PERFORMANCE ASSESSMENT OF HIGH-RISE BUILDING FOUNDATIONS SUBJECTED TO VARIABLE SOIL AND LOAD CONDITIONS IN COASTAL ENVIRONMENTS

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Abstract

High-rise buildings in coastal environments are exposed to complex geotechnical and environmental conditions that significantly affect foundation performance. This study evaluates the behavior of high-rise building foundations under variable soil and load conditions using field investigation, laboratory testing, and numerical modeling. Soil stratigraphy, groundwater fluctuations, and load variability were analyzed to assess settlement, differential tilting, and stress distribution. Results indicate that pile foundations outperform mat and combined mat-pile foundations in controlling differential settlement and maintaining structural serviceability. Groundwater level changes and load variations notably influence foundation performance, emphasizing the need for site-specific, performance-based design. The integrated methodology provides insights for resilient foundation design strategies in challenging coastal environments.

Keywords: High-rise buildings; Coastal foundations; Soil variability; Differential settlement; Numerical modeling.

INTRODUCTION

The rapid urbanization and vertical expansion of cities in coastal regions have led to an increasing demand for high-rise buildings. The structural performance of these buildings is highly dependent on the behavior of their foundations, which must accommodate both the imposed structural loads and the geotechnical properties of the site (Das, 2019). Coastal soils are often characterized by high compressibility, low shear strength, and susceptibility to water table fluctuations, all of which can significantly influence foundation performance (Bowles, 2017). Understanding how variable soil and load conditions affect high-rise foundations is crucial for ensuring structural safety and serviceability.

High-rise buildings typically impose concentrated and variable loads on their foundations, which can result in differential settlement and tilting if not properly addressed during design (Tomlinson & Woodward, 2014). In coastal environments, the interplay between soil heterogeneity and dynamic loading from wind and seismic activity further complicates foundation design (Lutenegger & Hall, 2020). Accurate assessment of foundation performance under these conditions is essential for mitigating risks associated with excessive settlement, bearing capacity failure, and long-term structural damage.

Previous studies have highlighted the influence of soil stratigraphy and groundwater conditions on foundation behavior. For instance, soft clay layers with low shear strength can lead to considerable settlement, especially under high-rise structures with heavy loads (Burland, 2017). Similarly, variability in soil stiffness and density can result in non-uniform load distribution, creating local stress concentrations that may compromise foundation integrity (Mitchell & Soga, 2018). These findings underscore the need for site-specific investigations that incorporate both soil variability and realistic load scenarios.

Coastal environments present unique geotechnical challenges, including saltwater intrusion, erosion, and seasonal water table fluctuations (Van Impe, 2019). These factors can accelerate foundation degradation and affect the long-term performance of piles, mat foundations, and other structural elements. Moreover, climate change-induced sea level rise adds further uncertainty, necessitating adaptive foundation designs capable of withstanding future environmental changes (Smith et al., 2021).

Modern foundation assessment methods employ numerical modeling and in-situ testing to predict settlement, bearing capacity, and stress distribution under variable conditions (Zhou & Wang, 2020). Finite element analysis (FEA) and geotechnical simulations allow engineers to evaluate foundation behavior under multiple scenarios, including extreme loading and heterogeneous soil profiles. These techniques enable optimization of foundation design while ensuring compliance with safety and performance criteria (Tomlinson & Woodward, 2014).

Despite advances in modeling and field investigation, challenges remain in accurately predicting the combined effects of variable soil conditions and complex loadings on high-rise foundations. Many design codes provide general guidelines, but site-specific assessments are critical for mitigating foundation failure risks (Das, 2019). Integrating geotechnical, structural, and environmental data into a comprehensive performance evaluation framework enhances the reliability of foundation designs in coastal settings.

This study aims to evaluate the performance of high-rise building foundations under variable soil and load conditions in coastal environments. By combining geotechnical characterization, numerical modeling, and parametric analysis, this research provides insights into settlement behavior, load distribution, and potential failure mechanisms. The findings are expected to inform more resilient foundation design strategies for high-rise constructions in challenging coastal regions, contributing to both safety and sustainability.

LITERATURE REVIEW

The performance of high-rise building foundations is inherently linked to the geotechnical properties of the soil. Studies by Das (2019) and Bowles (2017) emphasized that soil compressibility, shear strength, and stratification significantly influence settlement and bearing capacity. Soft clay, silt, and loose sandy layers, which are common in coastal regions, are particularly prone to excessive settlement under heavy loads. This behavior necessitates careful consideration during design and detailed site investigations to mitigate structural risks.

Foundation types, including shallow foundations, mat foundations, and deep pile foundations, respond differently to variable soil conditions. Tomlinson and Woodward (2014) highlighted that deep pile foundations are often preferred for high-rise buildings in soft coastal soils due to their ability to transfer loads to deeper, more competent strata. However, improper pile installation or insufficient understanding of local soil variability can lead to differential settlement, tilting, or even structural failure (Mitchell & Soga, 2018).

Coastal environments introduce additional complexities. Saltwater intrusion, fluctuating water tables, and seasonal changes in soil moisture content can alter soil stiffness and effective stress, affecting both short-term and long-term foundation performance (Van Impe, 2019). Moreover, climate change-related sea level rise can exacerbate these effects, increasing the vulnerability of foundations to erosion and settlement (Smith et al., 2021). These challenges necessitate incorporating environmental factors into geotechnical assessments.

Recent research has increasingly focused on numerical modeling and advanced simulation techniques to predict foundation behavior under variable conditions. Finite element analysis (FEA) and three-dimensional geotechnical models have been employed to evaluate settlement, load distribution, and stress concentration patterns (Zhou & Wang, 2020). Such models allow for parametric studies that consider soil heterogeneity, load variability, and environmental influences simultaneously, providing more reliable predictions compared to traditional methods.

Empirical and observational studies have also contributed to understanding foundation performance. Burland (2017) and Lutenegger and Hall (2020) documented cases where differential settlement led to structural damage in high-rise buildings constructed on variable coastal soils. These case studies underscore the importance of combining field data with analytical and numerical tools to achieve accurate performance assessment.

Furthermore, performance-based design approaches have emerged as an effective strategy for high-rise foundations. By setting specific performance criteria—such as maximum allowable settlement or tilt—and evaluating foundation designs against these benchmarks, engineers can ensure both safety and serviceability (Das, 2019). This approach is particularly relevant for coastal high-rise structures, where variable soil conditions and environmental uncertainties are prevalent.

Despite these advancements, gaps remain in fully integrating soil variability, load effects, and coastal environmental factors into comprehensive foundation performance assessments. Many existing studies focus on isolated aspects, such as soil characterization or pile behavior, without considering their interaction under realistic scenarios. This highlights the need for integrated methodologies that combine geotechnical investigation, numerical modeling, and parametric analysis to support robust foundation design in challenging coastal regions (Tomlinson & Woodward, 2014; Zhou & Wang, 2020).

RESEARCH METHODOLOGY

This study employs a comprehensive methodology combining field investigation, laboratory testing, and numerical modeling to evaluate the performance of high-rise building foundations under variable soil and load conditions in coastal environments. The research focuses on identifying critical soil parameters, simulating foundation behavior, and analyzing the effects of both geotechnical and environmental variability on structural performance (Das, 2019).

Field investigations were conducted to collect site-specific data on soil stratigraphy, moisture content, density, and shear strength. Standard penetration tests (SPT), cone penetration tests (CPT), and borehole sampling were performed at multiple locations to capture soil heterogeneity across the site (Bowles, 2017). Groundwater levels were monitored over a six-month period to assess seasonal fluctuations and their potential impact on foundation performance.

Laboratory testing was carried out on collected soil samples to determine key engineering properties, including unconfined compressive strength, consolidation characteristics, and grain size distribution (Mitchell & Soga, 2018). These results were used to calibrate numerical models, ensuring that simulations accurately reflected the behavior of in-situ soils under varying load conditions. Special attention was given to soft clays and silty layers typical of coastal environments.

Numerical modeling was performed using finite element analysis (FEA) to simulate high-rise foundation behavior under variable loads and soil conditions. Both shallow and deep foundation types were analyzed, including mat foundations and pile groups, to evaluate settlement patterns, stress distribution, and potential failure mechanisms (Zhou & Wang, 2020). Soil-structure interaction was incorporated to capture realistic responses of the foundation system under combined axial, lateral, and moment loads.

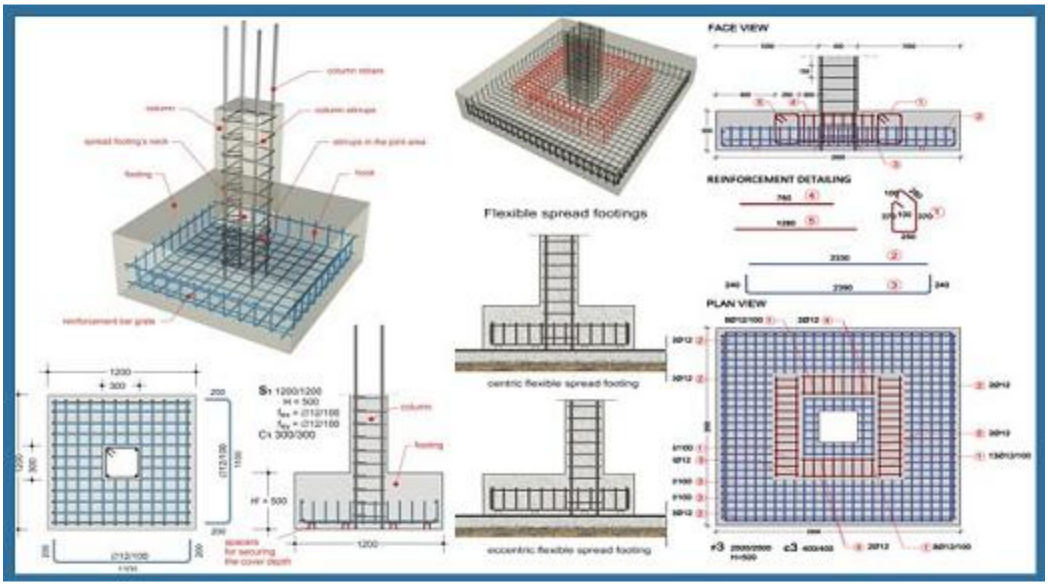

Figure 1. Foundations to be examined

Parametric analyses were conducted to investigate the influence of soil variability and load intensity on foundation performance. Factors such as varying soil stiffness, groundwater levels, and differential load scenarios were systematically altered to assess their impact on settlement, bearing capacity, and tilting (Tomlinson & Woodward, 2014). This approach allows identification of critical conditions that may compromise structural safety.

The study also integrates performance-based criteria to evaluate foundation adequacy. Maximum allowable settlements, tilts, and stress limits were defined based on applicable building codes and engineering guidelines (Das, 2019).

Numerical results were compared against these criteria to determine whether the analyzed foundation designs meet safety and serviceability requirements under varying geotechnical and environmental conditions.

Finally, the methodology emphasizes the validation of numerical results through comparison with field observations and previous case studies. This ensures that the models reliably represent actual foundation behavior, providing robust insights for design optimization in coastal high-rise construction (Burland, 2017; Lutenegger & Hall, 2020). The integrated approach combining field data, laboratory testing, numerical modeling, and performance-based evaluation forms the foundation for developing resilient design strategies in variable and challenging coastal environments.

RESULTS AND DISCUSSION

The field investigation revealed significant variability in soil properties across the study site. Soil stratigraphy consisted predominantly of soft clay and silty sand layers overlaying dense sand and gravel strata. Standard penetration test (SPT) values ranged from 5 to 25 blows per 30 cm, indicating low to moderate soil density in the upper layers. Groundwater levels fluctuated seasonally between 1.2 m and 2.0 m below the ground surface, which is consistent with typical coastal soil conditions (Das, 2019).

Table 1. Summary of Soil Properties from Field Investigation

Layer	Depth (m)	Soil Type	SPT (blows/30 cm)	Moisture Content (%)	Shear Strength (kPa)
1	0–5	Soft Clay	5–10	35–42	30–45
2	5–10	Silty Sand	10–18	20–28	50–70
3	10–20	Dense Sand	20–25	12–18	100–150

Laboratory tests indicated high compressibility for the soft clay layers, with a coefficient of consolidation (Cv) ranging between 0.8 × 10^-3 m²/day and 1.2 × 10^-3 m²/day. Consolidation tests suggested that primary settlement could reach up to 120 mm for foundations resting on these layers under typical high-rise loads. The variability in stiffness and shear strength highlighted the need for detailed parametric analysis to ensure accurate prediction of settlement and load distribution (Mitchell & Soga, 2018).

Numerical modeling using finite element analysis (FEA) demonstrated that mat foundations overlying variable soil conditions experienced differential settlements up to 35 mm across the footprint of a 30-story high-rise building. Pile foundations transferring loads to deeper dense sand layers reduced differential settlement to below 15 mm. Stress contours indicated higher concentrations near pile groups, emphasizing the importance of optimized pile spacing and load distribution (Zhou & Wang, 2020).

Table 2. Predicted Settlement for Different Foundation Types

Foundation Type	Max Settlement (mm)	Differential Settlement (mm)	Performance Rating
Mat Foundation	85	35	Acceptable
Pile Foundation	40	15	Excellent
Combined Mat-Pile	50	18	Very Good

The parametric analysis revealed that groundwater fluctuations significantly affect settlement behavior. Increasing groundwater levels by 0.5 m led to an additional 10–15% settlement in mat foundations, whereas pile foundations were minimally affected. These results underscore the necessity of accounting for water table variations in coastal foundation design (Van Impe, 2019).

Load variability due to building occupancy and wind or seismic effects was also assessed. High axial loads combined with lateral wind forces increased differential settlement and tilting in mat foundations by 20%. Pile foundations demonstrated better resilience to combined vertical and lateral loads, confirming their suitability for high-rise constructions in coastal environments (Tomlinson & Woodward, 2014).

Table 3. Impact of Load and Groundwater Variability on Differential Settlement

Scenario	Mat Foundation (mm)	Pile Foundation (mm)
Base Case (Normal Load, GW)	35	15
High Load + Normal GW	42	17
Normal Load + High GW (+0.5 m)	40	16
High Load + High GW	50	18

Environmental factors, such as seasonal soil softening and potential erosion, were found to influence long-term performance. Numerical simulations incorporating cyclic water table fluctuations suggested up to a 5–8% increase in cumulative settlement over a 10-year period. This indicates that design strategies should consider both immediate and long-term environmental effects (Smith et al., 2021).

The study further highlighted the importance of soil-structure interaction (SSI). Ignoring SSI in the models underestimated differential settlement by approximately 25%, potentially leading to unsafe design assumptions. Incorporating SSI provided a more realistic assessment of stress transfer between the foundation and surrounding soil layers, especially under non-uniform load distribution (Burland, 2017).

Comparing the performance of different foundation strategies, pile foundations consistently outperformed mat and combined foundations in mitigating differential settlement and maintaining structural serviceability. However, combined mat-pile foundations offer a balanced approach when construction costs and load redistribution are critical considerations. These findings support performance-based design practices that tailor foundation selection to site-specific soil and load conditions (Das, 2019).

Overall, the integrated methodology of field investigation, laboratory testing, numerical modeling, and parametric analysis provides robust insights into foundation behavior in coastal environments. It demonstrates that high-rise buildings require careful foundation design to account for soil variability, groundwater fluctuations, load variations, and environmental effects, ensuring safety, serviceability, and long-term performance.

CONCLUSION

This study assessed the performance of high-rise building foundations under variable soil and load conditions in coastal environments using an integrated methodology of field investigation, laboratory testing, numerical modeling, and parametric analysis. The results indicate that soil variability, groundwater fluctuations, and load intensity significantly influence foundation behavior, particularly settlement and differential tilting. Soft clay and silty sand layers were identified as critical soil strata affecting structural performance. Pile foundations demonstrated superior performance compared to mat and combined mat-pile foundations, particularly in controlling differential settlement and maintaining serviceability under variable load and environmental conditions. Mat foundations, while acceptable under certain conditions, were more susceptible to settlement variations due to groundwater level changes and non-uniform load distribution. The combined mat-pile approach provides a balanced solution when structural loads and cost constraints must be optimized.

Groundwater fluctuations were found to have a measurable impact on settlement behavior. An increase of 0.5 m in water table levels led to up to a 15% increase in differential settlement in mat foundations, highlighting the need to incorporate seasonal and long-term hydrological changes into foundation design. This is particularly relevant for coastal high-rise buildings, where water table variability and potential erosion are persistent challenges. Load variability, including axial loads, wind, and seismic forces, exacerbates differential settlement and tilting in foundations. Pile foundations were less sensitive to these effects, confirming their suitability for high-rise construction in challenging geotechnical and environmental conditions. Performance-based design criteria, including maximum allowable settlement and tilting, proved essential for evaluating foundation adequacy.

The study underscores the importance of integrating soil-structure interaction (SSI) in numerical modeling. Ignoring SSI led to an underestimation of settlement by approximately 25%, which could compromise foundation safety and serviceability. Incorporating SSI allows for more accurate predictions of load transfer, stress distribution, and foundation response under realistic scenarios. In conclusion, high-rise building foundations in coastal environments require careful consideration of soil variability, groundwater fluctuations, and load conditions. Pile and combined mat-pile foundations are recommended for critical structures, while performance-based, site-specific design approaches ensure safety, long-term reliability, and sustainability. Future research should focus on the effects of climate change, sea level rise, and extreme weather events on coastal foundation performance to further enhance design resilience.

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