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Systematic Literature Review On Pile Cap Design For Multi-Story Buildings Based On Load Combinations

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Abstract

Construction of multi-storey buildings in Indonesia has grown rapidly, increasing the structural complexity of foundation systems, particularly the pile cap, which distributes axial, lateral, and combined loads from the upper structure to the pile group. Previous studies mostly examined pile cap behaviour through single aspects, such as soil bearing capacity or conventional design methods, while integration of combined load scenarios remains underexplored. This study aims to systematically map the development of pile cap design research for multi-storey buildings based on load combinations. Its novelty lies in combining a Systematic Literature Review (SLR) following the PRISMA protocol with bibliometric analysis using VOSviewer and RStudio (bibliometrix), producing both qualitative synthesis and quantitative visualization of research trends, keyword networks, and collaboration patterns not jointly examined in prior pile cap literature. The method involved a two-stage search in the Scopus database covering 2021–2025, screening 1,326 articles down to 47 final articles for analysis. Results show structural analysis, seismic response, and pile foundations remain dominant themes, while numerical methods such as the Strut-and-Tie Model and Finite Element Method increasingly replace conventional approaches. The journal Buildings emerged as the most productive source, with a notable increase after 2023. Integration of combined loading conditions with pile cap design remains a significant research gap requiring further investigation.

Keywords: *Pile Cap, Load Combination, Multi-Storey Buildings, Systematic Literature Review*

INTRODUCTION

Construction in Indonesia has experienced rapid development, particularly in the construction of multi-storey buildings. The complexity of multi-storey buildings has also increased due to the annual growth rate [1]. The planning of multi-storey building structures must be able to withstand loads well and safely, technically in terms of quality and quantity [2]. The component that plays the most crucial role in this system is the foundation, because the foundation functions to channel all the load from the upper structure to the soil layer below safely and stably [3], [4]. One of the important foundation elements, namely the pile cap, is a reinforced concrete element that functions as a connection between the structural column and the pile group, while also distributing axial, lateral, and combined loads evenly across the piles [5], [6]. One of the important components related to the foundation is the pile cap, which functions as a connection between the structural column and the pile group and to distribute the load evenly from the upper structure to the piles [7]. Pile caps and foundations are also affected based on the results of soil bearing capacity tests in

accordance with the requirements for controlling settlement of the upper structure [8].

The pile cap design must also take into account earthquake load conditions to prevent flexural damage and collapse at the foundation joints [9], and pay attention to the quality of the concrete used to ensure overall structural strength [10] However, the foundation safety index value is related to the relatively high pile cap design in geotechnical planning [11]. Many previous studies regarding pile caps still focused on single aspects, such as studying soil bearing capacity based on N-SPT data [12], [13] or a purely conventional method approach [14]. The conventional method is considered less rational in planning multi-storey buildings [15]. Because the conventional approach is less effective when considering the distribution of loading conditions in the environment as a whole [16], [17]. As technology advances, the use of numerical simulations such as the Strut-and-Tie Model (STM) and the Finite Element Method (FEM) is increasingly dominant in studying pile cap behavior in more detail and comprehensively [18], [19], [20]. The pile cap structure also experiences vertical displacement which does not directly determine the horizontal capacity, this condition can affect the stability of the upper structure [21]. The design of the pile cap if designed around 10 times the diameter of the pile below the ground surface will affect the moment [22]. Effective design for pile caps using continuous structural elements, so that the design implementation finds safe limit conditions [23]. Along with the development of research, this confirms that the condition of combined loading in the combination of the Strut-and-Tie Method (STM) and the Finite Element Method (FEM) plays an important role in determining the optimal pile cap dimensions [24].

This situation demonstrates the need for a systematic literature review. Therefore, this study employed a Systematic Literature Review (SLR) approach, supported by bibliometric analysis using VOSviewer and RStudio.

METHOD

This study uses a Systematic Literature Review (SLR) approach, enhanced by bibliometric meta-analysis. The SLR approach was chosen because it allows for the transparent and replicable identification, evaluation, and synthesis of relevant literature.[25]. The SLR protocol in this study refers to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines which have been internationally recognized as the standard for reporting systematic reviews.

The primary data source for this study was the Scopus database, selected for its extensive coverage of civil engineering literature and rigorous indexing. The search period was limited to 2021–2025 to ensure data relevance and currency. The search was conducted on [search date] using a two-stage query as presented in Table 1.

Table 1. Scopus Database Results

No	Keywords / Queries	Number of Articles
1.	TITLE-ABS-KEY ("pile cap" OR "high-rise building" OR ("load combination" OR "load distribution") OR ("dimensional efficiency" OR "design optimization") AND ("structural analysis" OR "foundation design"))	4,009
2.	TITLE-ABS-KEY (("pile cap" OR "high-rise building" OR ("load combination" AND "load distribution") OR ("dimensional efficiency" AND "design optimization") OR ("structural analysis" AND "foundation design"))) AND SUBJAREA , "ENGI")) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (	1,326

OA , "all")) AND PUBYEAR > 2021 AND PUBYEAR < 2026 (LIMIT-TO (

Source: Scopus

The first-stage search used a broader query without year restrictions as an initial exploration, with a total of 4,009 articles. The second-stage search applied additional filters including: (1) engineering subject area (ENGI); (2) English language; (3) open access; and (4) publication year 2021–2025, resulting in 1,326 articles as an initial corpus for further selection. Article selection was based on inclusion and exclusion criteria explicitly defined prior to the screening process. Figure 1 presents these criteria in detail.

Kriteria Inklusi	Kriteria Ekslusi
Artikel Jurnal ilmiah	Prosiding konferensi, bab buku, dan laporan teknis
Topik berkaitan dengan desain pile cap dan/atau kombinasi beban pada bangunan bertingkat	Topik tidak relevan dengan desain pondasi atau struktur bawah
Publikasi selain 2021-2025	Publikasi sebelum tahun 2021
Bahasa Inggris	Bahasa selain Inggris
Akses terbuka (open access)	Artikel berbayar yang tidak tersedia teks lengkap
Menggunakan metode analisis kuantitatif, numerik, atau eksperimental	Artikel opini, editorial, dan komentar tanpa data empiris

Figure 1. Inclusion and Exclusion Criteria For Article Selection

The article selection process followed the four-stage PRISMA flowchart, consisting of identification, screening, eligibility, and inclusion. Figure 1 presents the PRISMA flowchart used in this study.

Figure 2. Research Flowchart

Based on search resultsOf the 1,326 identified articles, title and abstract screening was performed, resulting in a significant reduction in topically irrelevant articles. Bibliometric analysis was performed using two software tools:

a. VOSviewer: used to visualize and analyze scientific literature networks, including keyword co-occurrence, co-authorship, and citation network analysis. Input data formats include RIS, BibTeX, and CSV files exported directly from Scopus.

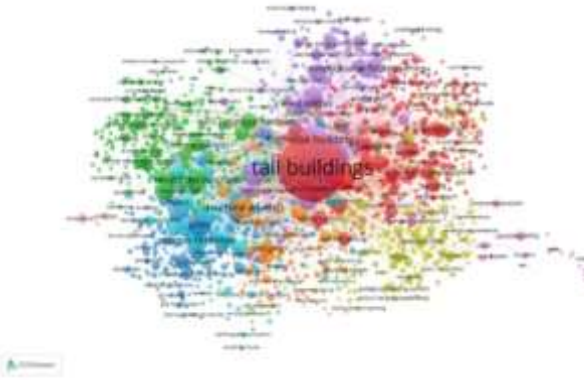
b. RStudio (bibliometrix package): used to produce thematic maps, word clouds, keyword distribution treemaps, publication source production development graphs, and international collaboration maps between countries.

RESULTS AND DISCUSSION

The analysis results used are structured bibliometric data in two main groups: results from VOSviewer and results from RStudio. Each visualization is accompanied by a critical interpretation that highlights substantive

implications for the development of pile cap design research.

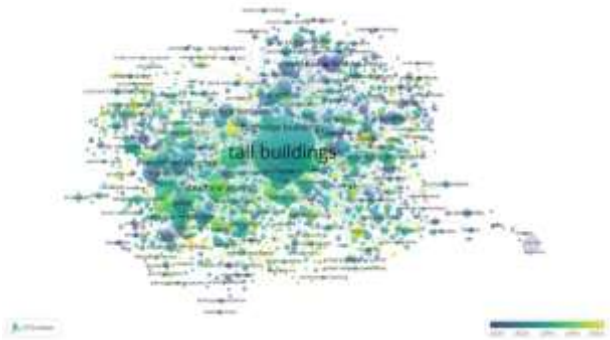
a. VOSviewer Analysis
- Keyword Co-occurrence Analysis



Source: VOSviewers

Figure 3. Mapping Topic Clusters and Their Relationships (Network Visualization)

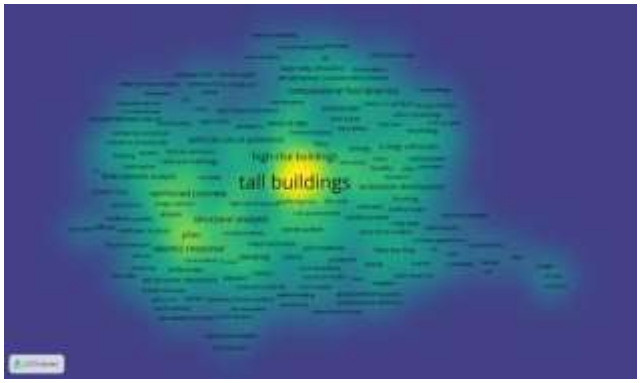
Figure 3 displays the keyword co-occurrence network from all the analyzed literature. Three dominant clusters can be identified. The first cluster (red) focuses on structural analysis and earthquake load analysis (structural analysis, seismic response, earthquake), reflecting the dominance of dynamic approaches in high-rise building foundation design studies. The second cluster (green) groups keywords related to numerical methods (finite element method, strut-and-tie model, numerical simulation), indicating a paradigm shift from conventional approaches to computational-based analysis. The third cluster (blue) focuses on deep foundation systems (pile foundations, pile group, bearing capacity), indicating that soil bearing capacity studies remain an important foundation in pile cap research. The strength of the relationships between clusters indicates that current pile cap design research is increasingly multidisciplinary, integrating geotechnical aspects, structural analysis, and computational methods simultaneously.



Source: VOSviewers

Figure 4. Topic Development Trends Based on Time (Overlay Visualization)

Figure 4 presents an overlay visualization showing the temporal dimension of topic development. Keywords in yellow-green (more recent average publication year) include FEM, pile group efficiency, and seismic pile-soil interaction, indicating that these topics are current research frontiers. Conversely, keywords in blue-purple, such as conventional design and soil bearing capacity, reflect established topics but are beginning to decline in frequency. These findings confirm the methodological transition in pile cap research from conventional approaches to more sophisticated numerical simulation methods, in line with the demands for precision in the design of modern high-rise structures.



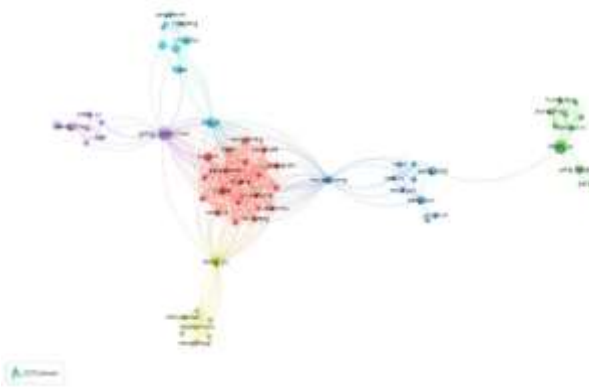
Source: VOSviewers

Figure 5. Publication Intensity Volume Per Topic (Density Visualization)

Figure 5 displays a density map showing research concentration based on publication intensity per keyword. The yellow areas with the highest density are identified in the topics of tall buildings and structural analysis,

confirming the position of these two topics as core research in the reviewed literature corpus. The relatively low density of load combination and combined loading topics, particularly in relation to pile cap design, specifically identifies a significant research gap. This indicates that although the topics of tall buildings and structural analysis are already saturated in terms of publications, the integration of combined load scenarios on pile cap elements remains an area that has not been optimally explored.

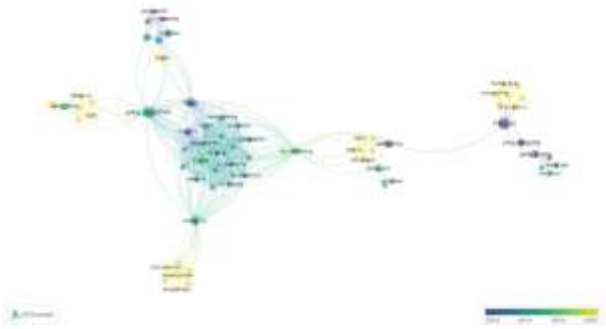
- Analysis from the author (Co-authorship)



Source: VOSviewers

Figure 6. Visualization of the Co-authorship Network

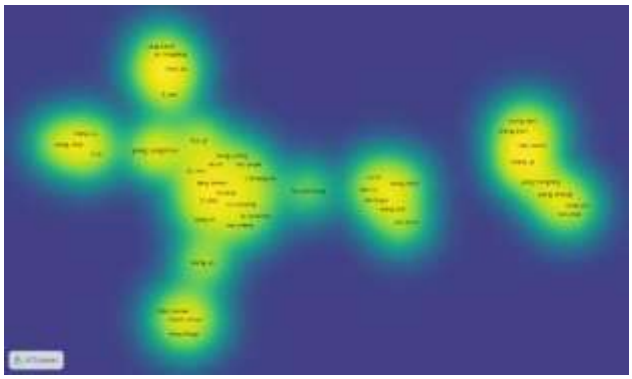
Figure 6 shows the collaborative network between authors on the topic under study. Analysis of the size and position of nodes reveals several key researchers acting as collaboration hubs—authors with large nodes connected to many other authors within a cluster. This pattern indicates that research productivity is not evenly distributed but rather concentrated within specific collaborative groups. There are also a number of isolated nodes, reflecting authors who are not yet connected to a broader collaborative network. This network fragmentation suggests the need to strengthen cross-institutional and cross-national collaboration in the future development of pile cap research.



Source: VOSviewers

Figure 7. Overlay visualization of the author collaboration network (Overlay visualization)

Figure 7 displays an overlay visualization of the co-author network coded by the average year of publication. The dominance of yellow in a number of key nodes indicates that these researchers have only been actively collaborating in the last few years (2023–2025), indicating the novelty and dynamism of the research network that is still developing. Conversely, the blue-purple nodes represent senior researchers who have contributed for a long time, but whose connections with younger groups are still limited. This pattern reinforces the finding that the topic of pile cap design using a load combination approach is experiencing an active growth phase, with the entry of new researchers bringing more sophisticated approaches and methodologies.



Source: VOSviewers

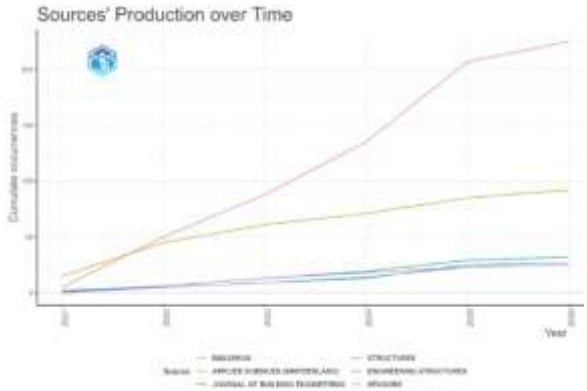
Figure 8. Author Collaboration Network (Density Visualization)

Figure 8 confirms the uneven distribution of collaboration density within the co-authorship network. The high-density yellow areas

correspond to productive groups of researchers who dominate publication output, while the green-blue areas reflect groups with lower levels of connectivity. This difference in density structurally indicates the risk of an echo chamber in theory and methodology development, where research innovations potentially circulate only among a specific core group without being widely disseminated to the broader research community. This is an important consideration for young researchers and civil engineering educational institutions to be more actively involved in international collaboration networks.

a. RStudio Bibliometric Analysis

- Development of Publication Source Production

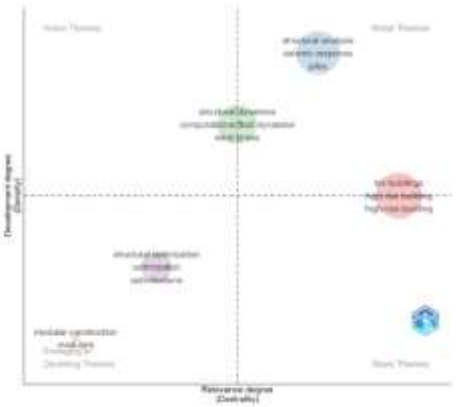


Source: Rstudio bibliometrics

Figure 9. Publication Number Development Graph (Sources' Production over Time)

Figure 9 shows a graph of the cumulative production of articles from various journal sources during the period 2021–2025. The Buildings journal consistently recorded the most significant growth compared to other sources, with a particularly sharp jump after 2023. This reflects the journal's thematic focus, which aligns with tall building research and structural design, and also indicates that Buildings is the most relevant and productive publication venue for the topics studied. Meanwhile, other journals showed more moderate and linear growth, indicating a more distributed contribution. The post-2023 surge generally correlates with the increasing global attention to the need for earthquake-resistant infrastructure and sustainable buildings, which has driven increased research output in the field of foundations and substructures.

- Research Thematic Map

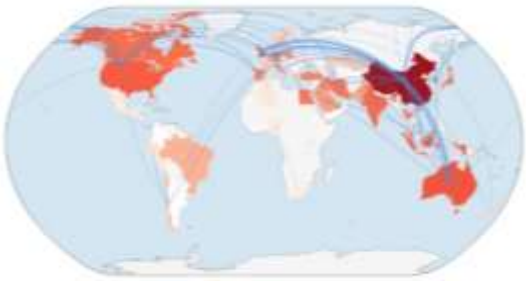


Source: Rstudio bibliometrics

Figure 10. Thematic Map of Research in the Field of High-Rise Building Structures

Figure 10 presents a thematic map that divides research topics into four quadrants based on relevance (centrality) and development (density). Motor Themes (top right) of structural analysis, seismic response, and piles are the most developed core themes; the presence of seismic response confirms the urgency of designing pile caps that can withstand combined earthquake loads. Niche Themes (bottom right), such as pile group efficiency and load transfer mechanisms, are specialist but have not yet become mainstream. Emerging/Declining Themes (top left), such as sustainable construction and energy efficiency, demonstrate a new trend of integrating sustainability aspects into structural design. Basic Themes (bottom left), such as soil mechanics and conventional design, represent a stable scientific foundation but are no longer the focus of active innovation. Overall, the integration of STM, FEM, and combined load analysis remains on the border between niche and motor themes, indicating significant research development opportunities in this area.

- Map of International Collaboration Between Countries



Source: Rstudio bibliometrics

Figure 11. International Research Collaboration

Figure 11 displays a map of international collaboration that presents two pieces of information simultaneously: the intensity of each country's publication contributions (red color gradation, where dark red indicates high volume) and the bilateral collaboration network (blue arc lines with thickness proportional to collaboration intensity). Countries in the East Asian region (China, South Korea, Japan) and Western countries (the United States, the United Kingdom, and Australia) appear to dominate publication contributions. The thickness of the collaboration lines connecting China with the United States and several European countries indicates the existence of a strong research partnership network. Conversely, the absence of significant collaboration lines involving Southeast Asian countries, including Indonesia, indicates that domestic researchers have not been integrated into the global research network related to pile cap design. This presents a strategic opportunity to improve the quality and impact of publications through international collaboration.

- Keyword Map (Word Cloud)

Source: Rstudio bibliometrics

Figure 12. Research Topic Keywords Word Cloud

Figure 12 visualizes the relative frequency of keyword occurrences in the reviewed literature corpus. "Tall buildings" appears as the keyword with the highest frequency, followed by "high-rise building" and "architectural design." Substantively, the dominance of the keyword "tall building" confirms that the context of pile cap applications in current research is more associated with complex vertical structures than low-rise buildings. Interestingly, the keywords "load combination" and "combined loading" appear with a relatively small size compared to the main topic, reinforcing the finding from the density map that the aspect of load combination on pile caps is still underrepresented in the literature and is a research gap that needs to be filled.

- *TreeMap* Keyword Frequency Distribution

Source: Rstudio bibliometrics

Figure 13. Treemap of Frequency Distribution of Research Keywords

Figure 13 presents the quantitative distribution of keywords in a treemap format, where the area of each box is directly proportional to the absolute frequency of occurrence. The findings indicate that high-rise building research predominantly focuses on lateral loads (seismic and wind), computational methods (finite element method, computational fluid dynamics), and deep foundation systems (piles, pile foundations). The relatively small proportion of boxes for the keywords pile cap and load combination quantitatively confirms that these two concepts have not yet become a primary focus, even though they are technically critical elements in high-rise building design. The broad and diverse distribution of keywords also reflects the increasingly interdisciplinary development of this field, encompassing aspects of sustainability (sustainable development), energy efficiency, and building user comfort.

CONCLUSION

This study has successfully mapped the development of pile cap design research in high-rise buildings based on load combinations systematically using the SLR approach and bibliometric analysis. Based on the selection of 47 final articles from 1,326 Scopus articles (2021–2025), three main findings were obtained. First, the dominant themes of current research are structural analysis, seismic response, and pile foundations, reflecting the urgency of earthquake-resistant pile cap design in the era of modern high-rise construction. Second, numerical simulation methods (STM and FEM) have replaced conventional approaches as the standard for analysis, but their integration with load combination scenarios is still limited in the literature. Third, the journal Buildings is the most productive and relevant source of publications, with a significant surge in output after 2023, indicating the dynamism of this field.

Based on the identified research gap analysis, future studies are suggested to (1) integrate axial, lateral, and earthquake loads simultaneously in pile cap modeling; (2) develop numerical models that validate experimental results under combined load conditions; and (3) expand research collaboration between institutions in Southeast Asia and global research centers to produce contextual and evidence-based solutions.

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