RATIONAL APPLICATION OF ANALYTICAL SOLUTIONS IN THE ESTIMATION OF BEARING CAPACITY

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ABSTRACT

Estimation of foundation capacity is an essential design criterion for any infrastructure. Typically, analytical solutions based on simplified assumptions have been used in estimating foundation capacity. Simplified assumptions in developing analytical solutions may require further investigation to validate the foundation capacity under different soil conditions. The development of computational capacity nowadays allows sophisticated numerical methods to capture the widespread behavior of any problem domain. Considering this fact, a series of numerical simulations in Finite Element Model (FEM) has been conducted to determine the bearing capacity of soils at different conditions. Mohr-Coulomb failure law has been employed as a constitutive model for soil particles, and representative boundary conditions have been considered. Besides that, a single sand layer has been utilized in the numerical environment for model validation. Two models are selected for numerical simulation; one model is simulated considering the overburdened soil layer, and the other is simulated without considering the same. A numerical model incorporating an overburdened soil layer provides better results. Subsequently, parametric studies of different soil and foundation properties have been carried out. With a set of parametric studies, a guideline may be provided to the practicing engineers to get an idea about the rational foundation capacity under different geological and geometrical conditions.

Keywords**:** *Bearing capacity, numerical method, Terzaghi's solution, PLAXIS 2D, parametric study.*

1. INTRODUCTION

Typically, foundations are built to meet criteria of usefulness and resilience to support structures and equipment. To support the implementation of architectural goals, especially in the context of structures, the foundations must function at their best. The importance of foundation settling increases as the foundation is subjected to working loads. In the soil, well-designed foundations provide stress-strain states that don't display linear elasticity or perfect plasticity. The ultimate load that a foundation can support is calculated by bearing capacity theory. Terzaghi and Meyerhof's equations for bearing capacity analysis are the two most widely used methods. These equations were the result of several experimental investigations which led to an empirical solution. For shallow foundations with uneven geometry sitting on varied subsoil, the bearing capacity may be calculated using the finite element approach (Chavda & Dodagoudar, 2018). Over the years, Terzaghi and Meyerhof's formulas have evolved, incorporating more accurate soil models and considering additional factors. The estimation of bearing capacity for shallow foundations has been refined through the development of alternative equations, numerical methods, and analytical approaches (Acharyya & Dey, 2017). In this regard, PLAXIS 2D simulation software plays a vital role. The complexity of soil sets it apart from other materials, requiring analytical methodologies that have been further developed in recent decades with the aid of computer technology and finite element programs. Selecting the appropriate computer program that incorporates the relevant material model and parameters is crucial to producing logical and realistic results. Constitutive models are critical to examining geotechnical structures and simulating soil behavior. As soil behavior can be quite intricate, there is a growing push to create more accurate models in business codes that take this into account. The traditional methods of calculating soil bearing capacity have included analyses of limit equilibrium, slip line approximations, and numerical methods. Because of technological improvements, geotechnical specialists have increasingly resorted to the Finite Element Method in recent years. This research holds great importance to underdeveloped regions facing challenges such as limited accessibility, lack of advanced soil investigation equipment, and a shortage of skilled professionals in the field.

Although several research has been carried out to determine the bearing capacity of soil by simulation software none of these predicts the overall variations of soil bearing capacity for different conditions. Purba & Perdana (2001) used elastoplastic finite element analysis (FEA) to examine how a strip footing behaved while it was sitting on a homogeneous clay surface in an undrained state. It was discovered that as the consistency of clay changes from hard to extremely soft and when the inclined load increases, the strip footings' ultimate bearing capacity diminishes. Yee (2017) performed a comparison of empirical analysis utilizing the Vesic, Hansen, Meyerhof, and Terzaghi models with the numerical analysis with PLAXIS 2D. The differences between each model are discussed in the study. The strip footing's bearing capacity was examined in three scenarios using various soil friction angles. Three distinct footing depths were utilized in the meantime for the settling study. Abdullah (2022) developed a numerical model by PLAXIS 2D to examine the bearing capacity of Sultana's Soil in the Najran region, Saudi Arabia, and obtained that foundation at 1.5 m embedment depth, exhibits little discrepancy between the PLAXIS 2D and Terzaghi values. However, it is necessary to conduct further research to understand the aptness of finite element modeling in determining the variations of soil's bearing capacity and its accuracy by comparing the results with the traditional methods.

This study can provide valuable insights into the numerical formulations of shallow foundations, leading to more promising results compared to traditional analyses. It aims to determine the most preferable and effective approximation method to implement in the study. The following objectives have been determined to carry out the investigation:

1. To utilize finite element analysis to determine the soil's ability to support loads.
2. To compare PLAXIS software-derived load-bearing capacity evaluations with traditional theories.
3. Using the present approach, to determine the load-bearing capacity of the soil.
4. To conduct a parametric study aimed at identifying the sensitivity of various factors in both material and geometric modeling influencing bearing capacity

2. METHODOLOGY

The methodology adopted for conducting the study is depicted in the workflow diagram in Figure 1.

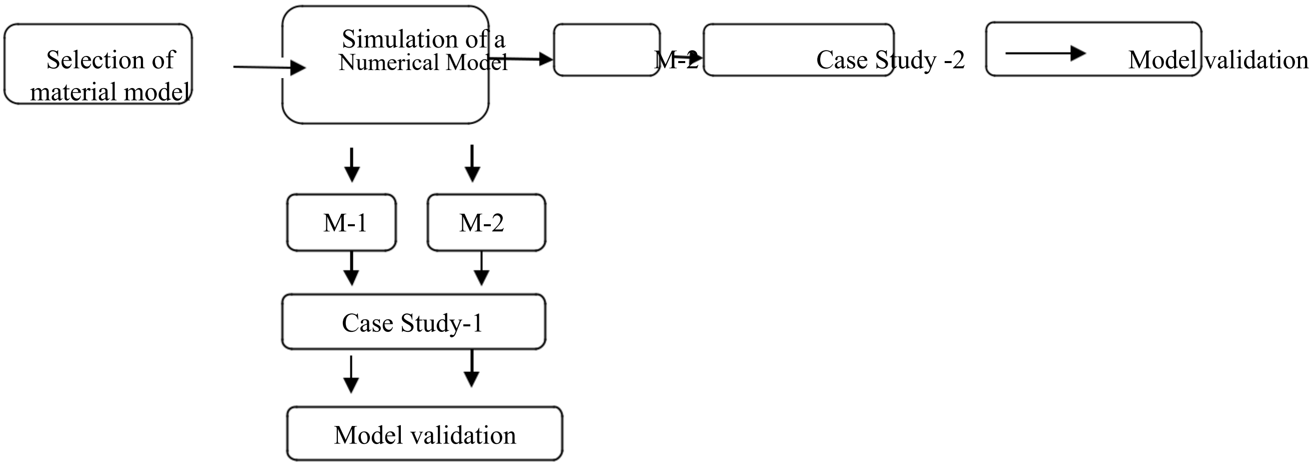


Figure 1: Workflow Diagram

2.1 Material Modelling

A material model is developed considering the friction angle and soil cohesion. Several Mohr-Coulomb model parameters are considered, such as the soil modulus of elasticity and the shear strength parameters such as cohesion and angle of internal friction. All the input parameters are chosen arbitrarily and represented in Figure 2.

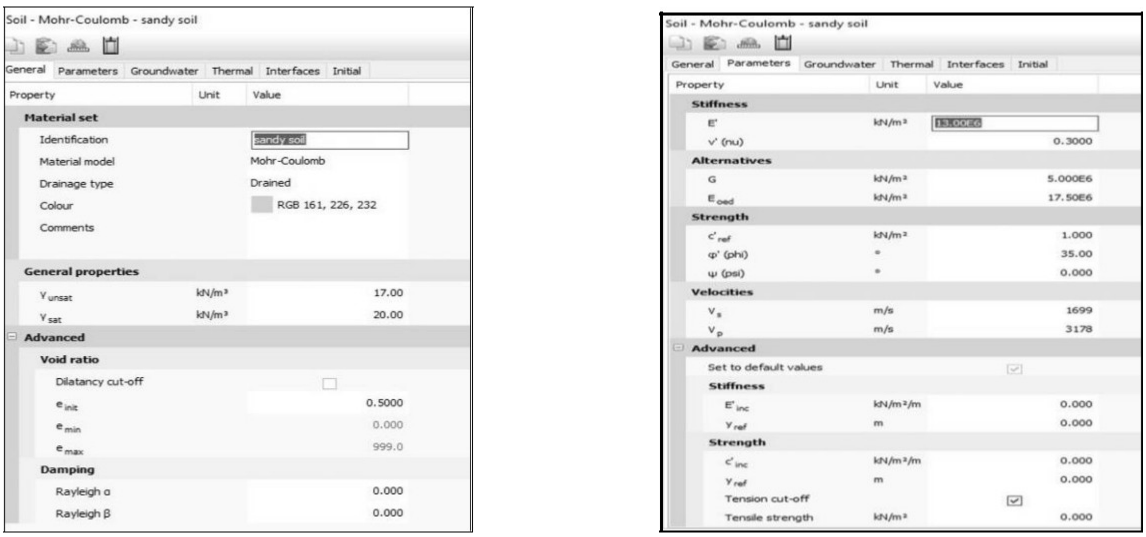


Figure 2: Input Parameters

2.2 Geometric Modelling

Two types of ground models are presented for simulation in this study which is shown in Figure 3.
Method-1: In this model geometry of overburdened soil over the top of the footing is not included and is denoted as M-1.
Method-2: In this model, the soil layer is sketched up to the ground surface and the model is denoted as M-2.

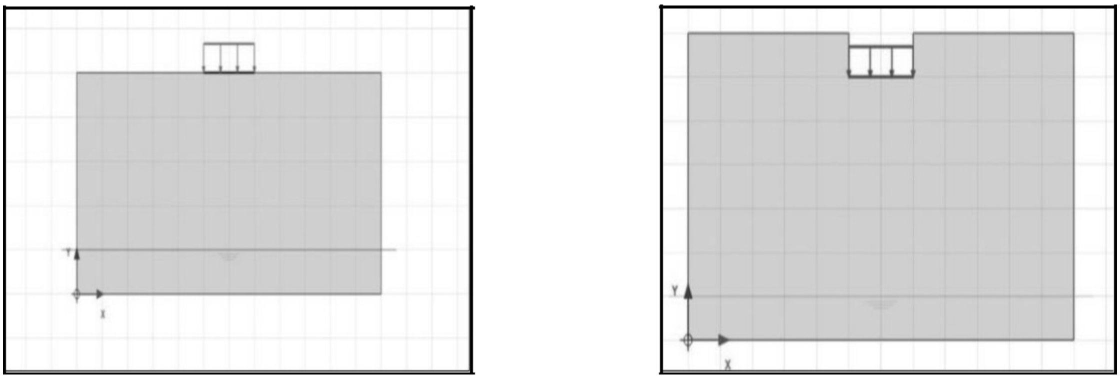


Figure 3: Geometric Representation of the models

2.3 Analytical Procedure

In this study, ultimate bearing capacity is determined by a graphical analysis of the load-settlement curve obtained from the simulation output. Two case studies are chosen for the investigation which are explained in the subsequent articles.

2.3.1 Case Study- 1

A rectangular footing is considered beneath 2 meters from the ground surface. It is expected that there is a 5m thick layer of uniform sandy soil beneath the footing. The depth of the groundwater is considered to be 6 meters below. The soil beneath the footing's bearing capacity is investigated for various friction angles. The use of empirical formulas is utilized to compare the two approaches.

2.3.2 Case Study- 2

Variation of Ultimate Bearing Capacity is investigated for different parameters which are mentioned below:
1. Effect of location of Ground Water Level
2. Effect of different depths of footing (D_f)
3. Effect of different friction angles (Ø`)

3. RESULTS

3.1 Case Study-1

3.1.1 Comparison Of Simulation Results with Empirical Equations

The ultimate bearing capacity of the simulated model is compared with the conventional equations of Terzaghi which is presented in Table 1. Bearing Capacity (Qu) in KN/m^2 is calculated by Terzaghi's (1943) solution which is stated in Equation 1.

$$q_u = c' N_C + q_o N_q + 0.5\gamma B N_\gamma \qquad (1)$$

Where,
C: Cohesion of soil,
γ: unit weight of soil, D: depth of footing,
B: width of footing

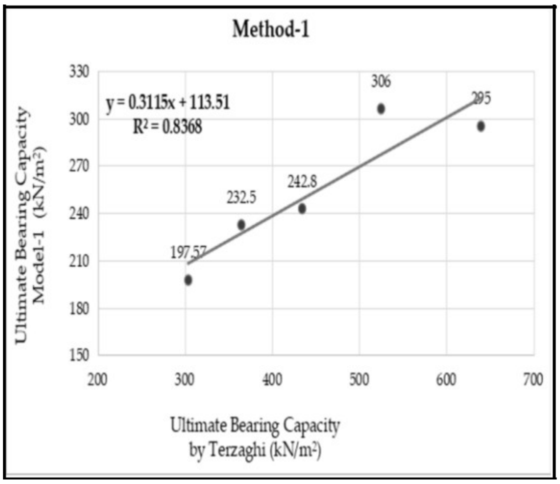
N_c, N_q, N_r: Terzaghi's bearing capacity factors depend on soil friction angle, φ which are calculated from equation 2, equation 3, and equation 4 respectively.

$N_c = \cot\varphi(N_q - 1)$ (2)
$N_q = e^{2(3\pi/4 - \varphi/2)\tan\varphi} / [2\cos^2(45 + \varphi/2)]$ (3)
$N_\gamma = (1/2)\tan\varphi(K_{pr}/\cos^2\varphi - 1)$ (4)
K_{pr}= passive pressure coefficient.

Table 1: Ultimate Bearing Capacity Comparison

(Ø`)	Qu (M-1)	Q_u (M-2)	Q_u (Terzaghi)
28	197.57	216.2	303.91
30	232.5	240	364.80
32	242.8	250	434.48
34	306	265	525.00
36	295	295	639.57

The graphical representation of the comparison of ultimate bearing capacity obtained by the Terzaghi equation with that of the PLAXIS 2D simulation is shown in Figure 4. It is visible from the graphs that Model 2 resembles a much better linear relationship suggesting the necessity to consider the overburden soil layer for bearing capacity estimation. Thus model 2 is considered for further investigation.



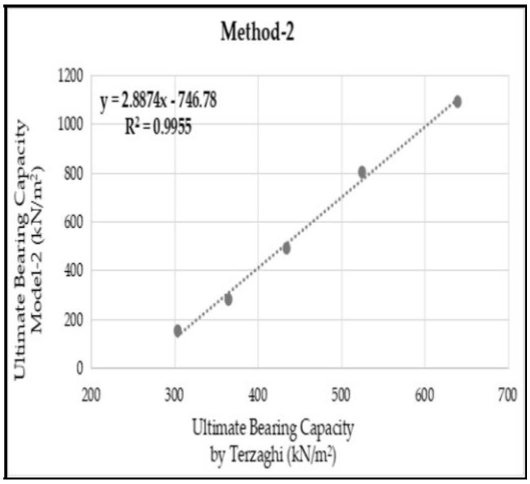


Figure 4: Graphical Comparison of the analytical results with PLAXIS 2D

3.2 Case Study-2

3.2.1 Effect of Ground Water Table (GWT) on Bearing Capacity

The variations in bearing capacity are observed due to an increase in the groundwater table under the existing ground level which is represented in Figure 5 by plotting Bearing Capacity vs Depth of GWT. The graph suggests the rise in the bearing capacity of soil with the increase in depth of the water table from ground level. The numerical solution curve also provides the validation of the conventional result by resembling a similar trend.

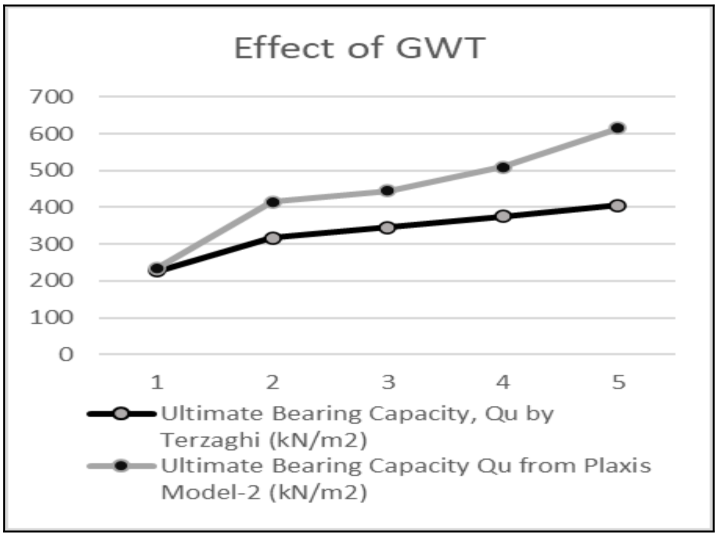


Figure 5: Variations in Bearing Capacity due to change in GWT

3.2.2 Effect of Depth of Footing on Bearing Capacity

The change of ultimate bearing capacity (Qu) in KN/m^2 is measured for different depths of footing considering the following parameters and is depicted in Figure 6. The Terzaghi estimation shows a different shift up to some extent but shows a similar trend in the later portion as the numerical simulation suggests. However, a general trend of the curve gives an idea about the changes of bearing capacity which can be useful for practical considerations during foundation design.

Depth of soil layer below footing = 2 m
Soil friction angle (Ø´) = 35º
Groundwater level lies 1 m below the footing
Width of footing, (B) = 2

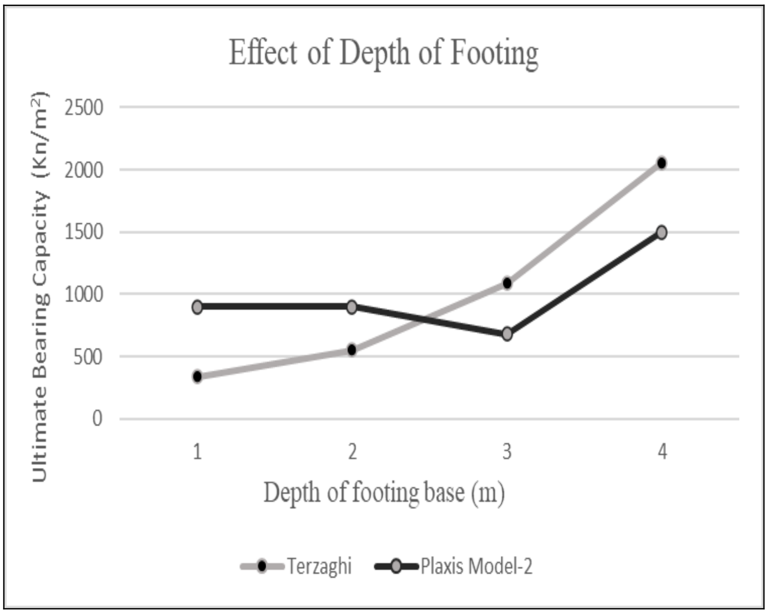


Figure 6: Variations in Bearing Capacity due to change in depth of footing

3.2.3 Effect of Soil Friction Angle on Bearing Capacity

The variations in ultimate bearing capacity (Qu) due to the change in soil friction angle are represented in Figure 7. The rise in the bearing capacity of soil due to the increase in friction angle by the Terzaghi equation is validated by the numerical simulation as both show a similar trend.

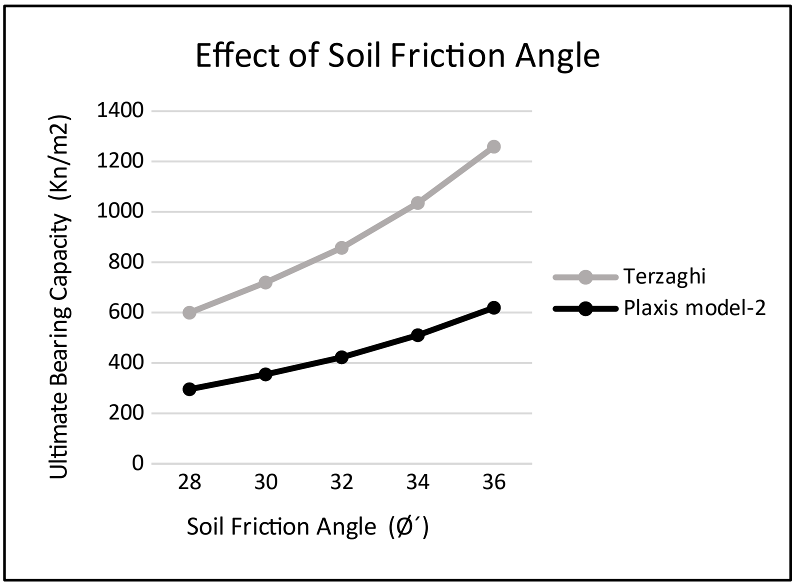


Figure 7: Variations in Bearing Capacity due to change in soil friction angle

3.3 Deformed Mesh

The Deformed mesh which showcases the transformation of the structure from its original shape is shown in Figure 8.

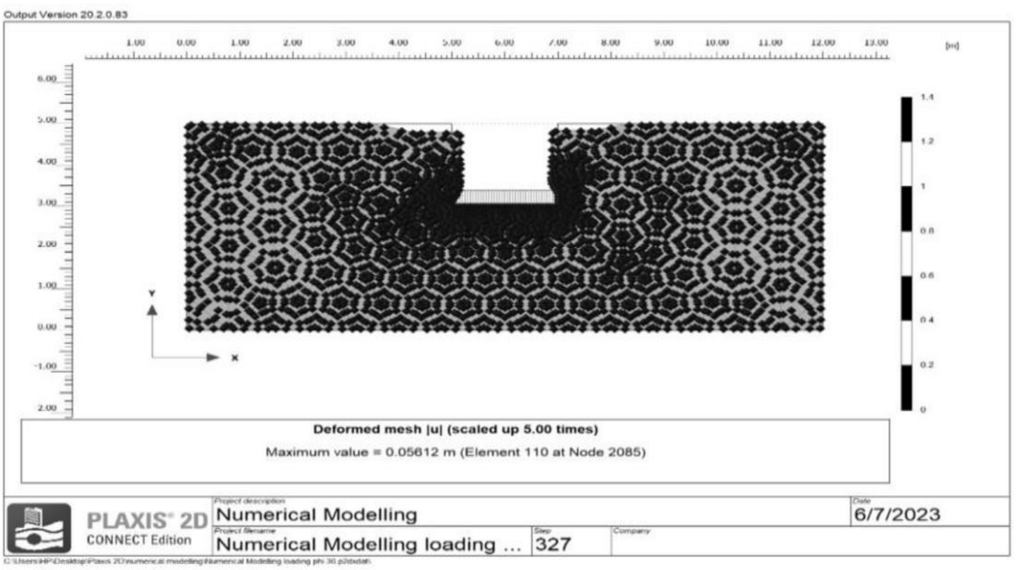


Figure 8: Deformed Mesh Condition

4. CONCLUSION

From the analysis of the results, it has been observed that when it comes to determining the ultimate bearing capacity of shallow foundations, the PLAXIS Software consistently provides an output that is in line with the conventional empirical formulas. Two case studies are considered to understand the finite element behavior of soil. In the first case, two models are developed which indicates that it is essential to consider the overburdened soil layer that lies upon the footing, as the conventional solution and numerical solution suggest a much better linear relationship in this case. This consideration is crucial as it leads to more precise results. In the second case, the variation in bearing capacity is observed for three different scenarios by both numerical modeling and the conventional Terzaghi equation. The analysis obtained three findings. First, the effect of the groundwater table is visible in the estimation of bearing capacity. The PLAXIS model validates the analytical result by generating a similar trend. Second, the change in footing depth has a significant role in determining the bearing capacity of soil. However, the numerical model doesn't fully comply with the trend of the Terzaghi solution. Finally, it is worth noting that the increase in bearing capacity due to the increase in soil friction angle is validated by numerical modeling. Thus, the use of a numerical model in the foundation design can greatly help geotechnical engineers to understand the possible change of bearing capacity due to various sub-surface conditions.

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