ASSESSMENT OF SCALE AND DEPTH EFFECTS ON BEARING CAPACITY OF SHALLOW FOUNDATIONS IN CLAYEY SOILS USING PLAXIS 3D

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الملخص

تعد الأساسات الضحلة عناصر حيوية لنقل الأحمال الإنشائية إلى التربة، إلا أن تصميمها في الترب الطينية يواجه تحديات بسبب التفاعلات المعقدة بين التربة والهيكل. تستخدم هذه الدراسة نمذجة العناصر المحدودة ثلاثية الأبعاد(PLAXIS 3D) ، ولتحليل تأثير حجم الأساس وعمق التأسيس على قدرة التحمل في كل من الظروف المستنزفة (طويلة الأجل) وغير المستنزفة (قصيرة الأجل). كانت أهم النتائج هي انه في الظروف غير المستنزفة، أظهرت قدرة التحمل القصوى (q_u) حساسية ضعيفة لحجم الأساس، بينما أصبح الهبوط (S25mm) العامل الحاسم في تصميم الأساسات الكبيرة. اما في الظروف المستنزفة، زادت q_u مع حجم الأساس، لكن قيود الهبوط قللت بشكل كبير من القدرة المسموح بها للأساسات الواسعة. كما أدى زيادة عمق التأسيس إلى تحسين قدرة التحمل بشكل غير خطي، مع تراجع الفائدة بعد 1.0–1.5 م، مما يشير إلى عمق مثالي يحقق توازنًا بين الكفاءة والتكلفة. بالإضافة لذلك نجد ان هذه الدراية تملأ فراغًا مهمًا في الهندسة الجيوتقنية من خلال تقديم إطار عددي متكامل لتحسين تصميم الأساسات الضحلة في الترب الطينية. تؤكد النتائج على أهمية مراقبة الهبوط في الأساسات الكبيرة وتقدم توصيات عملية لتحقيق أمان هيكلي مع جدوى اقتصادية. وهذه الرؤى ضرورية للمهندسين لتجنب مخاطر الهبوط المفرط مع تقليل التكاليف الإنشائية.

ABSTRACT

The analysis demonstrates that while ultimate bearing capacity (q_u) under undrained conditions shows minimal sensitivity to foundation size, settlement (S25mm) becomes increasingly critical for larger foundations, often governing the design capacity. In contrast, drained conditions reveal a more complex behavior where q_u increases with foundation size, but this theoretical gain is frequently offset by proportionally greater settlement effects that significantly reduce allowable capacity for wider footings. A particularly important finding concerns embedment depth, which nonlinearly enhances bearing capacity with diminishing returns beyond 1.0-1.5 m, suggesting an optimal depth range that balances structural performance with economic considerations.

These findings bridge a critical gap in geotechnical engineering by establishing a comprehensive numerical framework that clarifies the interdependent effects of size and depth on foundation performance. The research provides practical insights for engineers, particularly highlighting how settlement constraints often control design parameters more significantly than ultimate capacity, especially for larger foundations in clayey soils. By quantifying these relationships, the study offers valuable guidance for optimizing foundation designs to achieve structural safety while maintaining cost-effectiveness, particularly in projects where controlling differential settlement is paramount. The results emphasize the need for careful consideration of both short-term and long-term behavior in foundation design, with specific recommendations for embedment depth selection based on project-specific requirements and economic constraints.

KEYWORDS: Shallow foundations, Bearing capacity, Clayey soil, Foundation size, Embedment depth, PLAXIS 3D.

INTRODUCTION

Important structural elements that shift building loads to the underlying soil are shallow foundations. Numerous factors, such as the geometric properties of the soil-structure system, loading circumstances, and soil characteristics, influence the design and performance of shallow foundations. However, numerical and experimental studies show that the size and embedment depth of the soil structure are important factors affecting the behavior of the foundation.

Many facets of shallow foundation performance have been the subject of recent studies. [1] used finite-element analyses and model tests to investigate the bearing capacity of embedded circular footings on stiff-over-soft clay. According to their research, the normalized upper layer thickness (H/B), where H is the distance to the soft clay and B is the footing diameter, causes the bearing capacity factor (Nc) to increase nonlinearly. For example, Nc increased by about 30% as H/B rose from 0.5 to 2.0 at a strength ratio (s_{ut}/s_{ub}) of 4.75. Since stiffness's critical H/B ratio was found to be lower than the ultimate capacity, their study emphasized the significance of taking both serviceability and ultimate capacity into account when designing. The effect of footing size on bearing capacity was illustrated by [2], who found that when the size of square footings increased from 30 mm to 50 mm at the ideal moisture content (14%), the bearing capacity increased from 312.5 N/m² to 1075 N/m². On the other hand, a significant drop in capacity to 100–104 N/m² was observed at the plastic limit (27%), which was ascribed to a higher void ratio in the cohesive soil. [3] used finite element modeling to examine the bearing capacity of shallow foundations in strain-softening clays, further advancing our knowledge of scale effects. As the foundation width increased from 0.5 m to 8 m, their numerical results indicated that the correction factor (α) for bearing capacity decreased from 0.96 to 0.7, mainly because of progressive failure mechanisms within the soil.

Using three-dimensional modeling, [4] examined how the size of the isolated footing affected the clayey soil's bearing capacity. According to their findings, the permitted bearing pressure decreased from 575 kN/m² to 510 kN/m² for a maximum settlement of 50 mm when the footing dimensions were increased from 2×2 m to 3×3 m. The importance of a 2 m foundation depth in influencing how clayey soil behaves under load was also highlighted by this study. Conversely, [5] found that as foundation size decreased, shallow foundations' bearing capacity rose. The impact of scale effects in model tests was demonstrated, for instance, by the higher bearing capacity values of a 37.5 mm × 37.5 mm square footing under the same soil conditions as a 50 mm × 50 mm square footing. More recently, [6] used large-deformation finite-element (LDFE) analysis to investigate how soil stiffness (rigidity index Ir) affects foundation end bearing resistance in uniform clay. Since surface-reaching shear planes dominated the failure mechanisms, their results showed that soil stiffness had a negligible effect on bearing capacity for strip footings (shallow foundations), increasing it by only about 5% for Ir ranging from 50 to 500 at d/B = 0.5. Deep foundations, such as pile foundations, on the other hand, showed a notable reliance on stiffness; for rough piles at d/D=10, Nc increased by about 30% as I_r rose from 50 to 500. This was explained by plug formation and deeper soil flow mechanisms.

PROBLEM AND SIGNIFICANCE

A significant gap in the literature on geotechnical engineering is filled by this study; there isn't a single, comprehensive numerical framework that methodically looks at how foundation size and embedment depth work together to affect shallow foundation bearing capacity. For clayey soils, this framework is essential for both short-term undrained conditions and long-term drained conditions. Comprehensive numerical modeling is required because traditional analytical solutions frequently fall short in capturing the complex stress distribution and load-bearing capacities under changing geometric and soil parameters.

This research is important because it directly improves the precision and dependability of shallow foundation design. This study attempts to get around the drawbacks of traditional analytical methods by utilizing sophisticated numerical modeling techniques, particularly the PLAXIS 3D Finite Element Method. To optimize designs, guarantee structural stability, and avoid expensive failures, a thorough grasp of how foundation size and embedment depth affect soil behavior is essential. Additionally, the study tackles important facets of both short-term and long-term foundation performance by taking into account both undrained and drained conditions, which is crucial for contemporary geotechnical practice. The results will give engineers and practitioners important information that will result in shallow foundation solutions that are safer, more effective, and more affordable in a variety of geotechnical settings.

METHODOLOGY

This study examines the bearing capacity of shallow foundations using a numerical modeling framework, emphasizing how soil behavior is impacted by foundation size and embedment depth. PLAXIS 3D software is used to simulate the intricate soil-structure interaction using the Finite Element Method (FEM). Through a more thorough examination of stress distribution and load-bearing capacity, this method overcomes the drawbacks of traditional analytical solutions. Figure (1) illustrates the methodology used in this study.

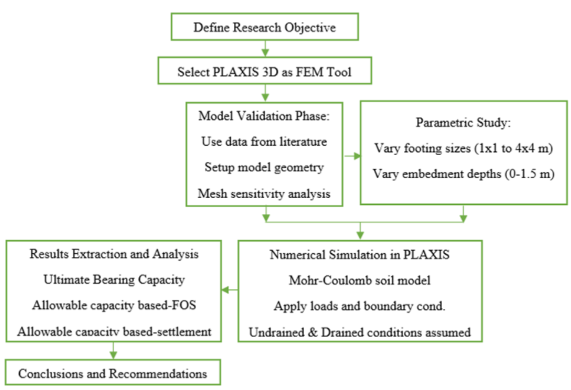


Figure 1: Schematic diagram of the study methodology: validation, parametrization, and simulation stages.

MODEL SETUP IN PLAXIS 3D

Every simulation was conducted using PLAXIS 3D, a well-known finite element program for geotechnical analysis that enables thorough modeling of stability and deformation in intricate soil-structure systems.

Elements and Mesh

A computational mesh was created by discretizing the modeled domain into finite elements. Ten-node tetrahedral elements with four Gauss points are used in PLAXIS 3D. A sufficiently refined mesh was used to guarantee the accuracy and dependability of the results. Convergence was confirmed through iterative refinement until additional changes produced insignificant output changes.

Model Size and Boundary Conditions

To reduce artificial constraints and guarantee realistic simulation results, it was essential to choose the right model size and boundary conditions. To find the ideal numerical soil model dimensions, a sensitivity analysis was carried out. An initial square domain of 17B×17B was chosen for the validation of the soil properties, and the silty clay layer was defined by [7] as having a constant depth. Conditions at the boundaries were carefully managed:

- Horizontal boundaries are typically fixed, meaning that movement is restricted perpendicular to the boundary while allowing for free tangential deformation.
- Bottom boundary: Fully Fixed (all displacements are completely restricted).
- Top surface: Unrestricted, except for the footing application.

Constitutive Models

The following constitutive models were chosen to accurately simulate material behavior:

- Soil: The behavior of the soil was mainly represented by the Mohr-Coulomb (MC) model. This linear elastic-perfectly plastic stress-strain relationship requires five key parameters: young’s modulus (E), Poisson’s ratio (ν), friction angle (ϕ), cohesion (c), and dilatancy angle (ψ). Both drained and undrained conditions were taken into consideration for clayey soil.
- Footing: The concrete footing's Young's modulus (E) and Poisson's ratio (ν) were used to model it as a linear elastic material.

Analysis of Drained and Undrained

The study included both drained and undrained analysis capabilities:

- Analysis without drain (Undrained C): This condition was used in situations where pore water pressure does not dissipate, such as short-term situations or rapid loading. It ignores the effects of pore pressure and uses total stress parameters for both shear strength and stiffness.
- Drainage analysis: This condition was predicated on fully consolidated clay soil (long-term stability), in which all pores allow water to dissipate. This method adheres to stress-dependent stiffness (E') and effective stress principles (c', ϕ').

SOIL MODEL VALIDATION

A validation procedure for clayey soils was carried out by using PLAXIS 3D to replicate a well-known study by [7] in order to guarantee the precision and dependability of the soil model.

Methodology of Validation

The validation methodology involved:

- Parameterization: For the silty clay soil in undrained conditions (Undrained-C), the Mohr-Coulomb constitutive model was applied. Important material characteristics were taken from [7] for both clayey soil and concrete footing. Using the equation for immediate settlement [8], the soil's Young's modulus (E_u) was calculated using Equation (1):

  $$E_u = C_s q B \left(\frac{1-\nu^2}{S_i}\right) \quad (1)$$

  The soil-footing interaction was taken into account with an interface strength factor (R_{inter}) of 0.6 [9].

- Model Geometry: [7] conducted extensive field experiments, which were replicated in the numerical soil model. By comparing pressure-settlement curves and bearing capacity values with experimental data using a fine mesh configuration, a sensitivity analysis was used to determine the ideal numerical model dimensions. A 15.3-meter-long by 6.20-meter-wide model of the clayey soil layer was created. While the equivalent square footing was 0.80 meters long and 0.80 meters wide, with the same thickness of 0.03 meters, the circular footing was 0.90 meters in diameter and 0.03 meters thick.
- Loading Simulation: The maximum displacement recorded by [7], 25mm, was applied downward as a surface-prescribed displacement.
- Mesh Sensitivity and Calibration: A sensitivity analysis verified that the numerical results were independent of mesh size. After assessing various refinement levels, a fine mesh configuration with roughly 20,990 elements was chosen. With a bearing capacity of roughly 273 kPa, this mesh density ensured a balance between the accuracy of results and computational efficiency.

Comparative Analysis and Cross-Validation

In order to validate the PLAXIS 3D simulations against the experimental study by [7], a comparison of bearing capacity predictions for clayey soils was conducted. The ultimate bearing capacity was ascertained using the double tangent method [10]. To evaluate the precision and coherence of the chosen methodology, quantitative comparisons and error analysis were carried out. Strong agreement was indicated by the error percentage of 5.814% for clayey soil.

FULL-SCALE FOUNDATION MODELING IN PLAXIS 3D

After the soil parameter was validated, four full-scale concrete footings (1 m × 1 m, 2 m × 2 m, 3 m × 3 m, and 4 m × 4 m) with a consistent thickness of 0.50 m were examined.

Soil Properties Parameterization

Clay soil was categorized as a cohesive material with low permeability. Both undrained (Undrained C) and drained conditions were applied. Distinct shear strength and stiffness parameters were used for each drainage condition, as detailed in Table (1) of the original document. The clay soil was classified as high-plasticity silty clay (CH) based on [11], with a liquid limit (LL) exceeding 50 and a plasticity index (PI) of 23. Effective stress principles (c', ϕ') and stress-dependent stiffness (E') govern behavior under drained conditions [12, 13]. Because transient pore pressure is critical for short-term stability, applying drained parameters (c′, ϕ′, E′) in undrained analysis leads to substantial inaccuracies. [14, 15]. In order to precisely capture both undrained (short-term) and drained (long-term) responses, contemporary geotechnical practice requires distinct parameter sets that are verified by site-specific testing [16,17]. Equations (2) and (3), as suggested by [18], were used to determine the drained internal friction angle (ϕ'_{oc}). These equations were applied based on the plasticity index (I_p) of the clay soil, which was classified as CH.

$$4 < I_p < 50 \qquad \emptyset'_{oc} = 45 - 14.\log I_p \ (degree) \tag{2}$$

$$50 \le I_p < 150 \qquad \emptyset'_{oc} = 26 - 3.\log I_p \ (degree) \tag{3}$$

Additionally, the former Danish code of practice for foundations offers a conservative estimate of the effective cohesion (c'_{oc}) derived from the undrained shear strength (c_u) based on a comparison of drained and undrained bearing capacity about plate loading tests on clay till [18], as given by Equation (4). The value of c_u was 60 kN/m², leading to a calculated effective cohesion of 6 kN/m² using this equation. This calculated value was directly used as the drained cohesion (c′) in the analysis (see Table (1)).

$$C'_{oc} = 0.1.C_u \qquad (Kpa) \tag{4}$$

Furthermore, Equation (5), as proposed by [19], can be used to calculate the drained Young's modulus (E'). By rearranging Equation (5), E′ was determined for the drained analysis. The calculated E′ value of 10487 kN/m² was implemented in the PLAXIS 3D model for the long-term drained condition simulations.

$$E_u = \frac{3}{2(1+V')}E' \qquad (Kpa) \tag{5}$$

Table 1: Clay soil and footing properties under two drainage scenarios.

	Material model	Mohr-Coulomb	Mohr-Coulomb
Clay Soil	Material Properties	Silty-Clay (CH)	Silty-Clay (CH)
	Drainage type	Undrained-C	Drained
	γ_{dry} (KN/m³)	14.22	14.22
	γ_{sat} (KN/m³)	18.66	18.66
	E (KN/m²)	12100	10487
	V	0.495	0.30
	Ø (Degree)	0	25.94
	C (KN/m²)	60	6
	ψ (Degree)	0	0
	R_{inter}	0.60	0.60
Footing	Material type	Concrete	Concrete
	Material model	Linear Elastic	Linear Elastic
	γ (KN/m³)	24	24
	E (KN/m²)	25×10^6	25×10^6
	V	0.15	0.15

Model Dimensions and Mesh Sensitivity

For the full-scale models, the ideal numerical domain dimensions were identified by means of a two-stage sensitivity analysis. The chosen domain had a vertical depth of 10B and lateral boundaries that were 13B × 13 B. A mesh sensitivity analysis was carried out to make sure the numerical results were unaffected by mesh size, and a fine mesh was used to improve accuracy. The study took into account different footing sizes, with element counts ranging from roughly 23,900 to 30,700, which corresponds to footing sizes ranging from 1 m × 1 m to 4 m × 4 m.

Embedment Depth Analysis

At different embedment depths (D_f) of 0.00, 0.50, 1.00, and 1.50 m, the bearing capacity was assessed. Through soil overburden pressure, this analysis sought to measure the direct impact of embedment depth on bearing capacity.

RESULTS AND DISCUSSION

The behavior of shallow foundations in clayey soil under drained and undrained conditions is examined in this section, with particular attention paid to the effects of foundation dimensions and embedment depth on the different bearing capacities (q_u, $q_u/3$, S_{25mm}, and q_{all}). These crucial factors and their effects on foundation performance are carefully examined in the study.

UNDRAINED CONDITIONS

Influence of Foundation Dimensions on Bearing Capacity

Different behaviors were found when the impact of foundation dimensions on bearing capacity under undrained conditions was examined. As demonstrated in Figures (2&3) and shown in Table (2), the ultimate bearing capacity (q_u) decreased slightly to 372 kPa for the 4m×4m foundation, from 370 kPa for a 1m×1m foundation to 376 kPa for a 3m×3m foundation. This implies that the ultimate bearing capacity of clayey soil under undrained conditions is less sensitive to foundation size than that of sandy soils.

Table 2: Bearing capacity of foundations with varying dimensions.

Footing size	Bearing capacity of foundations			
	Ultimate B.C. (Kpa)	Allowable B.C. (Kpa)	Allowable B.C. (Kpa)	Allowable design B.C. (Kpa)
	q_u	$q_u/3$	S_{25mm}	q_{all}
1m×1m	370	123.33	305	123.33
2m×2m	372	124	220	124
3m×3m	376	125.33	155	125.33
4m×4m	372	124	117	117

However, the allowable bearing capacity based on the settlement criterion (S_{25mm}) dropped dramatically as foundation size increased because the larger influence area led to more settlement under the same load. The controlling factor for larger foundations is settlement, as evidenced by the q based on S_{25mm} value dropping from 305 kPa for a

1m×1m foundation to 117 kPa for a 4m×4m foundation. On the other hand, the design for smaller foundations was controlled by the safety factor criterion ($q_u/3$).

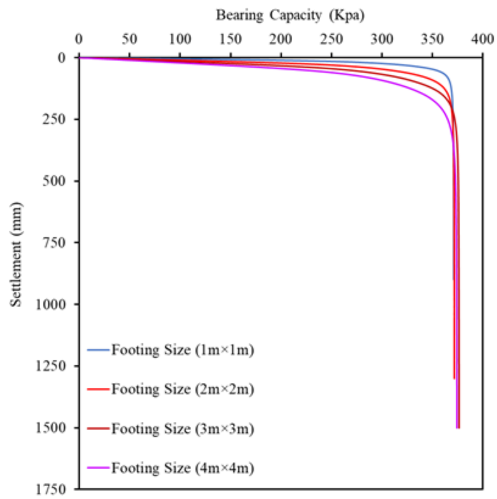


Figure 2: Load-Settlement Behavior of Shallow Foundations with Varying Dimensions (1m×1m to 4m×4m) in Clayey Soil.

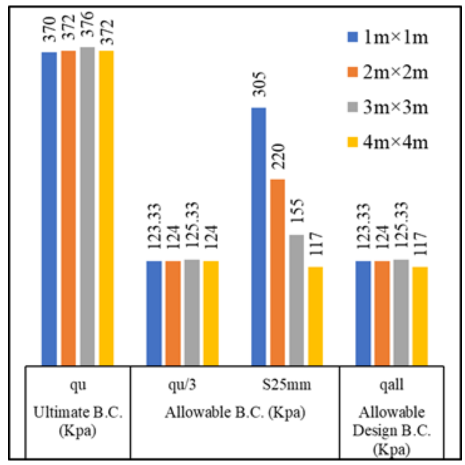
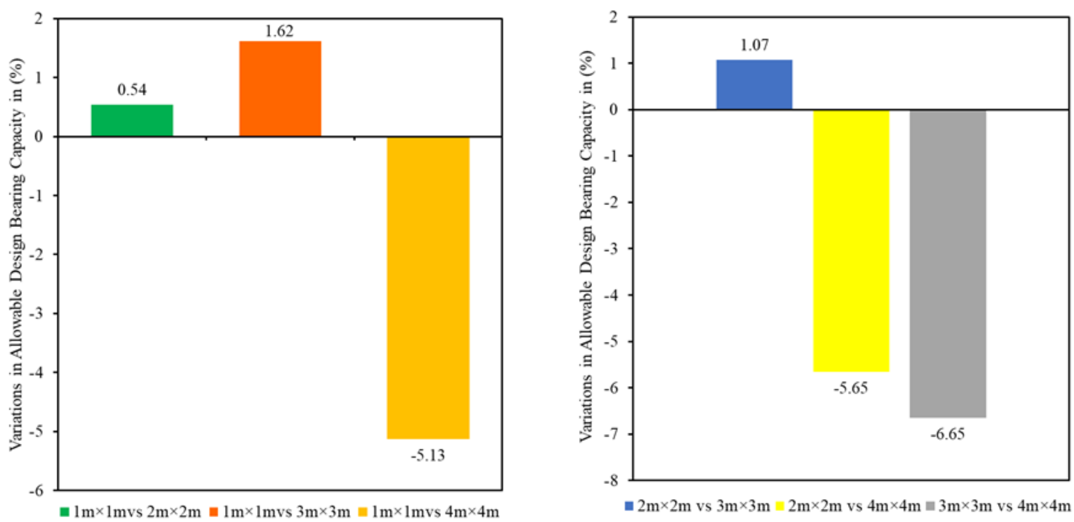


Figure 3: Ultimate and allowable bearing capacity of foundations with varying dimensions.

Figure (4) provides additional insight into these differences, demonstrating a notable 5.13% drop in q_{all} for the 4m×4m foundation and a negligible change for the 2m×2m and 3m×3m foundations when compared to the 1m×1m size. The foundation size was reduced by 6.65% when it was increased from 3 m × 3 m to 4 m × 4 m.



(a) (b)

Figure 4: Effect of foundation dimensions on bearing capacity.

Influence of Foundation Depth on Bearing Capacity

The analysis of foundation depth's influence on bearing capacity under undrained conditions revealed improvements for all foundation sizes.

Foundation Size 1m×1m: The ultimate bearing capacity (q_u) for a 1 m × 1 m foundation increased significantly with depth, from 370 kPa at the surface (D_f=0 m) to 755 kPa at D_f=1.5 m, as shown in Table (3) and Figures (5&6). S_{25mm} and $q_u/3$ both displayed increasing trends. At all depths, the factor of safety criterion ($q_u/3$) continuously controlled the allowable design capacity (q_{all}).

Table 3: Bearing capacity of 1m × 1m foundations at varying depths.

Foundation size (1m×1m)				
D_f (m)	Ultimate B.C. (Kpa)	Allowable B.C. (Kpa)	Allowable B.C. (Kpa)	Allowable design B.C. (Kpa)
	q_u	$q_u/3$	S_{25mm}	q_{all}
0	370	123.33	305	123.33
0.5	600	200	392	200
1	720	240	428	240
1.5	755	251.67	436	251.67

Significant percentage increases in q_{all} in comparison to surface foundations are shown in Figure (7a): 62.17% at 0.5m, 94.60% at 1.0m, and 104.06% at 1.5m embedment. Figure (7b), on the other hand, shows a nonlinear rate of improvement, with the incremental increase decreasing dramatically after 1.0 m depth (only 4.86% improvement between 1.0 m and 1.5 m). This implies a useful embedment limit at which there is little structural benefit to more depth.

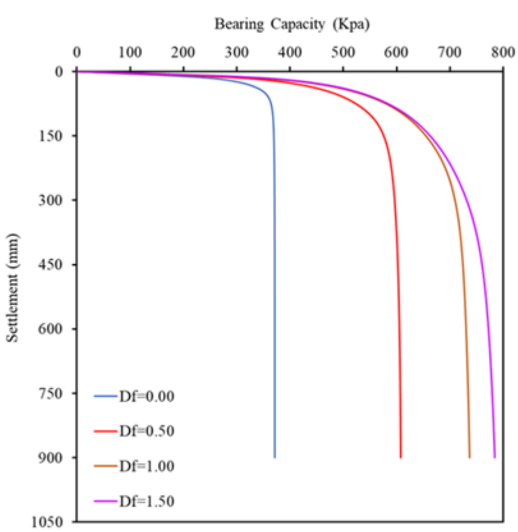


Figure 5: Bearing capacity–settlement behavior of 1m×1m foundations at varying depths.

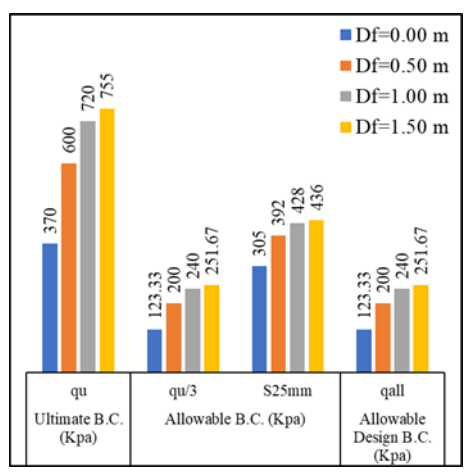
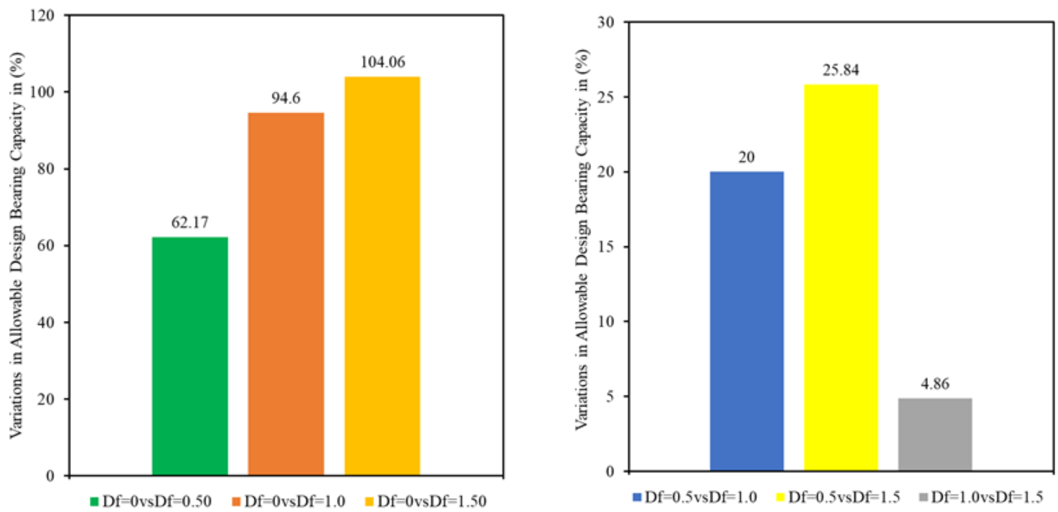


Figure 6: Ultimate and allowable bearing capacity of foundation size 1m×1m at varying depth.



(a) (b)

Figure 7: Effect of depth on bearing capacity of 1 m × 1 m foundations.

Foundation Size 2m×2m: Ultimate bearing capacity increases noticeably with depth, from 372 kPa at D_f=0m to 655 kPa at D_f=1.5m, as shown in Table (4) and Figures (8&9). Like the 1m × 1m foundation, q_{all} was still controlled by $q_u/3$, and both $q_u/3$ and S_{25mm} increased with depth.

Table 4: Bearing capacity of foundation size (2m × 2m) with varying depth.

Foundation size (2m×2m)				
D_f (m)	**Ultimate B.C. (Kpa)**	**Allowable B.C. (Kpa)**	**Allowable B.C. (Kpa)**	**Allowable design B.C. (Kpa)**
	q_u	**$q_u/3$**	**S_{25mm}**	**q_{all}**
0	372	124	220	124
0.5	518	172.67	246	172.67
1	612	204	267	204
1.5	655	218.33	279	218.33

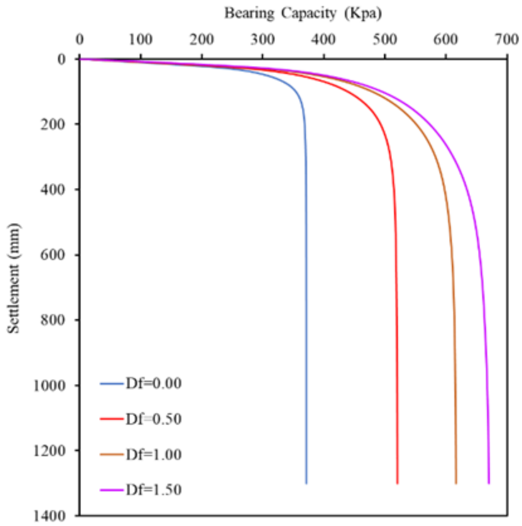


Figure 8: Bearing capacity–settlement behavior of 2 m × 2 m foundations at varying depths.

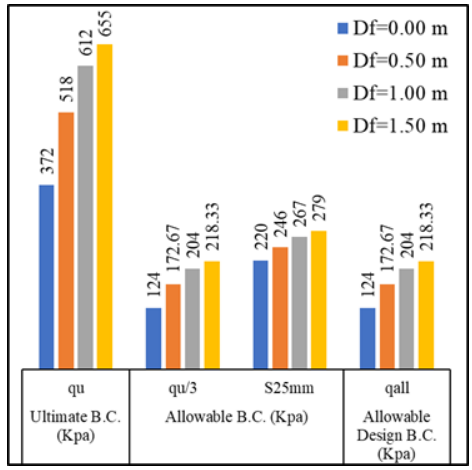
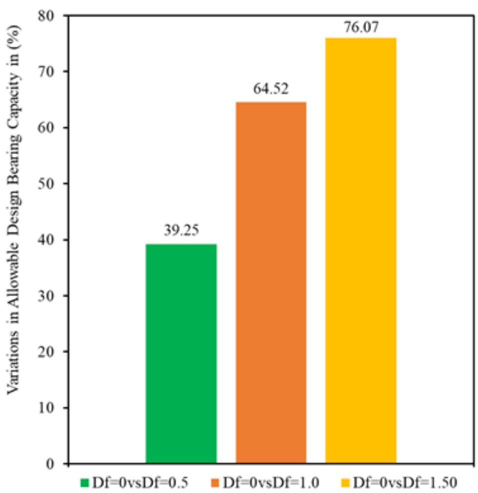
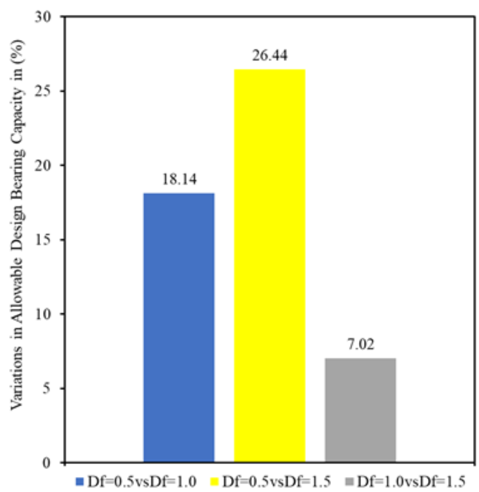


Figure 9: Ultimate and allowable bearing capacity of foundation size (2m × 2m) at varying depth.

At depths of 0.5, 1.0, and 1.5 meters, respectively, Figure (10a) shows q_{all} enhancements of 39.25%, 64.52%, and 76.07%. Reiterating the idea of diminishing returns at deeper depths, Figure (10b) shows the nonlinear improvement rate once more, with an improvement of 7.02% between 1.0 and 1.5 meters.



(a)



(b)

Figure 10: Effect of depth on bearing capacity of 2 m × 2 m foundations.

Foundation Size 3m×3m: Ultimate bearing capacity increased nonlinearly to 602 kPa at 1.5 m depth for the 3 m × 3 m foundation (Table (5), Figures (11&12). S_{25mm} demonstrated a steady increase, even though $q_u/3$ increased as well. Interestingly, the q_{all} determination changed, with settlement criteria taking precedence over all other factors at a depth of 1.5 m. This underscores the growing importance of settlement for deeper foundations.

Table 5: Bearing capacity of foundation size (3m × 3m) with varying depth.

Foundation size (3m×3m)				
D_f (m)	Ultimate B.C. (Kpa)	Allowable B.C. (Kpa)	Allowable B.C. (Kpa)	Allowable design B.C. (Kpa)
	q_u	$q_u/3$	S_{25mm}	q_{all}
0	376	125.33	155	125.33
0.5	481	160.33	166	160.33
1	554	184.67	177	177
1.5	602	200.67	187	187

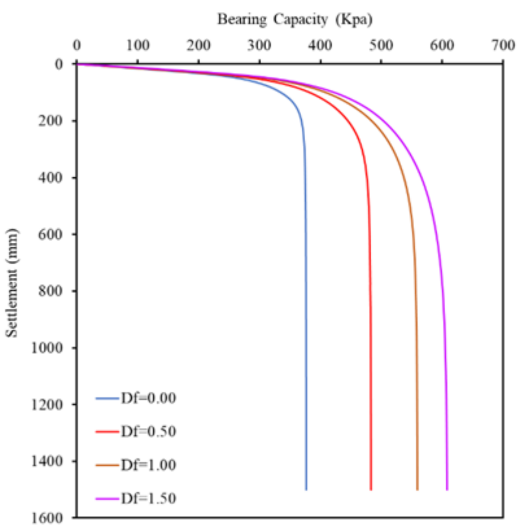


Figure 11: Bearing capacity–settlement behavior of 3 m × 3 m foundations at varying depths.

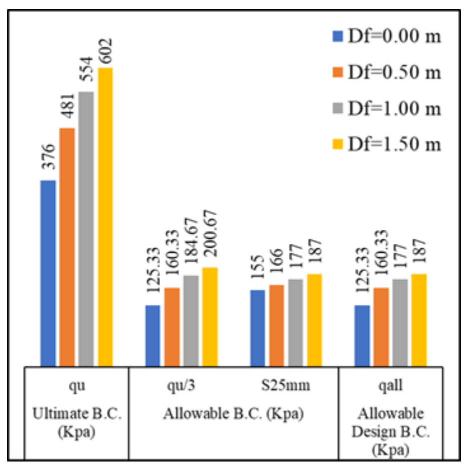
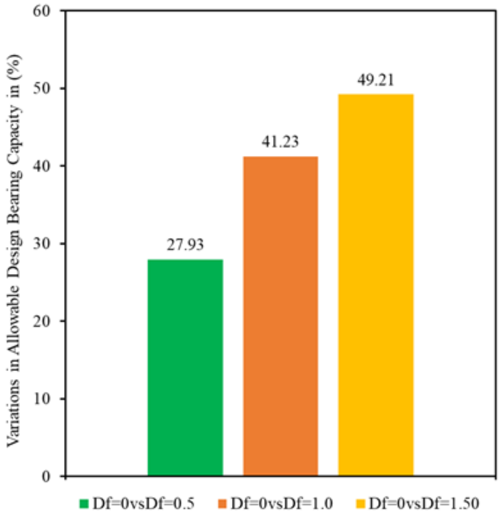
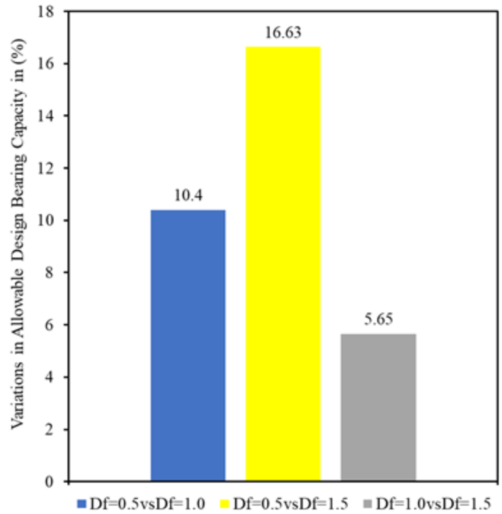


Figure 12: Ultimate and allowable bearing capacity of foundation size (3m × 3m) at varying depth.

At 0.5, 1.0, and 1.5 meters, respectively, Figure (13a) displays q_{all} improvements of 27.93%, 41.23%, and 49.21%. Only a 5.65% improvement between 1.0m and 1.5m is shown in Figure (13b), confirming the diminishing incremental increases.



(a)



(b)

Figure 13: Effect of depth on bearing capacity of 3 m × 3 m foundations.

Foundation Size 4m×4m: Ultimate bearing capacity consistently increases with depth, reaching 570 kPa at 1.5 m, as shown in Table (6) and Figures (14&15). S_{25mm} consistently determined q_{all} for this largest foundation size at all depths, highlighting the crucial role that settlement limitations play in large foundation design.

Table 6: Bearing capacity of foundation size (4m × 4m) with varying depth.

Foundation size (4m×4m)				
D_f (m)	**Ultimate B.C. (Kpa)**	**Allowable B.C. (Kpa)**	**Allowable B.C. (Kpa)**	**Allowable design B.C. (Kpa)**
	q_u	**$q_u/3$**	**S_{25mm}**	**q_{all}**
0	372	124	117	117
0.5	458	152.67	123	123
1	524	174.67	130	130
1.5	570	190	138	138

Allowable design bearing capacity improvements of 8.05%, 11.11%, and 17.95% at 0.5m, 1.0m, and 1.5m embedment, respectively, are displayed in Figure (15a). Compared to smaller foundations, these increments are not as noticeable. The marginal capacity enhancement for large foundations significantly diminishes beyond 1.0m depth, as shown by Figure (15b), which shows a distinctly nonlinear behavior with only 6.15% improvement between 1.0m and 1.5m.

Because of increased soil confinement and overburden pressure, increasing embedment depth increases bearing capacity in undrained conditions. However, the improvement rate declined nonlinearly beyond 1.0 m, indicating an ideal depth. At the same time, the design capacity for larger foundations was increasingly controlled by settlement criteria. The effect of depth on bearing capacity of 4 m × 4 m foundations is shown in Figure (16).

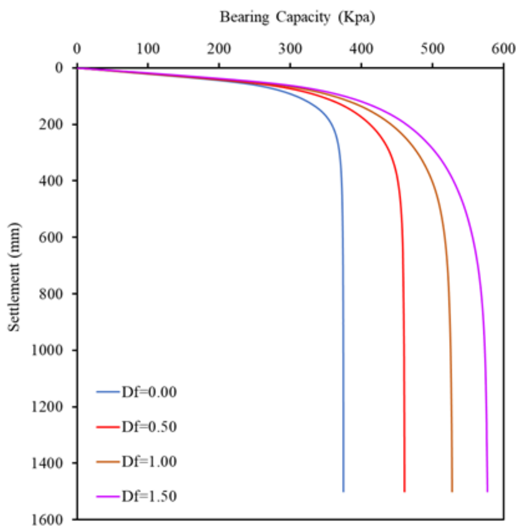


Figure 14: Bearing capacity–settlement behavior of 4 m × 4 m foundations at varying depths.

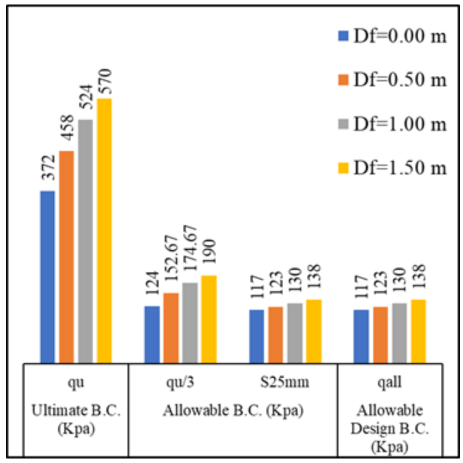
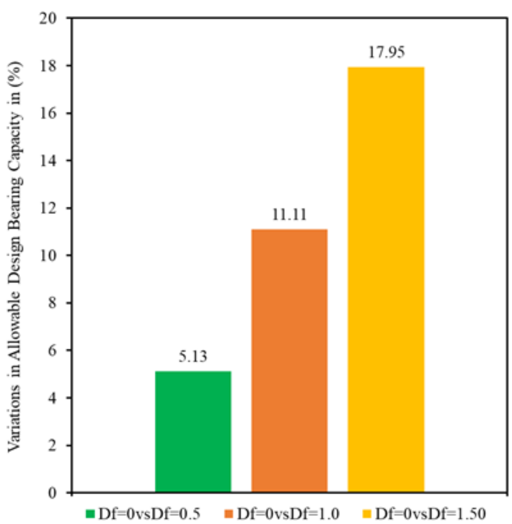
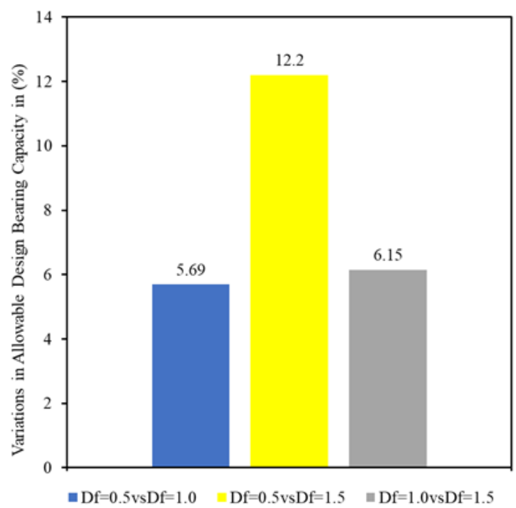


Figure 15: Ultimate and allowable bearing capacity of foundation size (4m × 4m) at varying depth.



(a)



(b)

Figure 16: Effect of depth on bearing capacity of 4 m × 4 m foundations.

DRAINED CONDITIONS

Influence of Foundation Dimensions on Bearing Capacity

In contrast to undrained situations, the bearing capacity of clayey soil foundations varies greatly with size under drained conditions. There was a noticeable size-dependent relationship as the ultimate bearing capacity (q_u) rose from 384 kPa for a 1 m × 1 m foundation to 570 kPa for a 4 m × 4 m foundation. Likewise, as foundation dimensions increased, so did the permissible bearing capacity ($q_u/3$). These results emphasize how crucial it is to take foundation size into account when calculating drained bearing capacity for clayey soils, as shown in Table (7) and Figures (17&18).

Table 7: Bearing capacity of foundations with varying dimensions.

Footing size	Bearing capacity of foundations			
	Ultimate B.C. (Kpa)	Allowable B.C. (Kpa)	Allowable B.C. (Kpa)	Allowable design B.C. (Kpa)
	q_u	$q_u/3$	S_{25mm}	q_{all}
1m×1m	384	128	173	128
2m×2m	428	142.67	126	126
3m×3m	502	167.33	97	97
4m×4m	570	190	77	77

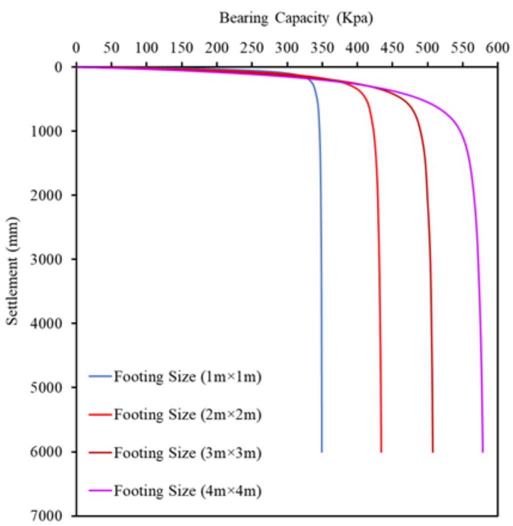


Figure 17: Bearing Capacity – Settlement Behavior of Foundations with Varying dimensions.

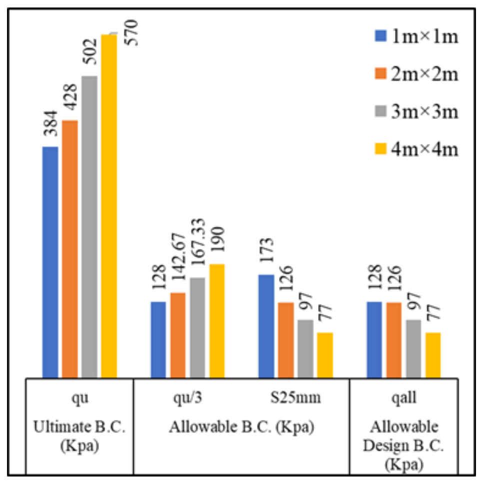
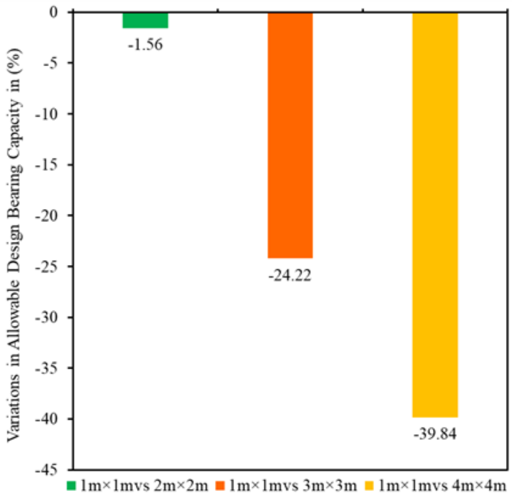


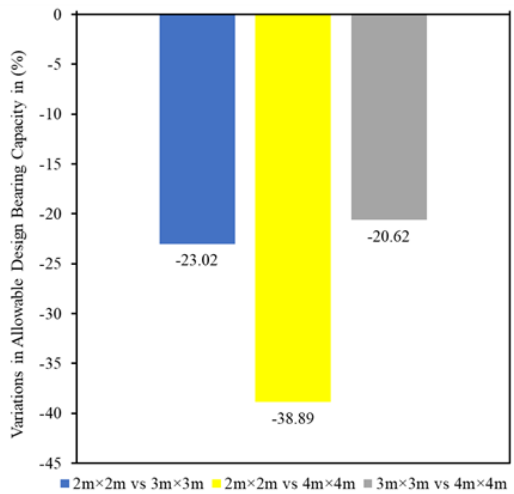
Figure 18: Ultimate and allowable bearing capacity of foundations with varying dimensions.

As foundation size increased, however, the permissible bearing capacity as established by the settlement criterion (S_{25mm}) decreased, falling from 173 kPa for a 1 m × 1 m foundation to 77 kPa for a 4 m × 4 m foundation. For larger foundations (2m×2m to 4m×4m), the settlement criterion (S_{25mm}) governed the allowable design bearing capacity (q_{all}), which drastically decreased. The design was governed by the factor of safety criterion ($q_u/3$) for the smallest foundation (1 m × 1 m).

These reductions are clearly shown in Figure (19). For example, the q_{all} of the 4m×4m foundation was 39.84% lower than that of the 1m×1m foundation. Between the

3m×3m and 4m×4m foundations, the biggest decrease (20.62%) was observed. These results demonstrate that, although ultimate capacity may rise with size in drained conditions, settlement considerations become crucial for larger foundations and frequently dictate the design.





(a) (b)

Figure 19: Effect of foundation dimensions on bearing capacity.

Influence of Foundation Depth on Bearing Capacity

An analysis of the impact of foundation depth in drained conditions also revealed a notable increase in bearing capacity, with settlement dictating the permissible design capacity.

Foundation Size 1m×1m: Ultimate bearing capacity increases significantly with depth, from 384 kPa at D_f=0m to 1710 kPa at D_f=1.5m, as shown in Table (8) and Figures (20&21). S_{25mm} and $q_u/3$ both rose as well. The analysis showed that the allowable design bearing capacity q_{all} changed from the factor of safety criterion ($q_u/3$) at the surface to the settlement criterion (S_{25mm}) at deeper depths.

Table 8: Bearing capacity of 1m × 1m foundations at varying depths.

Foundation size (1m×1m)				
D_f (m)	**Ultimate B.C. (Kpa)**	**Allowable B.C. (Kpa)**	**Allowable B.C. (Kpa)**	**Allowable design B.C. (Kpa)**
	q_u	**$q_u/3$**	**S_{25mm}**	**q_{all}**
0	384	128	173	128
0.5	792	264	216	216
1	1270	423.33	253	253
1.5	1710	570	279.5	279.5

Considerable q_{all} enhancements are displayed in Figure (22a): 68.75% at 0.5m, 97.66% at 1.0m, and 118.36% at 1.5m embedment. Figure (22b), on the other hand, shows diminishing incremental improvements beyond 1.0m depth (10.47% improvement between 1.0m and 1.5m), indicating a practical limit where more excavation results in less structural benefit in relation to cost.

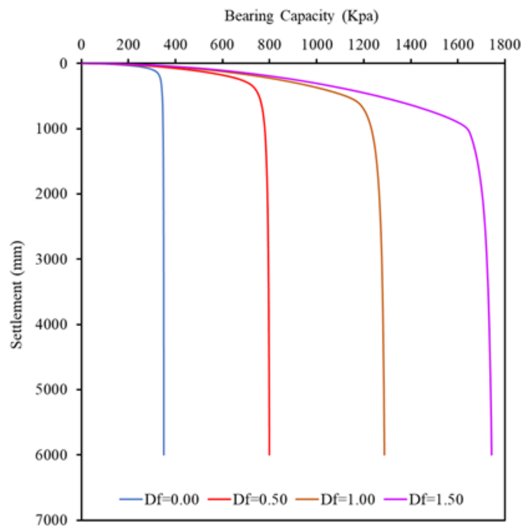


Figure 20: Bearing capacity–settlement behavior of 1 m × 1 m foundations at varying depths.

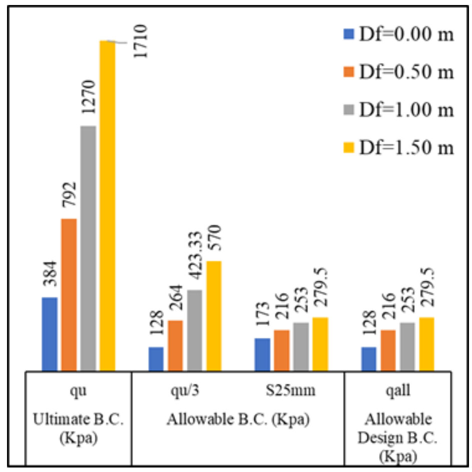
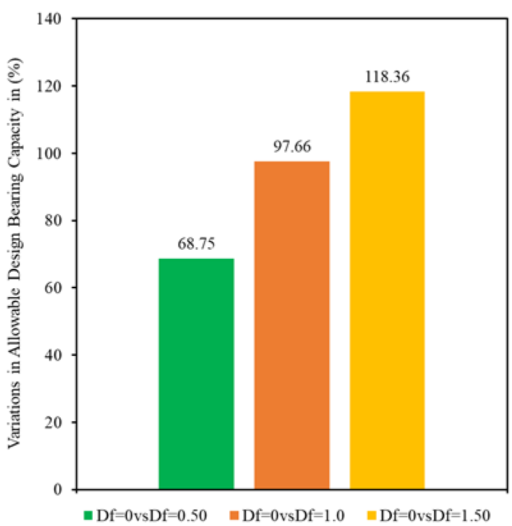
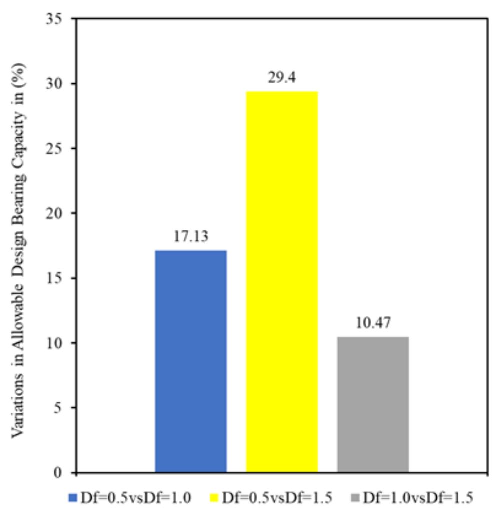


Figure 21: Ultimate and allowable bearing capacity of foundation size (1m × 1m) at varying depth.



(a)



(b)

Figure 22: Effect of depth on bearing capacity of 1 m × 1 m foundations.

Foundation Size 2m×2m: Table (9) and Figures (23&24) demonstrate that the 2m×2m foundation's q_u increased dramatically with depth, rising from 428 kPa at D_f=0m to 1485 kPa at D_f=1.5m. At every depth examined, q_{all} was consistently controlled by the settlement criterion (S_{25mm}), even though both $q_u/3$ and S_{25mm} increased.

Table 9: Bearing capacity of foundation size (2m × 2m) with varying depth.

Foundation size (2m×2m)				
D_f (m)	Ultimate B.C. (Kpa)	Allowable B.C. (Kpa)	Allowable B.C. (Kpa)	Allowable design B.C. (Kpa)
	q_u	$q_u/3$	S_{25mm}	q_{all}
0	428	142.67	126	126
0.5	788	262.67	144	144
1	1125	375	162	162
1.5	1485	495	180	180

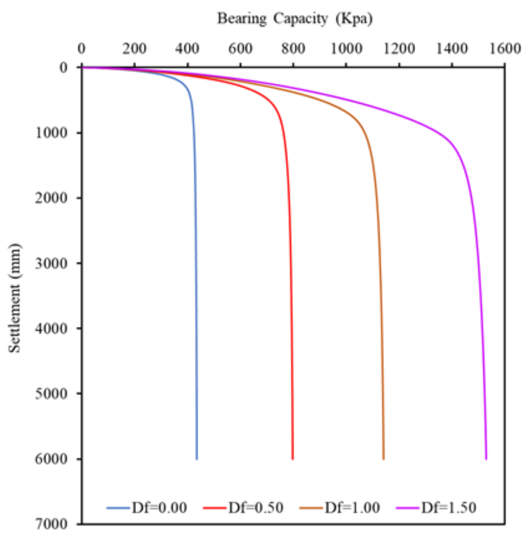


Figure 23: Bearing capacity–settlement behavior of 2 m × 2 m foundations at varying depths.

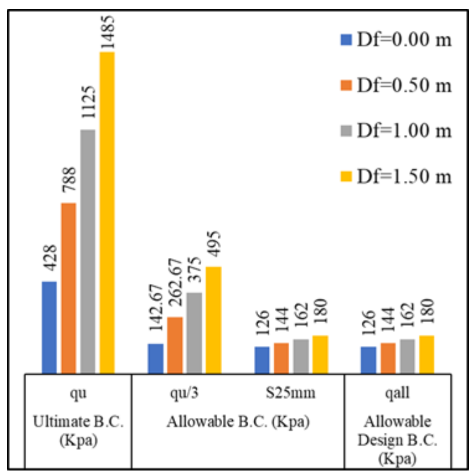
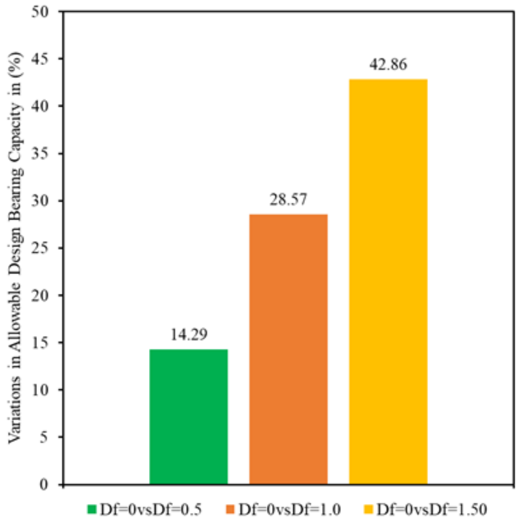
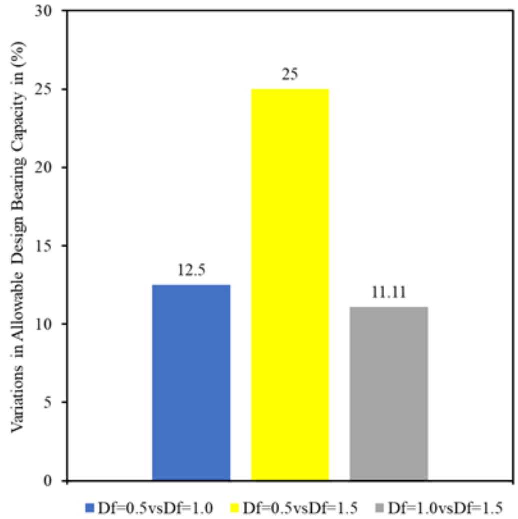


Figure 24: Ultimate and allowable bearing capacity of foundation size (2m × 2m) at varying depth.



(a)



(b)

Figure 25: Effect of depth on bearing capacity of 2 m × 2 m foundations.

At 0.5m, 1.0m, and 1.5m depths, respectively, Figure (25a) shows q_{all} enhancements of 14.29%, 28.57%, and 42.86%. With an improvement of 11.11% between 1.0 and 1.5 meters, Figure (25b) once more demonstrates the nonlinear improvement rate and diminishing increases.

Foundation Size 3m×3m: Ultimate bearing capacity increases nonlinearly with depth, reaching 1425 kPa at 1.5 m, as shown in Table (10) and Figures (26&27). At all depths, the settlement criterion (S_{25mm}) continuously controlled the allowable design bearing capacity (q_{all}).

Table 10: Bearing capacity of foundation size (3m × 3m) with varying depth.

Foundation size (3m×3m)				
D_f (m)	Ultimate B.C. (Kpa)	Allowable B.C. (Kpa)	Allowable B.C. (Kpa)	Allowable design B.C. (Kpa)
	q_u	$q_u/3$	S_{25mm}	q_{all}
0	502	167.33	97	97
0.5	826	275.33	107	107
1	1115	371.67	118	118
1.5	1425	475	129	129

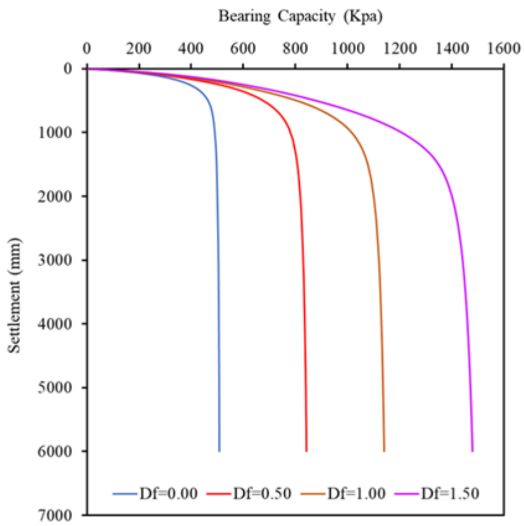


Figure 26: Bearing capacity–settlement behavior of 3 m × 3 m foundations at varying depths.

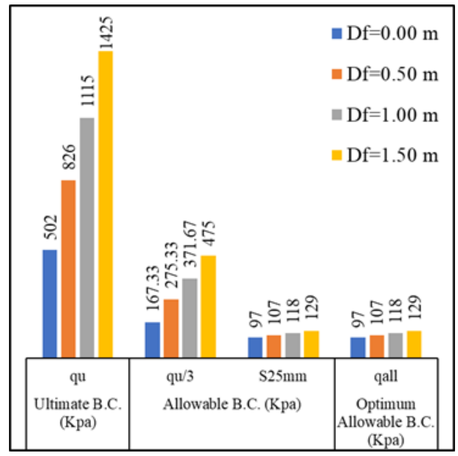
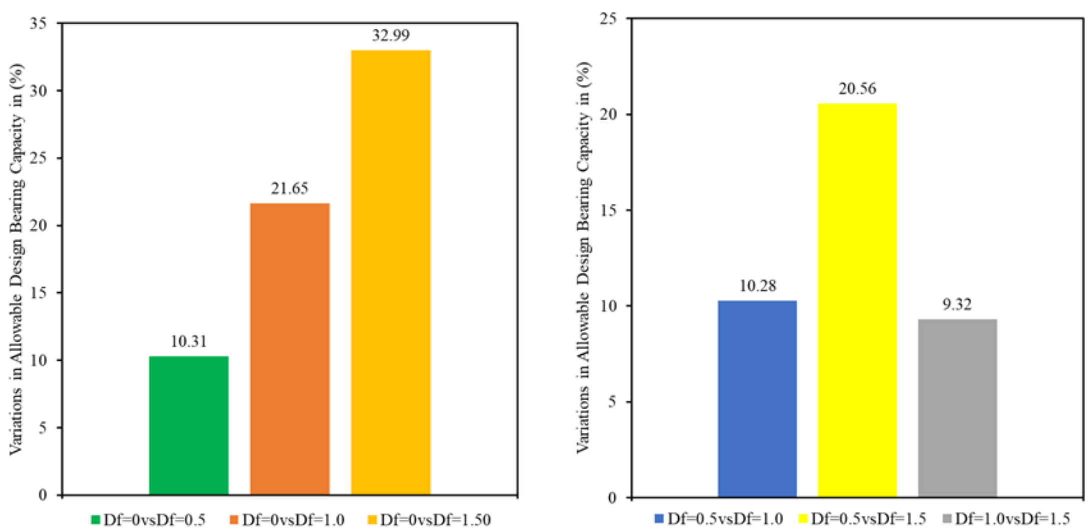


Figure 27: Ultimate and allowable bearing capacity of foundation size (3m × 3m) at varying depth.

At 0.5 m, 1.0 m, and 1.5 m depths, respectively, Figure (28a) shows q_{all} improvements of 10.31%, 21.65%, and 32.99%. Only a 9.35% improvement was seen between 1.0 and 1.5 meters, as shown in Figure (28b), which supports the diminishing incremental increase.



(a) (b)

Figure 28: Effect of depth on bearing capacity of 3 m × 3 m foundations.

Foundation Size 4m×4m: The q_u for the 4 m × 4 m foundation (Table (11), Figures (29&30) rose from 570 kPa at the surface to 1430 kPa at a depth of 1.5 m. In all depths taken into consideration, S_{25mm} consistently determined the ideal q_{all}, just like the other larger foundations under drained conditions.

Table 11: Bearing capacity of foundation size (4m × 4m) with varying depth.

Foundation size (4m×4m)				
D_f (m)	Ultimate B.C. (Kpa)	Allowable B.C. (Kpa)	Allowable B.C. (Kpa)	Allowable design B.C. (Kpa)
	q_u	$q_u/3$	S_{25mm}	q_{all}
0	570	190	77	77
0.5	865	288.33	83.2	83.2
1	1135	378.33	91	91
1.5	1430	476.67	99	99

As shown in Figure (31a), q_{all} shows increasing but decreasing improvements with depth; 8.05%, 18.18%, and 28.57% enhancement at 0.5m, 1.0m, and 1.5m embedment, respectively. There is only a 6.15% improvement between 1.0 and 1.5 meters, indicating nonlinear behavior as illustrated in Figure (31b). These results highlight that although increasing embedment depth for large foundations increases theoretical bearing capacity, settlement criteria consistently impose practical design limitations, and the marginal benefit of additional depth greatly diminishes beyond 1.0m.

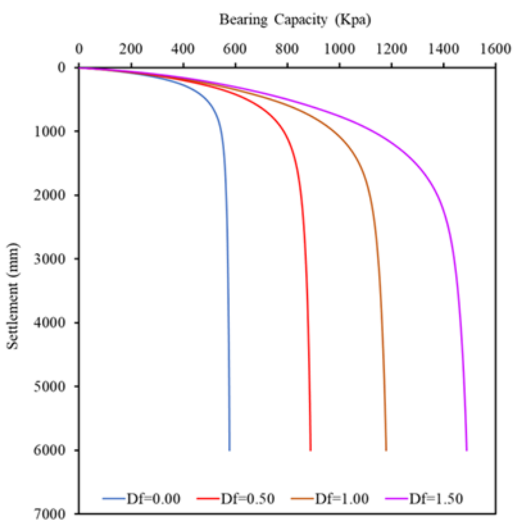


Figure 29: Bearing capacity–settlement behavior of 4 m × 4 m foundations at varying depths.

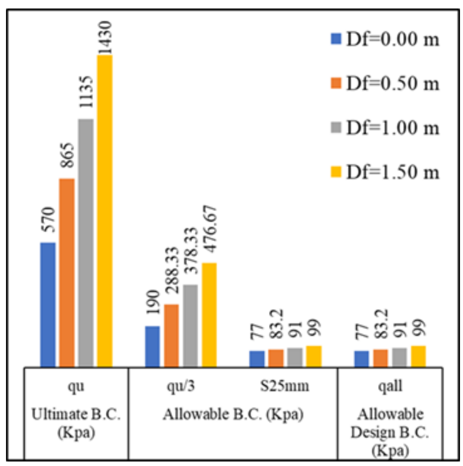
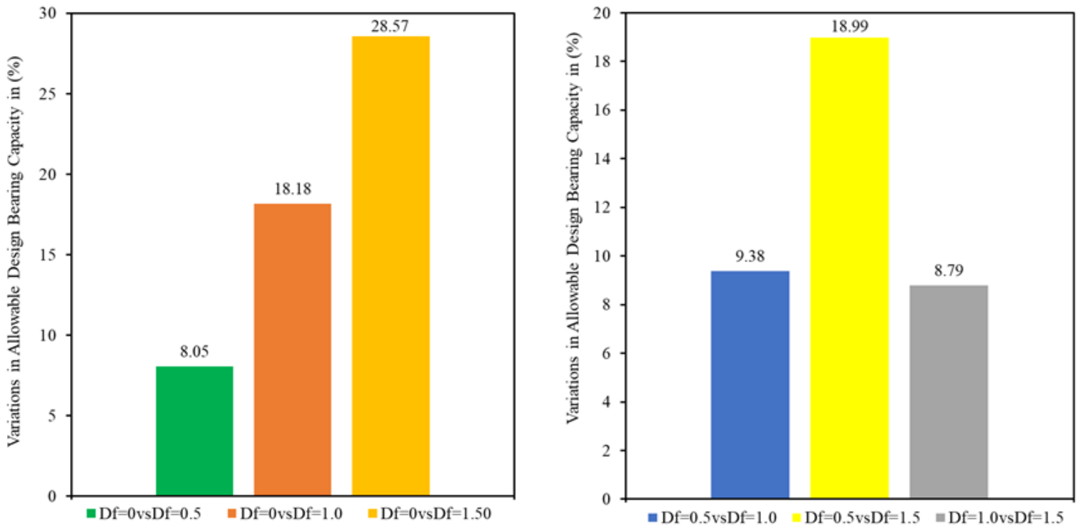


Figure 30: Ultimate and allowable bearing capacity of foundation size (4m × 4m) at varying depth.



(a) (b)

Figure 31: Effect of depth on bearing capacity of 4 m × 4 m foundations.

CONCLUSSION

This study reveals important distinctions between the behavior of shallow foundations in clayey soils under drained and undrained conditions, especially about their depth of embedment and dimensions. The ultimate bearing capacity (q_u) in undrained situations exhibited little reliance on foundation size, which is consistent with accepted soil mechanics principles that short-term capacity is determined by undrained shear strength. However, because settlement became the main design constraint for larger foundations, the allowable design bearing capacity (q_{all}) decreased, highlighting the need for settlement control for large structures subjected to rapid loading. Due to improved soil confinement, both q_u and q_{all} were greatly increased by deeper embedment. The additional advantages of deeper embedment decreased beyond about 1.0 to 1.5 meters, indicating an ideal practical depth, according to a clear nonlinear pattern. In contrast, under drained conditions, q_u rose as foundation dimensions increased, which was explained by the increase of frictional resistance. (q_{all}) was consistently governed by settlement criteria (S_{25mm}) for larger foundations, and it significantly decreased as foundation size increased, highlighting the importance of settlement for long-term stability in clayey soils. Like in undrained conditions, bearing capacity was significantly increased in drained conditions by embedment depth, which also showed a nonlinear, decreasing rate of improvement. In drained conditions, settlement criteria continued to be the most significant design constraint for larger foundations, even with increased embedment. There are important ramifications for foundation design optimization from this nonlinear relationship between depth and bearing capacity improvement that is seen in both scenarios. The marginal capacity enhancement significantly decreases beyond specific thresholds (e.g., 1.0m to 1.5m). In order to determine the optimal foundation depths that strike a balance between technical performance and economic viability and prevent needless excavation and construction costs, thorough cost analyses are crucial in engineering practice. In structural engineering applications, thorough analyses are essential when extending the foundation depth.

RECOMMENDATIONS

1. Future plans should place a strong emphasis on settlement criteria because they frequently determine the permissible bearing capacity, particularly for large shallow foundations in clayey soils.
2. To guarantee economical and effective designs, keep the foundation depth between 1.0 and 1.5 meters, where bearing capacity gains become negligible.
3. Because drained and undrained conditions have different effects on foundation behavior, design approaches should account for them.
4. Economic analyses should be used in future projects to identify the ideal foundation depths that strike a balance between construction costs and structural performance.
5. Because large foundations are more sensitive to settlement, use more conservative parameters and higher safety factors.
6. To improve design models and guidelines, look into critical embedment thresholds and nonlinear depth effects across a range of soil types.

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