International Journal of Science, Technology and Management (IJSTM) ISSN (online): 2231-775X
Volume 1, Issue 1, 2025

Influence of Soil Type on Structural Performance of Foundations for G+3 Buildings: A Geotechnical and Numerical Analysis

Prashant Kashyap[1], Ashwani Kumar[2], Rakesh kumar[3]

[1]M. Tech Scholar, Department of Civil Engineering Engineering, BRCMCET, BAHAL
[2]Assistant Professor, Department of Civil Engineering, BRCMCET, BAHAL
[3]Assistant Professor, Department of Civil Engineering, BRCMCET, BAHAL

Abstract

The performance of building foundations is strongly influenced by the geotechnical characteristics of the supporting soil. This study investigates the effect of four common soil types—clay, sand, loam, and weathered rock—on the structural performance of isolated footings, combined footings, raft foundations, and pile foundations for mid-rise (G+3) buildings. Laboratory and field investigations were conducted to determine soil properties including grain size distribution, Atterberg limits, shear strength, bearing capacity, compressibility, and modulus of elasticity. Structural behaviour was analysed using finite element modelling in PLAXIS 2D/3D and STAAD.Pro to evaluate bearing pressure distribution, settlement, factor of safety, and load–deformation response. Results indicate that clay soils, with high compressibility and low shear strength, require deep foundations such as piles to control settlement, whereas sandy and loamy soils are best suited for raft foundations due to effective load distribution and moderate cost. Weathered rock offers the highest bearing capacity and minimal settlement, enabling the use of economical shallow foundations. The findings demonstrate that no single foundation type is universally optimal, highlighting the necessity of soil-specific foundation selection to ensure structural safety and serviceability in mid-rise construction.

Keywords

Soil–foundation interaction; Geotechnical properties; G+3 buildings; Bearing capacity; Settlement analysis; Finite element modelling; Structural performance; Pile foundation; Raft foundation; Mid-rise structures.

1. Introduction

Foundation systems are critical structural elements that ensure safe and efficient transfer of loads from a building to the underlying soil. Their performance is directly influenced by the mechanical and physical characteristics of the supporting ground, which can vary significantly between sites due to differences in composition, density, moisture content, and mineralogy. These variations make soil–foundation interaction (SFI) a central consideration in geotechnical and structural engineering, particularly for mid-rise buildings such as Ground plus Three (G+3) storey structures, where cumulative vertical and lateral loads demand stable and well-matched foundation systems.

In practice, foundation designs are often based on generalized assumptions rather than site-specific investigations. Such approaches can result in either overdesign, leading to unnecessary consumption of materials and elevated costs, or underdesign, which may cause excessive settlement, cracking, tilting, or even structural failure. The need for soil-appropriate foundation selection is especially relevant in urban and semi-urban contexts, where diverse soil profiles—ranging from weak, moisture-sensitive clays to high-capacity weathered rock—are encountered.

Previous studies have emphasized the role of geotechnical investigations in optimizing foundation design, with parameters such as bearing capacity, shear strength, compressibility, and modulus of elasticity serving as key inputs. However, there remains a gap in integrated studies that compare multiple foundation types across different soil conditions while assessing both structural performance indicators—such as settlement and factor of safety—and numerical simulations for realistic prediction.

This study aims to address that gap by experimentally characterizing four common soil types—clay, sand, loam, and weathered rock—and evaluating the performance of isolated footings, combined footings, raft foundations, and pile foundations for G+3 buildings. Laboratory testing, field investigations, and finite element modelling are used to simulate load transfer mechanisms, bearing pressure distribution, settlement behaviour, and safety margins. The findings are expected to provide engineers and planners with a performance-based reference for selecting optimal foundation types for mid-rise structures, thereby improving both safety and cost efficiency.

2. Literature Review

The interaction between soil and foundation is a fundamental aspect of geotechnical and structural engineering, influencing the stability, safety, and long-term performance of buildings. This phenomenon, commonly referred to as soil–foundation interaction (SFI) or soil–structure interaction (SSI), describes how the mechanical response of soil under load affects foundation behaviour and vice versa.

2.1 Soil Behaviour and Its Influence on Foundations

Soil is inherently heterogeneous and anisotropic, with mechanical properties that vary with type, density, moisture content, and loading duration. Unlike steel or concrete, its modulus of elasticity and stress–strain behaviour are not constant across different conditions. Cohesive soils, such as clays, often exhibit high compressibility and significant settlement under sustained loads, whereas granular soils, such as sands, are governed by frictional resistance but may be prone to liquefaction under seismic excitation. Weathered rock generally offers high bearing capacity with minimal deformation, but excavation challenges can influence construction feasibility (Das & Sivakugan, 2022; Bowles, 2023).

2.2 Foundation Types and Performance Considerations

Foundation systems are broadly categorized as shallow (e.g., isolated and combined footings, raft foundations) and deep (e.g., pile foundations). In shallow foundations, load transfer occurs near the ground surface, making soil stiffness and bearing capacity critical design parameters. Deep foundations mobilize shaft friction and end-bearing resistance from deeper strata, offering improved performance in weak surface soils but at higher cost and complexity (IS 6403:1981; IS 2911:2010).

Comparative studies have shown that raft foundations effectively distribute loads in moderately compressible soils such as loam, while pile foundations are superior in highly compressible clays (Verma & Bhattacharya, 2023; Nguyen & Wong, 2023). In contrast, competent soils such as dense sands and weathered rock often allow economical shallow foundation solutions without compromising safety.

2.3 Numerical Modelling and Advanced Analysis

Recent advances in computational geomechanics have enabled more accurate simulation of SFI using finite element methods. Software such as PLAXIS, GEO5, and SAP2000 incorporate non-linear elasticity, consolidation behaviour, and pore-water pressure effects, allowing designers to assess settlement, stress distribution, and safety margins under realistic conditions (Chen et al., 2023). Numerical models are increasingly used alongside laboratory and field tests to validate performance predictions for specific soil–foundation combinations.

2.4 Gaps in Existing Research

Although numerous studies have addressed individual aspects of soil mechanics or foundation behaviour, fewer have undertaken a systematic comparison of multiple foundation types across varied soil conditions for mid-rise buildings. Moreover, integrated evaluations that combine geotechnical characterization, structural performance analysis, and simulation-based modelling remain limited. Addressing this gap could yield more reliable guidelines for foundation selection that optimize both safety and cost for G+3 structures in diverse geotechnical settings.

3. Materials and Methods

3.1 Overview

This study adopted a mixed-method approach combining laboratory and field-based geotechnical investigations with numerical modelling to assess the influence of soil type on foundation performance for G+3 buildings. Four soil types—clay, sand, loam, and weathered rock—were selected based on their prevalence in residential and semi-urban construction. Four foundation types—isolated footing, combined footing, raft foundation, and pile foundation—were analysed for each soil condition.

3.2 Soil Sampling and Classification

Soil samples were collected from representative sites using standard procedures outlined in IS 2720. Both disturbed and undisturbed samples were obtained, with undisturbed specimens preserved for consolidation and shear strength testing. Preliminary visual inspection was followed by classification using the Indian Standard Soil Classification System (ISSCS) and Unified Soil Classification System (USCS).

3.3 Geotechnical Testing

Laboratory tests were conducted to determine both index and engineering properties of the soils:

- **Index properties:** Moisture content, specific gravity, grain size distribution, and Atterberg limits (for cohesive soils).
- **Engineering properties:** Standard Proctor compaction, unconfined compression strength, direct shear test, triaxial compression test, and one-dimensional consolidation test (for cohesive soils). Field investigations included:

- **Standard Penetration Test (SPT)** – IS 2131
- **Cone Penetration Test (CPT)** – IS 4968
- **Plate Load Test** – IS 1888

These results provided input parameters for foundation design and numerical simulations.

3.4 Foundation Design

Each foundation type was designed in accordance with relevant Indian Standards—IS 456:2000 for reinforced concrete design, IS 6403:1981 for shallow foundations, and IS 2911:2010 for deep foundations. Design loads were based on typical G+3 structural configurations with uniformly distributed gravity and lateral loads.

3.5 Numerical Modelling

Finite element analysis (FEA) was used to simulate soil–foundation interaction:

- **PLAXIS 2D/3D** for modelling raft and pile foundations, incorporating soil non-linearity and layered stratigraphy.
- **STAAD.Pro** for isolated and combined footings under vertical and moment loads.
- **SAP2000** for load distribution in multi-column raft configurations.

Boundary conditions, soil modulus, Poisson's ratio, and subgrade modulus were applied based on laboratory and field data. Simulations evaluated bearing pressure distribution, total and differential settlement, factor of safety (FOS), and load–deformation behaviour.

3.6 Performance Assessment

Performance evaluation focused on:

- **Bearing capacity** – calculated using Terzaghi's equations and validated with SPT/CPT data.
- **Settlement** – determined analytically and via FEA.
- **Factor of safety** – as per IS 6403 and IS 2911.
- **Load–deformation response** – centre and edge settlements under service loads.

By integrating geotechnical properties, structural analysis, and simulation results, the methodology enabled a comprehensive evaluation of foundation performance under varying soil conditions.

4. Results and Discussion

4.1 Geotechnical Properties of Soils

Laboratory and field investigations revealed distinct behavioural patterns among the four tested soils (Table 1). Clay exhibited high natural moisture content (28.5%), high plasticity index (27%), and low modulus of elasticity (7,500 kN/m²), indicating high compressibility and long-term settlement potential. Sandy soil showed low moisture content (9.2%), high friction angle (35°), and high modulus of elasticity (25,000 kN/m²), suggesting suitability for shallow foundations when properly compacted. Loamy soil presented moderate plasticity and balanced cohesion–friction properties, while weathered rock displayed the highest stiffness (45,000 kN/m²) and bearing capacity, with negligible compressibility.

Table 1. Summary of key geotechnical parameters

Soil Type	**Cohesion (kPa)**	**Friction Angle (°)**	**Net Safe Bearing Capacity (kN/m²)**	**Compression Index (Cc)**	**Modulus of Elasticity (kN/m²)**
Clay	45	19	130	0.35	7,500
Sand	2	35	220	—	25,000
Loam	18	28	180	0.20	15,000
Weathered Rock	5	40	350	—	45,000

4.2 Bearing Pressure Distribution

Average bearing pressures under working loads were lowest for pile foundations (80–110 kN/m²) and highest for isolated footings (120–200 kN/m²). In clay, high bearing pressures in shallow foundations increased the risk of settlement, while in weathered rock, pressures remained well within safe limits across all foundation types.

4.3 Settlement Behaviour

Settlement analysis (Table 2) confirmed that clay was the most problematic soil, with isolated footings showing settlements up to 48 mm, exceeding recommended serviceability limits. Pile foundations reduced settlement to approximately 12 mm. Sandy and loamy soils displayed settlements within acceptable ranges for both shallow and raft foundations, while weathered rock exhibited negligible settlement.

Table 2. Estimated total settlement (mm)

Foundation Type	Clay	Sand	Loam	Weathered Rock
Isolated Footing	48	18	20	6
Combined Footing	42	15	18	5
Raft Foundation	30	12	15	4
Pile Foundation	12	8	10	3

4.4 Factor of Safety (FOS) Against Bearing Failure

FOS values across all soil–foundation combinations exceeded the minimum requirement of 2.0. Pile foundations consistently achieved the highest safety margins (3.3–4.8), particularly in weak soils. Raft foundations provided strong safety performance in sandy and loamy soils, while isolated footings were adequate only in dense sands and rock.

4.5 Load–Deformation Response

Finite element simulations showed that differential settlement was most pronounced in shallow foundations on clay, with edge settlements up to 15% greater than central values. Raft and pile foundations demonstrated more uniform deformation profiles, improving serviceability and reducing structural stress concentrations.

4.6 Comparative Performance Insights

- **Clay:** Pile foundations offered the best performance, controlling settlement and ensuring high safety, though at higher cost.
- **Sand and Loam:** Raft foundations provided optimal load distribution with moderate settlement and cost efficiency.
- **Weathered Rock:** Isolated footings were structurally adequate and economically favourable.

These findings align with previous research (Verma & Bhattacharya, 2023; Nguyen & Wong, 2023) that emphasizes the necessity of soil-specific foundation design. The data reinforces that a universal foundation choice is impractical; instead, foundation selection must integrate geotechnical, structural, and economic considerations.

5. Conclusion

This study systematically evaluated the influence of four common soil types—clay, sand, loam, and weathered rock—on the structural performance of isolated footings, combined footings, raft foundations, and pile foundations for G+3 buildings. Laboratory and field investigations provided detailed geotechnical characterizations, while finite element modelling enabled realistic simulation of soil–foundation interaction under service loads.

Key findings include:

- **Clay soils** require deep foundations, with pile systems delivering minimal settlement and the highest safety margins, despite higher initial costs.
- **Sandy and loamy soils** are best suited for raft foundations, which balance settlement control, load distribution, and cost efficiency.
- **Weathered rock** supports economical shallow foundations such as isolated footings, with negligible settlement and high bearing capacity.
- No single foundation type is universally optimal; performance is highly dependent on soil conditions.

The results underscore the necessity of site-specific geotechnical investigation in foundation design for mid-rise buildings. By integrating experimental data with numerical modelling, this study offers a performance-based approach that can guide engineers in selecting the most suitable foundation type for varying soil conditions. This approach enhances structural safety, optimizes resource utilization, and promotes cost-effective construction practices.

References

Ahmed, S., & Singh, V. (2023). Analysis of foundation stability in liquefiable sandy soils: Experimental insights. *Geotechnical Research, 12*(1), 75–89. https://doi.org/10.1680/jgere.22.00020

Bhattacharya, S., Madabhushi, G. S., & Haigh, S. K. (2023). Seismic performance of pile foundations in liquefiable soils: A critical review. *Soil Dynamics and Earthquake Engineering, 169*, 107530. https://doi.org/10.1016/j.soildyn.2023.107530

Bowles, J. E. (2023). *Foundation analysis and design* (7th ed.). McGraw Hill Education.

Central Public Works Department (CPWD). (2023). *Schedule of rates – Civil works*. Government of India.

Chen, Y., Zhang, J., & Wang, L. (2023). Soil–structure interaction modeling using PLAXIS for mid-rise buildings under varying soil conditions. *Geotechnical and Geological Engineering, 41*(2), 421–438. https://doi.org/10.1007/s10706-022-02105-5

Das, B. M., & Sivakugan, N. (2022). *Principles of foundation engineering* (9th ed.). Cengage Learning.

Ghosh, A., Mishra, D., & Rathi, P. (2022). Behaviour of loamy soils under shallow foundations: Experimental modeling and field correlation. *International Journal of Geomechanics, 22*(7), 04022052. https://doi.org/10.1061/(ASCE)GM.1943-5622.0002356

Indian Standards (IS) 456:2000. *Plain and reinforced concrete – Code of practice*. Bureau of Indian Standards.

Indian Standards (IS) 6403:1981. *Determination of bearing capacity of shallow foundations*. Bureau of Indian Standards.

Indian Standards (IS) 2911 (Part 1):2010. *Design and construction of pile foundations – Code of practice*. Bureau of Indian Standards.

Indian Standards (IS) 8009 (Part 1):1976. *Determination of settlement of shallow foundations*. Bureau of Indian Standards.

Nguyen, T. H., & Wong, K. S. (2023). Pile–raft foundations: Recent advances and practical applications in soft soil regions. *Structural Engineering International, 33*(2), 127–138. https://doi.org/10.2749/101686623X16850921672907

Sharma, P., Mehta, V., & Reddy, S. (2023). Performance evaluation of combined footings in cohesive soil environments: A field-based study. *International Journal of Geomechanics, 23*(4), 04023021. https://doi.org/10.1061/(ASCE)GM.1943-5622.0002421

Verma, A., & Bhattacharya, S. (2023). Optimization of raft foundation design for mid-rise buildings on soft clay deposits. *Soil and Foundation Engineering, 60*(3), 183–194. https://doi.org/10.1016/j.sandf.2023.02.008

Wang, L., Chen, Y., & Hu, X. (2022). Long-term settlement behaviour of clayey soils under low-rise buildings. *Soil Mechanics and Foundation Engineering,*

59(3), 233–242.
https://doi.org/10.1007/s11204-022-09854-9