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Evaluation of Pile Cap Dimensions and Reinforcement Using Conventional, Strut and Tie, and Finite Element Methods

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Abstract

Pile caps play a critical role in transferring axial forces, bending moments, and shear forces from superstructures to pile groups. This study comparatively evaluates the dimensions, reinforcement requirements, and structural response of pile caps with two, three, four, and five piles using the Conventional Method, Strut-and-Tie Model (STM), and Finite Element Method (FEM). The Conventional Method was used to assess flexural and shear capacity in accordance with ACI 318, while STM represented internal load transfer through compression struts and tension ties. Three-dimensional FEM models were developed in ABAQUS using the Concrete Damage Plasticity approach and were validated against a numerical model before analysis. The results show that pile configuration and analytical method significantly affect pile cap dimensions and reinforcement requirements. The five-pile configuration exhibited the largest differences, with STM producing a 1100 mm thick pile cap and 7,645 mm² reinforcement, compared with 900 mm thickness and 5,888 mm reinforcement from the Conventional Method and FEM. FEM produced maximum concrete stresses of 8.20, 2.41, 3.03, and 2.41 MPa for five-, four-, three-, and two-pile configurations, respectively. Reinforcement stresses were generally closer to Conventional Method results. The findings demonstrate that the three approaches provide complementary information for pile cap design and evaluation.

Keywords: Pile Cap, Conventional Method, Strut-and-Tie Model;, Finite Element Method, Reinforcement Design

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Introduction

Pile caps are critical components of deep foundation systems because they transfer axial forces, bending moments, and shear forces from superstructures to groups of piles and subsequently to the surrounding soil (Magade & Ingle, 2021; Zheng et al., 2024). Their structural performance is therefore strongly associated with the geometry of the pile cap, pile arrangement, material properties, reinforcement configuration, and load transfer mechanism. In conventional design practice, pile caps are commonly evaluated using sectional approaches in which flexural strength, one-way shear, and two-way shear are examined separately (Mogili & Hwang, 2021; Fayed et al., 2025).

This approach provides a practical and relatively simple procedure for structural design, but it relies on simplified assumptions regarding the distribution of internal forces and the structural behavior of the pile cap. Such assumptions may become less representative when pile caps behave as deep structural members in which the stress distribution is highly non-uniform (Ranasinghe et al., 2026; Poulos, 2008). The present study is motivated by the need to understand how these design assumptions influence the resulting dimensions and reinforcement requirements of pile caps with different pile configurations (Geevar et al., 2023; Mogili et al., 2025).

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The structural response of a pile cap is influenced by the number and arrangement of piles because changes in pile configuration modify the internal load-transfer paths between the column and the individual pile supports. In addition, pile cap thickness and reinforcement arrangement affect the development of compressive and tensile stress fields and consequently influence the capacity and deformation response of the structure. Excessive thickness or reinforcement may lead to inefficient use of materials, whereas insufficient dimensions or reinforcement may reduce the available capacity against shear, punching shear, or internal compression and tension mechanisms (Kim et al., 2023; Nzambi et al., 2022).

Previous studies have demonstrated that pile cap behavior cannot always be adequately represented by assuming the member to act as a fully rigid body, particularly when stress concentration, nonlinear force flow, and load redistribution become significant. These conditions are particularly relevant to pile caps with different numbers of piles, where changes in geometry produce different mechanisms of force transfer (Basha et al., 2023; Mogili et al., 2025).

The limitations of sectional design have encouraged the application of the Strut-and-Tie Model (STM) for reinforced concrete members containing discontinuity regions. Unlike the conventional approach, STM represents the internal force-transfer mechanism through compressive struts in concrete and tensile ties primarily associated with reinforcement. This approach is particularly relevant to relatively deep pile caps because it provides a rational representation of the load path from the column toward the pile supports (Geevar et al., 2023; Mogili & Hwang, 2021).

The model also enables the designer to evaluate the capacity of struts, ties, and nodal zones in accordance with the principles of structural equilibrium and the requirements of ACI 318 (Lourenço et al., 2023). Nevertheless, the selection of an appropriate strut-and-tie configuration and the resulting reinforcement demand may differ from those obtained using conventional sectional design. Consequently, direct comparison between the two approaches is necessary to determine how their different representations of structural behavior affect pile cap dimensions and reinforcement requirements (Yi et al., 2025; Fayed et al., 2025).

Finite Element Method (FEM) analysis provides another approach for investigating pile cap behavior by allowing the three-dimensional distribution of stresses, strains, and deformation to be examined numerically. In contrast to simplified analytical approaches, three-dimensional solid-element modelling can capture complex stress distributions within massive reinforced concrete members and provide additional information concerning the structural response (Andersen et al., 2022; Basha et al., 2023).

The use of ABAQUS enables pile caps to be evaluated through numerical simulation, including the response of concrete and reinforcement under applied loading. The thesis study established a validation procedure before applying the numerical model to the investigated pile cap configurations, and the resulting model was subsequently used for parameter analysis. The use of FEM therefore provides an opportunity to complement the conventional and STM approaches by examining structural responses that are difficult to represent through simplified design equations (Saeed, 2024; Suzuki et al., 2024).

Although conventional design, STM, and FEM have each been applied to reinforced concrete pile caps, differences among these approaches can result in different predictions of pile cap dimensions, reinforcement requirements, stresses, and deformation. The need for a comparative assessment becomes more important when the number of piles changes because

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the geometry and internal load-transfer mechanism are simultaneously altered (Yusmar & Isda, 2024; Yi et al., 2025).

The present study addresses this issue by evaluating pile caps supported by two, three, four, and five piles using the Conventional Method, Strut-and-Tie Model, and Finite Element Method. The study specifically compares the resulting pile cap dimensions, reinforcement requirements, and structural response associated with the different analytical approaches. The research is based on the analytical framework and validated numerical modelling procedure developed in the thesis, in which the pile cap configurations are subjected to the specified loading conditions and evaluated in terms of deformation, concrete stress, and reinforcement tensile stress (Fayed et al., 2025; Mogili et al., 2025).

Accordingly, the objective of this study is to comparatively evaluate the design requirements and structural response of pile caps with different numbers of piles using the Conventional Method, Strut-and-Tie Model, and Finite Element Method. The analysis is intended to identify how changes in pile configuration influence pile cap dimensions and reinforcement demand and to clarify the differences in structural response predicted by the three approaches. The study contributes to pile cap design practice by providing a comparative basis for selecting an appropriate analytical approach according to the required level of design simplicity, force-transfer representation, and numerical detail. The results are expected to support more informed and efficient pile cap design by demonstrating the respective characteristics and limitations of conventional sectional design, STM-based force-transfer modelling, and three-dimensional FEM analysis.

Methods

Research Design

This study employed an analytical and numerical approach to investigate the design requirements and structural response of reinforced concrete pile caps with different pile configurations. Four pile cap configurations consisting of two, three, four, and five piles were investigated. The analysis focused on the influence of pile configuration, pile cap thickness, and reinforcement on the structural response of the pile caps under the applied loading conditions. Three analytical approaches were considered, namely the Conventional Method, the Strut-and-Tie Model (STM), and the Finite Element Method (FEM). The Conventional Method was used to evaluate pile cap adequacy based on flexural and shear capacity in accordance with ACI 318. The STM was applied to represent the internal load-transfer mechanism through compression struts and tension ties. FEM was subsequently used to simulate the three-dimensional response of the pile caps and to evaluate stress distribution and deformation. The numerical models were developed using ABAQUS, and the FEM modelling procedure was validated before being applied to the investigated pile cap configurations. The overall research procedure consisted of defining the pile cap configurations and material properties, determining the applied loading and pile reactions, conducting the Conventional Method and STM analyses, developing the FEM models, validating the numerical model, and comparing the resulting structural responses. The principal response parameters considered were pile cap dimensions, reinforcement requirements, concrete stress, reinforcement stress, stress distribution, and deformation.

Pile Cap Models and Material Properties

The investigated pile caps consisted of two-, three-, four-, and five-pile configurations. The pile arrangement and geometry were varied according to the number of piles, while the

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corresponding column and pile positions were maintained in the numerical models. The pile spacing was 1050 mm for the five-pile configuration and approximately 900 mm for the other configurations. The conventional design dimensions were 3000 × 3000 × 900 mm for the five-pile pile cap, 1800 × 1800 × 600 mm for the four-pile pile cap, 1800 × 1680 × 500 mm for the three-pile pile cap, and 1800 × 900 × 450 mm for the two-pile pile cap. The material properties followed the parameters used in the thesis. The five-pile configuration used concrete with a compressive strength of 28 MPa and an elastic modulus of 24,870 MPa, whereas the two-, three-, and four-pile configurations used concrete with a compressive strength of 24.9 MPa and an elastic modulus of 23,452.95 MPa. The reinforced concrete unit weight was 2400 kg/m³. Reinforcing steel had a yield strength of 420 MPa, an ultimate strength of 525 MPa, and an elastic modulus of 200,000 MPa. For the FEM analysis, concrete was modelled using the Concrete Damage Plasticity (CDP) approach with the Hognestad stress–strain relationship. This formulation was used to represent the nonlinear response of concrete under loading and to obtain the stress and deformation response of the pile cap.

Loading and Analytical Design

The pile cap models were subjected to dead load, live load, and bending moment. The two-pile model was subjected to 502.4 kN dead load, 178.3 kN live load, and 30.8 kN moment. The corresponding loads for the three-pile model were 670.2 kN, 217.3 kN, and 20.8 kN, while the four-pile model was subjected to 840.0 kN, 313.4 kN, and 18.5 kN, respectively. The five-pile model was subjected to 2446.0 kN dead load, 778.0 kN live load, and 271.0 kN moment. The resulting pile reactions were determined according to the number and arrangement of piles. The Conventional Method was performed using sectional design principles based on ACI 318. The analysis considered two-way shear, one-way shear, and flexural capacity. The pile cap thickness was determined from the shear requirements, while the required longitudinal reinforcement was calculated from the factored bending moment generated by the pile reactions. The calculated reinforcement was compared with the minimum reinforcement requirement, and the governing value was adopted for the design. The adequacy of each configuration was evaluated by comparing the design capacity with the corresponding factored demand. The STM analysis represented the pile cap as a structural system consisting of compression struts, tension ties, and nodal regions. The struts represented the principal compression fields within the concrete, while the ties represented the tensile forces carried by the reinforcement. The model was established based on the load-transfer path between the column and pile supports, and the resulting strut, tie, and nodal forces were used to evaluate the required pile cap thickness and reinforcement. This approach allowed the internal force-transfer mechanism to be assessed differently from the sectional assumptions used in the Conventional Method.

Finite Element Modelling and Validation

The FEM analysis was conducted using ABAQUS. The pile cap was modelled using three-dimensional solid elements, while the pile locations were represented by support conditions corresponding to the investigated pile arrangements. The numerical models incorporated the pile cap geometry, concrete and reinforcement properties, reinforcement configuration, loading, and boundary conditions. The concrete material was represented using the CDP model combined with the Hognestad stress–strain relationship. Before the numerical analysis of the four pile cap configurations, the FEM modelling procedure was validated using a previously reported pile cap model analysed using the ATENA finite element software. The validation reference was based on the study used in the thesis for the solid-element modelling approach.

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The comparison focused on the load–deformation response between the reference model and the ABAQUS model. The thesis reported that the two models produced similar response trends, supporting the suitability of the ABAQUS modelling procedure for the subsequent pile cap analysis. Following validation, the FEM models were applied to the two-, three-, four-, and five-pile configurations. The numerical analysis was used to obtain the distribution of concrete stress, reinforcement stress, and deformation. These results were subsequently compared with the design dimensions and reinforcement requirements obtained from the Conventional Method and STM.

Comparative Evaluation

The three approaches were compared to identify differences in pile cap dimensions, reinforcement requirements, and structural response. The comparison considered the effects of pile number on the resulting pile cap thickness and reinforcement area, while the FEM results provided additional information regarding concrete stress, reinforcement stress, stress distribution, and deformation. The Conventional Method and STM were primarily compared in terms of their resulting design requirements, whereas FEM was used to provide a numerical representation of the structural response. The comparison was subsequently used to assess how differences in the assumed load-transfer mechanisms influenced the design and behaviour of pile caps with different numbers of piles.

Results and Discussion

Conventional Method Analysis

The Conventional Method was applied to evaluate the flexural and shear capacity of pile caps with five, four, three, and two piles. The analysis considered the factored axial load and moment, pile reactions, two-way shear capacity, pile cap thickness, and flexural reinforcement. The resulting design parameters for the four configurations are summarized in Table 1. The calculated two-way shear capacity exceeded the corresponding factored shear demand in all configurations, while one-way shear was not governing because the critical section was located outside the pile reaction line.

Table 1. Conventional Method results for the investigated pile cap configurations

Pile configuration	Pile cap dimensions (mm)	Factored axial load, Pu (kN)	Factored moment, Mu (kN)	Rmax (kN)	Rmin (kN)	φVc/Vu	Reinforcement, As (mm²)	fs (MPa)
5 piles	3000 × 3000 × 900	4180	758.8	1017	655	1.80	5888	326
4 piles	1800 × 1800 × 600	1509.4	51.8	392	363	1.40	2010	288
3 piles	1800 × 1680 × 500	1151.9	58.24	406	362	1.30	2010	298
2 piles	1800 × 900 × 450	888.2	86.24	492	396	1.40	1206	340

For the five-pile configuration, the factored axial load and moment were 4180 kN and 758.8 kN, respectively, producing maximum and minimum pile reactions of 1017 and 655 kN. The

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two-way shear demand was 3344 kN, while the governing design shear capacity was approximately 6012 kN, resulting in a capacity-to-demand ratio of 1.80. A pile cap thickness of 900 mm was therefore adopted. The required reinforcement area was 5517 mm², and 12D25 reinforcement with an area of 5888 mm² was provided. The resulting flexural capacity was 1770 kN compared with a factored moment of 1525 kN, while the calculated reinforcement stress was 326 MPa.

For the four-pile configuration, the factored axial load was 1509.4 kN and the factored moment was 51.8 kN, with maximum and minimum pile reactions of 392 and 363 kN. The governing two-way shear capacity was 2091 kN against a factored shear demand of 1509 kN, giving a ratio of 1.40 and resulting in a 600 mm pile cap thickness. The calculated flexural reinforcement requirement was initially 1336 mm²; however, the minimum reinforcement requirement of 1675 mm² governed the design, resulting in 10D16 reinforcement with an area of 2010 mm². The calculated reinforcement stress was 288 MPa.

The three-pile configuration produced a factored axial load of 1151.9 kN and a factored moment of 58.24 kN, with maximum and minimum pile reactions of 406 and 362 kN. The governing two-way shear capacity was 1480 kN compared with a factored demand of 1173 kN, giving a ratio of 1.30 and confirming the adequacy of the 500 mm pile cap thickness. The required flexural reinforcement was 1715 mm², exceeding the minimum requirement of 1351 mm². Therefore, 10D16 reinforcement with an area of 2010 mm² was provided, producing a reinforcement stress of 298 MPa.

For the two-pile configuration, the factored axial load and moment were 888.2 kN and 86.24 kN, respectively, with maximum and minimum pile reactions of 492 and 396 kN. The governing two-way shear capacity was 1212 kN against a factored demand of 888 kN, resulting in a ratio of 1.40 and confirming the adequacy of the 450 mm pile cap thickness. The calculated reinforcement requirement was 1182 mm², while the minimum reinforcement requirement was 1189 mm². Six D16 bars with a total area of 1206 mm² were therefore provided, resulting in a reinforcement stress of 340 MPa.

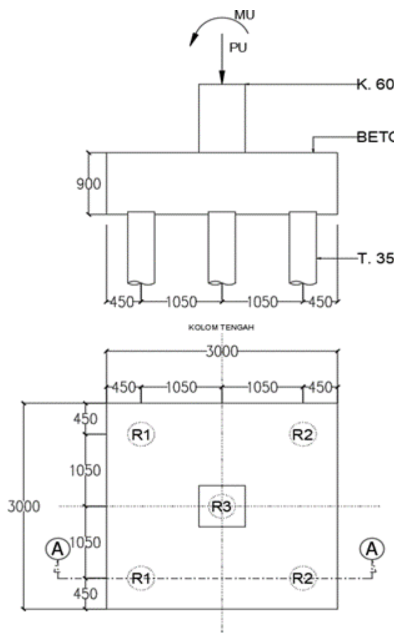

Figure 1. Geometry and reinforcement arrangement of the five-pile pile cap designed using the Conventional Method.

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the geometry and reinforcement arrangement adopted for the five-pile pile cap based on the Conventional Method. The pile cap has plan dimensions of 3000 × 3000 mm and a thickness of 900 mm, with the column positioned at the centre of the pile group. The reinforcement arrangement was determined from the governing flexural and minimum reinforcement requirements obtained from the sectional analysis. For the five-pile configuration, the adopted reinforcement area was 5888 mm², corresponding to 12D25 reinforcement, while the calculated reinforcement stress was 326 MPa. The design also satisfied the governing two-way shear requirement, with a capacity-to-demand ratio of 1.80.

The geometry shown in Figure 1 represents the conventional sectional-design assumption, in which the pile cap dimensions and reinforcement are determined primarily from flexural and shear capacity requirements. The resulting configuration provides the reference design for comparison with the STM and FEM approaches. The five-pile configuration was selected for graphical representation because it produced the largest pile cap dimensions and reinforcement area among the investigated configurations, corresponding to the substantially higher applied loading.

The Conventional Method therefore produced progressively smaller pile cap dimensions as the number of piles decreased. The resulting designs satisfied the reported shear and flexural checks for all configurations, with the five-pile configuration requiring the largest pile cap and reinforcement area because of its substantially higher applied load.

Strut-and-Tie Model Analysis

The STM analysis represented each pile cap as a truss consisting of compression struts and tension ties connected through nodal zones. The resulting strut geometry varied according to pile configuration. For the five-pile model, the strut inclination was 30.7°, with four inclined struts and one vertical strut. The calculated force in each inclined strut was 1637 kN, while the vertical strut carried 836 kN. The corresponding tensile force in the principal tie was 995.6 kN.

The five-pile STM model produced a pile cap thickness of 1100 mm. The effective concrete compression limits for the considered strut and nodal configurations were 17.85 MPa for a prismatic strut, 13.39 MPa for a bottle-shaped strut with reinforcement, and 10.71 MPa for a bottle-shaped strut without reinforcement. The critical nodal checks and strut capacity checks were satisfied. The principal inclined strut developed a compressive stress of 8.53 MPa, while the vertical strut developed 8.20 MPa, both below the corresponding effective compression limit. The required tie reinforcement was 3161 mm², and 6D29 reinforcement with an area of 3961.11 mm² was provided. The resulting reinforcement stress was 251.34 MPa.

For the four-pile configuration, the strut inclination was 48°, with four inclined struts. The load assigned to each strut was 377 kN, producing an inclined strut force of 508 kN and a tie force of 240.25 kN. The governing bottle-shaped strut capacity was 9.56 MPa, while the calculated compressive stress in the strut was 2.80 MPa. The nodal capacity checks were satisfied. The required tie reinforcement was 763 mm², and 4D16 reinforcement with an area of 803.84 mm² was provided. The resulting reinforcement stress was 298.88 MPa.

For the three-pile configuration, the strut inclination was 42°. Three inclined struts were used, with 384 kN assigned to each strut. The resulting strut force was 574 kN and the tie force was 301.54 kN. The calculated strut compressive stress was 3.13 MPa, while the governing bottle-shaped strut limit was 9.56 MPa. The nodal capacity was also adequate, with a calculated nodal capacity of 640 kN against a strut force of 384 kN. The required tie reinforcement was 957

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mm², and 6D16 reinforcement with an area of 1205.76 mm² was provided. The resulting reinforcement stress was 250.09 MPa.

For the two-pile configuration, the strut inclination was 38°, with two inclined struts. Each strut carried 444 kN, resulting in an inclined strut force of 721 kN and a tie force of 401.92 kN. The calculated compressive stress in the inclined strut was 3.92 MPa, which remained below the governing effective compression limit of 9.56 MPa. The nodal capacity was also adequate. The required tie reinforcement was 1276 mm², and 7D16 reinforcement with an area of 1406.72 mm² was provided. The resulting reinforcement stress was 285.71 MPa.

Table 2. Principal Strut-and-Tie Model results

Pile configuration	Thickness (mm)	Strut angle (°)	Principal strut force (kN)	Tie force (kN)	Strut stress (MPa)	Required tie reinforcement, As (mm²)	Provided As (mm²)	fs (MPa)
5 piles	1100	30.7	1637	995.60	8.53	3161	3961	251.34
4 piles	600	48	508	240.25	2.80	763	804	298.88
3 piles	500	42	574	301.54	3.13	957	1206	250.09
2 piles	450	38	721	401.92	3.92	1276	1407	285.71

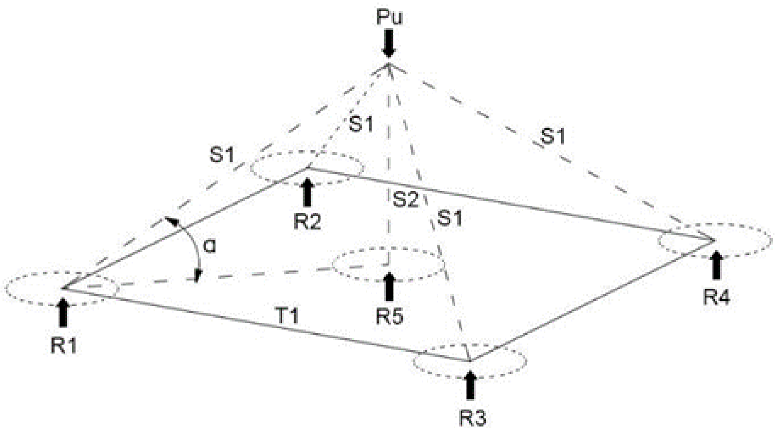

Figure 2. Strut-and-Tie Model and internal load-transfer mechanism of the five-pile pile cap.

The Strut-and-Tie Model adopted for the five-pile pile cap and illustrates the principal load-transfer mechanism between the column and pile supports. The applied column load is transferred through compression struts toward the individual pile supports, while tensile forces are carried by the reinforcement represented as tension ties. For the five-pile configuration, the adopted STM consisted of four inclined struts and one vertical strut, with an inclined strut angle of 30.7°. The calculated force in each inclined strut was 1637 kN, while the principal tie force was 995.6 kN.

Based on the STM analysis, a pile cap thickness of 1100 mm was required for the five-pile configuration. The principal inclined strut developed a compressive stress of 8.53 MPa, while the vertical strut developed 8.20 MPa, both remaining below the corresponding effective concrete compression limits. The required tie reinforcement was 3161 mm², and 3961 mm² was provided, resulting in a reinforcement stress of 251.34 MPa. These results indicate that the STM provides an explicit representation of the internal force-transfer mechanism and leads to design requirements that differ from those obtained using the Conventional Method.

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The STM results demonstrate that the internal force-transfer mechanism changes with pile configuration. The five-pile model generated the largest strut and tie forces because of its substantially greater applied load, while the smaller configurations produced lower individual strut forces. All reported strut and nodal checks were satisfactory, indicating that the adopted STM configurations provided sufficient compression capacity for the investigated models.

Finite Element Analysis

The FEM models were developed in ABAQUS using three-dimensional solid elements for concrete and truss elements for reinforcement. Concrete was represented using the Concrete Damage Plasticity model, while the reinforcement was incorporated through an embedded-region formulation. The geometry and reinforcement of the FEM models were based on the Conventional Method results.

The five-pile FEM model used a 900 mm pile cap thickness, a 600 × 600 mm column, and 350 × 350 mm piles. The reinforcement was embedded within the concrete model, allowing the reinforcement deformation to follow the surrounding concrete without relative slip. The FEM results showed that the maximum concrete stress occurred near the column–pile cap interface and developed diagonally toward the pile heads. The maximum stresses were 8.2 MPa in the inclined compression strut and 7.8 MPa in the vertical strut. These values were below the reported effective concrete compression capacity of 10.71 MPa. The maximum reinforcement stress was 322 MPa, while the maximum vertical deformation was 0.20 mm.

The four-pile model produced a maximum concrete stress of 2.41 MPa and a maximum reinforcement stress of 285 MPa. The maximum vertical deformation was 0.56 mm. The stress contours showed that compressive stress was concentrated around the column and followed diagonal paths toward the pile heads, while reinforcement stress was concentrated beneath the column and decreased toward the pile supports.

The three-pile model produced a maximum concrete stress of 3.03 MPa, reinforcement stress of 276 MPa, and vertical deformation of 0.40 mm. Similar to the other configurations, the concrete stress concentrated along diagonal paths between the column and pile heads, while reinforcement stress was greatest near the column region. The two-pile model produced a maximum concrete stress of 2.41 MPa, reinforcement stress of 303 MPa, and vertical deformation of 0.36 mm. The stress distribution again showed localized compression paths between the column and piles, while the reinforcement stress was concentrated near the column region.

Table 3. FEM structural response of the investigated pile cap configurations

Pile configuration	Pile cap thickness (mm)	Maximum concrete stress (MPa)	Maximum reinforcement stress (MPa)	Maximum vertical deformation (mm)
5 piles	900	8.20	322	0.20
4 piles	600	2.41	285	0.56
3 piles	500	3.03	276	0.40
2 piles	450	2.41	303	0.36

The FEM results indicate that the structural response was characterized by localized stress paths rather than uniform stress distribution. The compression stress concentrated between the column and pile heads, while the reinforcement beneath the column experienced the highest

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tensile stress. The deformation was also concentrated near the column and progressively decreased toward the pile supports. These numerical results provide direct evidence of the internal load-transfer mechanism represented by the STM.

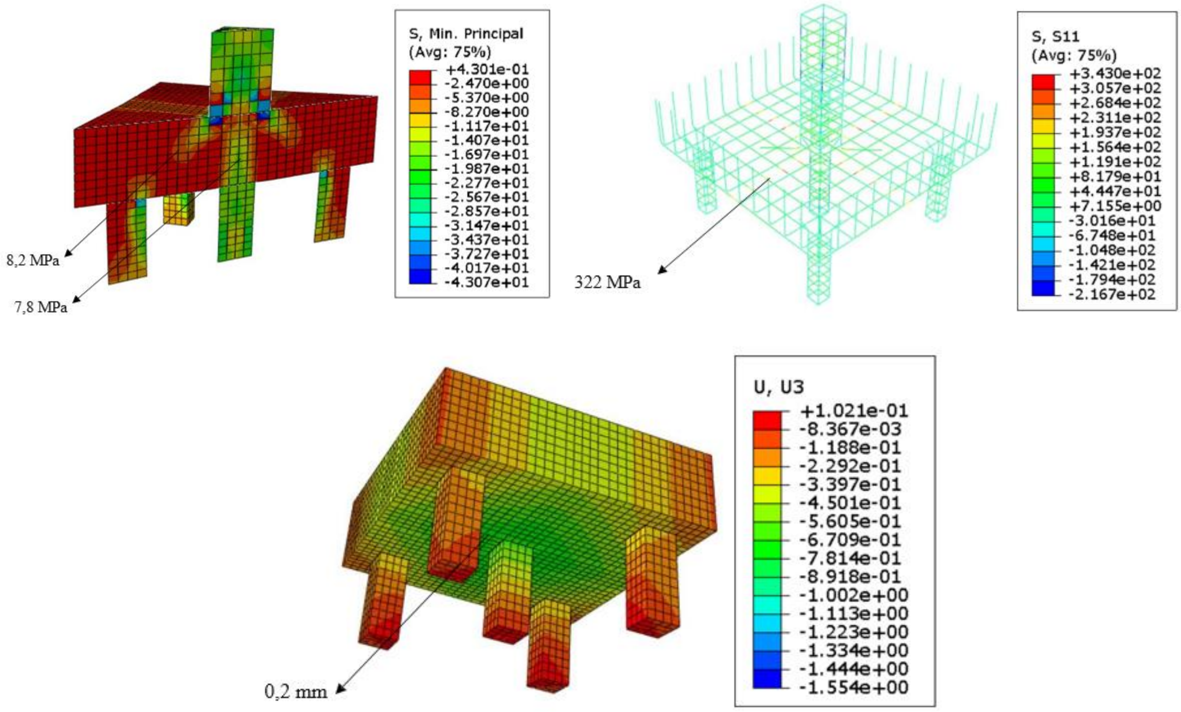

Figure 3. Finite element response of the five-pile pile cap: (a) concrete stress distribution, (b) reinforcement stress distribution, and (c) vertical deformation.

The five-pile configuration is selected as the representative FEM figure because it exhibits the highest concrete stress, highest reinforcement stress, and most pronounced compression-strut pattern among the investigated configurations. The remaining configurations are represented quantitatively in Table 3, avoiding repetitive contour figures while retaining the principal numerical findings.

Comparative Analysis of Conventional, STM, and FEM Results

The comparison among the three approaches demonstrates that pile configuration and analytical method both affected the resulting pile cap dimensions, reinforcement requirements, and stress response. The complete comparison is presented in Table 4.

Table 4. Comparative results of the Conventional Method, STM, and FEM

Pile configuration	Method	Dimensions (mm)	As (mm²)	fs (MPa)	Concrete stress (MPa)	φVc/Vu
5 piles	Conventional	3000 × 3000 × 900	5888	326	—	1.80
	STM	3000 × 3000 × 1100	7645	251	8.50	—
	FEM	3000 × 3000 × 900	5888	322	8.20	—

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4 piles	Conventional	1800 × 1800 × 600	2010	288	—	1.40
	STM	1800 × 1800 × 600	1733	299	2.80	—
	FEM	1800 × 1800 × 600	2010	285	2.41	—
3 piles	Conventional	1800 × 1680 × 500	2010	298	—	1.30
	STM	1800 × 1680 × 500	2267	250	3.13	—
	FEM	1800 × 1680 × 500	2010	276	2.74	—
2 piles	Conventional	1800 × 900 × 459*	1206	340	—	1.40
	STM	1800 × 900 × 459*	2202	285	3.90	—
	FEM	1800 × 900 × 459*	1206	303	3.03	—

*The thesis final rekapitulation reports 459 mm, whereas the detailed conventional and FEM sections identify 450 mm. This discrepancy should be resolved before final submission.

The five-pile configuration produced the largest difference between the methods. STM resulted in a 1100 mm thick pile cap with 7645 mm^2 of reinforcement, whereas the Conventional Method and FEM resulted in a 900 mm thick pile cap with 5888 mm^2 of reinforcement. The STM therefore required approximately 22.2% greater thickness and 29.8% greater reinforcement area than the other two approaches.

For the four-pile configuration, all three approaches produced the same pile cap dimensions, while STM required 1733 mm^2 of reinforcement compared with 2010 mm^2 from the Conventional Method and FEM. For three piles, the dimensions were again identical, but STM produced the highest reinforcement requirement of 2267 mm^2. The two-pile configuration produced the same final dimensions in the thesis rekapitulation, while the Conventional Method and FEM resulted in 1206 mm^2 reinforcement compared with 2202 mm^2 from STM.

The reinforcement stress results showed a closer relationship between FEM and the Conventional Method than between FEM and STM. For five piles, FEM produced 322 MPa compared with 326 MPa for the Conventional Method and 251 MPa for STM. For four piles, the corresponding values were 285, 288, and 299 MPa; for three piles, 276, 298, and 250 MPa; and for two piles, 303, 340, and 285 MPa. The thesis consequently identifies FEM reinforcement stress as generally closer to the Conventional Method than STM, particularly for the five-, three-, and two-pile configurations.

The FEM results further demonstrate that the stress field within the pile cap was highly localized. The compression stresses developed from the column toward the pile heads, forming diagonal load-transfer paths consistent with the strut mechanism. At the same time, the highest reinforcement stresses occurred beneath the column, corresponding to the tensile component of the internal force-transfer mechanism. The numerical response therefore provides complementary evidence for the load-transfer mechanism represented analytically by the STM.

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The overall results show that the three methods provide different representations of pile cap behaviour. The Conventional Method provides the resulting design dimensions and reinforcement through sectional flexural and shear checks, STM describes the internal load path through struts and ties, and FEM provides the detailed numerical distribution of stresses and deformation. The differences among the results become particularly evident when the pile configuration changes, confirming that pile number and internal load-transfer mechanism influence the design requirements and structural response of the pile cap.

Conclusion

The procedures for analyzing pile caps using the conventional method, the Strut-and-Tie Model (STM), and the Finite Element Method (FEM) employ distinct approaches. The conventional method analyzes pile caps based on standard flexure and shear theories, utilizing critical sections and force equilibrium. The STM approach models the load transfer mechanism from the column to the piles via a system of concrete compression struts and reinforcement tension ties, thereby better representing the force flow mechanism within the pile cap as a relatively deep element. Meanwhile, the FEM approach utilizes numerical modeling to obtain detailed distributions of stress, strain, and the response of both concrete and reinforcement. Analysis results indicate that all three methods are applicable to pile cap analysis, yet they yield different responses due to variations in underlying assumptions and analytical approaches. Pile cap reinforcement requirements, dimensions, and configurations are influenced by the number of piles and the chosen analysis method. Pile caps with 5-, 4-, 3-, and 2-pile configurations exhibit varying force distributions resulting from differences in geometry and load transfer paths from the column to the individual piles. Changes in the pile configuration alter the force distribution within the pile cap, the reinforcement requirements, and the critical zones requiring attention. The conventional method determines reinforcement needs based on internal forces derived from sectional analysis; STM bases requirements on tie capacity and strut capacity; and FEM determines or evaluates reinforcement needs based on stress and strain responses observed in the numerical model. Thus, the number of piles and the load transfer mechanism are primary factors influencing pile cap reinforcement requirements and configuration. Regarding the three methods described: the conventional method offers simplicity and practicality for the design process; STM provides a clearer understanding of force transfer mechanisms; and FEM yields the most detailed information on structural behavior. Consequently, employing all three methods in conjunction allows for a more comprehensive evaluation of the safety and behavior of pile caps with 5-, 4-, 3-, and 2-pile configurations.

Suggestions

Future studies are recommended to investigate a wider range of parameters, including concrete strength, reinforcement grade and diameter, pile cap dimensions, pile diameter, and loading variations, to determine their effects on reinforcement requirements and pile cap behaviour. Future Finite Element Method (FEM) modelling should incorporate concrete and reinforcement material parameters obtained from experimental testing, together with more detailed modelling of concrete–reinforcement and pile cap–pile interactions. The FEM and analytical results, particularly those obtained using the Conventional Method and Strut-and-Tie Model, should be validated against experimental test results or data from previous studies to determine the accuracy and reliability of each analytical approach. Future research should conduct a more comprehensive evaluation by comparing load capacity, reinforcement requirements, stress, strain, deformation, crack patterns, and failure modes of pile caps with different pile configurations.

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