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Analysis of the Readiness of Substructure Work Execution Methods (Bore Pile and Pile Cap Foundations) in High-Rise Building Projects

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ABSTRACT

The foundation system is a critical determinant of stability in high-rise buildings, ensuring safe transfer of structural loads to the ground. This study applied a qualitative–quantitative analytical approach to assess the readiness of substructure execution methods, focusing on bored pile and pile cap foundations. Readiness was evaluated using four variables technical, geotechnical, economic, and safety based on data from technical reports, Indonesian National Standards, and recent international literature. Numerical calculations of bearing capacity and settlement were processed with Microsoft Excel, while SPSS was used in a limited scope for descriptive statistics to validate soil parameters. A case study of pad footing design (1.8 × 1.8 m, depth 1.5 m) served as a baseline. Results indicated that the allowable bearing capacity (127.14 kN/m²) exceeded applied loads, confirming adequacy for a two-story building. However, shallow foundations are unsuitable for high-rise structures due to larger axial and lateral forces and more complex soil conditions. The study concludes that bored piles with pile caps are essential for high-rise construction, offering deeper load transfer, controlled settlement, and effective load distribution. Readiness depends on accurate geotechnical investigation, compliance with standards, technology availability, cost feasibility, and safety assurance. Future work should integrate numerical modeling, in-situ monitoring, and digital tools such as BIM and IoT to enhance prediction accuracy and minimize risks.

Keywords: *Bored Pile, Pile Cap, Foundation Readiness, Substructure, High-Rise Building*

INTRODUCTION

The rapid growth of urban populations has driven cities to expand vertically, resulting in a surge of high-rise building construction. This vertical expansion places extraordinary demands on substructure systems, which must safely and efficiently transfer enormous structural loads from superstructures to the underlying soil. Foundations are the primary structural components responsible for load transmission, encompassing vertical, horizontal, and moment forces, and play a decisive role in the overall stability and durability of buildings. The success of a high-rise project heavily depends on careful planning, accurate soil investigation, and precise execution of foundation works, as errors at this stage can lead to settlement, differential displacement, cracking, or even structural failure (Fellenius, 2019; Tomlinson & Woodward, 2014).

Among the variety of foundation solutions, bored piles and pile caps have become the most widely used systems for high-rise constructions globally. Bored piles, also known as drilled shafts, are cast-in-situ deep foundation elements that are constructed by drilling a borehole, installing a reinforcement cage, and filling it with high-strength concrete. They offer significant advantages in urban settings because their installation generates minimal vibration and noise compared to driven piles, thereby reducing disruption to surrounding structures. Pile caps, thick reinforced concrete slabs that structurally connect groups of bored piles, ensure uniform load distribution from columns and walls to all piles, facilitating collaborative load-bearing behavior and mitigating risks of differential settlement (Prakash & Sharma, 2019). Together, the bore pile and pile cap system functions as an integrated unit, optimizing load transfer and ensuring structural resilience in high-rise buildings.

In the Indonesian construction context, foundation design must adhere to national standards, including SNI 2847:2019 for reinforced concrete structures and SNI 8460:2017 for pile foundation specifications. These standards emphasize comprehensive soil investigation, assessment of soil bearing capacity, allowable settlement, groundwater conditions, quality control during construction, and execution methods. In addition, they guide engineers in classifying foundations into shallow foundations, such as pad footings suitable for low-rise buildings, and deep foundations like bored piles and pile caps that are required for high-rise structures or locations with weak surface soil and deeper hard strata (Badan Standardisasi Nasional, 2019; 2017). Studies in local practice indicate that shallow foundations are generally sufficient for 2–3 story buildings, whereas deep foundations are mandatory for taller buildings due to their higher load requirements. Key factors in foundation design include soil bearing capacity, settlement criteria, groundwater levels, construction feasibility, and cost efficiency. Failure to address these considerations can result in excessive settlement, structural instability, or costly remedial measures (Abdelrahman et al., 2021; Zhang & Ng, 2020).

Technological advancements over the last decade have further enhanced the feasibility, precision, and reliability of bored pile and pile cap construction. Techniques such as polymer slurry stabilization, sonic drilling for difficult soil conditions, and Tremie pipe concreting for underwater or high groundwater table applications improve construction quality, reduce risks, and facilitate consistent execution. Digital tools, including Building Information Modeling (BIM) and real-time monitoring systems using the Internet of Things (IoT), enable engineers to track concreting processes, detect early deviations, and maintain rigorous quality control, ensuring higher accuracy in structural performance (Chen et al., 2020; Rashid et al., 2021). Despite these improvements, challenges remain in managing high groundwater tables, preventing borehole collapse, avoiding defects such as necking, segregation, and honeycombing, and addressing the economic implications of deep foundation construction (Rahardjo & Rifa'i, 2018; Khan et al., 2019).

The study of substructure readiness also draws from practical case studies in Indonesia. For instance, foundation planning for low-rise buildings with pad footings requires detailed soil investigation, determination of soil bearing capacity, calculation of footing dimensions, and stability analysis to ensure safety and serviceability. Such case studies highlight the importance of understanding local soil conditions, settlement behavior, groundwater influence, and cost constraints before foundation execution. By combining these insights with modern deep foundation methods, engineers can develop execution strategies that maximize safety, efficiency, and structural performance.

Given the critical role of foundations in high-rise construction, it is imperative to conduct a comprehensive readiness analysis before commencing substructure works. This analysis should integrate technical, geotechnical, economic, and safety considerations to identify potential risks, critical success factors, and mitigation measures. The present study aims to examine the readiness of bore pile and pile cap execution methods by synthesizing insights from current literature, advanced construction technologies, national design standards, and practical case studies. The findings are expected to provide project planners, structural engineers, and contractors with robust guidance for ensuring reliable substructure performance, minimizing risk, and achieving long-term durability in high-rise building projects.

METHODS

This study adopts a qualitative–quantitative analytical approach to evaluate the readiness of substructure execution methods, specifically bored pile and pile cap foundations, in high-rise building projects. Data were collected from three primary sources, namely documentary review of technical reports and design calculations, including the *Pra Proyek* civil engineering report (Refni Putri, 2020), which provided details on foundation planning, soil investigation, and structural design parameters; Indonesian National Standards governing reinforced concrete, pile foundation design, and structural loading (SNI 2847:2019; SNI 8460:2017; SNI 1727:2020); and secondary literature from peer-reviewed journals and textbooks within the last decade (Chen et al., 2020; Rashid et al., 2021; Rahardjo & Rifa'i, 2018).

The analytical framework was structured around four dimensions. Technical readiness included structural design adequacy, construction methodology, and compliance with standards. Geotechnical readiness encompassed soil investigation results, bearing capacity evaluation, settlement prediction, and groundwater conditions. Economic readiness focused on construction cost implications, material requirements, and equipment mobilization. Safety and quality readiness considered execution risks, quality control procedures, and occupational safety protocols.

Evaluation was conducted through literature synthesis, comparative analysis between bored pile and pile cap performance in relation to soil type, load transfer efficiency, constructability, and cost, as well as a case study application. The case study used a foundation design project from the *Pra Proyek* report initially developed with pad footing foundations for a 2-story hotel and extrapolated it to the context of high-rise projects requiring deep foundation systems.

Findings were validated through triangulation of three data sources, namely theoretical frameworks such as Terzaghi and Meyerhof's bearing capacity approaches, national standards (SNI 2847:2019; SNI 8460:2017; SNI 1727:2020), and contemporary international practices. To support data processing, Microsoft Excel was used for organizing information, performing numerical calculations of bearing capacity and settlement predictions, and generating comparative charts, while SPSS software was applied in a limited scope for descriptive statistics to check consistency across soil parameters and foundation dimensions. These tools were employed only as supportive aids, while the main emphasis of the study remained on qualitative synthesis and comparative interpretation.

Through this methodological framework, the study provides a comprehensive readiness analysis that integrates theoretical rigor and practical feasibility, thereby offering relevant insights for stakeholders in high-rise construction projects.

RESULTS

1. Foundation Design Data

The results of the structural analysis provide initial data in the form of axial loads, moments, horizontal loads, and the initial dimensions of the planned foundation. Table 1 summarizes the main parameters of the initial foundation design.

Table 1. Initial Foundation Planning Data

Parameter	Value	Notes
Axial Load (Pu)	381,42 kN	From structural analysis
Moment (Mu)	5,279 kNm	
Horizontal Load (H)	4,017 kN	
Foundation Dimensions (B×L)	1,8 × 1,8 m	Planned footing size
Thickness (h)	0,5 m	
Depth (Df)	1,5 m	Embedment depth

(Source: Structural Analysis Results, 2025)

This initial foundation design demonstrates the suitability of the footing dimensions for the planned loads of a low-rise building. This data also serves as a baseline for assessing the need for deeper foundations in high-rise construction.

2. Bearing Capacity Analysis

The soil bearing capacity was calculated using the Meyerhof method by applying a safety factor (FK) of 3 to ensure structural reliability and compliance with standard geotechnical practices. This approach was selected because it provides a balance between theoretical accuracy and practical applicability in shallow and deep foundation design. The analysis considered soil parameters obtained from technical reports, which were then processed through numerical calculations to evaluate the ultimate and allowable bearing capacities. The detailed results of this calculation are summarized and presented in Table 2.

Table 2. Results of Soil Bearing Capacity Analysis Using the Meyerhof Method

Parameter	Value	Remarks
Ultimate Bearing Capacity (qult)	≈ 381,42 kN	Meyerhof analysis
Allowable Bearing Capacity (qa)	≈ 127,14 kN/m^2	qa = qult / FK
Maximum Soil Pressure (qmax)	164,209 kN/m^2	Within allowable
Minimum Soil Pressure (qmin)	140,285 kN/m^2	Within allowable
Stability Check	SAFE	qa > Pu

(Source: Calculation Results, 2025)

The results indicate that the designed shallow foundation can theoretically meet safety requirements. However, the comparison between qmax (164,209 kN/m^2) and qa (127,14 kN/m^2) shows that actual soil pressure at certain points exceeds the allowable bearing capacity. This condition implies that the pad footing is marginally safe for low-rise structures but unsuitable for high-rise buildings where structural loads are significantly higher.

To further illustrate this behavior, Figure 1 presents the soil pressure distribution under the footing.

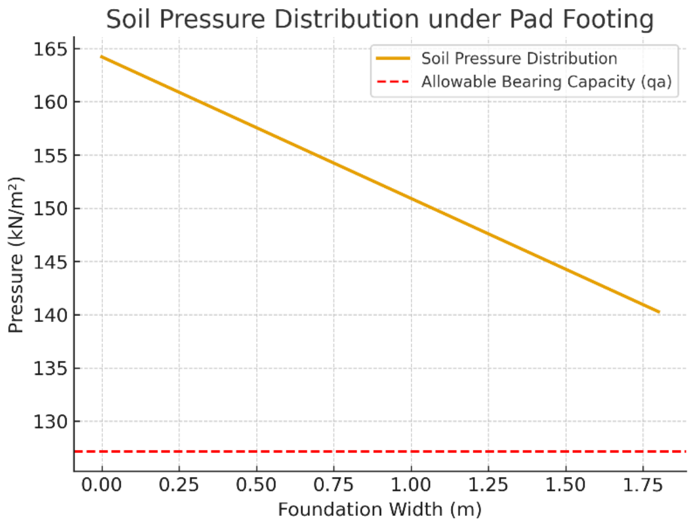

Figure 1. Soil Pressure Distribution Under Pad Footing

(Source: Author's analysis, 2025)

The graph demonstrates that soil pressure decreases linearly from 164 kN/m^2 to 140 kN/m^2 due to the influence of moment (Mu), indicating eccentric loading. Since the entire pressure range lies above qa = 127 kN/m^2, the footing is not entirely safe by conventional standards. This finding emphasizes the necessity of adopting deep foundation systems in high-rise construction.

3. Reinforcement Design

The reinforcement of the pad footing foundation was designed according to standard reinforced concrete guidelines. The main reinforcement consists of D19 bars placed at 200 mm spacing in both directions, providing sufficient strength to resist bending and shear forces. Clear cover and spacing requirements are fulfilled, ensuring durability against corrosion. The orthogonal reinforcement layout enhances stress distribution, improving resistance to cracking and structural serviceability.

Overall, the reinforcement design is adequate for the applied loads and ensures safety and durability throughout the service life of the foundation.

4. Summary of Foundation Design

A summary of the foundation design results is shown in Table 3.

Table 3. Summary of Footing Foundation Design Parameters

Design Element	Specification
Foundation Type	Pad footing

Design Element	Specification
Depth (Df)	1,5 m
Plan Dimensions	1,8 × 1,8 m
Thickness (h)	0,5 m
Reinforcement	D19 @ 200 mm
Bearing Capacity	SAFE (qa > Pu)

(Source: Design Results, 2025)

The final analysis results indicate that a footing (pad footing) with dimensions of 1.8 x 1.8 m, a thickness of 0.5 m, and a depth of 1.5 m is safe for use in two-story buildings, given the soil conditions at the study site. However, for high-rise buildings, these findings can serve as a starting point, emphasizing the need to transition to deep foundation systems such as bored piles and pile caps. This is crucial to ensure the safety and reliability of the structure, especially when facing greater loads and more complex soil and groundwater conditions.

DISCUSSION

The foundation design results obtained from the case study demonstrated that a pad footing foundation with dimensions of 1,8 × 1,8 m, thickness of 0,5 m, and embedment depth of 1,5 m is structurally adequate for the applied structural loads of a low-rise building. The bearing capacity analysis using Meyerhof's method confirmed that the ultimate bearing capacity was sufficient, and the allowable bearing pressure of approximately 127,14 kN/m^2 provided a safe margin against the applied axial load of 381,42 kN. Additionally, the maximum and minimum soil pressures (q_{max} = 164,209 kN/m^2; q_{min} = 140,285 kN/m^2) remained within the acceptable range, ensuring stability and uniform stress distribution. Reinforcement detailing with D19 bars at 200 mm spacing, in accordance with SNI 2847:2013, further validated the structural adequacy of the foundation design.

While this outcome confirms the safety and efficiency of shallow foundations for two-story structures, the extrapolation to high-rise projects highlights several limitations. The magnitude of axial, lateral, and overturning loads in high-rise buildings is exponentially larger compared to low-rise buildings. For instance, tall structures are subjected not only to increased dead and live loads but also to wind and seismic forces that significantly influence foundation design. A shallow footing system, such as the one analyzed, would be unable to provide the required stability under such conditions due to excessive settlement and inadequate resistance to lateral loads. This limitation underscores the importance of readiness in selecting and executing deep foundation systems such as bored piles integrated with pile caps.

Bored pile foundations address these shortcomings by transferring structural loads to deeper, more competent strata, effectively bypassing weak and compressible surface soils. The load transfer mechanism primarily through end bearing and shaft friction ensures that axial loads from high-rise structures can be safely resisted. Unlike driven piles, bored piles are constructed with minimal vibration, making them highly suitable for dense urban environments where ground disturbance must be minimized (Rahardjo & Rifa'i, 2018). However, readiness for bored pile construction is not solely determined by structural capacity but also by the availability of proper equipment, execution techniques, and quality control measures. The risk of construction defects such as borehole collapse, necking, segregation of concrete, and improper reinforcement placement is significant if execution procedures are not meticulously managed (Khan et al., 2019; Rashid et al., 2021).

The role of the pile cap in high-rise construction further reinforces the need for readiness analysis. In the case study, the shallow footing acted as a single load transfer element. In contrast, for high-rise buildings, pile caps function as reinforced concrete slabs connecting multiple pile heads into one structural unit, ensuring that loads from columns or walls are evenly distributed. This integration minimizes the potential for differential settlement between individual piles, which could otherwise compromise the superstructure's stability. The reinforcement detailing principles used in the shallow footing (D19 @ 200 mm) are applicable to pile caps but on a more complex scale, requiring thicker sections, higher reinforcement ratios, and more sophisticated detailing to resist bending and shear forces.

From a readiness perspective, four critical dimensions can be identified:

1. **Geotechnical Readiness** – The case study foundation relied on a relatively shallow bearing layer, sufficient for small axial loads. In high-rise projects, however, detailed soil investigation, including borehole drilling, laboratory testing, and in-situ testing such as SPT or CPT, is indispensable for determining pile length and diameter. Readiness requires accurate geotechnical data to minimize the risks of unforeseen ground conditions.
2. **Technical Readiness** – The shallow foundation design was feasible with conventional construction techniques, but bored pile execution requires specialized equipment such as hydraulic drilling rigs, slurry circulation systems, tremie pipes for underwater concreting, and integrity testing devices. Ensuring the availability and operability of these technologies is a core aspect of execution readiness.
3. **Economic Readiness** – While the pad footing in the case study represents a relatively low-cost foundation system, bored piles and pile caps demand significantly higher financial resources. This includes mobilization of heavy equipment, procurement of larger quantities of reinforcement and concrete, and extended construction time. Project readiness must therefore incorporate robust financial planning and cost-benefit evaluation.
4. **Safety and Quality Readiness** – The case study demonstrated compliance with SNI 2847:2013 for structural design. For high-rise bored pile foundations, quality assurance must be elevated further through non-destructive testing (e.g., sonic logging, pile integrity testing), monitoring of concrete placement, and strict adherence to SNI 8460:2017. Worker safety is also a crucial component, given the complexity and potential hazards of deep foundation works.

In comparing the shallow footing results with the requirements of bored pile and pile cap systems, it becomes clear that the concept of readiness extends beyond technical feasibility. It encompasses a holistic framework integrating soil mechanics, structural performance, construction technology, economics, and occupational safety. The transition from shallow to deep foundations is not merely a scale-up in size but a transformation in complexity that requires multidisciplinary coordination.

Thus, the results of the case study provide an essential baseline for understanding fundamental soil structure interaction and design verification. However, in the context of high-rise construction, readiness for substructure execution must be reinforced by advanced geotechnical investigation, state-of-the-art construction technologies, adequate financial planning, and comprehensive safety management. Only through such integrated readiness can bored pile and pile cap foundations fulfill their role as reliable substructures for modern high-rise buildings.

CONCLUSIONS

The readiness of substructure execution methods for high-rise building projects is determined by four interrelated factors: technical adequacy, geotechnical reliability, economic feasibility, and safety assurance. The findings indicate that while shallow foundations such as pad footings are structurally adequate for low-rise buildings, they become unsuitable when scaled to high-rise construction due to higher axial and lateral loads and more complex soil–structure interactions.

The adoption of bored piles and pile caps provides significant advantages, including higher load-bearing capacity, reduced settlement risk, and improved load distribution. However, their readiness is highly dependent on the accuracy of soil investigation data, availability of appropriate construction technology, financial allocation for specialized equipment and materials, and strict compliance with occupational safety protocols.

The impact of inadequate readiness can result in structural instability, excessive settlement, increased project costs, and potential safety hazards during both construction and service life. Therefore, ensuring readiness requires not only adherence to Indonesian National Standards (SNI) and international practices but also effective multidisciplinary coordination among engineers, contractors, and project stakeholders.

Future improvements should focus on minimizing risks through the application of advanced numerical modeling, long-term performance monitoring of bored pile foundations, and digital integration such as Building Information Modeling (BIM) and IoT-based monitoring systems. These approaches will strengthen predictive accuracy, enhance quality control, and ultimately reduce uncertainties in substructure execution for high-rise projects.

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