

Numerical Analysis of Eccentricity Influence on Bearing Capacity and Settlement of Tropical Soils: A Case Study of Northern Part of Penka-Michel, West Cameroon

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How to cite this paper: Suffeu Talla, T. B., Kenfack, J. V., Teikeu Ngueveu, E. D., Aboubakar, A., & Wouatong, A. S. L. (2025). Numerical Analysis of Eccentricity Influence on Bearing Capacity and Settlement of Tropical Soils: A Case Study of Northern Part of Penka-Michel, West Cameroon. *Journal of Geoscience and Environment Protection*, 13, 30-45. <https://doi.org/10.4236/gep.2025.136004>

Received: March 13, 2025

Accepted: June 10, 2025

Published: June 13, 2025

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Abstract

This study investigates the effect of load eccentricity on the bearing capacity and settlement of soils beneath shallow foundations using numerical modeling with Plaxis 2D. Six soil samples were collected from different sites in Penka-Michel (West Cameroon) and classified according to the Unified Soil Classification System (USCS). The soils are predominantly fine-grained, comprising clayey sands (SC), low to highly plastic clays (CL, CH), and highly plastic silty-clayey materials (OH). Numerical analysis reveals that bearing capacity ranges from 3.5 to 10 bars, while settlement varies between 4 cm and 24.09 cm. Results indicate that footing behavior depends not only on soil type but also on load eccentricity. For sandy soils, settlements remain within acceptable limits when eccentricity is low. However, an eccentricity exceeding 10 cm leads to an 8% reduction in bearing capacity and a significant increase in settlement, particularly in fine soils. These findings suggest that eccentric footings exceeding 10 cm should be avoided in tropical fine soils to minimize structural damage to buildings.

Keywords

Bearing Capacity, Settlement, Shallow Foundation, Load Eccentricity, Numerical Modeling, Plaxis 2D

1. Introduction

Soil behavior under structural loads is a critical aspect of geotechnical engineer-

ing, as foundations play a fundamental role in ensuring building stability. Soils are three-dimensional bodies formed through the combined effects of climate, vegetation, fauna, topography, and human activity over extended periods (Ndiaye, 2013; Kamtchueng et al., 2015). In tropical regions, lateritic soils are the most widespread and are commonly used in civil engineering, particularly in road construction (Issiakou, 2016; Mahamadou 2016). In Cameroon, as in many other tropical-zone countries, lateritic soils cover approximately 70% of the national territory (Sikali & Djalal, 1986; Tockol, 1993; Onana et al., 2015; Katte et al., 2020). The rapid rate of urbanization has significantly increased infrastructure development, necessitating a deeper understanding of soil behavior under structural loads. Shallow foundations are among the most commonly employed foundation types due to their cost-effectiveness and ease of construction. However, their performance is highly dependent on soil type and the distribution of applied loads (Waheed & Asmael, 2019; Khalid et al., 2020; Al-Dawoodi et al., 2021). Load eccentricity, which occurs when the applied force does not align with the centroid of the footing, is a frequent challenge in foundation engineering. It often results from architectural constraints or structural modifications imposed by building owners, who may not always be aware of the implications for stability. The presence of eccentric loads alters the stress distribution within the soil, leading to reductions in bearing capacity and increased settlement, both of which can compromise structural integrity (Terzaghi, 1943; Meyerhof, 1953; Abdi, 2019; Mansouri, 2019; Ibrahim & Al-Obaydi, 2021; Salih et al., 2023).

Previous research has extensively explored methods for evaluating bearing capacity and settlement of shallow foundations. Classical analytical methods such as those proposed by Terzaghi (1943) and Meyerhof (1953) provide empirical formulas for estimating bearing capacity. However, these approaches often fail to fully capture the complex behavior of soils under eccentric loads, particularly in tropical regions where soil properties vary significantly. Laboratory-based settlement analysis, while informative, is also limited in its ability to represent *in-situ* soil behavior since it relies on small-scale sample testing, which does not always accurately reflect field conditions (Salih, 2021). Furthermore, settlement prediction remains a crucial challenge due to the progressive and continuous compressibility of fine-grained tropical soils (Tchouani Nana & Callaud, 2004).

Numerical modeling has emerged as a powerful tool for analyzing soil-structure interaction under various loading conditions (Waheed & Asmael, 2019). Finite Element Method (FEM)-based simulations allow for a more precise assessment of the influence of different factors, including footing shape, water table depth, slope distance, and load inclination, on foundation performance (Mehdi et al., 2013; Abdi, 2019; Mansouri, 2019). Among these numerical techniques, Plaxis 2D has proven to be particularly effective in evaluating shallow foundation behavior under complex loading scenarios (Al-Dawoodi et al., 2021).

This study aims to analyze the impact of eccentricity on the bearing capacity and settlement of shallow foundations in tropical soils, using numerical modeling

with Plaxis 2D. The research focuses on the fine-grained soils of Penka-Michel, West Cameroon, where variations in soil composition significantly influence geotechnical behavior. By quantifying the effects of increasing eccentricity on foundation performance, this study seeks to improve design recommendations and enhance the durability of structures built on tropical soils.

2. Natural Framework

The study area, located in the commune of Penka-Michel (West Cameroon), extends between UTM coordinates 635200-641600 and N602000-608000 and covers an area of 54 km². It is drained by a main watercourse called “Metchié”, with secondary watercourses forming a subdendritic to parallel hydrographic network (Figure 1).

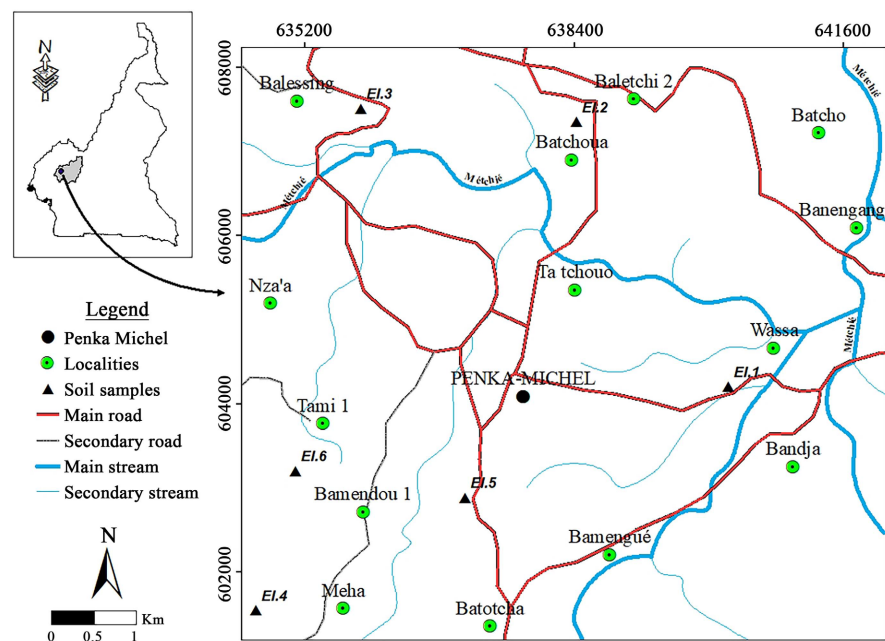


Figure 1. Location and soil samples map.

3. Materials and Methods

3.1. Soil Types

The geotechnical behavior of soils is highly influenced by their composition, granulometry, and plasticity. In this study, six soil samples were collected from different locations within the Penka-Michel region (West Cameroon) to characterize their physical and mechanical properties. The classification of these soils follows the Unified Soil Classification System (USCS), which differentiates soil types based on grain size distribution and plasticity indices.

3.1.1. Soil Characterization

The collected soil samples exhibit significant variations in fines content, with a predominance of clay and silt fractions. The first three samples (EI.01, EI.02, and

EI.03) consist primarily of fine-grained soils. Sample EI.01, obtained from Wassa (5°27'54.7"N, 10°15'57.75"E), and sample EI.03, from Balessing (5°29'41.229"N, 10°13'36.137"E), are classified as highly plastic clays (CH), whereas sample EI.02, from Batchoua (5°29'37.46"N, 10°14'58.062"E), consists of highly plastic silty and clayey materials (OH). These fine soils exhibit high water retention capacity and significant plasticity, making them prone to settlement and volume changes under loading conditions.

The remaining three samples (EI.04, EI.05, and EI.06) are predominantly sandy-clayey soils with lower plasticity. Sample EI.04, obtained from Meha (5°26'28.376"N, 10°12'54.27"E), and sample EI.06, from Tami 1 (5°27'20.686"N, 10°13'9.224"E), are classified as clayey sands (SC). Sample EI.05, collected from Bamendou (5°27'10.28"N, 10°14'15.769"E), consists of low-plasticity clays (CL). These soils exhibit better load-bearing capacity compared to fine-grained soils due to their granular nature, which provides higher shear resistance and reduced compressibility.

3.1.2. Granulometry and Plasticity Analysis

Grain size distribution and Atterberg limits (Table 1) were used to assess the physical properties of the soils (Table 1). The proportion of fines (<0.08 mm) varies significantly among the samples, ranging from 41.8% in EI.06 (clayey sand) to 90.2% in EI.02 (silty clay). These high fines content in fine-grained soils contributes to their low permeability and high plasticity. The liquid limit (wL) ranges from 48.4% in EI.05 to 61.5% in EI.03, while the plasticity index (PI) varies between 18.9% (EI.05) and 30.8% (EI.02), indicating considerable differences in soil plasticity.

Table 1. Physical parameters and geotechnical classifications of the soils studied.

Samples	Granulometric test							Atterberg limits			USCS Classification
	10 mm	8 mm	5 mm	2 mm	1 mm	0.5 mm	0.08 mm	WL (%)	WP (%)	PI (%)	
E.I01	100	100	100	99.6	98.8	95.0	77.1	51.5	26.4	25.1	CH
E.I02	100	100	100	99.5	98.2	96.2	90.2	51.6	20.8	30.8	OH
E.I03	100	100	100	100	99.7	97.9	84.3	61.5	35.6	25.9	CH
E.I04	100	99.9	98.2	92.9	81.9	72.2	58.7	57.3	34.9	22.4	SC
E.I05	100	100	100	100	97.8	89.4	64.1	48.4	29.5	18.9	CL
E.I06	100	99.7	98.0	88.0	73.5	62.3	41.8	50.0	26.9	23.1	SC

3.1.3. Statistical Analysis and Plasticity Analysis

The fines content (<0.08 mm) averages 69.37%, with a standard deviation of 18.18%, indicating significant variation in soil composition. The liquid limit (wL) has a mean value of 53.38% and a standard deviation of 5.16%, suggesting moderate variability among samples. Meanwhile, the plasticity index (PI) averages 24.37%, with a standard deviation of 4.35%, highlighting a range from low-plasticity clays to highly plastic silty-clay soils.

The statistical distribution highlights the heterogeneity of the soils in the study area, with a marked distinction between fine-grained and sandy-clayey soils. The results confirm that fine soils (CH and OH) exhibit higher plasticity and fines content, whereas sandy-clayey soils (SC and CL) are more stable with lower compressibility. These findings emphasize the importance of soil classification in predicting foundation behavior and settlement potential under loading conditions.

3.2. Mechanical Properties of Materials

The mechanical behavior of soils plays a crucial role in determining the stability and performance of shallow foundations. Soil strength and deformability are influenced by several factors, including cohesion, internal friction angle, compressibility, and stiffness. In this study, the mechanical properties of the six selected soil samples were evaluated using laboratory tests and numerical modeling. The results are summarized in **Table 2**.

3.2.1. Soil Strength and Stiffness Parameters

The soils in the study area exhibit significant variations in their geomechanical properties, reflecting differences in composition and structure. The cohesion values range from 20.09 kPa (EI.04) to 27.40 kPa (EI.01), indicating that fine-grained soils have higher cohesion due to their clay content. Cohesion is a critical parameter for soil shear strength, as it determines the soil's ability to resist deformation under load (Terzaghi, 1943; Meyerhof, 1953).

The internal friction angle (ϕ) varies between 15.33° (EI.01) and 31.86° (EI.04). Fine-grained soils (CH and OH) generally exhibit lower friction angles due to their high plasticity and particle cohesion, whereas sandy-clayey soils (SC and CL) have higher friction angles, which contribute to their improved load-bearing capacity (Imanzadeh et al., 2015; Abdi, 2019; Ibrahim & Al-Obaydi, 2021).

Compressibility is assessed using the oedometric modulus (E_{eod}), which measures the soil's resistance to deformation under loading. The values range from 2306 kPa (EI.01) to 4765 kPa (EI.05), highlighting the greater stiffness of sandy soils compared to fine-grained soils. This difference is expected, as sandy soils exhibit immediate settlement due to particle rearrangement, whereas clay-rich soils undergo progressive settlement over time (Tchouani Nana & Callaud, 2004).

3.2.2. Influence of Saturation and Density

Soil density influences both bearing capacity and settlement behavior. The dry unit weight (γ_{unsat}) varies from 13.39 kN/m³ (EI.02) to 20.60 kN/m³ (EI.06), while the saturated unit weight (γ_{sat}) ranges from 18.32 kN/m³ (EI.02) to 23.14 kN/m³ (EI.06). The higher densities observed in sandy soils (EI.04, EI.05, EI.06) indicate a more compact structure with lower compressibility, whereas fine-grained soils tend to retain more water, leading to lower densities and increased settlement potential.

3.2.3. Statistical Analysis of Mechanical Parameters

To better understand soil property variability, a statistical analysis was conducted on the mechanical parameters. The average cohesion is 24.56 kPa, with a standard deviation of 2.88 kPa, showing moderate variation, with higher values in fine-grained soils and lower values in sandy-clayey soils. The internal friction angle (ϕ) has a mean of 22.94° and a standard deviation of 6.43°, highlighting significant differences between fine-grained and sandy soils. The oedometric modulus (E_{eod}) averages 3343 kPa, with a standard deviation of 978 kPa, reflecting a wide range of compressibility among soil types. Additionally, the dry unit weight (γ_{unsat}) has a mean of 16.81 kN/m³ with a standard deviation of 2.89 kN/m³, while the saturated unit weight (γ_{sat}) averages 20.53 kN/m³ with a standard deviation of 1.86 kN/m³, confirming the higher density and superior compaction of sandy soils.

3.2.4. Implications for Foundation Design

The statistical analysis confirms that soil behavior varies significantly across the study area, with fine-grained soils demonstrating higher cohesion and lower friction angles, while sandy-clayey soils exhibit greater stiffness and load-bearing capacity. These differences directly influence foundation settlement and stability. Fine soils, due to their lower strength and higher compressibility, are more susceptible to settlement and deformation, particularly under eccentric loading conditions (Waheed & Asmael, 2019; Al-Dawoodi et al., 2021).

Given these variations, foundation design in Penka-Michel must account for the specific geotechnical properties of each soil type. Foundations on sandy-clayey soils can support higher loads with minimal settlement, whereas those on fine-grained soils require careful consideration of bearing capacity reductions and settlement control measures, such as soil improvement techniques or deeper foundation solutions.

Table 2. Soil and footing geomechanical characteristics.

	E1	E2	E3	E4	E5	E6	Sole
Model	M.C.	M.C.	M.C.	M.C.	M.C.	M.C.	Isotropic elastic
Condition/behavior	Drained	Drained	Drained	Drained	Drained	Drained	/
γ_{unsat} (kN/m ³)	14.9	13.39	13.83	16.76	18.40	20.60	/
γ_{sat} (kN/m ³)	19.17	18.32	18.36	20.67	21.51	23.14	/
Cohesion (kPa)	27.40	26.18	26.79	20.09	25.57	21.31	/
Internal angle of friction ϕ (°)	15.33	18.78	18.81	31.86	24.12	28.74	/
Oedometric modulus (E_{eod} (kPa))	2306	2680	2330	4084	4765	3898	/
Young's modulus E (kPa)	1556.16	1205.84	902.69	2847.39	3216.07	2631.33	/
Fish coefficient (ν)	0.33	0.33	0.33	0.33	0.33	0.33	/
Normal stiffness. EA (kN/m)	/	/	/	/	/	/	7.5*10 ⁶
Flexural rigidity EI (kNm)	/	/	/	/	/	/	10 ⁶
Weight w (kN/m/m)	/	/	/	/	/	/	10

3.3. Numerical Modeling

Numerical modeling is a powerful tool in geotechnical engineering, enabling a detailed assessment of soil-structure interaction under various loading conditions. Unlike traditional analytical methods, which rely on simplified assumptions, numerical techniques provide a more accurate representation of complex soil behavior by incorporating non-linearity, heterogeneity, and load distribution effects (Waheed & Asmael, 2019; Al-Dawoodi et al., 2021). In this study, Plaxis 2D, a finite element method (FEM)-based software, was employed to analyze the influence of eccentricity on the bearing capacity and settlement of shallow foundations resting on tropical soils in Penka-Michel.

3.3.1. Finite Element Method and Mesh Discretization

Plaxis 2D is widely used for geotechnical analysis, as it solves plane-strain and axisymmetric problems related to soil stability and deformation. The FEM discretization method involves dividing the soil domain into small triangular elements (meshes), where differential equations governing stress-strain relationships are solved numerically. The accuracy of the model depends on mesh refinement, with finer meshes providing better stress distribution but increasing computational cost. In this study, 15-node triangular elements were used to enhance precision in stress and strain calculations.

The soil was modeled as a 5×5 m homogeneous, isotropic medium, on which a square 1×1 m shallow foundation was placed. The boundary conditions were set to prevent displacement along the model's edges while allowing free movement in the vertical direction at the top surface. Ground layers affected by the analysis are well above the water table. However, the groundwater has no impact on the behavior of the shallow foundations, as they are located more than 30 m below the footings.

The Mohr-Coulomb (M.C.) constitutive model was selected to describe soil behavior, as it provides a reasonable approximation for small-strain problems in geotechnical engineering (Abdi, 2019; Mansouri, 2019).

3.3.2. Model Assumptions and Input Parameters

The numerical model integrated key geotechnical parameters from laboratory tests, including soil density, cohesion, internal friction angle, and Young's modulus. Soil behavior was represented as a linear elastic-perfectly plastic material following the Mohr-Coulomb failure criterion. A flexible footing was modeled under a vertically applied load with varying eccentricities (0 cm, 10 cm, 20 cm, 30 cm). Fully drained conditions were assumed, neglecting excess pore water pressures during loading. A uniformly distributed vertical load of 100 kPa was applied, simulating typical structural loading conditions in tropical regions.

3.3.3. Simulation of Eccentric Loading

Eccentric loading is a major factor influencing soil settlement and bearing capacity, as it causes uneven stress distribution beneath the foundation. In Plaxis 2D,

eccentricity (e) was simulated by offsetting the point of load application relative to the foundation centroid. Three eccentricity values were analyzed:

- $e = 0$ cm: Central loading, resulting in symmetrical stress distribution.
- $e = 10$ cm, 20 cm, 30 cm: Increasing eccentricity, causing stress concentration and progressive reduction in contact area.

The model calculates stress-strain relationships at Gaussian integration points, rather than at the mesh nodes, ensuring accurate assessment of stress redistributions caused by eccentric loading. The failure mechanism and settlement trends were examined by analyzing the plastic deformation zones and displacement contours generated by the simulation.

3.3.4. Expected Behavior and Validation Approach

The numerical results were validated by comparison with classical analytical solutions (Terzaghi, 1943; Meyerhof, 1953). As expected, increasing eccentricity led to a reduction in bearing capacity due to a decrease in effective footing width, an increase in settlement causing differential deformation, and a non-uniform stress distribution that shifted the load toward the footing edge, potentially compromising stability. The analysis of failure patterns, displacement contours, and stress-strain distributions provided valuable insights into the effects of eccentric loading on shallow foundations in tropical soils.

4. Results and Discussion

4.1. Results

The numerical simulations conducted in this study provide a detailed assessment of the influence of load eccentricity on the bearing capacity and settlement of shallow foundations resting on tropical soils. The results reveal significant variations in soil response depending on both the type of soil and the magnitude of the eccentricity. The main findings, including bearing capacity and settlement values for different eccentricity levels, are presented in **Table 3**.

4.1.1 Influence of Eccentricity on Bearing Capacity

The numerical analysis shows a clear trend of bearing capacity reduction with increasing eccentricity. For centered footings ($e = 0$ cm), the bearing capacity ranges from 4.20 bars (EI.01) to 10.00 bars (EI.04), demonstrating the inherent variability in soil strength across the study area. However, as eccentricity increases to 10 cm, 20 cm, and 30 cm, a progressive decrease in bearing capacity is observed. In fine-grained soils (EI.01, EI.02, EI.03), every 10 cm increase in eccentricity results in an approximate 5% reduction in bearing capacity, while in sandy-clayey soils (EI.04, EI.05, EI.06), the decrease is more pronounced, reaching 8% per 10 cm increment. This confirms previous studies indicating that load eccentricity significantly reduces effective contact pressure and load-bearing efficiency (Meyerhof, 1953; Abdi, 2019; Mansouri, 2019).

For the maximum eccentricity analyzed ($e = 30$ cm), the bearing capacity drops to 3.50 bars (EI.01) and 7.97 bars (EI.04), representing an overall reduction of

16.7% and 20.3%, respectively, compared to the centered loading case. The reduction is more severe in sandy soils due to their lower cohesion and increased sensitivity to stress redistribution under eccentric loads (Waheed & Asmael, 2019; Al-Dawoodi et al., 2021).

4.1.2. Influence of Eccentricity on Settlement

Settlement values increase significantly as eccentricity grows, with fine-grained soils exhibiting the highest deformation. For centered loading, settlement values range from 4.00 cm (EI.04) to 8.95 cm (EI.01). However, when eccentricity reaches 30 cm, maximum settlements of 24.09 cm (EI.01) and 10.00 cm (EI.06) are recorded.

Fine-grained soils (CH and OH) exhibit higher settlement due to their lower stiffness and higher compressibility, which is consistent with previous research indicating that settlement in saturated fine soils is one of the most critical parameters affecting structural stability (Tchouani Nana & Callaud, 2004). In contrast, sandy-clayey soils show lower settlement values due to their granular structure, which provides greater resistance to deformation under load.

The results confirm that eccentric loading increases differential settlement, leading to non-uniform stress distribution beneath the foundation. This effect is particularly problematic for fine soils, where large settlements can lead to excessive tilting and potential structural damage (Salih, 2021).

4.1.3. Statistical Analysis of Bearing Capacity and Settlement

Statistical analysis of data in **Table 3** revealed significant variability in bearing capacity and settlement. For centered loading ($e = 0$ cm), the mean bearing capacity was 6.61 bars (standard deviation 2.38 bars, CV 36.0%), and mean settlement was 6.12 cm (standard deviation 2.02 cm). Eccentric loading ($e = 30$ cm) resulted in a 27.3% reduction in mean bearing capacity (4.81 bars) and a 122.5% increase in mean settlement (13.62 cm), with a higher dispersion in settlement values (CV 41.7%) likely due to soil heterogeneity.

These statistical results confirm that bearing capacity reduction and settlement increase are strongly dependent on soil type and eccentricity level. Fine-grained soils are more susceptible to settlement due to their lower stiffness, while sandy-clayey soils exhibit greater resistance to deformation but still experience significant bearing capacity loss under eccentric loads.

4.1.4. Implications for Foundation Design

This study highlights the crucial role of load eccentricity in shallow foundation design for tropical soils. Eccentricity exceeding 10 cm should be avoided in fine-grained soils to mitigate excessive settlement and instability. While sandy-clayey soils exhibit greater stability, significant bearing capacity reductions necessitate reinforcement or increased footing size. Differential settlement, especially across heterogeneous soil layers, must be considered in structural analysis. These findings corroborate previous research (Mehdi et al., 2013; Abdi, 2019; Mansouri, 2019), demonstrating that foundation stability depends not only on soil type but also on load distribution.

Table 3. Bearing capacity and settlement as a function of eccentricity.

		EI.01	EI.02	EI.03	EI.04	EI.05	EI.06
e = 0 cm	qu (bars)	4.20	5.00	4.20	10.00	7.25	9.00
	Δh (cm)	8.95	7.60	8.80	4.00	4.22	5.16
e = 10 cm	qu (bars)	4.00	4.80	4.00	9.79	6.25	8.77
	Δh (cm)	11.76	9.82	11.74	5.43	5.18	6.36
e = 20 cm	qu (bars)	3.80	4.20	3.80	8.79	6.00	5.10
	Δh (cm)	15.37	12.55	15.28	6.68	6.37	7.83
e = 30 cm	qu (bars)	3.50	3.50	3.50	7.97	5.55	4.85
	Δh (cm)	24.09	17.80	23.85	8.25	8.37	10.00

4.2. Discussion

The numerical results obtained in this study confirm the significant impact of load eccentricity on the bearing capacity and settlement of shallow foundations. These findings align with established theoretical and experimental research, demonstrating that increasing eccentricity reduces soil strength while amplifying differential settlement. To better understand these effects, the numerical results were compared with Terzaghi's (1943) and Meyerhof's (1953) analytical methods, and a statistical analysis was conducted on the discrepancies observed in Table 4.

4.2.1. Effect of Eccentricity on Bearing Capacity

Figure 2(a) illustrates the inverse relationship between eccentricity and bearing capacity, reinforcing previous studies that highlight the loss of load-bearing efficiency as load application shifts away from the footing centroid (Abdi, 2019; Mansouri, 2019). When eccentricity increases from 0 cm to 30 cm, the mean bearing capacity drops from 6.61 bars to 4.81 bars, representing an average reduction of 27.3%.

A comparison with analytical methods shows that Plaxis 2D results are generally lower than Terzaghi's predictions but closer to Meyerhof's estimations. The relative deviation between numerical and analytical results increases with eccentricity:

- For $e = 0$ cm, the difference between Plaxis and Terzaghi is 26%, while the deviation from Meyerhof is only 9%.
- For $e = 30$ cm, the discrepancy between Plaxis and Meyerhof reaches 39%, indicating that analytical methods may overestimate bearing capacity under eccentric loading.

This increasing deviation suggests that traditional methods might not fully account for stress redistribution effects and progressive soil failure in eccentric footings. The numerical simulations, by considering full soil-structure interaction, provide a more refined estimation of load-bearing performance, particularly in tropical fine soils, which exhibit complex deformation mechanisms (Waheed & Asmael, 2019; Al-Dawoodi et al., 2021). These results are similar to those obtained by Bandaru & Pollayi (2025) who, using numerical simulation, show the impact

of load eccentricity on the bearing capacity of foundations.

4.2.2. Impact of Eccentricity on Settlement

Figure 2(b) demonstrates a substantial increase in settlement with load eccentricity, especially in compressible fine-grained soils (CH and OH), exhibiting progressive plastic deformation (Issiakou, 2016; Tchouani Nana & Callaud, 2004). Mean settlement increased 122.5% from 6.12 cm ($e = 0$ cm) to 13.62 cm ($e = 30$ cm), with silty-clayey soils reaching a critical 24.09 cm. Eccentric loading (**Figure 3**) shifts the failure mechanism from symmetrical stress distribution ($e = 0$ cm) to asymmetrical stress concentration and tilting ($e = 30$ cm), increasing the risk of structural instability and differential settlement damage, especially in buildings with rigid superstructures (Salih, 2021), underscoring the importance of considering load eccentricity in foundation design. Eccentric loading has an adverse effect on foundations. As shown in this study, eccentricity increases settlement. These results are in agreement with those found by Rahaman et al., (2023).

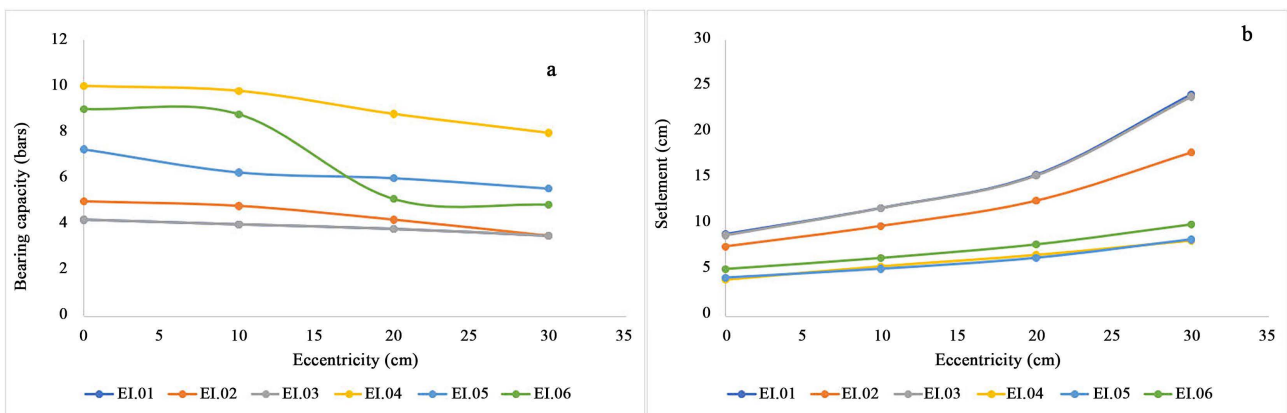


Figure 2. Variation of bearing capacity (a) and settlement (b) with eccentricity.

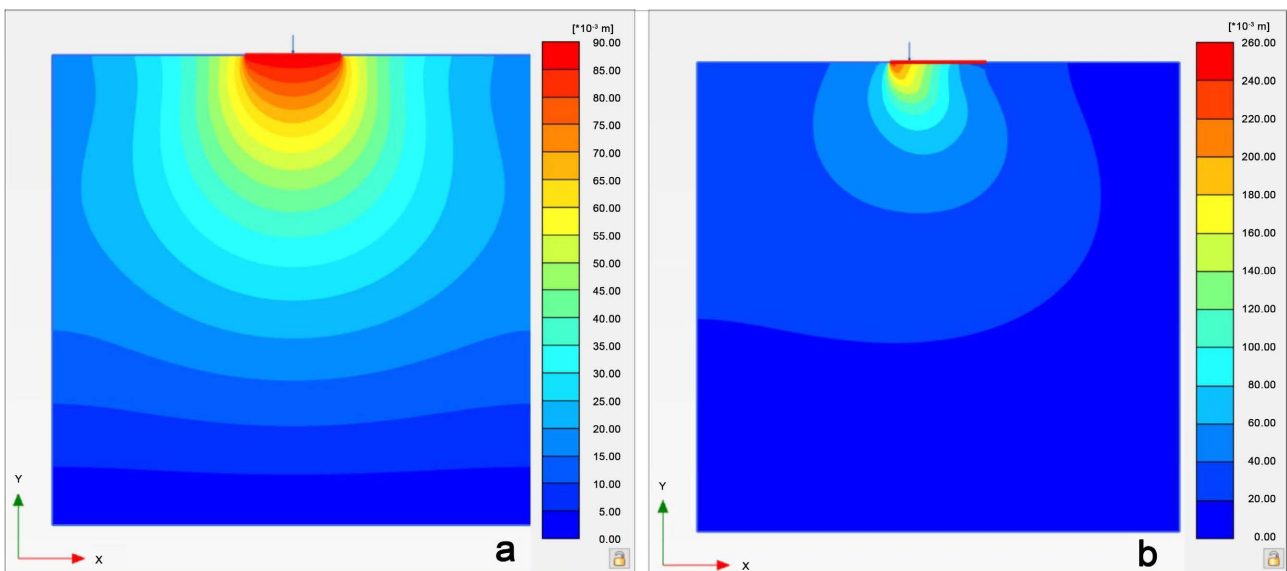


Figure 3. Variation Fracture mechanisms: (a) Centered vertical load; (b) Eccentric vertical load.

4.2.3. Statistical Analysis of Numerical vs. Analytical Results

Statistical analysis of **Table 4** data compared numerical (Plaxis) and analytical (Terzaghi, Meyerhof) bearing capacity predictions. For centered loading ($e = 0$ cm), Terzaghi overestimated bearing capacity by 33.4% compared to Plaxis (6.61 bars, standard deviation 2.38 bars), while Meyerhof showed only a 9% deviation (7.36 bars). As eccentricity increased, the deviation between Plaxis and Meyerhof rose to 14% ($e = 10$ cm) and 39% ($e = 30$ cm), indicating Meyerhof's decreasing accuracy at higher eccentricities, likely due to simplified stress redistribution assumptions (Mehdi et al., 2013; Abdi, 2019). Settlement analysis (Plaxis) revealed a mean of 6.12 cm (standard deviation 2.02 cm) for $e = 0$ cm and 13.62 cm (CV 41.7%) for $e = 30$ cm, highlighting increased variability under eccentric loading, particularly in fine-grained soils due to delayed consolidation. These results underscore the need for numerical models, especially for accurately predicting settlement in soft soils under asymmetric loading.

Table 4. Influence of eccentricity on the load-bearing capacity of a vertically loaded footing.

	EI.01	EI.02	EI.03	EI.04	EI.05	EI.06	Average	
$e = 0$ cm	qu (Plaxis)	4.20	5.00	4.20	10.00	7.25	9.00	6.61 bars
	qu (Terzaghi)	4.44	5.38	4.41	15.68	9.19	13.79	8.82 bars
	qu Meyerhof	3.95	4.64	3.92	12.75	7.62	11.27	7.36 bars
	$\Delta\%$ (Plax/Ter)	6%	8%	5%	57%	27%	53%	26%
	$\Delta\%$ (Plax/Meyer)	6%	7%	6%	18%	4%	16%	9%
$e = 10$ cm	qu (Plaxis)	4.00	4.80	4	9.79	6.25	8.77	6.27 bars
	qu Meyerhof	3.90	4.61	3.87	12.36	7.5	10.97	7.20 bars
	$\Delta\%$ (Plax /Meyer)	3%	4%	3%	26%	20%	25%	14%
$e = 20$ cm	qu (Plaxis)	3.80	4.20	3.8	8.79	6	5.1	5.28 bars
	qu Meyerhof	3.85	4.57	3.82	11.98	7.37	10.66	7.04 bars
	$\Delta\%$ (Plax /Meyer)	1%	9%	1%	36%	23%	109%	30%
$e = 30$ cm	qu (Plaxis)	3.50	3.50	3.5	7.97	5.55	4.85	4.81 bars
	qu Meyerhof	3.80	4.53	3.77	11.59	7.25	10.35	6.88 bars
	$\Delta\%$ (Plax /Meyer)	8%	29%	8%	45%	31%	113%	39%

4.2.4. Engineering Implications for Shallow Foundations

This study emphasizes the critical need to account for load eccentricity in designing foundations, especially in high-plasticity, low-stiffness tropical soils. Design recommendations include minimizing eccentricity, particularly avoiding values over 10 cm in fine-grained soils (resulting in approximately 8% - 10% bearing capacity loss per 10 cm increment). Numerical modeling should complement analytical methods, given the tendency of latter to overestimate bearing capacity and underestimate settlement under high eccentricity. Reinforcement (e.g., soil stabilization, deep foundations, geosynthetics) is recommended where eccentric loads are unavoidable, especially in fine silty-clayey soils. Finally, structural design must

account for potential differential settlement, especially in structures with rigid frames or masonry walls, to prevent cracking and long-term serviceability issues. These findings support previous research (Ibrahim & Al-Obaydi, 2021) indicating that foundation behavior is governed by both soil type and load application.

5. Conclusion

This study has provided a comprehensive numerical analysis of the influence of load eccentricity on the bearing capacity and settlement of shallow foundations in tropical soils, using Plaxis 2D. The results highlight the significant role that eccentricity plays in modifying soil behavior, demonstrating that even moderate eccentricity can lead to substantial reductions in bearing capacity and excessive differential settlement. These findings have critical implications for foundation design, particularly in regions where fine-grained soils with high plasticity and compressibility are predominant. The numerical simulations show that bearing capacity decreases progressively as eccentricity increases, confirming theoretical predictions (Meyerhof, 1953; Abdi, 2019). For fine-grained soils (CH, OH), every 10 cm increase in eccentricity leads to an average 5% reduction in bearing capacity, while in sandy-clayey soils (SC, CL), the reduction is 8% per 10 cm increment. At $e = 30$ cm, bearing capacity decreases by up to 27.3%, emphasizing the structural risks associated with excessive eccentricity. Settlement values increase significantly with eccentricity, with the most pronounced deformations occurring in highly plastic fine-grained soils. Fine silty-clayey soils exhibit settlements exceeding 24 cm at $e = 30$ cm, far exceeding tolerable limits for shallow foundations. The differential settlement caused by eccentric loading induces asymmetrical deformations, leading to structural tilting and potential failure, particularly for rigid buildings. Comparison with (Terzaghi, 1943; Meyerhof, 1953) analytical methods reveals that classical approaches tend to overestimate bearing capacity under eccentric loads. The numerical results are more consistent with experimental observations, highlighting the importance of using finite element modeling (FEM) for complex load conditions. The discrepancy between Meyerhof's analytical method and numerical results increases with eccentricity, reaching 39% at $e = 30$ cm, suggesting that empirical approaches may not fully capture progressive failure mechanisms in eccentric footings.

Given the significant impact of eccentricity on shallow foundation performance, the following key recommendations should be considered in geotechnical design:

First, load eccentricity should be minimized whenever possible to avoid excessive settlement and bearing capacity reduction. Structural engineers should aim to keep eccentricity below 10 cm, particularly in fine-grained soils, to prevent severe deformations. If eccentricity is unavoidable, foundation dimensions should be adjusted to compensate for the reduction in effective contact area.

Second, numerical modeling should supplement traditional analytical methods, as classical approaches do not fully capture the non-linear effects of eccentric load-

ing. Finite element analysis (FEA) should be systematically integrated into foundation design, particularly for structures exposed to variable loading conditions.

Third, in high-risk areas with highly plastic fine soils (CH, OH), ground improvement techniques such as preloading, compaction, or geosynthetic reinforcement should be considered to enhance bearing capacity and reduce settlement. In cases where shallow foundations are inadequate, alternative foundation solutions such as deep foundations or raft foundations should be explored.

Finally, differential settlement should be anticipated in structural design, particularly for buildings with rigid frames or masonry walls, to mitigate stress concentrations. Engineers should incorporate flexible joints or reinforced footing systems to counteract potential tilting effects. Additionally, regular monitoring of settlement behavior should be conducted in structures built on fine-grained tropical soils to prevent long-term stability issues.

The soils are often heterogeneous, with local variations in properties, moisture, temperature and other environmental factors that can affect the long-term behavior of these soils when these factors are modified. These factors contribute some limitations to the finite element approach, and numerical models may not accurately predict long-term soil behavior in the event of environmental changes or progressive overloading. However, in the case of this study, these factors have no impact on the results obtained, as the samples tested are intact, homogeneous and the surcharge unchanged over time.

Declaration of Interest Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sector.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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