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INFLUENCE OF FOOTING SPACING AND ADJACENT FOOTING INTERACTION ON SETTLEMENT OF SHALLOW FOUNDATIONS: A NUMERICAL STUDY USING PLAXIS 3D

*Quang-Thanh Truong[1], Trung-Quan Tran[2]

[1]Department of Civil Engineering, University of Architecture Ho Chi Minh City, Ho Chi Minh City, Viet Nam;
[2]Can Tho City Department of Construction, Can Tho City, Viet Nam

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ABSTRACT: Settlement behavior of shallow foundations is a critical consideration in geotechnical design, particularly when multiple footings are constructed in close proximity. Conventional design methods often neglect the interaction between adjacent foundations, which may lead to inaccurate predictions of settlement behavior. This study investigates the interaction effects of multiple shallow foundations using three-dimensional finite element modeling in PLAXIS 3D. A parametric analysis was conducted for a 4 × 4 footing group by varying the spacing-to-width ratio (s/b) ranging from 1.0 to 3.0. The results show that foundation interaction significantly increases settlement compared with isolated footings due to the overlap of stress zones in the underlying soil, which leads to greater deformation and redistribution of stresses. At a spacing ratio of s/b = 2.0, the central footing exhibits the largest settlement amplification, approximately 77.85%, indicating strong interaction effects within the group. As the spacing ratio increases (s/b ≥ 3.0), the stress overlap reduces and the interaction effect becomes negligible, resulting in behavior similar to isolated footings. These findings demonstrate that neglecting footing interaction may lead to underestimation of settlement in dense foundation systems. Therefore, considering interaction effects is essential for improving the accuracy of settlement prediction and optimizing foundation layout in practical engineering design, especially in dense urban environments.

Keywords: Shallow Foundation, Footing Spacing, Settlement, Adjacent Footing Interaction, Numerical Analysis

1. INTRODUCTION

Settlement of shallow foundations is a critical issue in geotechnical engineering, as it directly influences the serviceability, structural integrity, and long-term performance of supported structures [1]. Excessive total settlement or differential settlement may lead to functional problems, structural damage, and increased maintenance costs. In conventional foundation design practice, shallow footings are commonly analyzed as isolated elements, assuming that the influence of surrounding foundations is negligible. While this assumption may be acceptable for structures with sufficiently large foundation spacing, it becomes increasingly questionable in dense urban environments, where multiple footings are often constructed in close proximity [2, 3]. Under such conditions, the interaction between adjacent foundations modifies the stress distribution and deformation characteristics of the supporting soil, resulting in settlement behavior that may differ significantly from that of isolated footings.

The settlement behavior of shallow foundations has been a central topic in geotechnical engineering research for many decades. Classical theoretical frameworks for settlement analysis were developed by Terzaghi [4] and later extended by Poulos and Davis [5] as well as Das and Sivakugan [6]. These pioneering studies established fundamental principles governing immediate and consolidation settlements and provided simplified analytical frameworks that have been widely adopted in engineering practice due to their simplicity and ease of application. Nevertheless, such analytical approaches are generally based on idealized assumptions, including soil homogeneity, linear elastic behavior, and independent foundation response. As a result, they may not adequately capture the complex soil–structure interaction mechanisms that occur when multiple foundations share the same soil mass in real construction scenarios.

To better understand these interaction mechanisms, numerous experimental and analytical investigations have been conducted. Early experimental studies by Das and Larbi-Cherif [7] and Selvadurai and Rabbaa [8] demonstrated that closely spaced foundations may generate overlapping stress zones in the soil, which significantly alters the load-settlement response compared with isolated footings. Subsequent experimental and numerical studies conducted by Kumar and Bhoi [9], Srinivasan and Ghosh [10], Reddy et al. [11], Pusadkar et al. [12], and Subhan [13] further confirmed that footing spacing, soil properties, and foundation geometry play important roles in controlling settlement magnitude and deformation patterns. Additional analytical work by Nainegali et al. [14] highlighted the complexity of interference effects between asymmetrically spaced foundations resting on nonhomogeneous soil deposits.

Although experimental studies provide valuable insights into the physical mechanisms of footing interaction, their direct application to full-scale engineering problems is often limited due to scale effects, boundary constraints, and difficulties in realistically simulating in-situ soil conditions. With advances in computational techniques, numerical modeling has therefore become an increasingly important tool for analyzing soil–foundation interaction problems. In particular, the finite element method (FEM) enables detailed representation of soil behavior by incorporating nonlinear material models, stress redistribution, and complex boundary conditions. In this context, PLAXIS 3D has been widely applied in both research and engineering practice due to its robust numerical capabilities for simulating soil–structure interaction problems [15]. The use of three-dimensional finite element modeling allows explicit consideration of spatial stress redistribution and deformation compatibility within the soil mass, which is essential for accurately capturing interaction effects between adjacent foundations.

Recent studies have demonstrated that numerical analyses using PLAXIS-based finite element models can provide reliable predictions of settlement and differential deformation behavior compared with simplified analytical approaches. For example, Putra Pratama et al. [16,17] investigated differential settlement of historical pagoda foundations using PLAXIS 3D, highlighting the importance of load redistribution and reloading effects within complex foundation systems. Using PLAXIS 3D, Intui et al. [18] demonstrated that the Hardening Soil model (HSM) outperforms the Mohr-Coulomb model (MCM) in predicting settlement during groundwater recovery in soft clay, despite similar performance during drawdown. Similarly, Mohamed [19] demonstrated that foundation base geometry strongly influences stress distribution and deformation patterns in expansive soils.

Despite these important contributions, a considerable portion of existing research focuses primarily on single isolated foundations or simplified configurations, often neglecting the influence of neighboring foundations in practical foundation layouts. Consequently, settlement predictions based solely on isolated footing assumptions may underestimate the actual deformation behavior in densely constructed urban environments. Furthermore, many previous numerical studies have relied on two-dimensional analyses, which may not fully capture the three-dimensional interaction mechanisms occurring within groups of foundations.

In this context, the present study investigates the influence of footing spacing and adjacent foundation interaction on settlement behavior using a three-dimensional finite element approach. Numerical simulations are performed using PLAXIS 3D to analyze the interaction effects within a 4 × 4 shallow foundation system under realistic loading conditions. The spacing-to-width ratio (s/b) is systematically varied to quantify settlement amplification caused by foundation interference and to identify the spacing thresholds beyond which interaction effects become negligible. Particular attention is given to the settlement behavior of foundations located at corner, edge, and central positions within the footing group. The findings of this study contribute to a better understanding of settlement mechanisms in closely spaced foundation systems and provide practical guidance for optimizing foundation layouts in dense urban developments.

2. RESEARCH SIGNIFICANCE

Closely spaced shallow foundations interact through the supporting soil mass, resulting in settlement responses that differ from those predicted by conventional isolated footing analyses. However, such interaction effects are often neglected in routine foundation design. This study applies the Finite Element Method (FEM) to quantify the influence of footing spacing and adjacent foundation interaction on settlement behavior. Two analytical scenarios are examined: isolated footing conditions and interacting foundation systems under identical geotechnical and loading parameters. Three representative footing locations—central, edge, and corner—are analyzed to capture the spatial variability of interaction effects. The results provide a clearer understanding of interaction-induced settlement amplification and highlight the limitations of isolated footing assumptions. These findings contribute to more accurate settlement prediction and improved design of shallow foundations in civil and industrial engineering applications.

3. MATERIAL AND METHODS

This study employs a three-dimensional finite element method (FEM) to investigate the settlement behavior of shallow foundations, with particular emphasis on the interaction effects between adjacent footings. The numerical analysis is conducted under identical geological and loading conditions representative of the selected study area. The adopted modeling framework allows systematic evaluation of settlement responses resulting from variations in footing spacing and relative footing positions.

3.1 Problem Geometry

The study considers a hypothetical building supported by a regular square column grid. Square shallow footings with a width $b = 2.2$ m are adopted.

The initial grid spacing between columns is set to $s = 4.4$ m.

To investigate the influence of interaction effects within the foundation system, three representative footing locations are selected for detailed analysis:

1. Center footing, surrounded by adjacent foundations on all sides.
2. Edge footing, located along the perimeter of the foundation grid.
3. Corner footing, positioned at the corner of the grid system.

The foundation layout adopted in this study is intentionally idealized to isolate and quantify the interaction effects between adjacent footings. By eliminating potential influences from geometric irregularities or soil heterogeneity, the analysis focuses specifically on the effects of footing spacing and relative footing position within the foundation group. Through systematic evaluation of center, edge, and corner locations, the study clarifies the mechanisms of stress redistribution within interacting foundation systems.

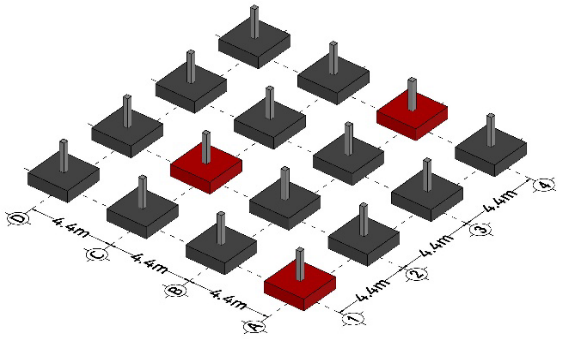


Fig. 1 Three-dimensional schematic representation of the pad foundation system

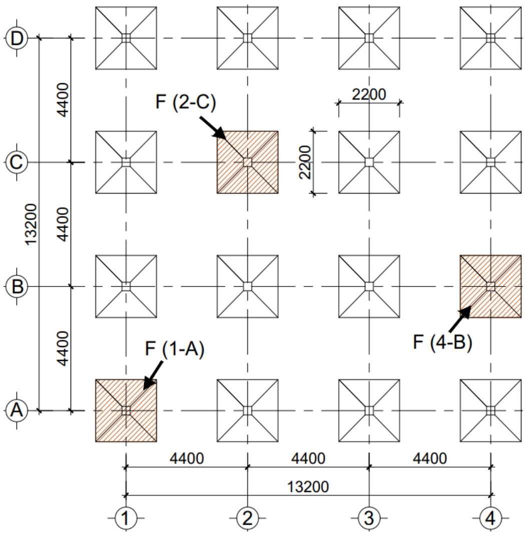


Fig. 2 Plan layout of the pad foundation system showing footing arrangement

Such a simplified configuration represents common layouts encountered in building structures with regular column grids. The controlled analytical framework ensures that settlement variations are directly attributable to footing spacing and spatial arrangement, thereby providing insights relevant to practical foundation engineering design.

Figures 1 and 2 illustrate the three-dimensional conceptual model and the plan layout of the pad foundation system used in the numerical analysis.

3.2 Soil and Numerical Modeling

The subsurface conditions of the study site are idealized as a multilayered soil profile consisting of three distinct strata. The soil parameters used in the numerical model are adopted from examples presented in the PLAXIS 3D Tutorial Manual (2016). These parameters represent typical geotechnical conditions and are selected to ensure reproducibility of the numerical simulations while allowing a focused investigation of footing spacing effects on settlement behavior.

The upper soil layer consists of a sand stratum with a thickness of 2.0 m. This layer has an unsaturated unit weight of 17.0 kN/m³ and a saturated unit weight of 20.0 kN/m³. The effective cohesion is assumed to be 1.0 kN/m² and the friction angle is 31°.

Beneath this layer lies a deposit of medium-plasticity clay with a thickness of 12.0 m. The clay layer has an unsaturated unit weight of 16.0 kN/m³ and a saturated unit weight of 18.0 kN/m³, with an effective cohesion of 5.0 kN/m² and a friction angle of 25°.

The third layer consists of a relatively thick stratum of dense sand representing the deeper supporting soil. This layer is characterized by an unsaturated unit weight of 17.0 kN/m³ and a saturated unit weight of 20.0 kN/m³, with an effective cohesion of 1.0 kN/m² and a friction angle of 30°.

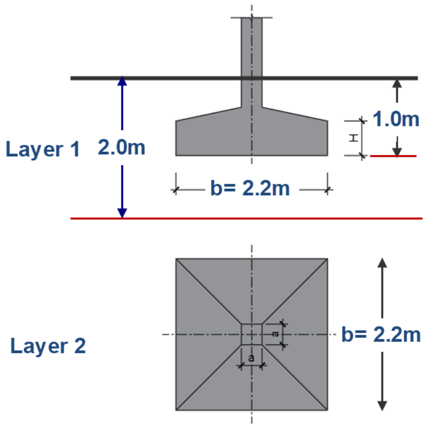


Fig. 3 Geometrical dimensions and embedment depth of the typical square footing

The geometrical dimensions of the footing and the embedment depth used in the numerical model are illustrated in Figure 3. A summary of the soil stratification and the corresponding geotechnical parameters is presented in Table 1.

Table 1. Soil Profile and Geotechnical Properties

Layer No.		Layer thickness	Soil Name and Engineering Characteristics
Layer 1	🟦	2.0 m	Upper Sand: Near-surface layer; γ_{unsat} = 17.0 kN/m^3; γ = 20.0 kN/m^3; φ' = 31°
Layer 2	🟩	12.0 m	Clay: A thick stratum of cohesive soil. γ = 16.0 kN/m^3; γ_{unsat} = 18.0 kN/m^3; c' = 5 kPa; effective friction angle φ' = 25°
Layer 3	🟨	Very thick	Dense Sand: γ = 20.0 kN/m^3; γ_{unsat} = 17.0 kN/m^3 Effective friction angle φ'= 30°; c' = 1.0 kPa;

Numerical simulations were performed using the finite element method implemented in PLAXIS 3D. The subsurface stratigraphy was idealized as a three-layer soil system, where the Mohr–Coulomb (MC) constitutive model was adopted to represent the non-linear mechanical response of the soil. The relevant geotechnical properties and material parameters used in the numerical model are summarized in Table 2.

Table 2. Geotechnical and material input parameters

Property	Upper sand (Layer 1)	Clay (Layer 2)	Stiff sand (Layer 3)	Concrete
Soil model	Mohr Coulomb	Mohr Coulomb	Mohr Coulomb	Linear elastic
Drainage type	Drained	Drained	Drained	Non-porous
γ_{unsat} (kN/m^3)	17.0	16.0	17.0	27.0
γ_{sat} (kN/m^3)	20.0	18.0	20.0	–
E'_{ref} (kPa)	$1.3\cdot10^4$	$1.0\cdot10^4$	$7.5\cdot10^4$	$3.1\cdot10^7$
Poisson's ratio	0.30	0.35	0.30	0.10
c'_{ref} (kPa)	1.0	5.0	1.0	–
φ' (°)	31	25	30	–
Ψ (°)	0	0	0	–
Strength determination	Rigid	Rigid	Rigid	Rigid
K_0	Auto	Auto	Auto	Auto

In this study, the clay layer (Layer 2) is modeled using drained parameters to evaluate long-term consolidation settlement. This approach captures the maximum interaction effects between adjacent foundations after excess pore pressure dissipation, representing the critical serviceability condition. While undrained analysis reflects short-term response, the drained condition is more suitable for assessing total settlement and long-term stress redistribution.

The Mohr–Coulomb model was selected due to its computational efficiency and its proven capability to provide reliable predictions of settlement behavior in layered soil profiles. Although more advanced constitutive models are available, the MC model remains widely used in preliminary geotechnical analyses, particularly when site-specific laboratory data are limited. In addition, a sensitivity assessment based on the selected Young's modulus (E) and friction angle (φ) confirms that the obtained numerical results are consistent and that the adopted parameters reasonably represent the investigated soil conditions.

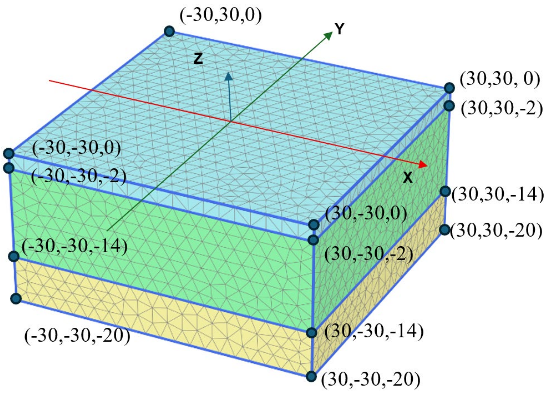


Fig. 4 A three-layer soil foundation model in the analysis

The three-dimensional numerical domain used in the finite element analysis is illustrated in Fig. 4, which illustrates the geometry of the foundation model and the spatial coordinate system adopted in the simulations. The coordinates (x,y,z) are expressed in meters. The model dimensions and boundary conditions were selected to minimize boundary effects and ensure numerical stability during the simulation process.

3.3 Simulation cases

To achieve the research objectives, the numerical investigation considers two primary simulation scenarios as follows:

- Case A (Isolated): Settlement analysis of a single footing without considering adjacent foundations.

- Case B (Interacting): Settlement analysis of a selected footing while all neighboring footings are simultaneously loaded.

The finite element software PLAXIS 3D was used to perform the settlement simulations. The three-dimensional soil domain extends sufficiently beyond the loaded area to minimize boundary effects. Boundary conditions were defined by fixing the lateral boundaries in the horizontal direction while allowing vertical movement, whereas the bottom boundary was fully restrained in all directions.

The foundation system was modeled using concrete volume elements with material properties summarized in Table 2. Square pad footings with a width of b = 2.2 m were adopted and embedded at a depth of 1.0 m below the ground surface. For numerical simplicity, the loading condition was represented by a concentrated load of 968 kN applied at the center of each footing unit.

A uniform base pressure of 200 kPa was adopted to represent typical service-level bearing pressures for shallow foundations supporting medium-rise structures. This value falls within the commonly reported range of 100–300 kPa in geotechnical design practice [1, 6] and ensures the practical relevance of the numerical simulations.

A mesh consisting of 10-node tetrahedral elements was employed, with local refinement around the footings to improve computational accuracy. All simulations were conducted using fully elasto-plastic analysis under drained conditions.

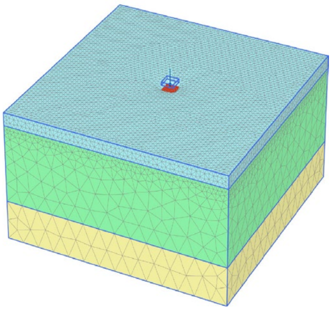


Fig. 5 Isolated shallow foundation model neglecting the influence of adjacent foundations. (Case A)

Numerical accuracy was verified through a mesh convergence assessment, which showed that further mesh refinement resulted in settlement variations of less than 1%. The structural loading was applied in a single plastic phase using the software's automatic incremental load-stepping procedure, allowing stable numerical convergence and accurate representation of nonlinear soil–structure interaction.

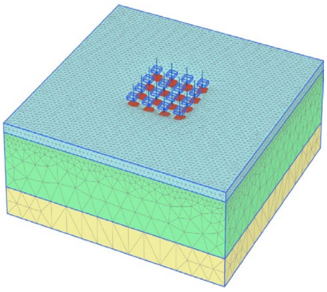


Fig. 6 Numerical modeling of all footings of the structure in PLAXIS 3D. (Case B)

3.4 Parametric study

A parametric analysis was performed to evaluate the influence of foundation spacing on settlement behavior and load interaction. The center-to-center spacing (s) between footings was systematically varied and expressed using the normalized spacing ratio s/b.

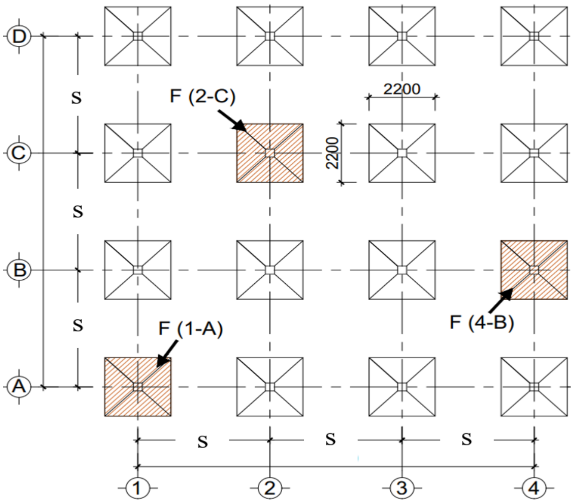


Fig. 7 Plan view of footing arrangement for the parametric study with varied spacing-to-width ratios.

The spacing ratios investigated were s/b = 1.0, 1.5, 2.0, 2.5, and 3.0, while the footing width was kept constant at b = 2.2 m in all simulations to ensure consistency in evaluating group interaction effects.

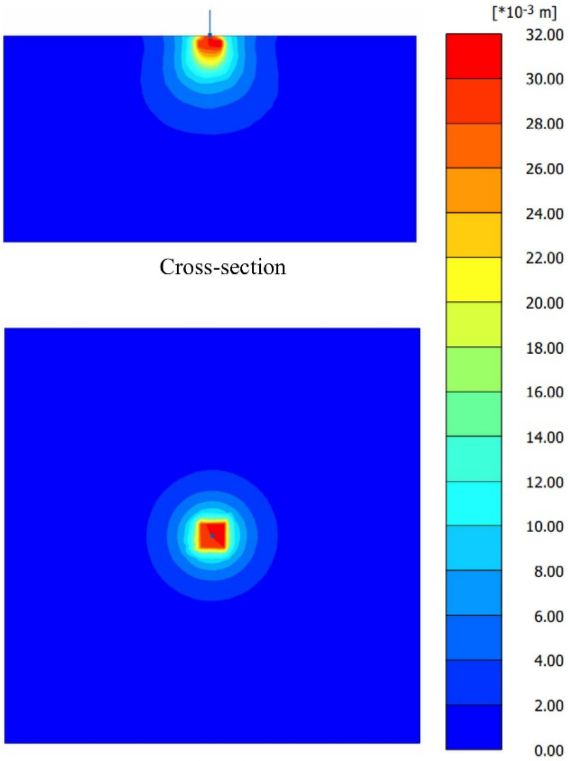
The selected s/b range from 1.0 to 3.0 represents typical practical foundation layouts encountered in urban developments and captures the transition from strong footing interaction to nearly independent foundation behavior, as reported in previous studies.

The plan arrangement of the footings adopted for the parametric analysis is illustrated in Figure **7**, where the spacing variation between adjacent foundations is systematically investigated.

4. RESULTS AND DISCUSSIONS

4.1 Impact of Neighboring Footings

The results for Case A are illustrated in Fig. 8.

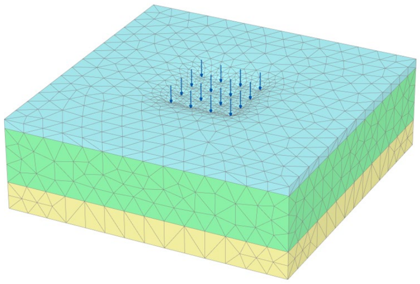


Cross-section

Plan view

Fig. 8 Settlement contours of the isolated foundation in cross-sectional and plan views (Case A)

Fig. 8 shows the settlement contours of the isolated footing (Case A). Fig. 9 presents the deformed mesh and settlement profile of the interacting foundation system (Case B).

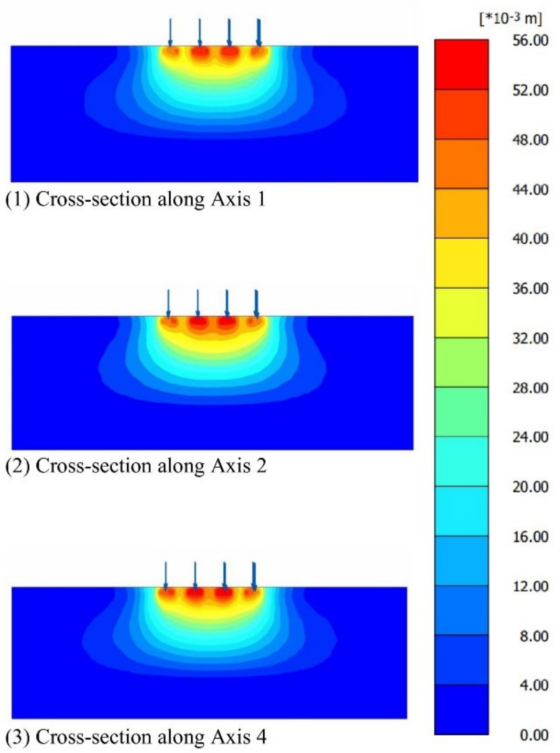


Deformed mesh |u| (scaled up 50.0 times)

Maximum value = 0.05493 m (at Node 114)

Fig. 9 Deformed mesh and settlement profile for the foundation system (Case B).

The observed settlement patterns in Figs. 8–10 indicate that stress bulbs beneath adjacent footings overlap significantly when the spacing ratio (s/b) is small, leading to increased vertical deformation at the center of the footing group. This behavior is consistent with classical soil–structure interaction theory, where overlapping stress zones result in amplified settlements compared to isolated footings (Das and Sivakugan, 2016; Bowles, 1996).



(1) Cross-section along Axis 1

(2) Cross-section along Axis 2

(3) Cross-section along Axis 4

Fig. 10 Vertical soil displacement contours for Case B: Cross-sections along Axes 1, 2, and 4 taken from the foundation plan layout shown in Fig. 7.

Table 3. Footing settlement under Isolated and Interacting Conditions

Footing Type	Isolated Settlement (mm)	Interacting Settlement (mm)	Increase (%)
F(2-C) - Center	30.11	53.55	77.85
F(4-B) - Edge	30.11	46.91	55.80
F(1-A) - Corner	30.11	42.00	39.49

Notes: Footing F (2–C), located at the intersection of Axis 2 and Axis C, is classified as a center footing. Similar notation applies to all other foundations. In this study, footing settlement is taken as the displacement of the node at the footing center.

The initial results for a footing spacing of 4.4 m and a square footing size of b = 2.2 m indicate a significant increase in settlement when the influence of adjacent footings is taken into account. These results are presented in Table 3 and Figure 12.

The numerical results indicate a profound difference in the geomechanical response of the soil between the isolated footing (Case A) and the interacting foundation system (Case B). The key findings are discussed below:

- Significant Settlement Augmentation: When considering the influence of neighboring footings at a spacing of s = 4.4 m (s/b = 2.0), a substantial increase in settlement is observed across all footings compared to the isolated case. The isolated footing yields a baseline settlement of 30.11 mm, whereas the interacting footings exhibit significantly higher values.

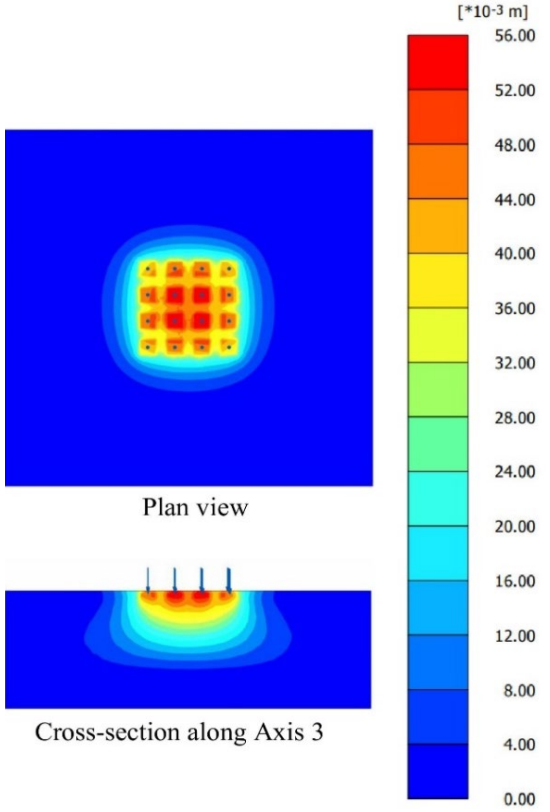


Fig. 11 Settlement contours for the complete foundation system (Case B): Plan view and longitudinal cross-section along Axis 3.

Notes: The locations of the cross-sections correspond to the axes defined in the plan view (Fig. 7). The color scale indicates displacement in 10^{-3}m, and precise peak values are provided in Table (3-6).

- Group Interaction and Stress Overlap: The proximity of adjacent foundations leads to a superposition of stress zones within the underlying soil medium. The settlement contours in Figures 10 and 11 demonstrate that the influence zones merge, forming a continuous "bulb" of high vertical displacement beneath the entire foundation group rather than isolated pockets.

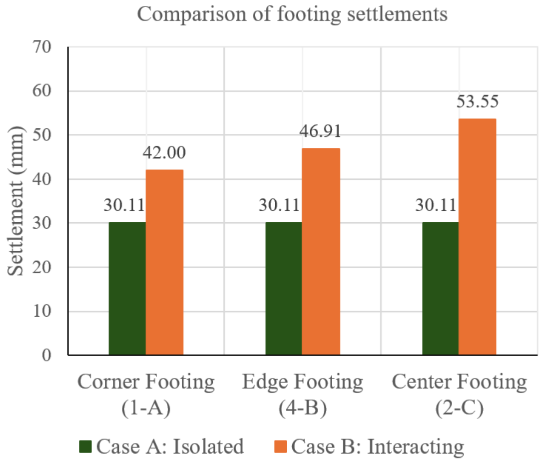


Fig. 12 Comparison of footing settlements for Case A and Case B

- Spatial Variation of Settlement: The magnitude of group interaction is highly sensitive to footing position. Compared to the isolated case (30.11 mm), the center footing (F 2-C) exhibits the most critical response with a 77.85% increase in settlement to 53.55 mm. Edge (F 4-B) and corner (F 1-A) footings show relatively lower yet significant increments of 55.80% (46.91 mm) and 39.49% (42.00 mm), respectively. This spatial disparity highlights the accumulation of stress overlap toward the center of the foundation grid.
- The deformed finite element mesh illustrates a collective subsidence bowl, with the ground surface sloping toward the center of the loading area. A maximum total displacement (|u|) of 0.05493 m is recorded at the core of the foundation grid (Fig. 9).

4.2 Influence of s/b Ratio

The PLAXIS 3D simulation results, detailing the absolute settlements and the corresponding settlement reduction levels at the centers of the corner, edge, and center footings under varying spacing ratios (s/b), are summarized in Tables 4, 5, and 6, and further illustrated in Fig. 13, 14 and 15.

The numerical investigation into the interaction between neighboring foundations reveals several critical insights into the serviceability of footing groups:

+ Spatial Distribution of Settlement: Group interaction significantly amplifies vertical displacement compared to the isolated case (30.11 mm). The center footing (F 2-C) experiences the most severe impact due to multi-directional stress overlap, reaching a maximum settlement of 53.55 mm (+77.85%) at s/b = 2.0.

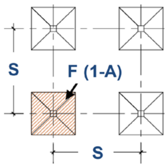
+ Influence of Spacing Ratio (s/b): Settlement magnitudes exhibit a non-linear inverse relationship with the s/b ratio. At a close spacing of s/b = 1.0, settlements peak drastically, with the center footing reaching 133.31 mm—over four times the isolated baseline.

+ Convergence and Interaction Limits: As the spacing increases to s/b = 3.0, the interaction effect diminishes, and settlement values for all footing types (corner, edge, and center) begin to converge toward the isolated Case A value. This suggests that at s/b ≥ 3.0, the foundation units start to behave independently.

Settlement Reduction Trends: The percentage decrease in settlement relative to the s/b = 1.0 configuration is most rapid between s/b = 1.0 and 2.0. For the corner footing (F 1-A), the reduction exceeds 66% when the spacing is doubled.

Table 4. Footing Settlement F (1-A) under Interacting Conditions

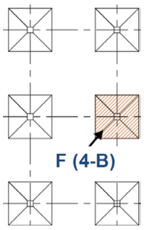
s/b	Settlement (mm)	Reduction (%)
(1)	*(2)*	*(3)*
1.0	125.81	0.00
1.5	57.56	54.25
2.0	42.00	66.62
2.5	35.10	72.10
3.0	31.65	74.84



Column (3) presents the percentage reduction in settlement, calculated as (125.81 − *Column (2)*)/*Column (2).*

Table 5. Footing Settlement F (4-B) under Interacting Conditions

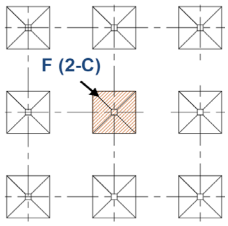
s/b	Settlement (mm)	Reduction (%)
(1)	*(2)*	*(3)*
1.0	130.74	0.00
1.5	66.81	48.90
2.0	46.91	64.12
2.5	38.25	70.74
3.0	33.94	74.04



Column (3) presents the percentage reduction in settlement, calculated as (130.74 − *Column (2)*)/*Column (2).*

Table 6. Footing Settlement F (2-C) under Interacting Conditions

s/b	Settlement (mm)	Reduction (%)
(1)	*(2)*	*(3)*
1.0	133.31	0.00
1.5	77.79	41.65
2.0	53.55	59.83
2.5	43.60	67.29
3.0	36.45	72.66



Column (3) presents the percentage reduction in settlement, calculated as (133.31 − *Column (2)*)/*Column (2).*

Note: In Tables 3–5, the values in Column (3) represent the percentage reduction in settlement relative to the baseline case at $\mathbf{s/b = 1.0}$, calculated as:

$$\text{Reduction}(\%) = \frac{\text{Settlement}_{s/b=1.0} - \text{Settlement}_{\text{current}}}{\text{Settlement}_{s/b=1.0}} \times 100$$

Furthermore, the reduction in settlement with increasing spacing (Tables 4–6 and Fig. 13) demonstrates a nonlinear relationship, reflecting the gradual transition from group behavior to isolated footing response. Similar findings have been reported in numerical and experimental studies using FEM-based approaches, confirming the reliability of PLAXIS 3D simulations in capturing soil–foundation interaction mechanisms (Brinkgreve et al., 2016; Pinheiro dos Santos et al., 2025).

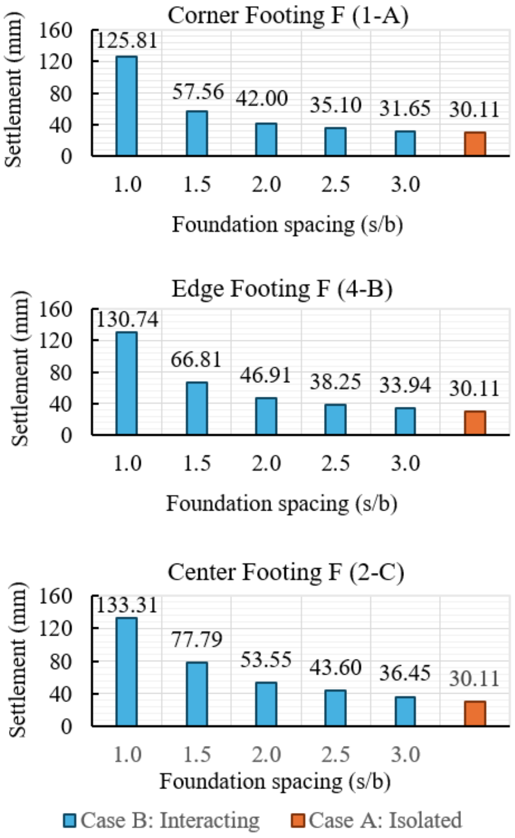


Fig. 13 Variation of footing settlements with spacing ratio (s/b) for corner, edge, and center locations compared to the isolated case (Case A).

Fig. 13 shows that footing settlement decreases with increasing foundation spacing ratio (s/b) for corner, edge, and center locations. The settlement responses gradually approach the isolated footing condition as the spacing increases.

As illustrated in Figs. 11–13, the interacting footing cases exhibit higher settlement values than the isolated case, particularly at s/b ≤ 2.0. This trend agrees with previous studies on closely spaced foundations, which reported that interaction effects diminish as spacing increases beyond approximately 2–3 times the footing width (Kumar and Bhoi, 2008; Selvadurai et al., 1983).

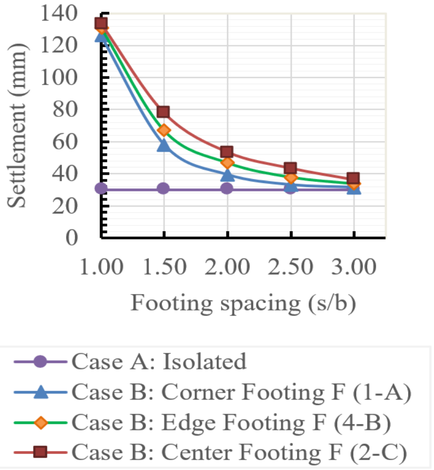


Fig. 14 Footing settlement vs. spacing ratio (s/b) for corner, edge, and center positions (Case A).

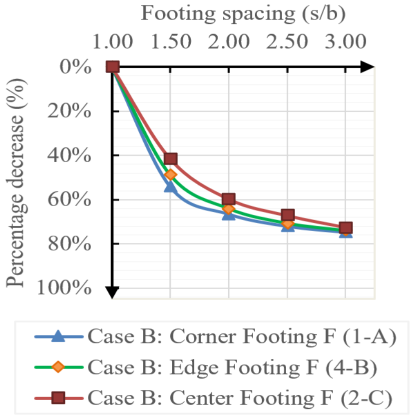


Fig. 15 Settlement reduction levels at the centers of the corner, edge, and center footings under varying spacing ratios (s/b)

4.3 Discussions

- The analysis adopts drained conditions for the clay layer to evaluate long-term consolidation settlement, which is critical for assessing foundation serviceability. Under drained conditions, excess pore water pressure dissipates, resulting in a relatively stiffer short-term response and lower immediate settlement. Nevertheless, this approach is appropriate for the study objectives, as it captures long-term stress redistribution and interaction effects among adjacent foundations in cohesive soils.
- The numerical model extends to a depth of 20 m (approximately 9–10 times the footing width) to minimize boundary effects. According to conventional geotechnical practice, stresses induced by shallow foundations typically dissipate within 10–20% of the effective overburden pressure. Therefore, deformation of the deeper stiff sand layer was considered negligible and modeled as a relatively rigid base.
- The results indicate that settlement amplification due to footing interaction can be significant when foundations are closely spaced. The identified amplification factors provide useful guidance for evaluating soil–structure interaction effects during preliminary foundation design and for optimizing footing spacing in dense urban environments.
- The parametric study shows that when the spacing-to-width ratio reaches s/b ≈ 3.0, the settlements of corner, edge, and central footings converge toward the isolated footing response, indicating negligible interaction effects. This threshold is consistent with previous studies reporting that interaction effects typically diminish when footing spacing exceeds approximately three times the footing width.

4.4 Limitations of the Study

Although this study provides useful insights into the interaction of closely spaced shallow foundations, several limitations should be noted. The foundation layout is idealized and symmetrical, whereas real structures may involve irregular geometries and spacing. The FEM analysis in PLAXIS 3D has not been validated with field or experimental data, and the soil parameters are based on standard database values rather than site-specific conditions. Moreover, the study focuses only on settlement behavior, while other aspects such as differential settlement, structural stiffness, and more complex soil–structure interaction require further investigation.

5. CONCLUSIONS

This study employed PLAXIS 3D to evaluate the settlement behavior of shallow foundations considering adjacent footing interaction in layered soils. The results show that conventional isolated footing design may underestimate settlement due to stress overlap effects, with the maximum increase of about 77.85% observed at s/b = 2.0. Increasing the spacing ratio from s/b = 1.0 to 2.0 significantly reduces settlement (over 66% for corner footings), while interaction effects become negligible at s/b ≥ 3.0, suggesting this as a practical minimum spacing for design. Interaction is most significant at close spacing (s/b ≤ 1.0) and decreases with increasing distance between footings. Although the study focuses on square footings, similar mechanisms apply to other geometries, with potentially stronger effects in rectangular foundations and soft or layered soils requiring larger spacing. Overall, the findings provide practical guidance for foundation design in dense urban conditions. Future research should incorporate advanced soil models and field validation, as well as investigate different foundation geometries and loading conditions.

6. ABBREVIATIONS

PLAXIS 3D – Three-dimensional finite element software
s/b – Spacing-to-width ratio
FEM – Finite Element Method
MC – Mohr–Coulomb model

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