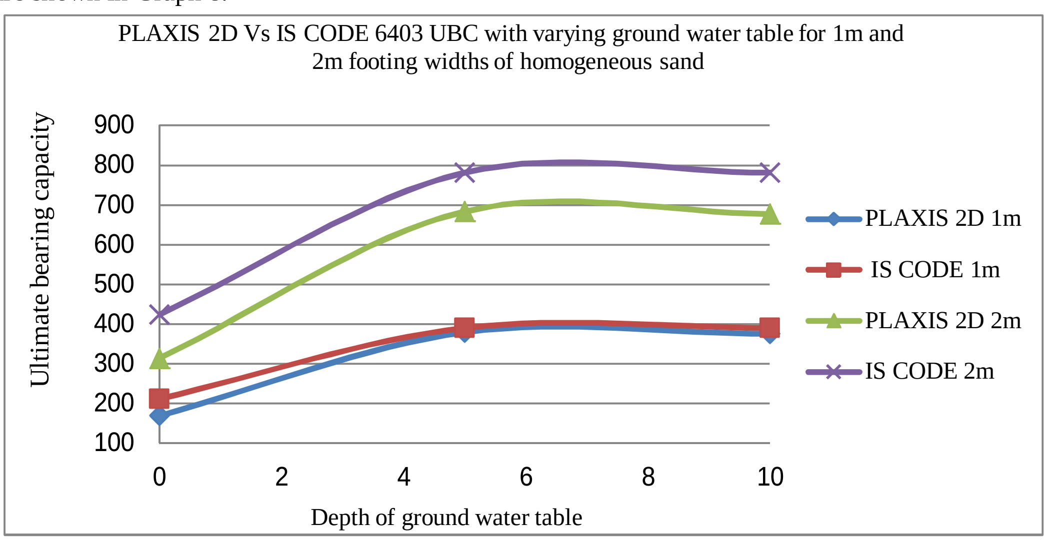
The difference between the analytical and numerical results becomes more noticeable for higher cohesion values. Overall, the comparison demonstrates the variation in UBC obtained by the analytical and numerical approaches for homogeneous clay.



Graph 7: Comparison of PLAXIS 2D Vs IS 6403 UBC of homogeneous clay for 1m and 2m footing widths

2) Homogeneous sand

The impact of GWT depth on the UBC of homogeneous sand was studied for 1 m and 2 m wide strip footings**.** The PLAXIS 2D Vs IS 6403 results are shown in Graph 8.



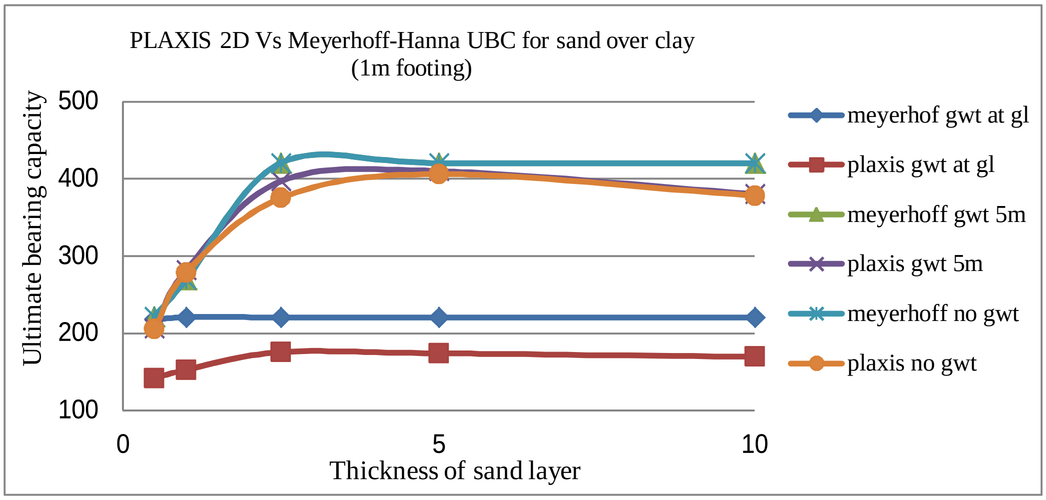
Graph 8: Comparison of PLAXIS 2D Vs IS 6403 UBC of homogeneous Sand for 1m and 2m footing widths

The results show that the groundwater table has a significant influence on the bearing capacity of homogeneous sand. When the GWT ia at GL, the UBC procured by PLAXIS 2D is considerably least than obtained from the IS 6403 calculations for both footing widths. As the GWT is lowered to 5m below GL, the bearing capacity increases substantially due to the reduced influence of groundwater on the buoyant unit weight of the soil profile. Further lowering of the groundwater table to 10 m produces only a small change in the PLAXIS 2D results, indicating that its influence becomes relatively insignificant at greater depths.

3) Sand over clay - Analytical method using Meyerhof- Hanna

a) Sand over clay – 1m footing

The ultimate bearing capacity obtained from PLAXIS 2D was compared with the Meyerhof–Hanna analytical method for different thicknesses of the upper sand layer under three groundwater conditions for 1m footing width. The results are provided in graph 9.

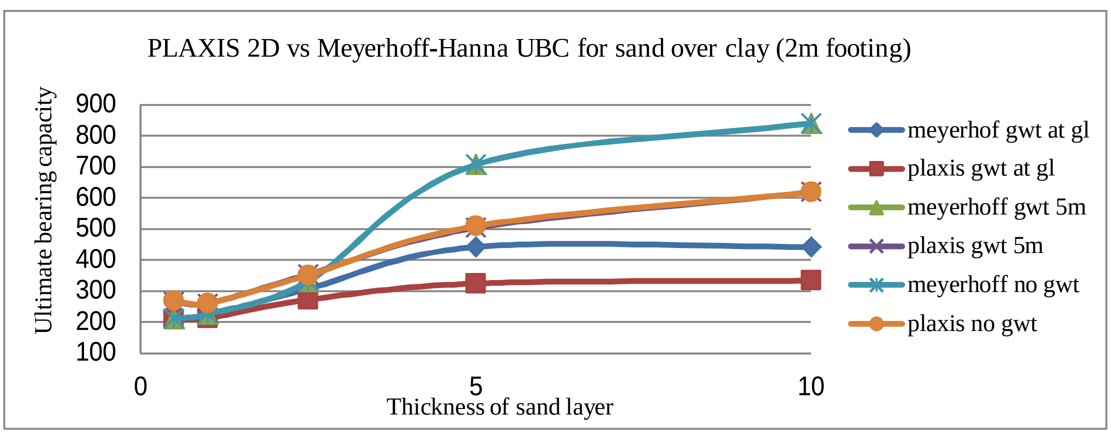


Graph 9: Comparison of PLAXIS 2D Vs Meyerhof–Hanna UBC for Sand over Clay with Varying Sand Layer Thickness and Groundwater Table Conditions (B = 1 m)

The comparison was made for different sand-layer thicknesses and groundwater table conditions. The PLAXIS 2D and analytical results show a generally similar pattern, although some differences are observed in the values for individual cases. These differences can be attributed to the assumptions and simplified treatment of soil interaction in the analytical method, while PLAXIS 2D considers the interaction between the soil layers and the resulting stress and deformation behaviour through numerical analysis. The comparison therefore shows the similarity between the analytical and numerical observations for the sand-over-clay soil profile.

b) Sand over clay - 2m footing

The ultimate bearing capacity obtained from PLAXIS 2D was compared with the Meyerhof–Hanna analytical method for different thicknesses of the upper sand layer under three groundwater conditions for 2m footing width. The results are presented in graph 10.



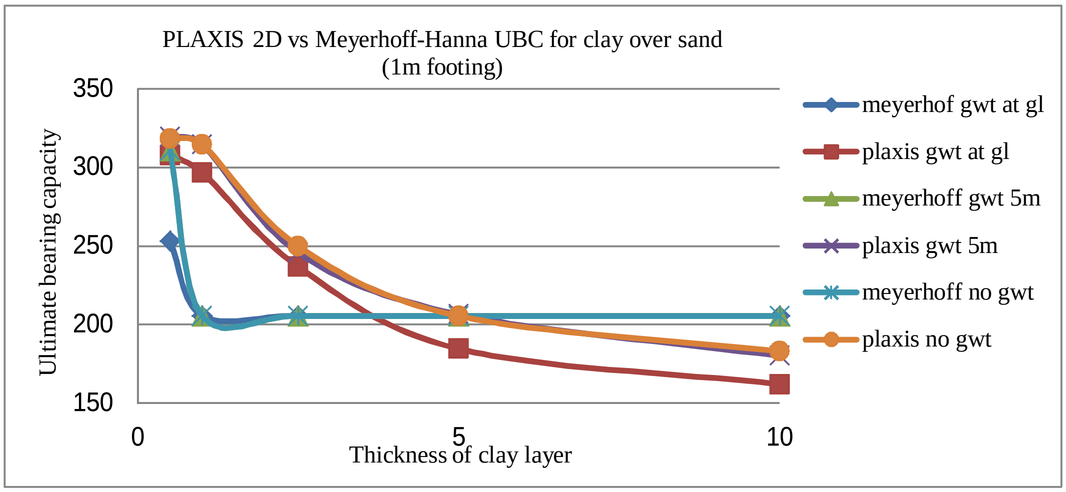
Graph 10: Comparison of PLAXIS 2D Vs Meyerhof–Hanna UBC for Sand over Clay with Varying Sand Layer Thickness and Groundwater Table Conditions (B = 2 m)

For the 2 m wide footing, the PLAXIS 2D ultimate bearing capacity values were compared with those obtained from the Meyerhof–Hanna method for different sand-layer thicknesses and groundwater conditions. The results show that the values from both methods are fairly close for some cases, while larger differences can be seen for certain sand-layer thicknesses, particularly for the deeper groundwater conditions.
The difference between the two methods is more noticeable as the thickness of the sand layer increases. This may be because the Meyerhof–Hanna method is based on simplified analytical assumptions, whereas PLAXIS 2D considers the interaction between the two soil layers and their deformation behaviour during loading.
The comparison shows that the two methods give different bearing capacity values for some cases, while following a broadly similar trend for the layered soil system.

4) Clay over sand – Analytical method using Meyerhof- Hanna

a) Clay over sand – 1m footing

The ultimate bearing capacity obtained from PLAXIS 2D was compared with the Meyerhof–Hanna analytical method for different thicknesses of the upper clay layer under three groundwater conditions for 1m footing width. The results are show in graph 11.

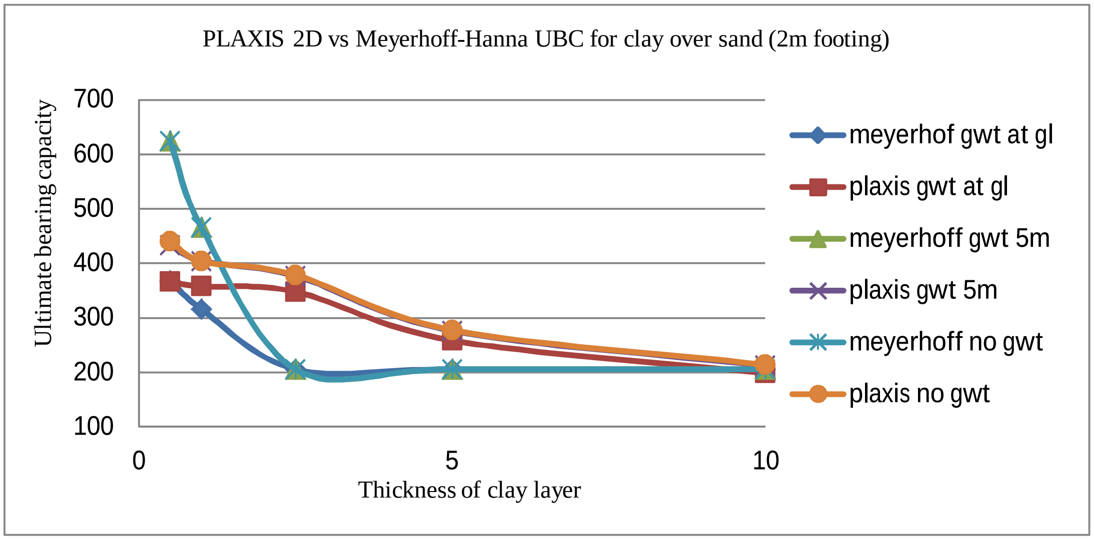


Graph 11: Comparison of PLAXIS 2D Vs Meyerhof–Hanna UBC for clay over sand with Varying clay Layer Thickness and Groundwater Table Conditions (B = 1 m)

For the 1 m wide footing, the ultimate bearing capacity obtained from PLAXIS 2D was compared with the values calculated using the Meyerhof–Hanna method for different thicknesses of the underlying sand layer and groundwater conditions. The comparison shows that the two methods give relatively close values approximately, particularly at larger sand-layer thicknesses, while noticeable differences are observed in other cases.
The analytical method gives a more simplified representation of the interaction between the clay and sand layers, whereas PLAXIS 2D accounts for the stress distribution and deformation behaviour within the layered soil system. The differences between the two approaches are therefore expected, particularly where the thickness of the underlying sand layer changes the contribution of the lower soil layer.
Overall, the comparison provides a direct assessment of the analytical and numerical approaches for estimating the UBC of the clay-over-sand profile.

b) Clay over sand – 2m footing

The results of UBC acquired from PLAXIS 2D were compared with the Meyerhof–Hanna analytical method for different thicknesses of the upper clay layer under three groundwater conditions for 2m footing width. The results and observations are shown in graph 12.



Graph 12: Comparison of PLAXIS 2D Vs Meyerhof–Hanna UBC for clay over sand with Varying clay Layer Thickness and Groundwater Table Conditions (B = 2 m)

For the 2 m wide footing, the UBC obtained from PLAXIS 2D was compared with the values calculated using the Meyerhof–Hanna method for different thicknesses or soil profiles of the underlying sand layer and groundwater conditions. The results show close agreement between the two methods for some cases, particularly for smaller sand-layer thicknesses under the groundwater table at ground level. However, larger differences are observed for some of the other cases, especially when the sand layer becomes thicker. These differences may be due to the simplified assumptions used in the Meyerhof–Hanna method, while PLAXIS 2D considers the interaction between the clay and sand layers and the deformation of the soil during loading. Overall, the comparison shows that the analytical and numerical methods give different bearing capacity values for certain layered soil conditions, while providing a useful comparison for the clay-over-sand profile.

VI. CONCLUSION

Based on the numerical analyses performed using PLAXIS 2D and the analytical calculations for homogeneous and hetrogeneous soil profiles under different GWT conditions, the conclusions are presented below:

1) The UBC of homogeneous clay increases with increasing groundwater depth and cohesion. For clay with C =40 kPa, the bearing capacity increased from 284.03 to 295.23 kPa for a 1 m footing and from 305.54 to 328.34 kPa for a 2 m footing as the GWT was lowered from ground level to 6m below ground level.
2) The presence of groundwater has a more pronounced effect on the bearing capacity of sand than on clay. For a 1 m footing, the PLAXIS 2D bearing capacity increased from 169.4 kPa at groundwater level at ground surface to 379.4 kPa without groundwater, while for a 2 m footing it increased from 313.6 to 684.25 kPa.
3) An increase in footing width from 1 m to 2 m resulted in higher UBC for both homogeneous and layered soil profiles. The magnitude of increase, however, varied with soil type, layer configuration, and groundwater condition.
4) For sand over clay, the UBC was strongly influenced by the thickness of the topmost sand layer. For the investigated case, the PLAXIS 2D values for sand thicknesses of 0.5, 1.0, 1.5 and 2.0 m were 141.8, 152.6, 155.36 and 159.95 kPa for GWT at GL case respectively, indicating that the variation in bearing capacity with increases in sand layer thickness.
5) For clay overlying sand, the UBC was governed by the thickness and strength of the top clay stratum together with the contribution of the underlying sand layer. The results indicate that the bearing capacity response of a layered foundation cannot be evaluated solely from the properties of the uppermost soil layer.
6) The comparison of PLAXIS 2D and IS 6403 for homogeneous soils showed comparable trends with respect to groundwater depth and footing width. For groundwater at ground surface, the bearing capacities for the 1 m footing were 169.4 kPa and 212.07 kPa, and for the 2 m footing were 313.6 kPa and 424.16 kPa, from PLAXIS 2D and IS 6403, respectively.

7) The comparison of PLAXIS 2D with the Meyerhof–Hanna method for layered soils showed generally similar trends with changes in layer thickness, footing width, and groundwater condition, although differences in the magnitude of UBC were observed due to the assumptions and simplifications adopted in the analytical formulation.
8) The study demonstrates that groundwater depth, soil strength, footing width, and layer thickness and arrangement of soil profile are the major parameters influencing the ultimate bearing capacity of shallow foundations. The results also indicate that the use of numerical analysis along with analytical methods provides a useful basis for assessing foundation behaviour in both homogeneous and layered soil conditions.

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