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NUMERICAL ANALYSIS OF LOAD BEHAVIOR DUE TO PILE ECCENTRICITY IN A 2X2 PILE GROUP

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ABSTRACT

A foundation is a structural element that transfer a building's load to the ground. A common type of foundation is a pile foundation combined with a pile cap. During construction, the pile position may be eccentric due to field conditions without requiring changes to the pile cap design. However, this eccentricity can change the distribution of forces in the foundation system, affecting the structure's safety and stiffness. This problem often arises due to unsuitable soil conditions or physical constraints. Finite element software is used to model the behavior of the structure in various pile point eccentricity scenarios. Eccentricities beyond this require reevaluation of the pile cap design and the foundation system as a whole. This may include adjusting the number of points to ensure the reaction is correct.

Aims: This study aimed to analyze the effect of shifting pile positions on the performance of foundation structures when the pile cap design remains unchanged.

Methodology and results: The pile position eccentricity scenario was carried out in stages: 0 cm (control), 10 cm, 20 cm, 25 cm, 30 cm, 40 cm, and 50 cm from the planned position. Simulation results show that, for eccentricity between 10 and 40 cm, the change in force distribution remains within safe limits (less than 20%). However, at an eccentricity of 50 cm, several piles showed an increase in axial force of up to 23.81% of the design value. Within certain limits, the pile point eccentricity is still acceptable without changing the pile cap design. Based on the simulation results, the safe tolerance limit for pile position eccentricity is up to 40 cm from the design position.

Conclusion, significance, and impact study: Shifts beyond this limit require reevaluation of the pile cap design and the foundation system as a whole.

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1. INTRODUCTION

The foundation is an essential part of a building's structure that safely and stably channels the load from the upper structure to the ground [1] [2] [3]. Soil conditions and building loads significantly influence the choice of foundation type [4] [5] [6]. A pile foundation, which is combined with a binding concrete element in the form of a pile cap to unite the upper end of the pile and distribute the load evenly, is one type of foundation that is often used in the construction of multi-story buildings or structures with large loads [7] [8] [9]. Construction practice often involves deviations from the initial design due to various field constraints, such as soil conditions that differ from the investigation data, limited access to heavy equipment, and physical obstacles like boulders or underground utilities [10] [11] [12]. One such deviation is the difference between the planned and actual pile positions, while the pile cap design remains consistent with the initial working drawings [13] [14] [15].

Although this eccentricity may appear minor, it can significantly impact the overall behavior of the foundation system, especially in how axial and lateral forces are distributed among individual piles [16] [17] [18]. The resulting load imbalances can lead to overstressed piles, reduced overall structural efficiency, and compromised safety margins [19] [20] [21]. Alarmingly, such deviations often go unnoticed or are not followed by a reanalysis or redesign of the pile cap system due to time, cost, or technical capacity constraints on-site [22] [23] [24]. Previous studies have generally focused on ideal or symmetrically loaded pile systems, assuming consistent pile placement and ignoring practical deviations. Little attention has been given to quantifying the amount of eccentricity that can be structurally tolerated before a redesign of the pile cap is necessary. This creates a research gap that must be addressed, especially for field engineers who need practical yet reliable guidelines for making decisions. This is due to the limited time, cost, and technical understanding available in the field [25] [26] [27]. Therefore, this study aims to investigate the structural implications of pile placement eccentricity while maintaining a fixed pile cap design [28] [29] [30]. The study employs a finite element to simulate various eccentricity scenarios and evaluate their impact on load distribution across the pile group [31] [32].

The analysis results indicate that up to an eccentricity of 40 cm from the design position, the force distribution remains within safe tolerances. However, at an eccentricity of 50 cm, several piles experienced an increase in axial force of over 23%, which suggests the need for a redesign evaluation if the deviation surpasses this threshold. These findings provide engineers with a

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practical benchmark, offering a quantitative guideline for tolerances in pile placement that does not necessitate a complete redesign of the pile cap. This bridges the gap between theoretical design assumptions and field realities.

2. RESEARCH METHODOLOGY

This quantitative experimental study is based on numerical methods and employs a software-assisted finite element simulation approach. The primary objective is to analyze how changes in load distribution within the foundation system result from eccentricity in pile positioning relative to the pile cap, while keeping the pile cap's geometric design unchanged.

2.1 Research Design

The research adopts a numerical experimental design. The pile cap and pile group are modeled under controlled conditions, with the main variable being the distance the piles are placed from the original design point.

2.2 Research Object

The modeled structure is a reinforced concrete pile cap structure supported by a group of vertical piles. The number, dimensions, and material properties of the piles and the pile cap are kept constant, according to standard design practices for multistory buildings and relevant codes (e.g., SNI or ACI standards).

2.3 Research Variables

a. Independent variable: Pile position eccentricity (0 cm, 10 cm, 20 cm, 25 cm, 30 cm, 40 cm, and 50 cm).
b. Dependent variable: Axial force distribution on each pile.
c. Evaluation threshold: An increase in axial force of more than 20% compared to the original distribution is considered structurally significant and triggers the need for a redesign.

2.4 Research Procedure

The study follows these steps:

a. Literature review: Gather references on pile cap behavior, pile eccentricity, and structural load distribution in foundation systems.

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b. Initial modeling: Design the geometry of the pile cap and the initial pile layout based on standard structural configurations.
c. Scenario setup: Systematically shift the pile position by a set distance in each model scenario without modifying the pile cap geometry.
d. Simulation and analysis: Run finite element simulations to analyze the structural response and extract axial force data for each pile.
e. Performance evaluation: Compare the results of each eccentricity scenario to the control model (0 cm) to assess whether the force distribution remains within the acceptable threshold.

2.5 Data Analysis Techniques

The simulation output data, specifically the axial force (N) on each pile, are analyzed by comparing each scenario to the baseline (0 cm displacement). The analysis focuses on detecting increases in force concentration and identifying imbalances in the foundation system.

a. If the change in force distribution is ≤20%, the eccentricity is considered structurally acceptable.
b. If the force increases by more than 20% or shows significant asymmetry, the foundation system requires redesign or reinforcement.

2.6 Statistical and Validity Considerations

As this study is based entirely on computational simulation and does not involve human subjects, ethical considerations are not applicable. However, the model is validated by referencing established design standards and previously published research. A sensitivity analysis is also performed to assess the consistency and robustness of the results across varying eccentricity levels.

3. RESULTS AND DISCUSSION

This section presents the findings from finite element simulations of various pile position eccentricity scenarios relative to the original design point. These simulations use a fixed pile cap configuration. The analysis focuses on the redistribution of axial forces across the pile group under eccentric conditions and on evaluating safe tolerance limits.

3.1. Initial Modeling of Structure

The initial modeling stage is based on the structural foundation plan shown in Figure X. This plan illustrates a reinforced concrete pile cap measuring 300 cm x 300 cm with a thickness of 60 cm. The pile cap is supported by four bored piles, each with a diameter of 40 cm. The pile incorporates tie beams, or sloofs, measuring 30 cm × 50 cm. These beams are arranged orthogonally in both the X and Y directions, forming a rigid frame that distributes loads from the upper column structure. Each pile is positioned symmetrically around the central column footprint, measuring 80 cm × 80 cm, and is placed 110 cm from the center, forming a square pile layout. The tie beams are embedded between the piles and the column base to enhance load transfer and minimize differential settlement. During the modeling process, the geometric configuration from the drawing is maintained as the control (baseline) model for the simulation. To simulate field deviations, the right-side pile position is shifted horizontally (in the X-axis direction) to represent common issues encountered during field installation due to equipment misalignment or subsurface obstacles. This shift introduces eccentricity into the pile arrangement, thereby altering the uniformity of load paths within the foundation system. The objective of this modeling approach is to quantify the effect of displacement in one direction on the axial force distribution across all piles without altering the geometry or stiffness of the pile cap. Displacement magnitude is varied incrementally to evaluate structural tolerance, as will be discussed in the subsequent simulation analysis.

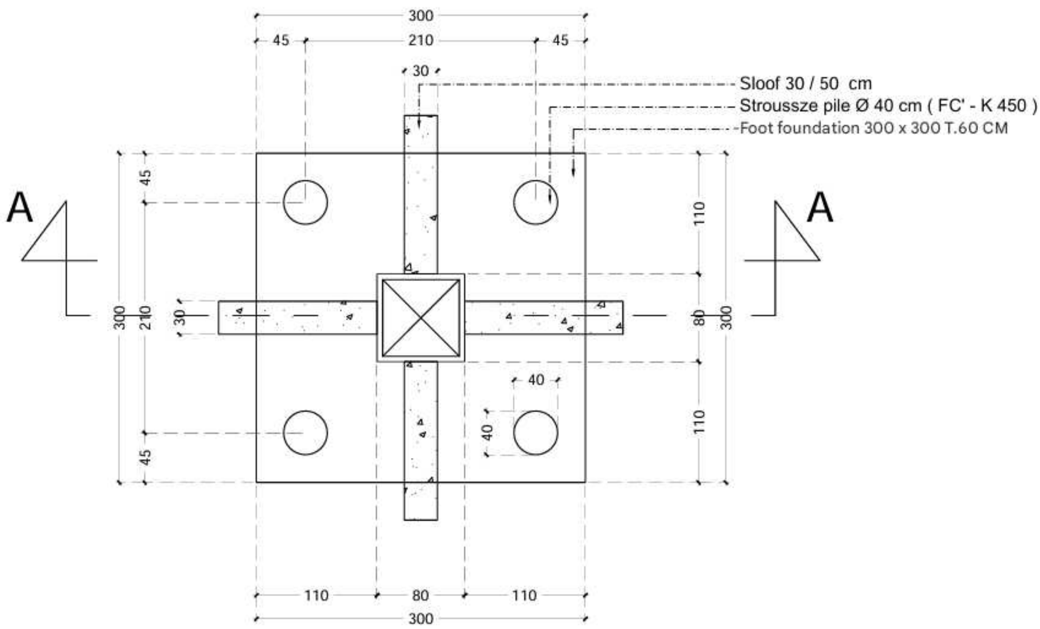

Figure 1: Initial foundation design details.

Figure 1 shows that the initial foundation design specifies a pile distance of 105 cm from the pile center point. However, field conditions do not permit adherence to this design. Several pile point eccentricity scenarios were created to evaluate the strength and safety of the pile design modeling, without altering the planned dimensions of the pile cap.

3.2. Pile Eccentricity Simulation

A foundation model comprising a pile cap and four symmetrically arranged piles was used for the simulation. The control model, which did not include eccentricity, was used as a reference for the ideal axial force distribution. Then, modeling was carried out with variations in the pile position eccentricity in stages: 10 cm, 20 cm, 25 cm, 30 cm, 40 cm, and 50 cm. Table 1 summarizes the results of comparing the maximum axial force on the pile for each scenario.

Table 1: Simulation scenario of pile point eccentricity.

Parameters	Values						
Scenario of Pile Point Shift (m)	0,00	0,10	0,20	0,25	0,30	0,40	0,50
Number of Piles	4	4	4	4	4	4	4
Pile cap Dimension (m)	2 x 2	2 x 2	2 x 2	2 x 2	2 x 2	2 x 2	2 x 2
Initial Pile Distance from Centre Point (m)	1,05	1,05	1,05	1,05	1,05	1,05	1,05
Pile Shear Distance to Centre Point (m)	1,05	1,00	0,95	0,93	0,90	0,85	0,80
Total Vertical Force (kN)	630,00	630,00	630,00	630,00	630,00	630,00	630,00
Initial Eccentricity (e1, m)	0,53	0,53	0,53	0,53	0,53	0,53	0,53
New Eccentricity (e2, m)	0,53	0,50	0,48	0,46	0,45	0,43	0,40
Initial Moment (M1 = P*e1, kNm)	330,75	330,75	330,75	330,75	330,75	330,75	330,75
New Moment (M2 = P*e2, kNm)	330,75	315,00	299,25	291,38	283,50	267,75	252,00
Moment Change (%)	0,00	-4,76	-9,52	-11,90	-14,29	-19,05	-23,81

The simulation was conducted on a reinforced concrete pile cap model with fixed geometry and pile arrangement. To evaluate the influence of increasing eccentricity on the axial load distribution on each pile, the pile positions were systematically shifted by 0 cm (control), 10 cm, 20 cm, 25 cm, 30 cm, 40 cm, and 50 cm.

The results show that the axial force distribution remained relatively uniform and within acceptable limits up to a displacement of 40 cm. Specifically, at eccentricities of 10 cm, 20 cm, and 30 cm, changes in axial force on individual piles were recorded, ranging from 5% to 18%. This is still below the 20% structural tolerance threshold typically used in foundation engineering

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assessments. These results suggest that the pile cap can redistribute loads efficiently within this range of eccentricity.

However, at an eccentricity of 50 cm, a significant imbalance was observed. Some piles experienced increases in axial force of up to 23.81%, while others showed reductions of over 15%. This indicates a non-uniform load path and potential overstressing of certain piles. This excessive deviation in force exceeds the safe tolerance threshold, indicating the need for a redesign of the pile cap or a reevaluation of the pile arrangement.

3.3 Load Distribution and Force Imbalance

In the ideal model (0 cm), the load is evenly distributed across the four piles. However, when the pile shifts, the length of the working arm moment between the center of the pile cap and the pile support point changes. This causes the load to become eccentric and concentrates force on one side. This is presented in Table 2 below.

Table 2: Foundation force distribution

Eccentricity (m)	Maximum Axial Force (kN)	Maximum Lateral Force (kN)	Maximum Bending Moment (kNm)	Highest Foundation Reaction (kN)	Percentage Increase in Axial Force (%)
0,00	157,50	315,00	330,75	157,50	0,00
0,10	157,55	315,00	315,00	165,00	4,76
0,20	157,60	315,00	299,25	172,50	9,52
0,25	157,62	315,00	291,38	176,25	11,90
0,30	157,64	315,00	283,50	180,00	14,29
0,40	157,69	315,00	267,75	187,50	19,05
0,50	157,74	315,00	252,00	195,00	23,81

The following shows the force distribution after applying the force according to the shift scenario. Based on the above results, the force distribution increases linearly with distance; however, the increase is slightly exponential due to the interaction between the piles.

The increased load concentration on select piles at higher eccentricities threatens structural integrity. Overstressed piles may result in localized settlement or even structural failure under extreme conditions. From a design perspective, this level of load variation cannot be ignored, especially for critical infrastructure or multistory buildings where stringent safety margins are required. The findings of this study reinforce the importance of accounting for pile position tolerances during the design and construction phases of a project. While minor deviations are standard and acceptable, this study identifies 40 cm as the upper safe limit for pile displacement under the modeled pile cap and loading conditions. Beyond this limit, redistribution of internal forces becomes structurally critical and requires reanalysis.

3.4 Structural Safety Evaluation

The simulation results determined that the tolerance limit for pile eccentricity, beyond which excessive force redistribution occurs, is approximately 40 cm. If this limit is exceeded, the force distribution becomes imbalanced, and some piles exceed their design capacity. Therefore, the pile cap design and structural reinforcement must be revised if the eccentricity exceeds this value. This phenomenon is important in construction practice because pile eccentricity is often unavoidable due to soil conditions, heavy equipment, or field constraints. These results provide practitioners with a basis for determining the tolerance limit for eccentricity and recommend monitoring the geometry during drilling and driving to stay within the design safety limits.

4. CONCLUSION

This study examines how pile position eccentricities affect the force distribution in a foundation system with a fixed pile cap. Based on numerical modelling results using finite element analysis, the following conclusions were drawn:

a. Pile position eccentricities significantly impact the distribution of axial forces within the foundation system. Displacing pile positions introduces imbalances, primarily when loads are concentrated on the side of the pile closer to the center of the pile cap. In scenarios where eccentricities range from 10 cm to 40 cm, the structure performs safely, with axial force increases remaining below 20% of the design value. This indicates compliance with acceptable tolerance limits based on structural engineering standards.
b. However, at an eccentricity of 50 cm, the axial force increases by up to 23.81%, surpassing the defined tolerance limit and indicating potential overstress and local failure. This confirms that eccentricities beyond 40 cm compromise the structural integrity of the pile group and require corrective action.
c. The study establishes that the maximum tolerance for pile position deviation without modifying the original pile cap design is 40 cm. Deviations exceeding this threshold lead to critical load redistribution within the foundation system.
d. These findings provide a quantitative benchmark for acceptable pile installation

tolerances under fixed cap conditions. This underscores the structural importance of positioning piles precisely according to design specifications.

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