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Research Article

Determination of the Displacement of Shallow Foundations Sitting on Unsaturated Soils Using Analytical and Numerical Analysis Methods

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ABSTRACT

The bearing capacity of a foundation is crucial for ensuring the stability and safety of structures. However, shallow foundations on unsaturated soils pose challenges due to the complicated behavior of such soils. To address this issue, engineers have developed analytical and numerical methods of analysis, which can be used to determine the bearing capacity of these foundations. This study explored the advantages and disadvantages of these methods, offering a thorough understanding of their role in ensuring the safety and longevity of structures built on unsaturated soil. The analysis in this study was conducted using finite element method simulations on soil sections with varying groundwater levels and degrees of saturation. The results obtained from PLAXIS 2D simulations revealed the effects of fluctuations in groundwater levels and changes in saturation degree on foundation displacements, emphasizing aspects often overlooked in empirical approaches. Under unsaturated conditions, as the degree of saturation decreased, the soil was better able to maintain its structural integrity, resulting in reduced foundation displacements. However, at near-complete saturation (%99), displacements increased significantly, highlighting the risks to foundation stability in soils with high saturation levels, particularly in flood-prone areas. Variability in excess pore water pressure in sections with high saturation indicated potential soil instability under high stresses, impacting structural integrity. Furthermore, finite element analyses showed that classifying soil as drained or undrained impacted foundation displacements. In conclusion, the comprehensive analysis provided by numerical methods emphasized the limitations of empirical approaches and underscored the importance of advanced simulation tools in modern geotechnical practices.

1. Introduction

As urban populations expand and the global population surpasses 8 billion, the demand for civil structures has increased significantly. Bridges, towers, and dams are just a few examples of the vital infrastructure required to sustain our modern world. However, one crucial element that cannot be overlooked is the foundation. Without a sturdy foundation, these structures risk collapse and failure. It is imperative that foundations are meticulously designed and constructed, as they are essential for ensuring the safety and durability of our built environment.

Terzaghi's research in 1943 [1] was a significant achievement in geotechnical engineering since it presented the first comprehensive theory for assessing the bearing capacity of shallow foundations. Terzaghi's work mainly focused on analyzing continuous foundations, which have specific dimensions, including width (B) and depth (D_f). However, his estimation of bearing capacity factors overlooked a critical aspect: the soil shear strength beneath the foundation. This omission meant that Terzaghi's approach did not

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fully capture the complexity of soil behavior and its influence on bearing capacity calculations [2].

Building upon Terzaghi's work, Meyerhof proposed a more comprehensive theory on bearing capacity. He emphasized the importance of considering shear strength to achieve more reliable and precise estimates of bearing capacity factors. Meyerhof's contributions significantly enhanced the understanding of soil behavior under foundations, leading to more accurate and dependable designs [3].

Further advancements were made by Hansen in 1970, who developed a formula that parallels Meyerhof's (1951) bearing capacity calculation. Hansen's formula additionally considered factors such as slope angle, soil slope, and foundation eccentricity. The bearing capacity calculation method developed by Vesic [4] resembles Hansen's method but includes different approaches for calculating the foundation stress factors (b_i), soil slope factors (g_i), and load slope factors (i_i). Unlike Hansen, Vesic did not consider the eccentricity effect in bearing capacity calculations but accepted the foundation dimensions [5].

Research by Broms in 1963 [6] investigated the impact of the degree of saturation on the bearing capacity of flexible pavements. In 1987, Steensen-Bach researched the load-bearing capacity of shallow foundations on two types of sands under both saturated and unsaturated conditions [7]. Gan et al. [8] aimed to determine the shear strength parameters of unsaturated glacial clay using a modified shear box test apparatus. Building on this, Fredlund and Rahardjo in 1993 proposed a shear strength equation for unsaturated soils by expanding the traditional shear resistance equation. They included the effect of capillary stress in the apparent cohesion term, thus extending the total stress approach [6-9].

Unsaturated soil (UNS) mechanics is commonly considered a part of saturated soil mechanics, and saturated soil parameters are preferred in calculations. After many studies in the 1960s, the results found a big difference between saturated and unsaturated soils, if the soil has more than %98 voids filled with water and when the air bubbles are not directly connected, they are called saturated soil. If the volume is %95 or less, the soil loses its saturated characteristics, and as a result, it is referred to as unsaturated soil [10]. However, after many studies, the results have discovered a very thick layer formed between water and air, called the water-air interface. When conducting tests on the mass–volume relationships of UNS, the water-air interface is typically disregarded due to its minimal volume [10-12].

Manavirad and Noorzad's study in 2014 aimed to investigate the impact of geotextile combinations on two nearby strip foundations situated on the surface of soft clay using the Plaxis 3D program. Despite these advancements, limited research has investigated the role of Plaxis in unsaturated soil conditions. The impact of unsaturated soil behavior on foundation performance remains an area needing further exploration, particularly using advanced simulation tools like Plaxis to enhance understanding and improve foundation design practices. This gap in research highlights the need for continued studies to ensure that foundation designs are robust and reliable under various soil conditions [12].

Engineers used to design projects based on bearing capacity until the 1950s. They stated that if the bearing capacity is sufficient, the foundation will not settle. However, Hough, Fredlund and Rahardjo [9, 13] emphasized the need to consider both aspects together. In the design of engineering structures, the settlement rate is as important as the settlement amount. Especially in cases of excessive settlements, structural and/or non-structural damage may occur in situations where settlement is rapid or even if settlement is not rapid. Settlement (St) has three components: immediate settlement (distortion settlement) (Si), consolidation settlement (time-dependent) (Sc), and secondary settlement (time-dependent) (Ss) [14-17].

Researchers have identified three types of bearing capacity settlements (failures): general shear settlement, punching shear settlement and regional (partial, local). When it comes to shallow foundations, understanding bearing capacity is crucial. Fortunately, over time, experts like Terzaghi have developed theories and solutions for various load conditions, including the widely used theories: Meyerhof, Brinch Hansen , and Vesic [4, 16-20].

Over the past five years, Garakani et al. [21] examined the bearing capacity of shallow foundations on unsaturated soils through a new analytical solution and three-dimensional numerical simulations. The analytical and numerical models were validated using experimental results from physical modeling and in-situ plate loading tests on unsaturated soils.

Ravichandran et al. [22] demonstrated that using Monte Carlo simulation to determine the bearing capacity of a footing in unsaturated soil was an effective approach for applying unsaturated soil mechanics to engineering problems. Their study showed that accounting for unsaturated soils in design could increase the bearing capacity of a footing by at least 2.3 times compared to Meyerhof's equation. The research focused on homogeneous soil with one-dimensional flow, but the method could be extended to two-dimensional and three-dimensional cases.

Du et al. [23] investigated the bearing capacity of shallow foundations on unsaturated soils by considering the variation in shear strength due to matric suction. Recognizing that matric suction typically varies with depth, the study utilized the discretization technique of limit analysis, which was well-suited for addressing spatial variations in soil parameters. This approach enabled a more realistic evaluation of bearing capacity for shallow foundations on unsaturated soils by accounting for the depth-dependent changes in shear strength. However, continued research, particularly into the behavior of unsaturated soils and advanced simulation tools like Plaxis, is essential for further advancements in geotechnical engineering.

In this study, the aim was to determine the bearing capacity of shallow foundations located on an unsaturated soil layer. The analyses, conducted using Plaxis 2D software, aimed to achieve the following points: evaluate the behavior of unsaturated soils, accurately estimate the bearing capacity of shallow foundations resting on unsaturated soils, and examine the behavior of unsaturated soil in sections with different groundwater levels. Additionally, the study analyzed the effects of water level on the soil and displacement and examined the changes in soil with different degrees of saturation (from %99 to %50) and the resulting changes in displacement and pore water pressure.

2. Materials and Methods

Various methods [6-9], both theoretical and empirical, were employed to investigate the behavior of soil. These approaches continuously evolve to simplify the intricate nature of the soil and its behavioral characteristics. However, with the emergence of computer and software technologies, numerical methods have become a valuable tool in solving geotechnical problems by offering more realistic and efficient solutions, similar to other engineering challenges. In these methods, differential equations describe the behavior of physical systems, which are analyzed through numerical techniques.

The Finite Element Method (FEM) is an effective technique for solving continuous systems described by mathematical expressions. FEM achieved this by breaking down continuous systems into a finite number of interconnected components, or elements, linked by nodes. Consequently, the system is partitioned into these finite elements, and equations are derived for each element. These individual equations are then combined to form system-level equations. This approach simplified the original differential equations, which apply to a continuous domain, into a manageable set of linear equations. [24, 25].

2.1. Plaxis software

This study employed Plaxis 2D version 24.01.00.1060, utilizing 15-node elements for numerical analysis. Plaxis 2D is an advanced software tool designed for modeling two-dimensional geotechnical problems, supporting both static and dynamic analyses. Its use of non-linear soil material models allows for the accurate determination of stress-deformation values at any point within the soil.

Plaxis 2D is recognized globally as a premier tool for stress-strain analysis, particularly in understanding how soil materials respond under various loading conditions and different saturation levels. The software's capability to model soil-structure interaction is crucial for foundation design and construction, allowing engineers to assess the load-bearing capabilities of soils, determine bearing capacity, and ensure the safe design of structures.

2.2. Geometric model

For the shallow foundation in this case study, a geometric model was utilized with the following parameters: -10 m as the minimum value of X, 10 m as the maximum value of X, 0 m as the minimum value of Y, and 10 m as the maximum value of Y. The foundation width was 2 meters, and it was placed directly on the foundation surface. Figure 1 illustrated the geometry of the model. Node number 1052, located at coordinates (0,10), was selected to present the results.

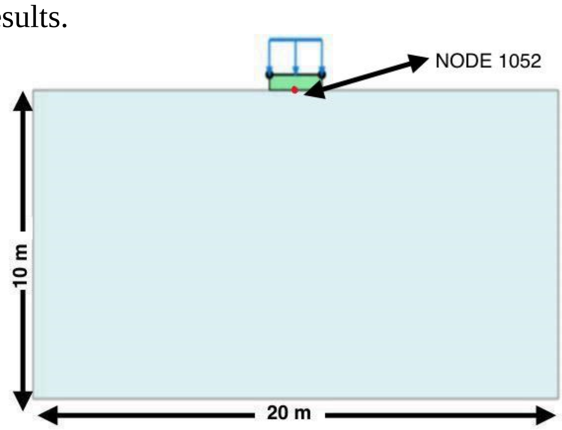

Figure 1. Geometric model of soil and model footing

In the FEM analysis, the undrained behavior of the clay soil was modeled using the Mohr-Coulomb (MC) model. The "Undrained A" condition was selected, meaning that the material behavior was defined by practical values for stiffness and strength. To ensure soil incompressibility, a substantial bulk stiffness for water was automatically applied, and (excess) pore pressures were calculated, even above the phreatic surface. Soil parameters were detailed in Table 1.

For concrete parameters, a linear-elastic nonporous model was chosen, indicating material behavior in which pore pressures could not occur. Other parameters were detailed in Table 2.

Table 1. Material properties of the soil layer

Parameters	Name	Value	Unit
General			
Soil model	Model	Mohr-Coulomb	-
Drainage type	Type	Undrained A	-
Unsaturated unit weight	γ_{unsat}	16	kN/m^3
Saturated unit weight	γ_{sat}	19	kN/m^3
Mechanical			
Young's modulus	E'_{ref}	5000	kN/m^2
Poisson's ratio	ν	0.3	-
Cohesion	c'_{ref}	5.0	kN/m^2
Friction angle	φ'	23	°
Dilatancy angle	ψ	0	°

Table 2. Material properties of the footing

Parameters	Name	Value	Unit
General			
Soil model	Model	Linear-elastic	-
Drainage type	Type	Non-porous	-
Unsaturated unit weight	γ_{unsat}	24	kN/m^3
Saturated unit weight	γ_{sat}	24	kN/m^3
Mechanical			
Young's modulus	E'_{ref}	30.10^6	kN/m^2
Poisson's ratio	ν	0.2	-

Determining the initial stresses is crucial in geotechnical engineering finite element analyses to approximate natural conditions. The initial stress represents the undisturbed soil's equilibrium state under its self-weight. Plaxis 2D offers different methods to determine initial stress based on the problem's characteristics. The K_0 procedure is appropriate when the ground surface, ground layers, and groundwater level are all parallel and horizontal. The gravity loading method determines initial stress in cases where the K_0 Procedure's idealized assumptions do not apply, such as non-horizontal ground surfaces, non-parallel ground layers, or non-conforming groundwater levels. The gravity loading method is used when the ground surface has slopes, inclinations, or non-horizontal features or when ground layers and groundwater levels deviate from parallelism to accurately account for real-world conditions in finite element analyses [26].

3. Results and Discussion

The load-bearing capacity of the strip foundation was determined by modeling the soil and the foundation in Plaxis 2D. Initially, the stress causing failure in a saturated condition was investigated, and a load of 100 kN/m² was selected for all models to ensure comparability of the results. The model was then subjected to the load using the parameters discussed earlier. However, it was essential to note that the results obtained from the Plaxis 2D model differed from those obtained from the experimental modeling test. In each model, the difference between the results for the displacement and the pore pressure P_{excess} was observed. The node (1052) has been strategically chosen for the graphics and tables.

3.1. Strip foundation results for no water under the foundation

In this study, the observed displacement data illustrate a clear trend: displacement decreased as soil saturation decreased from %99 to %50. Specifically, maximum displacement was recorded at 125.7 mm when the saturation level was %99, and it diminished to 106.1 mm at a saturation of %50. These findings are presented comprehensively in Figures 2 to 4, where Figure 2 explicitly highlights the soil's unsuitability in its current state to support structural loads, showcasing the total displacement under a strip foundation. As indicated, displacement was consistently reduced in %5 saturation intervals, with the findings confirming that the highest soil displacement occurs at the highest saturation level. This reduction in displacement with decreased saturation levels suggests a direct relationship between the soil's water content and structural integrity. The maximum displacement at near-complete saturation (%99) poses significant concerns for foundation stability in such conditions. This substantial displacement under high moisture conditions underscores a critical vulnerability: as saturation increases, the soil's ability to bear structural loads significantly weakens. This is crucial for engineering considerations in areas prone to high groundwater presence or flooding. As soil saturation levels increased, particularly approaching near-complete saturation (%99), the soil exhibited significantly greater displacement. This indicated that the soil's structural integrity under load was compromised.

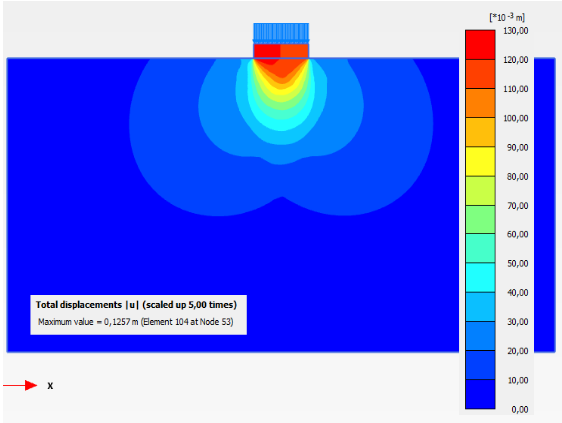

Figure 2. Total displacement for the strip foundation with no water at SR=%99

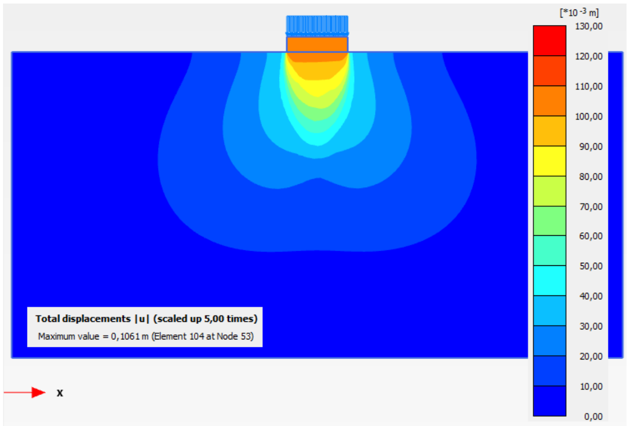

Figure 3. Total displacement for the strip foundation with no water at SR=%50

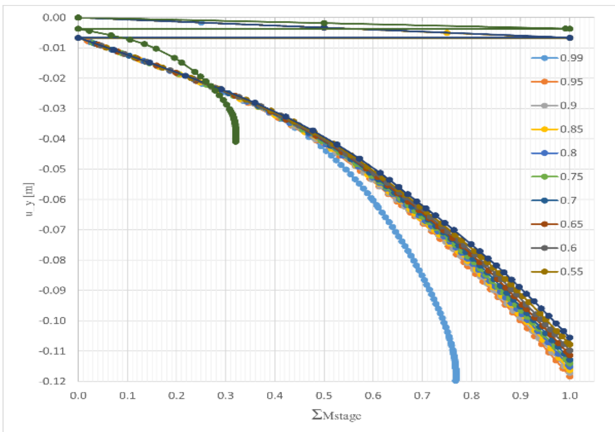

Figure 4. Displacement for each saturation at node 1052

This study explored the fluctuations in excess pore pressure, P_{excess}, across a range of soil saturation levels and assessed its implications for soil behavior, which was vital for ensuring safe design and construction practices in geotechnical engineering. P_{excess} was delineated as the difference between the total pore water pressure and hydrostatic pore water pressure, offering critical insights into the soil's capacity to sustain structural loads.

Figures 5 and 6, complemented by the associated data Table 3, illustrated significant variations in P_{excess} as soil saturation decreased from %99 to %50. A pronounced maximum of 61.57 kPa at a saturation level of 0.99 decreased sharply as saturation reduced, indicating that soil stability was highly responsive to changes in moisture levels.

The substantial decrease in P_{excess} from 61.57 kPa at near-full saturation to more stable values at lower saturations underscored the potential vulnerability of the soil's structural integrity at higher moisture levels. This reduction suggested that higher saturation levels may significantly impair the soil's ability to support structural loads, heightening the risk of soil failure. This finding was particularly crucial for the design of foundations in regions prone to fluctuating water levels.

A comprehensive understanding of P_{excess} variations helped the evaluation of the potential risks of liquefaction or excessive settlement under load, which were critical considerations for the safety and stability of geotechnical structures.

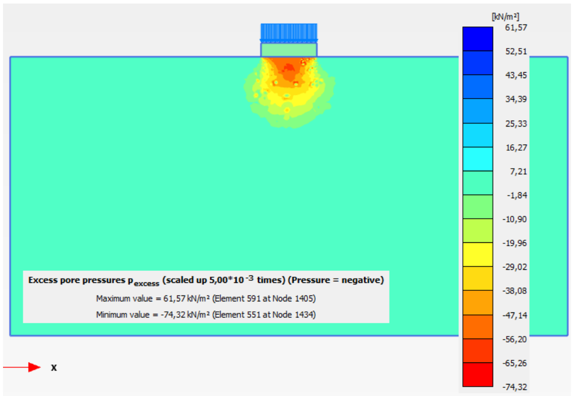

Figure 5. P_{excess} pore pressure with no water at SR=%99

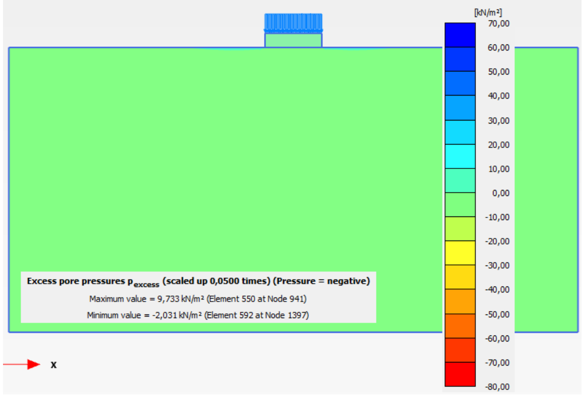

Figure 6. P_{excess} pore pressure with no water at SR=%50

Table 3. Changing values for P_{excess} with different saturation

Saturation %	P_{excess} pore pressure Maximum value kPa	Minimum value kPa
99	61.57	-74.32
95	7.405	-1.483
90	6.984	-1.400
85	6.692	-1.364
80	6.268	-1.322
75	6.083	-1.323
70	6.438	-1.298
65	7.723	-1.237
60	9.010	-1.181
55	10.39	-1.517
50	9.733	-2.031

3.2. Strip foundation results for GWL= -5 m

At a saturation level of %99, a significant displacement of 169 mm was recorded, as depicted in Figure 7. This pronounced displacement under nearly saturated conditions indicated substantially reduced soil stiffness and strength, suggesting that foundation stability was compromised in moist conditions.

The analysis extended to a lower saturation level of 0.50, where the maximum displacement diminished to 98.14 mm (Figure 8). This reduction underscored the increased soil stability at lower moisture levels, affirming that less saturated conditions were more conducive to maintaining soil support capabilities.

Figure 9 illustrates the trend of decreasing displacement as saturation reduced from %99 to %50. This trend was crucial for understanding the inverse relationship between moisture content and the soil's ability to sustain load. The data clearly demonstrated that higher moisture levels significantly impair the soil's load bearing.

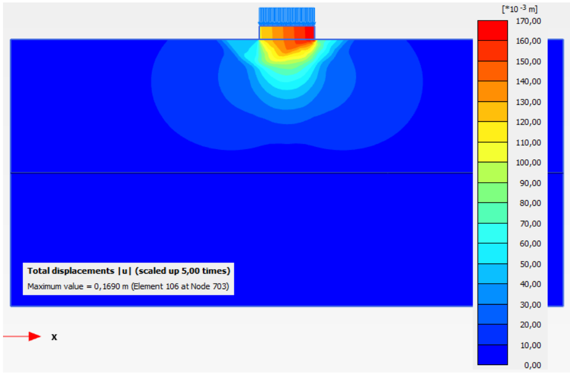

Figure 7. Total displacement for the strip foundation (GWL= -5 m, SR=%99)

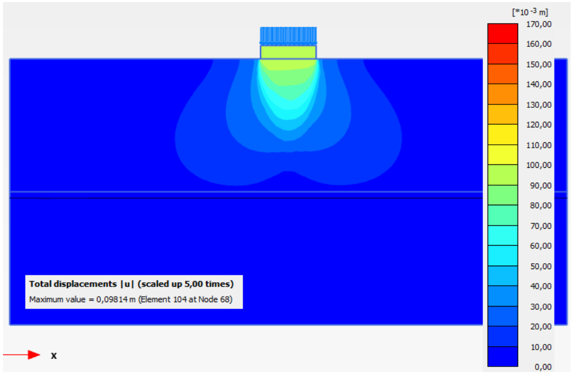

Figure 8. Total displacement for the strip foundation (GWL= -5 m, SR=%50)

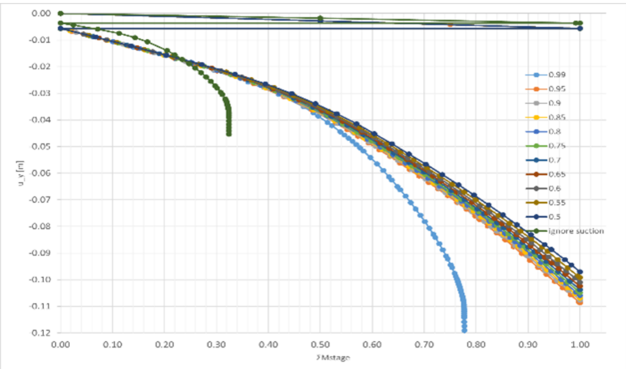

Figure 9. Displacement for each saturation at node (1052)

Figures 10 and 11, alongside the accompanying data in Table 4, presented a comprehensive analysis of the variations in excess pore pressure (P_{excess}) across saturation levels from %99 to %50. At a saturation of %99, P_{excess} achieved a maximum of 63.44 kPa and plunged to a minimum of -88.03 kPa, underscoring significant fluctuations and potential instability in highly saturated soils.

As saturation decreased, there was a notable trend where the maximum P_{excess} values consistently increased, transitioning from lower pressures at higher saturations to a maximum of 12.99 kPa at a saturation of %50. Conversely, the minimum P_{excess} values exhibited a decreasing trend in negativity, indicating a stabilization of pore pressures as the soil moisture decreased.

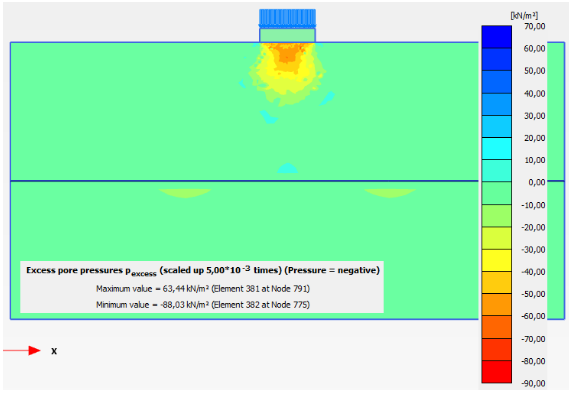

Figure 10. P_{excess} pore pressure (GWL= -5 m, SR=%99)

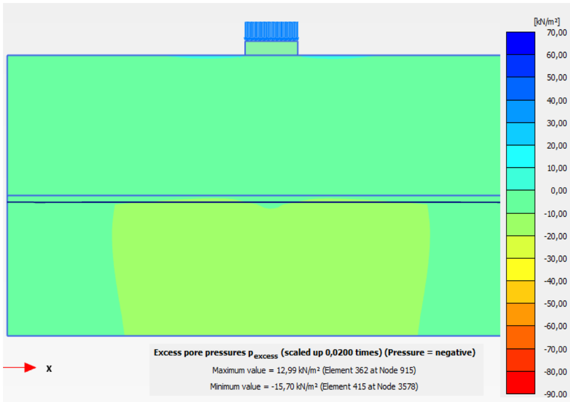

Figure 11. P_{excess} pore pressure (GWL= -5 m, SR=%50)

Table 4. Changing values for P_{excess} with different saturation

	P_{excess} pore pressure	
Saturation %	Maximum value kPa	Minimum value kPa
99	63.44	-88.03
95	4.793	-15.20
90	4.965	-15.15
85	5.393	-15.12
80	5.967	-15.12
75	6.603	-15.16
70	7.874	-15.23
65	9.896	-15.32
60	10.26	-15.43
55	11.23	-15.55
50	12.99	-15.70

3.3. Strip foundation results for GWL= -2 m

At a saturation level of 0.99, the foundation experienced a considerable displacement of 198.9 mm, as shown in Figure 12. This significant displacement under nearly saturated conditions suggested substantially reduced soil stiffness and strength, indicative of compromised foundation stability.

The displacement at a saturation level of 0.50 was documented in Figure 13, where the maximum displacement was recorded at 127.3 mm. The decreased displacement at this lower saturation level underscored enhanced soil stability, indicating that less saturated conditions were more conducive to supporting structural loads effectively.

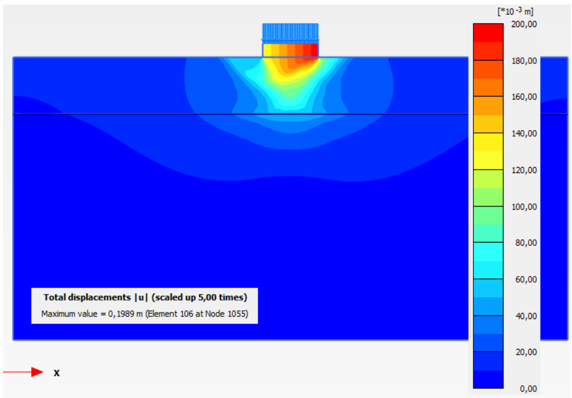

Figure 12. Total displacement for the strip foundation (GWL= -2 m, SR=%99)

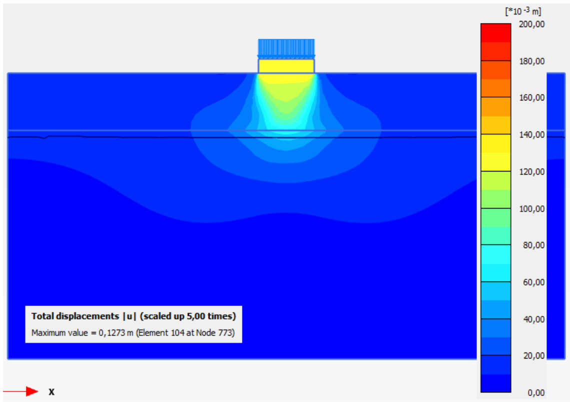

Figure 13. Total displacement for the strip foundation (GWL= -2 m, SR=%50)

Figure 14 illustrates the trend of decreasing displacement as saturation reduced from %99 to %50. This trend was crucial for understanding the inverse relationship between moisture content and the soil's ability to sustain load. The data clearly demonstrated that higher moisture levels significantly impair the soil's load bearing.

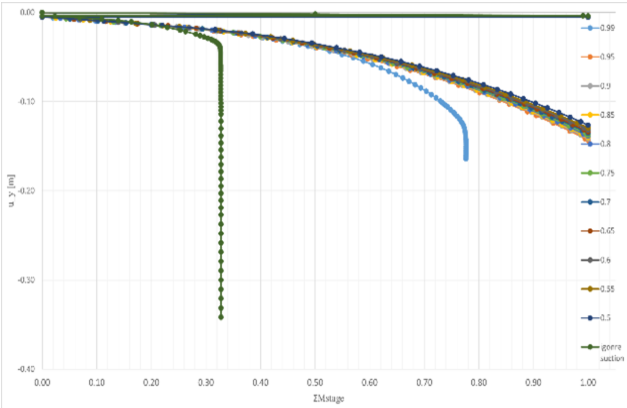

Figure 14. Displacement for each saturation at node 1052

Figures 15 and 16 depict P_{excess} at saturation levels of %99 and %50, respectively. These figures captured the dynamic changes within the soil matrix under varying moisture conditions. At a saturation of 0.99, P_{excess} peaked at 84.61 kPa and plummeted to a minimum of -81.39 kPa, indicating significant pressure fluctuations that could compromise soil compaction and structural integrity.

The data in Table 5 detailed the progression of P_{excess} values from a saturation of %99 to %50. There was a marked increase in the maximum P_{excess} values as saturation decreased, suggesting a trend toward soil stabilization with diminishing moisture content. Conversely, the minimum values showed decreasing negativity, which was correlated with reduced saturation, implying a reduction in fluid pressure and potential adjustments in the soil's void ratio.

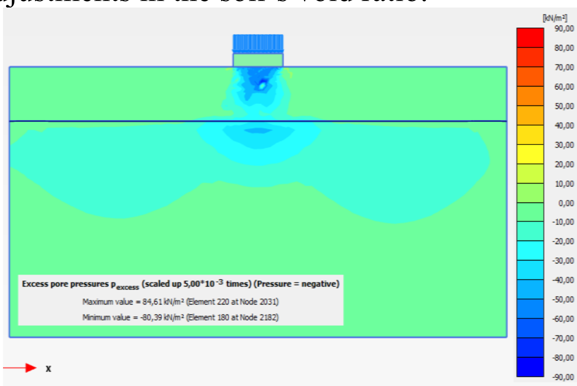

Figure 15. P_{excess} pore pressure (GWL= -2 m, SR=%99)

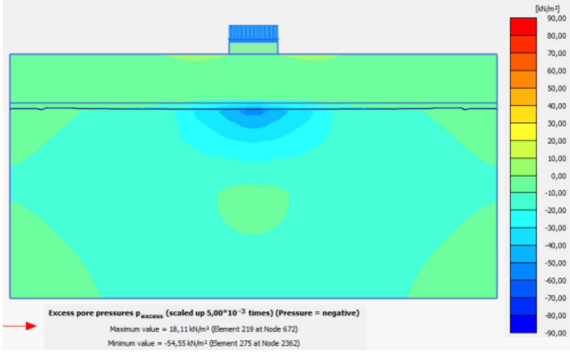

Figure 16. P_{excess} pore pressure (GWL= -2 m, SR=%50)

Table 5. Changing values for P_{excess} with different saturation

Saturation %	P_{excess} pore pressure Maximum value kPa	Minimum value kPa
99	84.61	-81.39
95	5.460	-57.03
90	6.202	-56.82
85	7.280	-56.61
80	8.887	-56.39
75	10.15	-56.16
70	11.60	-55.97
65	13.11	-55.72
60	14.03	-55.42
55	16.07	-55.04
50	18.11	-54.55

3.4. Strip foundation results for GWL= 0 m

In this model, the soil reached full saturation, with the results showing a total displacement of 45.95 mm at a saturation level of 0.99, as detailed in Figures 17. These figures illustrated the displacement pattern of the strip foundation under nearly saturated conditions. The magnitude of displacement observed indicated a significant reduction in soil stiffness and strength, highlighting the challenges inherent in maintaining structural stability in saturated soils. The soil exhibited a total displacement of 45.95 mm at a saturation level of %99. This finding was visually represented in Figures 18, which detailed the displacement pattern of the strip foundation under these conditions. The extent of displacement observed underscores a notable decrease in soil stiffness and strength due to the high moisture content, emphasizing the structural stability challenges in saturated environments.

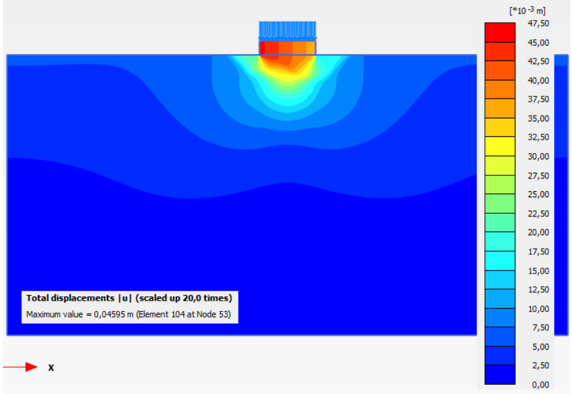

Figure 17. Total displacement for the strip foundation (GWL= 0 m, SR=%99)

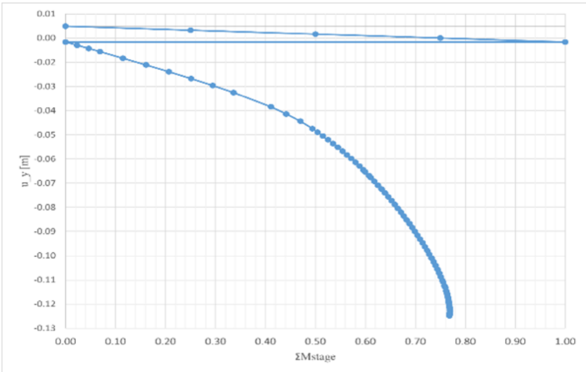

Figure 18. Total displacement for the strip foundation fully saturated

Figure 19 presented the variations in excess pore pressures (P_{excess}) in fully saturated soil conditions, which were crucial for understanding the impact of saturation on soil behavior and the associated structural implications.

The data showed a P_{excess} with a maximum value of +29.41 kPa and a minimum of -52.42 kPa in fully saturated conditions. This significant pressure range suggested dynamic soil responses under full saturation, reflecting potential soil structure or composition variability.

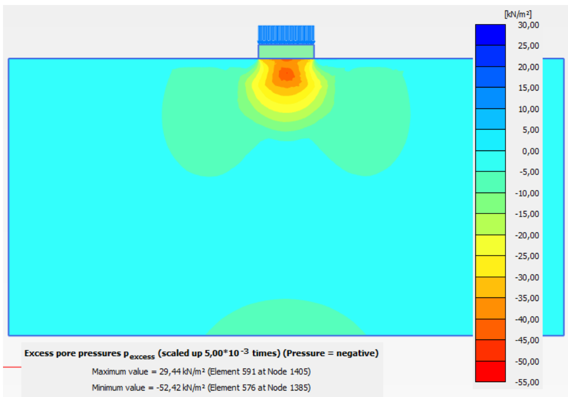

Figure 19. P_{excess} pore pressure fully saturated

3.5. Displacements for Undrained Condition

Displacement without suction (no water):

The blue line on the displacement curve progressively increased with saturation, showing a significant rise beyond 95% saturation and peaking sharply around 100%. This trend indicated that the soil structure may become considerably unstable as it approached and surpassed full saturation, mainly where soil suction effects are minimal or absent.

A pronounced maximum for p excess of 61.57 kPa at a saturation level of %99 decreased sharply as saturation reduced, indicating that soil stability was highly responsive to changes in moisture levels.

Displacements (GWL= -5 m):

The displacement (orange line) when GWL =-5 m consistently rised with increased saturation, accentuating as the soil approached full saturation, followed by a sharp escalation (Fig. 20a). This pattern indicated that deeper soil layers were affected more severely by rising water content, likely due to more significant hydrostatic pressure and diminishing mechanical strength.

Displacements (GWL= -2 m):

At a shallower depth of 2 m (grey line), displacement increased more moderately with saturation but showed a dramatic rise as it approaches total capacity. This steeper increase suggested a critical threshold beyond which soil stability rapidly degraded, possibly due to reduced overburden pressure and greater susceptibility to moisture changes.

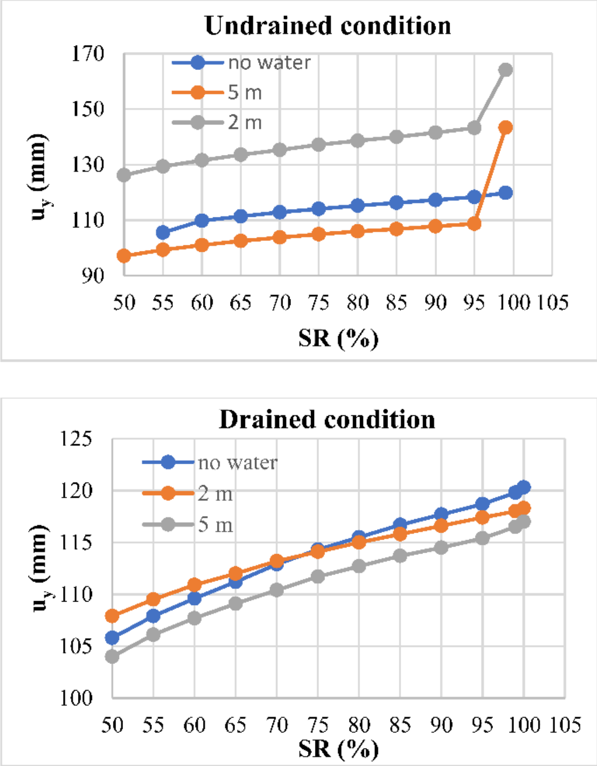

Figure 20. Displacement for strip foundation under different water global level a) Undrained condition b) Drained condition

3.6. Displacements for Drained Condition

Figure 20b also presented the results of repeated analyses for the drained condition. The two graphs compared the effects of different conditions on vertical deformation as the degree of saturation increased. In the undrained condition, a sharp increase in deformation was observed as the degree of saturation approached %100 when groundwater was present, whereas in other cases, the increase was more gradual. In the drained condition, linear increases in deformation were observed under all conditions. When these two graphs were evaluated together, it was evident that the drained condition generally resulted in lower deformation values compared to the undrained condition. This comparison highlighted the critical impact of the presence and location of water on the measured deformation.

The incremental displacements for various saturation levels across the three scenarios yielded several key observations:

Displacements (no water level):

Displacements generally increased with saturation, peaking at a saturation level of %65, then displaying a mixed trend. This pattern suggested that the soil reached a critical weakening point before regaining some stability at higher saturations.

Displacement (GWL= -5 m):

Displacements followed a similar trend but were consistently higher across saturation levels compared to the no-water scenario. The peak displacement at a saturation of %75 indicated increased sensitivity to the presence of water.

Displacements (GWL= -2 m):

This scenario showed the highest displacements, with a dramatic peak at a saturation of %75. The proximity of the water table significantly affected mechanical behavior, resulting in more significant deformations.

The incremental displacement data underscored the water table depth's significant role in the foundations' stability. As the water table rised, notably in the (GWL at 2 m) scenario, the soil exhibited more significant deformation under identical saturation conditions. The data suggested that soil behavior and foundation performance depended heavily on saturation and were substantially exacerbated by higher water tables.

Table 6. Incremental displacements (m) after factor safety at different saturation and water global level

Incremental displacements (m)			
Saturation %	With no water	Water at 5 m	Water at 2 m
95	0.516	0.5974	0.6094
90	0.4938	0.5788	0.7166
85	0.5072	0.699	0.6492
80	0.457	0.7685	0.8386
75	0.518	0.8555	1.0445
70	0.5182	0.831	0.8312
65	0.8792	0.8975	0.7764
60	0.9158	0.6706	0.38565
55	0.5905	0.7585	0.8055
50	0.5138	0.7136	0.7855

The presented Figure 21 and Table 7 offered a detailed view of the modulus of subgrade reaction $\sum Mf$ and the factors of safety (FoS) across different saturation levels for three distinct scenarios: no water table (no water), water table at 5 meters (water at 5 m), and water table at 2 meters (water at 2 m) These results were critical for understanding the effects of water content on soil behavior and the subsequent impact on shallow foundation safety.

Tablo 7 and Figure 21 showed $\sum Mf$ plotted against varying levels of saturation for each scenario. All three curves indicated a decreasing trend in soil stiffness as saturation increased, suggesting diminished soil strength under higher water contents. The distinct separation between the curves highlighted the significant influence of water table depth on soil behavior, with deeper water tables corresponding to reduced soil stiffness.

Table 7. Factor of safety at different saturation and water global level.

Factor of safety (undrained)			
Saturation %	With no water	Water at 5 m	Water at 2 m
95	1.291	1.295	1.201
90	1.307	1.311	1.211
85	1.32	1.325	1.221
80	1.334	1.341	1.232
75	1.351	1.358	1.243
70	1.37	1.376	1.254
65	1.392	1.396	1.268
60	1.415	1.422	1.284
55	1.443	1.45	1.304
50	1.481	1.489	1.329
Factor of safety (drained)			
Saturation %	With no water	Water at 5 m	Water at 2 m
95	1.488	1.497	1.513
90	1.45	1.456	1.474
85	1.42	1.426	1.444
80	1.395	1.401	1.418
75	1.374	1.379	1.396
70	1.353	1.36	1.378
65	1.336	1.343	1.361
60	1.319	1.327	1.345
55	1.308	1.312	1.33
50	1.292	1.297	1.314

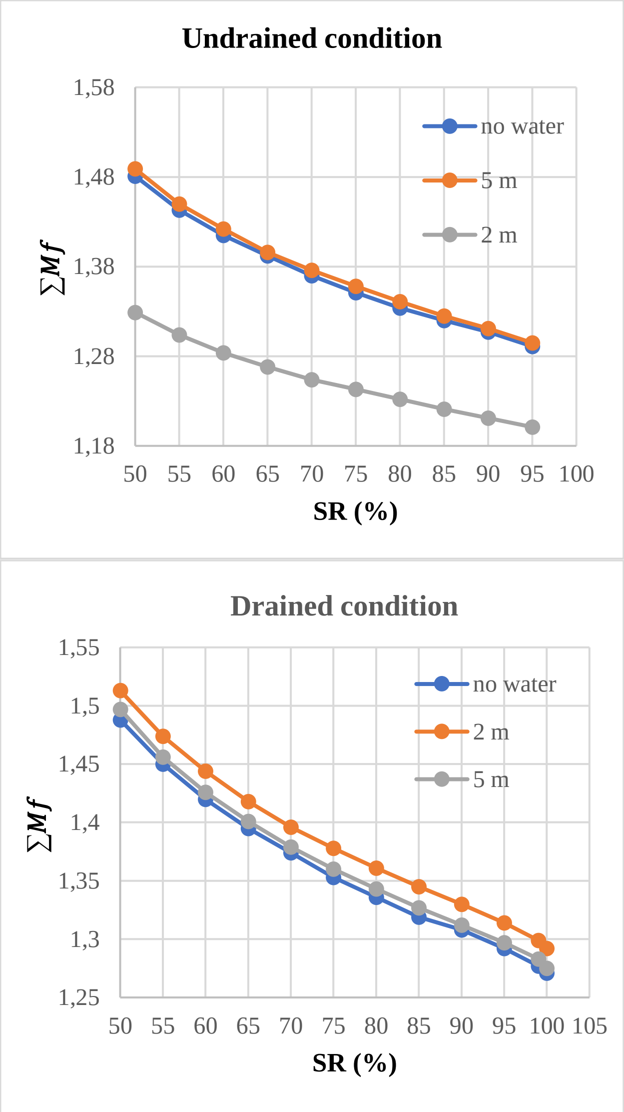

Figure 21. Factor of safety with different water table level

Limited studies have investigated the bearing capacity of shallow foundations on unsaturated soils using Plaxis. To the best of our knowledge, this research is the first to examine the bearing capacity of shallow foundations on unsaturated soils using Plaxis. However, a study by Mahmood et al. [27] showed that partial saturation significantly influenced the bearing capacity of skirted foundations. As saturation decreased, bearing capacity increased due to enhanced matric suction in unsaturated soils. Skirted foundations improved capacity by providing lateral confinement and higher shear resistance. Bearing capacity rose with decreasing saturation until a certain threshold, beyond which it declined due to reduced effective stress. Both numerical and experimental results supported these findings, highlighting the need to consider partial saturation in foundation design. These results were consistent with our study, which found that displacements at 50% saturation were lower than at 99% saturation.

Furthermore, Safarzadeh and Aminfar [28] found that lowering the groundwater table increased the bearing capacity of shallow square footings by reducing pore water pressure and enhancing effective stress. As the water table dropped further, bearing capacity improved, though at a diminishing rate. Their experimental and numerical results confirmed the effectiveness of lowering the water table for increasing foundation strength, particularly in high water table areas. These findings were consistent with out study, which observed higher displacements with a water table 2 meters below the foundation compared to scenarios with no water table or a water table 5 meters below.

Additionally, Tang et al. [29] found that hydraulic hysteresis and drainage conditions significantly impacted the bearing capacity of shallow foundations in unsaturated soils. Fully drained conditions offered the highest bearing capacity by effectively dissipating pore water pressure and maintaining higher effective stress. Partially drained and undrained conditions reduced bearing capacity due to increased pore water pressure. Similarly, these findings aligned with our study, which observed lower displacements under drained conditions compared to undrained ones.

4. Conclusion

The analysis effectively contrasted the use of PLAXIS 2D with traditional empirical methods for soil behavior and foundation design, offering a valuable perspective on the advancements in computational tools within geotechnical engineering. PLAXIS 2D simulations provided detailed insights into the influence of water table fluctuations and saturation changes on soil stability and displacement, aspects often overlooked in empirical approaches.

1. In the case of “no water”, under unsaturated conditions, soil structural integrity was maintained with reduced displacement observed as saturation levels decrease. However, near-complete saturation (%99) substantially

increased displacement, underscoring the risks to foundation stability in highly saturated soils, particularly in flood-prone areas.

2. With water 5 m below the foundation (GWL=-5 m), lower moisture levels enhanced soil stability, as evidenced by decreased displacement when saturation levels drop from %99 to %50. The variability in P_{excess} at high saturation highlighted potential risks of soil instability, which were crucial for structural integrity under heavy loads.

3. With water 2 m below the foundation (GWL= -2 m), reduced saturation levels (%50) corresponded to lower displacement and more stable soil conditions. The fluctuating P_{excess} values at a saturation of %99 indicated significant pressure changes that could affect soil compaction and structural integrity.

4. At the same foundation level with complete saturation (%99), significant displacement reflected decreased soil stiffness and strength, highlighting challenges in maintaining structural stability in highly saturated environments.

PLAXIS 2D offered a more dynamic, detailed, comprehensive and realistic assessment of soil behavior and foundation safety under various environmental conditions compared to empirical methods. This transition enhanced the geotechnical engineering toolkit, allowing for more accurate and reliable foundation designs. The comprehensive analysis provided by PLAXIS 2D underscored the limitations of empirical methods and the importance of advanced simulation tools in contemporary geotechnical practice.

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No conflict of interest or common interest has been declared by the authors.

The Declaration of Ethics Committee Approval
This study does not require ethics committee permission or any special permission.

The Declaration of Research and Publication Ethics
The authors of the paper declare that they comply with the scientific, ethical and quotation rules of SAUJS in all processes of the paper and that they do not make any falsification on the data collected. In addition, they declare that Sakarya University Journal of Science and its editorial board have no responsibility for any ethical violations that may be encountered, and that this study has not been evaluated in any academic publication environment other than Sakarya University Journal of Science.

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