International Research Journal of Innovations in Engineering and Technology (IRJIET)

ISSN (online): 2581-3048
Volume 10, Issue 7, pp 26-35, July-2026
https://doi.org/10.47001/IRJIET/2026.107004

Impact of Soil Flexibility on Seismic Behavior of Multi-Story Reinforced Concrete Structures

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***Abstract* - The relationship between the ground and structural system is crucial for the seismic performance of high-rise reinforced concrete edifices. Traditional seismic design approaches typically assume a fixed-base condition, overlooking the flexibility of the underlying soil layers. Soil-structure interaction (SSI) can significantly affect the seismic response by altering natural frequencies, damping ratios, and the overall dynamic behaviour of the structure. This study investigates the influence of soil-structure interaction (SSI) on the seismic performance of high-rise reinforced concrete (RC) edifices, highlighting various soil conditions, structural configurations, and ground motion characteristics. Finite element modelling and time history analyses are employed to simulate real seismic events, highlighting the necessity of including soil flexibility into design approaches to improve structural safety. A thorough parametric analysis is conducted by modelling high-rise reinforced concrete structures of varying heights and stiffness on multiple soil types, including soft clay, medium-dense sand, and hard rock. The results demonstrate that structures on softer soils experience increased lateral displacements, prolonged fundamental periods, and elevated base shear demands relative to those on stronger soils. Moreover, the extent of soil-structure interaction escalates with taller and more flexible structures. The study investigates the critical role of foundation system types—namely shallow vs deep foundations—in mitigating adverse soil-structure interaction impacts. Critical findings indicate that neglecting SSI may lead to an underestimation of seismic demands, hence compromising structural integrity during major earthquakes.**

Recommendations are provided for incorporating SSI considerations into the seismic design of high-rise reinforced concrete structures based on the findings. The study emphasises the necessity for integrated modelling approaches that account for the interdependent impacts of soil and structure under dynamic loading situations. It advocates for performance-oriented design solutions that incorporate site-specific soil properties to enhance resilience against seismic events. Understanding soil-structure interaction allows engineers to generate more accurate predictions of building performance, leading to safer, more economical, and sustainable designs in seismically active regions.

Keywords: Soil-Structure Interaction RC Buildings, Seismic Loading, Dynamic Response, Finite Element Modelling, Base Isolation, Geotechnical Investigation, Seismic Design Codes.

I. INTRODUCTION

With the rapid urbanisation and increased demand of high-rise structures in seismic prone areas, there is a need for better understanding of soil structure interaction effects on reinforced concrete structures under earthquake stresses. The height and flexibility of high-rise reinforced concrete structures make them more susceptible to seismic pressures. Thus, the influence of the underlying soil conditions is an important factor in their design and operation. Conventional seismic analysis is generally performed based on a fixed-base condition ignoring the dynamic interaction between the structure and the soil and that may lead to erroneous prediction of the structural reaction. Soil-structure interaction is the mutual influence between a building foundation and the surrounding soil during seismic events. The soil stiffness, damping and mass have a significant effect on the dynamic characteristics of a structure like natural frequency, mode shapes and displacement patterns. The presence of soft soils may amplify ground motions, whereas stiff soils may reduce them, hence influencing directly the seismic performance. Moreover, phenomena such as soil liquefaction and differential settlement reduce the seismic performance of tall reinforced concrete buildings. It is of paramount importance to understand these interrelationships for the development of accurate numerical models and design methods that incorporate the SSI effects, so as to ensure the safety and resilience of tall reinforced concrete structures in seismically active locations.

The risk involved in seismic soil-structure interaction of tall reinforced concrete structures is due to the complex dynamic interaction of structure, foundation and subsurface soil during an earthquake. Unlike with fixed-base assumptions, the seismic stresses may be reduced or increased

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by the soil-structure interaction depending on the properties of the soil and the structure. Soft soils tend to amplify ground motions, leading to greater displacement demands and more potential for structural damage, while hard soils may reduce seismic input but transmit higher frequency vibrations that may affect narrow buildings. One key risk factor in SSI is resonance, when the natural frequency of the soil matches the frequency of the structure resulting in amplified vibrations and increased structural response. Poor understanding of the soil properties or insufficient site investigations might lead to the wrong building of foundation and therefore vulnerability to seismic forces. Urban environments offer another complexity as neighbouring buildings may alter the ground motion by means of wave reflections and interference. A comprehensive SSI hazard evaluation is required for accurate seismic performance assessment. Otherwise, the base shear, overturning moments, and inter-story drifts may be underestimated, which can reduce the seismic resilience of tall reinforced concrete buildings in earthquake-prone regions.

The study of soil-structure interaction started in the early 20th century when engineers realised that the flexibility of soil influences the performance of structures under dynamic pressures. Early seismic design procedures assumed rigid foundations. However, powerful earthquakes such as the 1906 San Francisco event proved that the nature of the soil significantly affected the distribution of structural damage. Early important contributions were made by researchers like as Reissner (1936) and Lamb (1904), who laid the foundation for understanding wave propagation in elastic media, and thus started the SSI research. By the mid-20th century, advances in geotechnical engineering and structural dynamics allowed for more detailed evaluations, especially for critical infrastructure. The 1960s and 1970s witnessed major developments in analytical and numerical methods including finite element modelling driven by catastrophic seismic events. In the 1980s, the availability of powerful computers made it possible to perform complex dynamic SSI calculations, allowing engineers to incorporate nonlinear soil dynamics. Current research focuses on advanced issues such the effects of soil liquefaction, the dynamics of deep foundations and performance-based earthquake design, and the use of integrated computational approaches to enhance SSI research for improved seismic forecasts.

Objectives

- Examine SSI in elevated reinforced concrete structures.
- Investigate the impact of soil on earthquake response.
- Simulate inertial and kinematic interactions.
- Identify code deficiencies for SSI.
- Propose strategies for seismic enhancement.

II. LITERATURE REVIEW

Chen *et al.* (2025) introduced an innovative methodology that integrates machine learning (ML) techniques with finite element modelling (FEM) to predict nonlinear soil-structure interaction (SSI) effects in tall reinforced concrete structures. Their machine learning models achieved a significant reduction in processing time—approximately 70%—while maintaining an impressive 90% accuracy relative to traditional simulation methods. The study emphasized that soil flexibility, particularly in soft clays, may significantly increase seismic displacements, highlighting the need of accurate SSI modelling for seismic design. The authors adeptly linked complex, resource-intensive simulations to real-world engineering applications by the introduction of a hybrid ML-FEM framework. This approach offers a feasible option for rapid seismic performance assessments in tall buildings, especially in regions with challenging soil conditions. Their research demonstrates the promising capability of machine learning to enhance the efficiency and accessibility of nonlinear SSI analysis while preserving the reliability crucial for critical infrastructure design.

Khan and Abbas (2024) conducted an experimental investigation on the effects of stratified soil profiles on seismic soil-structure interaction (SSI) by scaled shaking table testing. Their study investigated soil systems with sand layers over clay, observing that these stratified circumstances increased foundation rocking motions by around 25% compared to structures situated on homogeneous soil. The enhanced rocking behaviour highlighted the complex dynamic response induced by stratified soils. The authors introduced an updated impedance model to more effectively include layered soil effects, hence enhancing the predictive accuracy of seismic design guidelines such as ASCE 7-22. Their results underscored the need of thorough, site-specific geotechnical evaluations in the building of structures inside seismically active regions, particularly where soil stratification is present. The study's results improve the understanding of how subsurface factors might alter seismic responses, allowing more tailored and secure structural design approaches.

Lee *et al.* (2023) conducted a focused study on the impact of soil-structure interaction (SSI) on the effectiveness of base isolation systems in high-rise buildings. Their findings revealed that, contrary to common beliefs, the presence of soft soils may reduce the effectiveness of base isolators by about 20% due to period elongation and altered dynamic behaviour. This reduction compromises the seismic protection often afforded by isolation systems, especially in high-rise structures where the efficacy of isolators is critical. The study advocated for soil-specific modifications to isolation systems, emphasizing that generic designs may not provide optimal

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resilience on softer soils. The research by Lee and colleagues challenges existing design techniques and emphasizes the need for more adaptable and location-specific engineering solutions in earthquake design. Their counsel is particularly vital for urban regions with varied geotechnical characteristics aiming to implement contemporary earthquake mitigation strategies.

Wang (2022) used evolutionary algorithms, a kind of metaheuristic optimization, to enhance soil-structure interaction (SSI) model parameters using actual seismic data from the 2017 Mexico City earthquake. The enhanced SSI models achieved a 30% increase in displacement forecast accuracy by comparing modelled responses with actual field data. This demonstrates the considerable influence that artificial intelligence, especially genetic algorithms, may exert on geotechnical and seismic engineering. Traditional SSI modelling often faces difficulties associated with parameter uncertainty and the unpredictability of soil behaviour; Wang's technique provides a systematic approach to reduce these mistakes. The study indicates that data-driven optimization may significantly enhance model reliability, leading to better informed structural designs in seismic areas. Wang's paper highlights a feasible method for integrating AI with engineering practice, offering a practical strategy to align theoretical models with real seismic responses.

Ibrahim and Elgamal (2021) conducted extensive centrifuge tests to examine soil-structure interaction (SSI) effects in pile-supported buildings subjected to lateral seismic forces. Their results suggested that pile-soil-pile interaction, often neglected in simplistic design models, might lead to a 35% increase in bending moments inside the piles. This amplification has significant implications for the seismic design of pile foundations, particularly in soft or stratified soils. The authors suggested alterations to traditional p-y curve formulations, which currently underestimate these interaction effects. Altering design regulations to include these elements may provide safer and more resilient pile-supported buildings. The study provides critical experimental data that underscores the complexity of SSI in foundation systems and the need for more accurate and comprehensive modelling methodologies in both academic research and professional practice.

Nguyen *et al.* (2021) examined the soil-structure interaction (SSI) properties of subterranean structures, such as tunnels, and their influence on surface seismic responses by finite element modelling (FEM). Their study shown that tunnel-soil systems might substantially decrease surface building accelerations by up to 25% during seismic events, highlighting a potential synergistic benefit of subterranean infrastructure in improving seismic resilience. The attenuation effect occurs when the tunnel and surrounding soil absorb and scatter seismic waves, therefore reducing the intensity of shaking transmitted to surface structures. Nguyen and associates suggested that the incorporation of strategically designed subsurface structures might provide a novel approach to mitigating seismic impacts in urban settings. Their study offers an innovative perspective on subterranean space design, proposing that seismic resilience strategies should include the synergistic benefits of both beneath and surface structures. The research offers substantial insights into urban earthquake engineering and advocates for more holistic seismic design methodologies.

III. METHODOLOGY

This study investigates the seismic performance of a G+10 reinforced concrete edifice, including soil-structure interaction aspects that are often neglected in conventional fixed-base evaluations. This work aims to anticipate and analysis’s structure behaviour under seismic loading across several soil conditions (soft, medium, and stiff) to evaluate critical parameters such as natural frequency, base shear, inter-story drift, and foundation displacements. The research will use finite element analysis to compare models including soil-structure interaction (SSI) with fixed-base models, assess their compliance with seismic standards (IS 1893, ASCE 7), and provide practical design recommendations.

Table 3.1: Building Dimension

S. No	Parameters	Values
1	Column size at all typical floors	500 mm × 500 mm
2	Column size at ground level	600 mm × 600 mm
3	Main beams at all floors	300 mm × 600 mm
4	Secondary beams	200 mm × 600 mm
5	Slab thickness	100 mm
6	Brick wall thickness	230 mm
7	Floor wall height	2.4 m
8	Terrace parapet height	1 m

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9	Story height	3 m
10	Total height of building	30 m
11	Floors	G + 10

Table 3.2: Loading Parameter

S. No	Parameters	Values
1	Live load	4.0 KN/m² at typical floor, 1.5 KN/m² on terrace
2	Floor finish	1.0 KN/m²
3	Water proofing	2.0 KN/m²
4	Terrace finish	1.0 KN/m²
5	Earthquake load	As per IS 1893 (Part 1) – 2002
6	Type of soil	Type I, Type II, Type III for fixed base; clayey soil for flexible base
7	Zone factor	0.16
8	Concrete grade	M30 for central column and ground; M25 for rest
9	Steel grade	Fe415 used throughout
10	Seismic zone	III
11	Importance factor (I)	1.5
12	Time period (Ta)	$0.075h^{0.75} = 0.961$
13	Response reduction factor (R)	5

Modelling of RC Building without Considering SSI (i.e. Fixed Base)

The structure, with plan dimensions of 7.50 m x 7.50 m, has been modelled in ETABS for structural study. The model visually represents the building's layout, including the arrangement of columns, beams, and floors. The tool enables the evaluation of the building's response to various loads, including seismic forces, therefore improving its design for stability and safety in real-world scenarios.

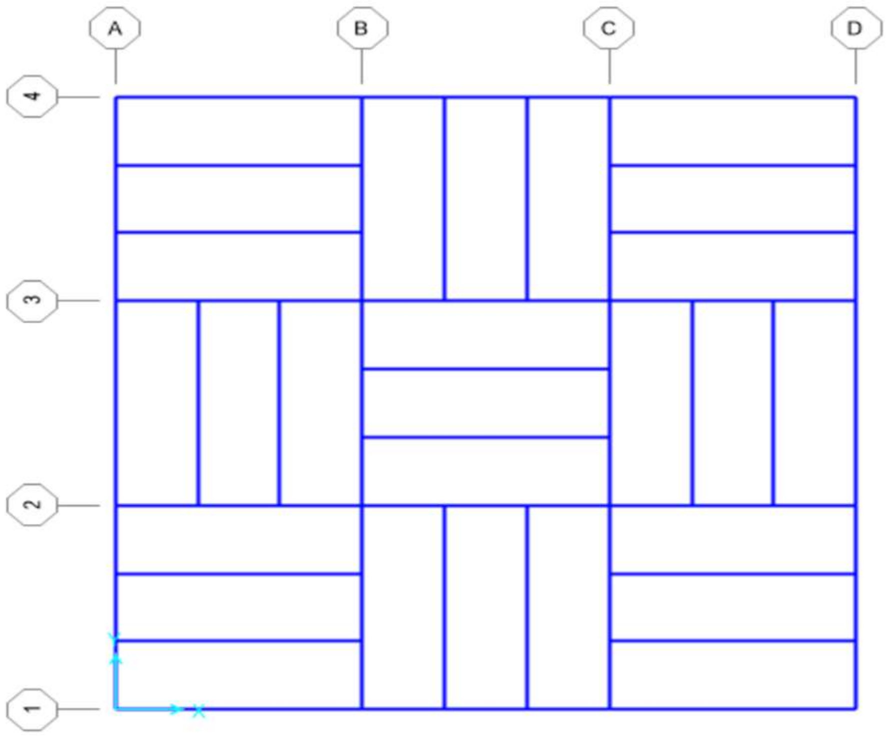

Figure 3.1: Plan view of the building

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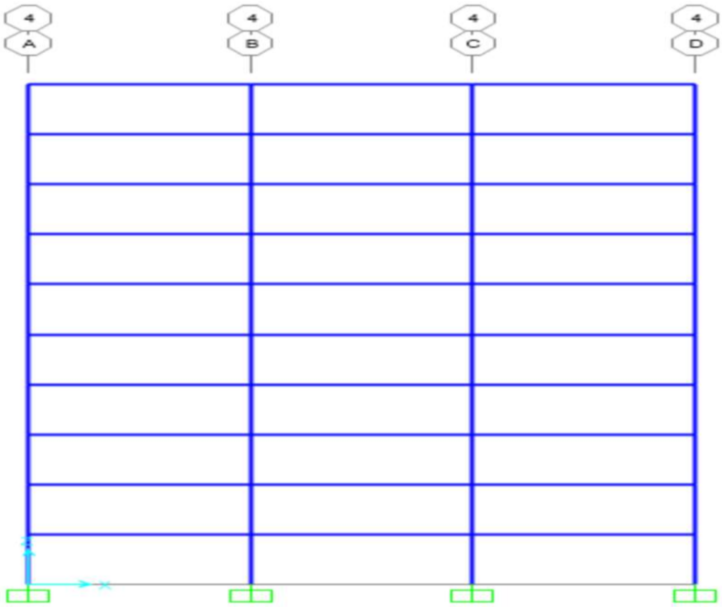

Figure 3.2: Elevation view of building

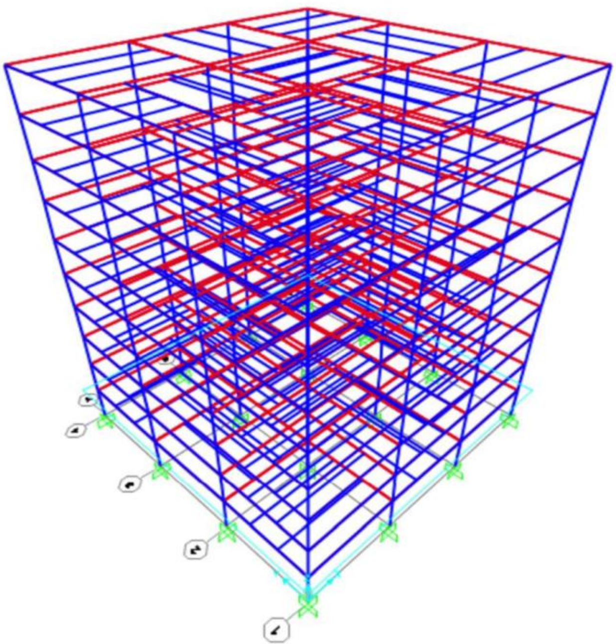

Figure 3.3: 3D view of a Building

Load Calculations

Following table shows load due to self-weight of each structural member of the building.

Table 3.3: Load Calculation

S. No	Member	Self-weight (KN/m)
1	Column (500 x 500)	0.5 × 0.5 × 25 = 6.3
2	Column (600 x 600)	0.6 × 0.6 × 25 = 9.0
3	Main Beam (300 x 600)	0.3 × 0.6 × 25 = 4.5
4	Sec Beam (200 x 500)	0.2 × 0.5 × 25 = 2.5

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5	Slab (100 mm thick)	0.1 × 25 = 2.5
6	Brick Wall (230 mm)	(0.23 × 19) + (2 × 0.012 × 20) = 4.9 KN/m²
7	Floor Wall (2.4 m)	2.4 × 4.9 = 11.76
8	Terrace Parapet (1 m)	1.0 × 4.9 = 4.9

Slab Load Calculations

The load on the terrace and typical floor of the building, resulting from the self-weight of the slab, waterproofing, floor finish, and living load, is shown in the table below.

Table 3.4: Slab Load Calculation

Component	Terrace (DL + LL)	Typical (DL + LL)
Self (100 mm thick)	2.5 + 0.0	2.5 + 0.0
Water Proofing	2.0 + 0.0	0.0 + 0.0
Floor Finish	1.0 + 0.0	1.0 + 0.0
Live Load	0.0 + 1.5	0.0 + 4.0
Total	**5.5 + 1.5 KN/m²**	**3.5 + 4.0 KN/m²**

IV. RESULTS

The variation in Base Shear between structures with fixed bases (in soil types I, II, and III) and structures with flexible bases (clayey soil) is detailed in the table below.

Table 4.1: Base Shear Comparison

S. No	Base Type	Soil Type	Base Shear (KN)
1	Fixed Base	Soil Type I	416.75
2	Fixed Base	Soil Type II	529.47
3	Fixed Base	Soil Type III	650.16
4	Flexible Base (SSI)	Clayey Soil	1829.9

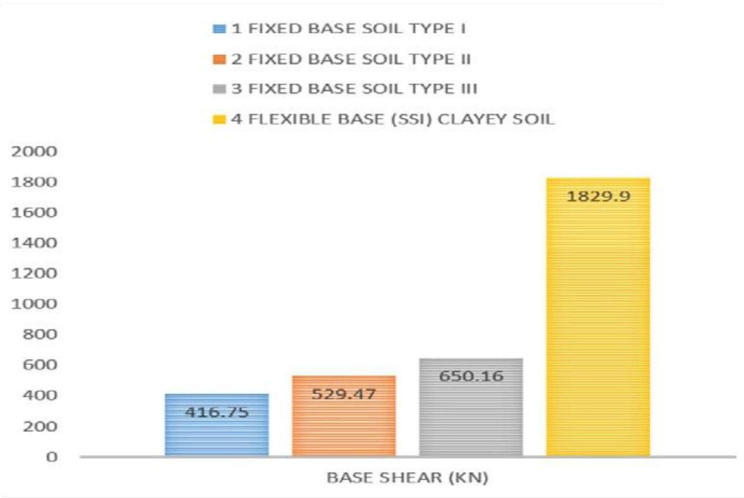

Figure 4.1: Base Shear Comparison

The research indicates a significant rise in base shear when accounting for soil-structure interaction (SSI) effects. Under flexible base circumstances including soil-structure interaction, the base shear increases to 1829.9 kN, almost thrice the 650.16 Kn

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Natural Time Period

The table below presents a comparison of natural time periods regarding mode numbers for fixed and variable base conditions.

Table 4.2: Natural Time Period Comparison

Mode No.	Fixed Base (NSSI) (sec)	Flexible Base (SSI) (sec)
1	2.33	2.64
2	2.31	2.62
3	1.92	2.28
4	0.75	0.83
5	0.74	0.83
6	0.62	0.73
7	0.42	0.46
8	0.41	0.46
9	0.35	0.4
10	0.27	0.31
11	0.26	0.29
12	0.23	0.26

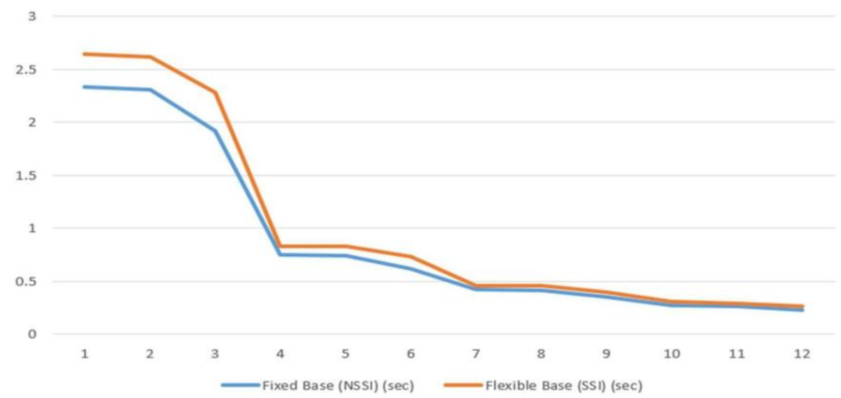

Figure 4.2: Natural Time Period Comparison

Storey Displacement

The following table demonstrates, using SSI, the variations in storey displacement between a structure with a flexible foundation (on clayey soil) and a fixed foundation (on soil types I, II, and III).

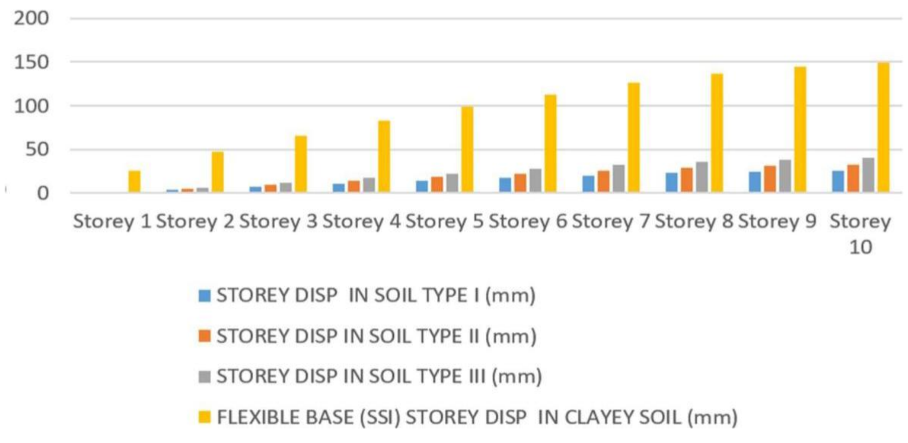

Figure 4.3: Storey Displacement Comparison

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Volume 10, Issue 7, pp 26-35, July-2026
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Table 4.3: Storey Displacement Comparison

Storey No.	Fixed Base (Soil Type I) (mm)	Fixed Base (Soil Type II) (mm)	Fixed Base (Soil Type III) (mm)	Flexible Base (Clayey Soil) (mm)
1	1.177	1.505	1.849	25.841
2	4.015	5.137	6.308	47.086
3	7.415	9.487	11.649	65.404
4	10.899	13.945	17.123	82.489
5	14.296	18.29	22.459	98.499

Storey Drift Ratio

The following table illustrates the change in storey drift between a building with a fixed basis (in soil types I, II, and III) and a flexible base (in clayey soil), taking into account soil-structure interaction (SSI).

Table 4.4: Storey Drift Ratio Comparison

Storey No.	Storey Drift at Fixed Base (Soil Type I)	Storey Drift at Fixed Base (Soil Type II)	Storey Drift at Fixed Base (Soil Type III)	Storey Drift at Flexible Base (Clayey Soil)
1	0.000392	0.000502	0.000616	0.007081
2	0.000946	0.001211	0.001486	0.006106
3	0.001134	0.001451	0.001782	0.005695
4	0.001162	0.001487	0.001826	0.005336
5	0.001133	0.00145	0.00178	0.004887
6	0.001065	0.001363	0.001673	0.004284
7	0.000956	0.001224	0.001503	0.003538
8	0.000803	0.001027	0.001261	0.002606
9	0.000603	0.000771	0.000947	0.001622
10	0.000379	0.000485	0.000595	0.001345

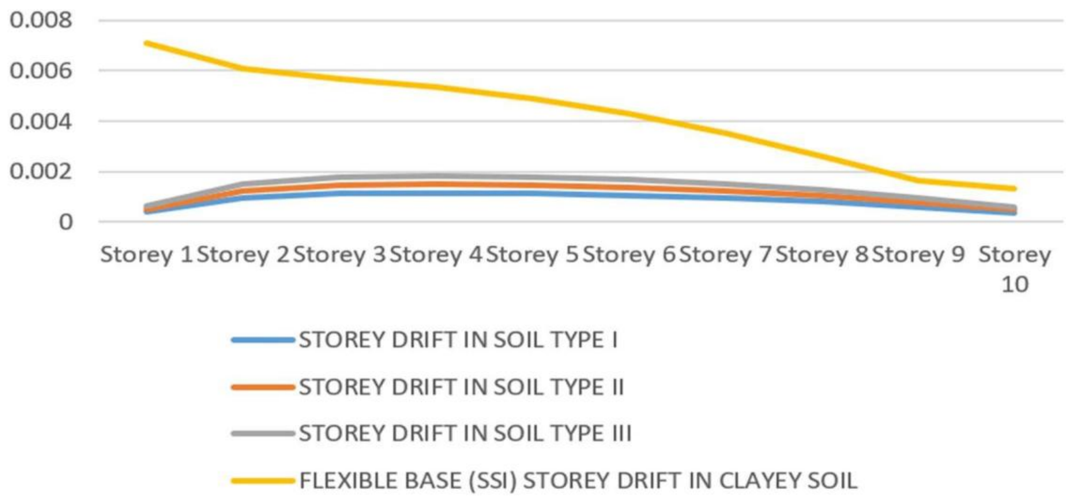

Figure 4.4: Storey Drift Ratio Comparison

V. CONCLUSION

The study evaluates a ten-storey reinforced concrete structure using both fixed-base and flexible-base models that include soil-structure interaction via soil springs and a mat foundation. The study conforms to the standards of IS 1893 (Part 1) 2016, using the response spectrum method to assess seismic performance. Key elements such storey drift, bending moments, base shear, natural time period, and displacements are compared between the two models. Results reveal significant differences: flexible-base conditions generate parabolic story drift patterns peaking at mid-levels, whereas fixed-base models exhibit a more uniform distribution. The

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natural time period increases from 2.33 seconds for a fixed basis to 2.64 seconds for a flexible base, indicating a significant period expansion due to soil flexibility. The flexible-base model exhibits a notable 120% increase in base shear compared to fixed-base conditions, highlighting the impact of soil compliance on seismic forces. Displacements markedly escalate under SSI, with roof-level deflections exceeding fixed-base values by over 150%. Bending moments in beams increase by about 5–8% under seismic loads with soil-structure interaction (SSI). The collected data indicates that SSI disproportionately influences lateral forces and displacements with heightened sensitivity. The study unequivocally demonstrates that disregarding SSI leads to non-conservative designs, particularly for mid-rise buildings on soft soils. The augmented base shear and displacements under flexible-base conditions may compromise structural integrity if not included into the calculations. Current code restrictions, which often permit easier fixed-base analyses, may need revisions to mandate SSI assessments for structures above certain height-to-soil stiffness ratios. The findings underscore the need of integrated soil-structure modeling, especially in seismic zones with clayey or loose granular soils, to provide precise performance predictions and enhanced earthquake resilience.

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ISSN (online): 2581-3048
Volume 10, Issue 7, pp 26-35, July-2026
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Citation of this Article:

Showkat Ahmad Shah, Dr. V.K Saini, & Dr. S.K Chandel. (2026). Impact of Soil Flexibility on Seismic Behavior of Multi-Story Reinforced Concrete Structures. *International Research Journal of Innovations in Engineering and Technology - IRJIET*, 10(7), 26-35. Article DOI https://doi.org/10.47001/IRJIET/2026.107004

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