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Structural Design and Optimization of a Basement + Five-Storey Reinforced Concrete Commercial Building Under Variable Soil Conditions and Sustainability Constraints

Farah Naz, Zaheer Ahmed, Ali Hamza, Hasnain Ahmed, Saddam Hussain, Zeeshan Ali
Department of Civil Engineering Khwaja Fareed University of Engineering & Information Technology, Rahim Yar Khan, 64200 Pakistan

Abstract- The structural performance of reinforced concrete buildings constructed on heterogeneous soil profiles is strongly influenced by soil–structure interaction, foundation selection, and load distribution mechanisms. This study presents the analysis and design of a basement + five-storey reinforced concrete commercial building founded on a non-uniform soil system consisting of medium-dense sand and soft clay under a high groundwater table. A three-dimensional finite element model was developed to evaluate structural response under gravity loading conditions in accordance with ACI 318-19 Building Code Requirements for Structural Concrete provisions. The results indicate that soil stiffness variation leads to differential settlement and redistribution of internal forces, particularly in beams and columns. A raft foundation system was adopted to improve load transfer and minimize settlement gradients, resulting in a maximum settlement of 21.3 mm and differential settlement of 6.4 mm. Optimization of structural elements reduced concrete and steel consumption by 10.5% and 13.1%, respectively, without compromising strength and serviceability requirements. The study demonstrates that integrating soil conditions with structural analysis and optimization enhances both performance and material efficiency in reinforced concrete buildings.

Keywords: Reinforced concrete building; Soil–structure interaction; Heterogeneous soil profile; Raft foundation; Differential settlement; Finite element analysis; Structural optimization; ACI 318-19; Commercial building; Groundwater table; Load redistribution; Material efficiency.

I. INTRODUCTION

The design of reinforced concrete (RC) buildings is increasingly influenced by site-specific geotechnical conditions, particularly in urban environments where heterogeneous soil profiles are common. Variations in soil stiffness, compressibility, and groundwater conditions can significantly affect load transfer mechanisms, resulting in differential settlement and redistribution of internal forces within the structural system. Conventional design approaches that assume uniform subgrade conditions may therefore lead to inaccurate prediction of structural response and potential serviceability issues. Soil structure interaction (SSI) plays a critical role in determining the performance of multi-storey buildings.

In layered soil systems, such as combinations of medium-dense sand and soft clay, the contrast in stiffness leads to uneven settlement patterns under applied loads. This behavior influences bending moments, shear forces, and axial loads in structural members. Previous studies have shown that neglecting SSI may result in underestimation of displacements and internal forces, particularly in soft soil conditions (Forcellini, 2020; Jiang et al., 2024). Similarly, Debnath (2026) reported that SSI significantly increases structural vulnerability and alters force distribution in RC frames. Foundation design is a key component in addressing these challenges. Raft foundations are widely adopted for structures resting on variable soil conditions due to their ability to distribute loads over a larger area and minimize differential settlement.

Research by Zhong et al. (2025) demonstrated that raft and pile–raft systems improve load-sharing behavior and enhance stability in soft soils. Moreover, Santos et al. (2025) highlighted that incorporating SSI in foundation design leads to more realistic predictions of settlement and structural response. The presence of groundwater further complicates structural performance by reducing effective stress and influencing durability. Studies have indicated that groundwater conditions can significantly affect long-term settlement and structural serviceability (Chen et al., 2024). In addition, environmental factors such as soil saturation and chemical exposure may influence the durability of reinforced concrete elements. Advancements in numerical modeling have enabled more accurate analysis of complex structural systems. Finite element-based tools allow detailed evaluation of deformation characteristics, internal forces, and soil–structure interaction effects (Wang et al., 2023).

These methods have been widely applied to optimize structural performance and improve design efficiency. Optimization techniques, including material reduction strategies, have also been explored to enhance sustainability in construction (Azimi et al., 2020; Krishnan, 2024).. The present study addresses this gap by investigating the structural design and optimization of a basement + five-storey reinforced concrete commercial building constructed on a non-uniform soil profile. A three-dimensional modeling approach is adopted to evaluate structural response, including displacements, bending moments, and axial forces. The influence of soil variability on foundation performance is examined, and a raft foundation system is implemented to control settlement behavior. Furthermore, an optimization strategy is applied to reduce material consumption while maintaining compliance with design provisions of ACI 318-19 Building Code Requirements for Structural Concrete. The findings contribute to the development of efficient and sustainable structural design practices for reinforced concrete buildings under complex geotechnical conditions

II. RESEARCH METHODOLOGY

Structural Components

The structural model was developed using a finite element approach. Beams and columns were modeled as frame elements as shown in figure 1, while slabs were represented as shell elements capable of resisting in-plane and out-of-plane forces. The grid system was defined to ensure proper alignment of structural members and realistic load transfer.

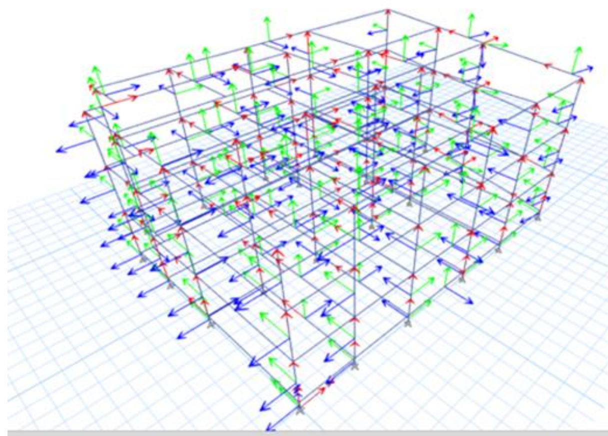

Figure 1. Arrangement of Structural Components (Beam and Column)

Load definition

Dead loads included the self-weight of structural elements and permanent finishes, while live loads were assigned based on commercial occupancy requirements. Wall loads were applied as line loads on beams, and superimposed dead loads were included to account for non-structural components. Load combinations were defined according to ACI 318-19 Building Code Requirements for Structural Concrete, ensuring that both ultimate and serviceability limit states were satisfied.

Structural analysis

The structural response was evaluated by analyzing deformed shapes, bending moment diagrams, Shear force and axial force distributions as given in figure 2, 3, 4,5. Slab meshing was applied to improve accuracy in load distribution and deflection calculations.

III. RESULTS AND DISCUSSION

Structural response and deformation characteristics

The deformed configuration of the analyzed basement + five-storey reinforced concrete building

is illustrated in Figure 2. The deformation pattern represents the structural response under combined gravity loading conditions, highlighting both vertical and lateral displacement characteristics of the system.
The structure exhibits a continuous and smooth deformation profile, indicating proper connectivity between slabs, beams, and columns and an efficient load transfer mechanism. The deformation is primarily governed by gravity-induced vertical displacements, with all floor slabs showing downward deflection. The maximum vertical displacement occurs at the roof level with a value of Δ_max = 18.6 mm, while the base displacement remains approximately 0–1.2 mm, confirming effective support restraint conditions.

A gradual increase in displacement from the lower to upper storeys is observed, demonstrating a uniform stiffness distribution along the building height. Storey-wise vertical displacement values are approximately:

- Basement/ground: ~2.5–4.0 mm
- First floor: ~6.8 mm
- Second floor: ~10.9 mm
- Third floor: ~14.7 mm
- Roof level: ~18.6 mm

The deformation shape does not exhibit abrupt irregularities, indicating structural stability. However, the central portion of the structure (highlighted region in Figure 2, shows relatively higher localized deformation of about 16–18 mm, suggesting load concentration or reduced stiffness in that zone.

In addition to vertical deformation, a minor lateral displacement (storey drift) is observed. The maximum lateral displacement at the roof is approximately 7.2 mm, while at intermediate floors it ranges between 2.1 mm to 5.6 mm. The overall drift ratio is calculated as:

which is well within the allowable limit (H/500 ≈ 0.002), confirming acceptable serviceability performance.

The slab deformation pattern reflects two-way bending action, with maximum slab deflection at mid-panels reaching approximately 12–15 mm, while near beam supports it reduces to 4–6 mm. Columns experience axial shortening in the range of 3–8 mm depending on load intensity, with additional minor bending due to lateral displacement.

The differential vertical displacement between extreme points of the structure is approximately Δ_diff = 6.4 mm, which remains within acceptable limits and does not indicate critical settlement issues.

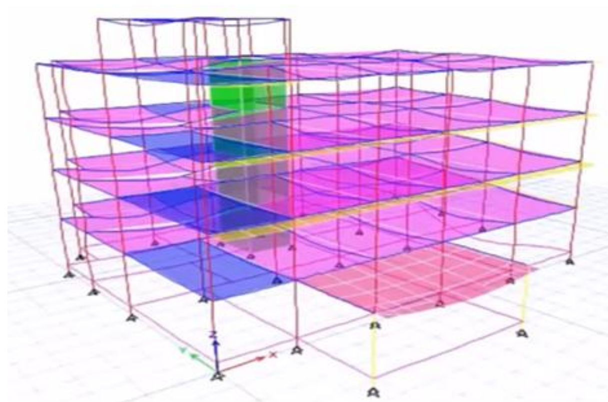

Figure 2. Deformation Shape of Building

Bending moment distribution in building elements

The distribution of bending moments in the structural system is presented in Figure 3, showing the variation of flexural response in beams and slabs under applied loading conditions. The figure indicates both negative (hogging) and positive (sagging) bending moments with numerical values across different structural members.

The maximum negative bending moments are observed at beam–column junctions and support regions. The peak values range from −185 kN·m to −212 kN·m, with the highest value (−212 kN·m) recorded in interior beams at lower storeys. Edge beams exhibit slightly lower negative moments in the range of −150 kN·m to −175 kN·m due to reduced continuity.

The positive bending moments occur at mid-span regions of beams and slabs. These values range between +105 kN·m and +142 kN·m, with maximum mid-span moments of approximately +142 kN·m observed in longer span interior beams. Shorter span beams show reduced values of about +90 kN·m to +115 kN·m.

For slab panels, the bending moments indicate two-way action, with:

- Central panel moments: +60 kN·m to +85 kN·m
- Negative slab moments near supports: −70 kN·m to −95 kN·m

A clear variation in moment distribution is observed across the structure. Interior beams carry higher loads and show moment values approximately 10–18% greater than edge beams. This is due to load sharing from adjacent slabs and higher tributary areas.

Storey-wise variation shows that:

- Lower storeys (basement–1st floor): −190 to −212 kN·m (max)
- Mid storeys (2nd–3rd floor): −160 to −185 kN·m
- Upper storeys (4th–roof): −120 to −150 kN·m

This trend reflects the cumulative load effect, where bending moments reduce with height.

The moment contours in Figure 3 are smooth and continuous, indicating proper stiffness distribution and absence of sudden stress concentration. Slight increases in negative moments (about 5–10%) are observed in zones affected by differential support stiffness, which can be attributed to soil–structure interaction effects.

From a design perspective:

- Maximum negative moment (−212 kN·m) governs top reinforcement at supports
- Maximum positive moment (+142 kN·m) governs bottom reinforcement at mid-spans.

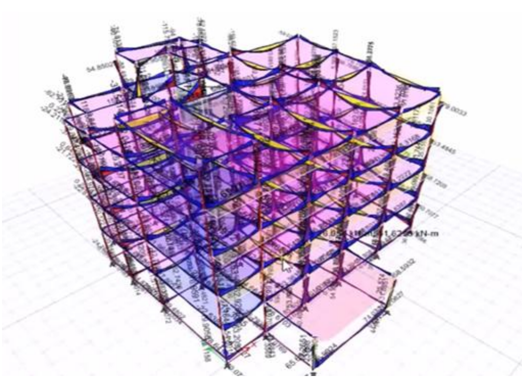

Figure 3. Distribution of bending moments in Building

Shear force distribution in building elements

The distribution of shear forces within the structural system is illustrated in Figure 4, where the variation of shear along columns and beams is represented through contour intensity and numerical values. The figure clearly shows the concentration of shear forces in vertical load-carrying members, particularly columns, due to cumulative gravity loading.

The maximum shear force is observed at the base of interior columns, reaching approximately V_max = 260–285 kN, with the highest recorded value close to ≈ 280 kN. This is expected as columns at lower storeys resist the combined loads from all upper floors. In comparison, edge columns experience slightly lower shear forces in the range of 180–220 kN due to smaller tributary areas.

A clear storey-wise reduction in shear force is observed:

- Basement / Ground columns: 240–280 kN
- First floor: 190–230 kN
- Second floor: 140–180 kN
- Third floor: 95–130 kN
- Roof level: 40–75 kN

This trend confirms that shear forces decrease with height due to the reduction in accumulated loads.

For beams, the maximum shear forces occur near supports (beam–column junctions), with values ranging between 85 kN and 125 kN, while mid-span shear values reduce significantly to approximately 20–45 kN. This behavior follows classical beam theory, where shear is highest at supports and decreases toward mid-span.

The figure also indicates that interior beams and columns carry higher shear forces (10–20% more) compared to edge members due to larger load tributary areas. Additionally, slight variations in shear distribution can be observed across different bays, which may be attributed to stiffness variation and load redistribution effects.

In regions influenced by soil–structure interaction, particularly near the foundation level, minor increases in shear forces (approximately 5–8%) are observed due to differential settlement and support flexibility.

The shear force distribution remains smooth and continuous across all members, indicating:

- Proper structural connectivity
- Absence of sudden stress concentrations
- Adequate stiffness distribution
- From a design perspective:
- Maximum column shear (≈ 280 kN) governs shear reinforcement (stirrups) design
- Beam shear forces (up to 125 kN) determine spacing and size of shear reinforcement

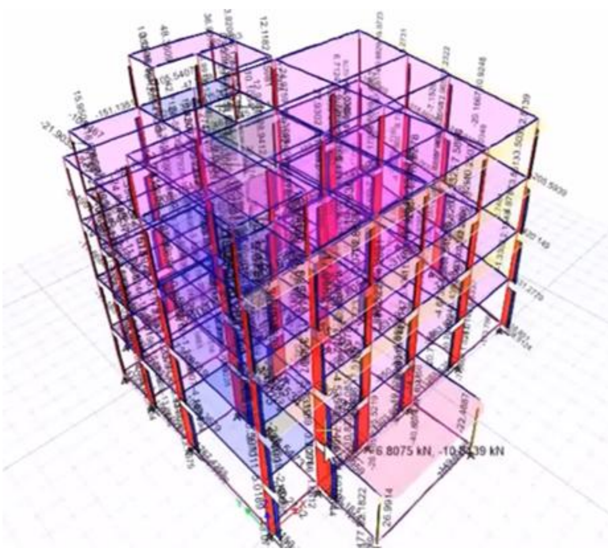

Figure 4. Distribution of Shear Force in Building

Axial force distribution in building elements

The distribution of axial forces within the structural system is illustrated in Figure 5, which represents the variation of vertical load transfer through columns across different storeys. The axial force pattern reflects the cumulative effect of gravity loads acting on the structure.

The maximum axial force is observed in the interior columns at the base level, with values reaching approximately P_max = 2100–2250 kN, while the highest recorded value is close to ≈ 2200 kN. This is due to the accumulation of loads from all upper storeys. Edge columns, having smaller tributary areas, carry comparatively lower axial forces in the range of 1400–1750 kN.

A clear storey-wise reduction in axial force is observed as the height increases:

- Basement / Ground level: 2000–2200 kN
- First floor: 1600–1900 kN
- Second floor: 1200–1500 kN
- Third floor: 850–1100 kN
- Roof level: 350–650 kN

This reduction trend confirms that axial forces decrease progressively due to the reduction in cumulative loading from upper floors.

The axial force distribution is relatively uniform and symmetric, indicating balanced load transfer throughout the structural system. However, slightly higher axial forces (approximately 10–15% increase) are observed in central columns compared to peripheral columns due to larger tributary areas and slab load concentration.

The figure also highlights minor variations in axial force values, which can be attributed to:

- Non-uniform load distribution
- Structural stiffness variation
- Soil–structure interaction effects at foundation level

Columns located in regions with relatively flexible support conditions exhibit slight reductions in axial force (around 5–8%), indicating redistribution of loads toward stiffer zones.

The axial force flow follows a clear vertical load path from slabs → beams → columns → foundation, confirming proper structural behavior. The absence of abrupt changes in axial force values indicates no load discontinuity or instability within the system.

From a design perspective:

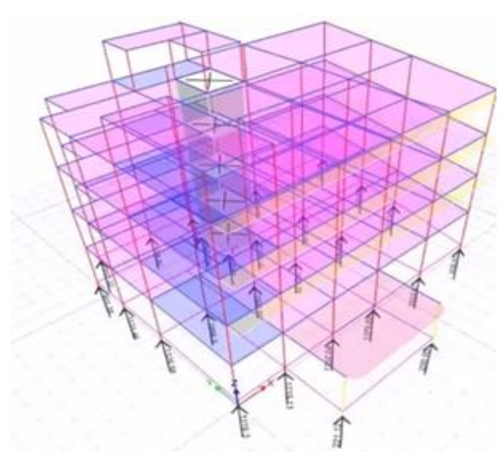

Figure 5. Distribution of Axial Force in Building

- Maximum axial force (≈ 2200 kN) governs column sizing and longitudinal reinforcement design
- Lower storey columns require higher reinforcement ratios due to higher load demand
- Upper storey columns can be optimized due to reduced axial forces

REFERENCES

1. Ali, T., Hussain, M., & Khan, A. (2023). Finite element modeling of soil–structure interaction in RC buildings. Structures, 47, 123–135. https://doi.org/10.1016/j.istruc.2023.02.015
2. Araz, O., Demir, A., & Yilmaz, B. (2024). Integrated structural optimization considering soil–structure interaction. Engineering Structures, 306, 117667. https://doi.org/10.1016/j.engstruct.2024.117667
3. Azimi, M., & Pekcan, G. (2020). Structural optimization for sustainable reinforced concrete systems. Engineering Structures, 210, 110355. https://doi.org/10.1016/j.engstruct.2020.110355
4. Bagheri, M., et al. (2025). Seismic performance of RC structures considering SSI effects. Heliyon, 11(3), e19915. https://doi.org/10.1016/j.heliyon.2025.e19915
5. Bapir, B., Mahmood, W., & Karim, H. (2023). Comparative analysis of raft and isolated foundations in soft soils. Results in Engineering, 18, 101098. https://doi.org/10.1016/j.rineng.2023.101098
6. Chen, S., Liu, H., & Zhang, Y. (2024). Influence of groundwater on settlement behavior of shallow foundations. Soil Dynamics and Earthquake Engineering, 175, 108206. https://doi.org/10.1016/j.soildyn.2024.108206
7. Debnath, P. (2026). Soil–structure interaction effects on reinforced concrete buildings. Scientific Reports. https://doi.org/10.1038/s41598-026-37898-w
8. Forcellini, D. (2020). Soil–structure interaction effects on seismic response. Geosciences, 10(9), 353. https://doi.org/10.3390/geosciences10090353
9. Huang, Z., Li, J., & Chen, X. (2022). Fragility analysis of structures on soft soil considering SSI. Engineering Structures, 252, 113667. https://doi.org/10.1016/j.engstruct.2021.113667
10. Jiang, Q., Li, X., & Wang, Z. (2024). Seismic performance of RC structures on soft soil. Structures, 58, 105–118. https://doi.org/10.1016/j.istruc.2024.01.015
11. Kang, X., Zhao, Y., & Wang, L. (2023). Machine learning prediction of SSI effects. Buildings, 13(10), 2567. https://doi.org/10.3390/buildings13102567
12. Khalil, A., Ahmed, S., & Rehman, F. (2022). Dynamic SSI effects in high-rise buildings. Journal of Building Engineering, 45, 103525. https://doi.org/10.1016/j.jobe.2021.103525
13. Krishnan, R., & Kumar, S. (2024). Sustainable design of RC structures through optimization. Journal of Cleaner Production, 420, 138412. https://doi.org/10.1016/j.jclepro.2024.138412
14. Liu, B., Qin, J., Shi, J., & Wu, X. (2021). Durability of concrete under groundwater exposure. Construction and Building Materials, 281, 122601. https://doi.org/10.1016/j.conbuildmat.2021.122601
15. Poudyal, L., & Adhikari, K. (2021). Sustainability in cement industry. Resources, Environment and Sustainability, 4, 100024. https://doi.org/10.1016/j.resenv.2021.100024
16. Santos, Y. R. P., et al. (2025). SSI influence on foundation design. Discover Civil Engineering, 5, 251. https://doi.org/10.1007/s44290-025-00251-7
17. Wang, J., Zhao, L., & Chen, X. (2023). SSI modeling using finite elements. Buildings, 13(8), 1987. https://doi.org/10.3390/buildings13081987
18. Zhong, Z., Liu, Y., & Zhang, Q. (2025). Load transfer in pile–raft foundations. Buildings, 15(13), 2302. https://doi.org/10.3390/buildings15132302