WWW.IJRPR.COM

International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

Influence of Soil–Structure Interaction on the Seismic Performance of Fixed-Base and Flexible-Base RC Buildings of Different Plan Shapes and Heights

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ABSTRACT—

Conventional seismic analysis of reinforced concrete (RC) buildings assumes a rigid, fixed base, which neglects the deformability of the supporting soil. This study examines how soil–structure interaction (SSI) affects the seismic response of RC frame buildings of rectangular, L-shaped and T-shaped plan, with heights of G+3, G+7, G+11 and G+15. Digital models were developed and analysed in STAAD.Pro using the seismic coefficient method and response spectrum analysis in accordance with IS 1893 (Part 1):2016. Soil flexibility was represented by translational and rotational springs at the base and compared against fixed-base models. Storey shear, storey displacement, natural time period, storey drift ratio and storey stiffness were compared across configurations. Flexible-base models showed longer time periods (about 17% higher), considerably larger displacements (about 16% for G+3 rising to about 60% for G+15) and a lower base shear (about 5%) than fixed-base models, with drift ratios and stiffness also affected by SSI; the L-shaped building generally recorded the largest displacements. The effects grew with building height. Life cycle assessment (LCA) and embodied carbon are introduced as sustainability considerations, although no LCA calculations are presented in this study. The results show that fixed-base assumptions may underestimate deformation demands, particularly in tall and plan-irregular RC buildings.

Keywords— soil–structure interaction; RC buildings; plan irregularity; response spectrum analysis; STAAD.Pro; storey drift; life cycle assessment

1. INTRODUCTION

Earthquake ground motion subjects buildings to dynamic inertial forces in addition to gravity loads, and these lateral forces can cause severe damage or collapse of RC structures, with serious human and economic consequences. The Bureau of Indian Standards divides India into four seismic zones (II to V), of which Zone V is the most seismically active. Reliable prediction of structural response therefore depends on analysis methods that represent both the structure and its supporting medium realistically. Seismic analysis is commonly divided into static approaches (the seismic coefficient method and pushover analysis) and dynamic approaches (response spectrum and time history analysis). The seismic coefficient method is adequate for regular low- to medium-rise buildings governed by the first mode, whereas response spectrum analysis accounts for multiple modes and is better suited to taller or more complex configurations.

SSI describes the mutual influence between the motion of the supporting soil and the response of the structure. In the conventional fixed-base model, the foundation is idealised as rigid, so the soil cannot translate or rotate under seismic excitation. In a flexible-base model, the soil is represented by equivalent translational and rotational springs whose stiffness depends on soil properties such as shear modulus, shear wave velocity and Poisson's ratio. Increasing soil flexibility lengthens the natural period and increases lateral displacement and deformation demand. Neglecting SSI has been reported to overestimate stiffness and underestimate damping [1]–[6], [9], which makes fixed-base analysis an unconservative idealisation for deformation-governed checks.

Building height governs the fundamental period and the way SSI and cracking amplify deformation; taller buildings are more flexible and show larger drifts [3], [8], [10]. Plan irregularity, such as L-shaped and T-shaped layouts, produces uneven stiffness and mass distribution and may induce torsion, increasing deformation demand relative to regular layouts [5], [6]. Concrete cracking reduces the effective flexural stiffness of beams, columns and walls once the cracking moment is exceeded, leading to larger lateral displacement and inter-storey drift and to potential second-order effects [3], [8], [10], [12]. The influence of cracked-section properties is therefore recognised in the literature as an important factor in seismic response, and it is reviewed in Section 2.4.

Seismic performance is judged here through five response parameters: storey displacement (lateral movement of each floor), storey shear (distribution of seismic force along the height), storey stiffness (resistance of each floor to lateral movement), storey drift ratio (relative displacement of consecutive floors divided by storey height) and natural time period (a global indicator of flexibility). Together they identify critical storeys and permit systematic comparison of building configurations and base conditions.

The construction sector is a major consumer of energy and raw materials, and cement, steel and masonry make a large contribution to building CO_2 emissions. Embodied energy and embodied carbon describe the energy and emissions arising from material extraction, processing, manufacturing, transport and construction. LCA considers these impacts across the whole building life cycle, from material production to end-of-life, and web platforms

such as One Click LCA support such assessments. Seismic design itself can raise embodied carbon through larger sections and heavier reinforcement [4]. In this paper, LCA and embodied carbon are introduced as environmental context for the structural comparison; no LCA inventory or impact calculation is presented.

Research problem. Fixed-base assumptions are still widespread in design practice, yet their effect on RC buildings of differing plan shape and height is not consistently quantified.

Research gap. Existing studies in the reviewed set address SSI with open-ground-storey buildings, slopes, setbacks, shear walls, or a limited set of plan shapes, mostly with SAP2000, ETABS or LS-DYNA and largely pushover or time history methods [1], [2], [5]–[7], [9]. Within the reviewed literature, no study varies plan shape (rectangular, L, T) and height (G+3 to G+15) together under fixed and flexible bases, using the seismic coefficient and response spectrum methods in STAAD.Pro, while also considering embodied carbon.

Objectives. The study aims (i) to model rectangular, L-shaped and T-shaped RC frame buildings of G+3, G+7, G+11 and G+15 in STAAD.Pro; (ii) to analyse them under fixed-base and spring-supported flexible-base conditions; (iii) to compare storey shear, displacement, time period, drift ratio and stiffness; and (iv) to introduce LCA and embodied carbon as sustainability considerations relevant to the structural findings.

Contribution. The paper provides a systematic comparison of SSI effects across plan shapes and heights for RC frames and quantifies the growth of SSI effects with height. Findings are presented in later sections.

2. REVIEW OF RELATED WORK

The twelve studies in the reference list are discussed thematically below.

2.1 Soil flexibility and soil–structure interaction

Rao et al. [1] (2021) studied 3-, 5- and 8-storey open-ground-storey RC buildings with fixed, hinged, hard-, medium- and soft-soil bases using SAP2000 with static nonlinear pushover analysis. SSI effects were small on hard soil and largest on soft soil, with longer periods, larger displacements, reduced base shear and more plastic hinging, and were stronger for slender buildings. Dhakal and Chaulagain [6] (2023) used SAP2000 response spectrum analysis on regular, T-, L-, H- and plus-shaped buildings on fixed, hard, medium and soft soils. Period, displacement and drift increased and base shear decreased as soil softened, for every plan shape. Jayalekshmi and Chinmayi [9] (2014) analysed 4- to 16-storey frames with and without shear walls in LS-DYNA across soils from hard rock to soft. Soft soil lengthened periods and lowered base shear, central core walls gave higher stiffness and base shear than corner walls, and Eurocode 8 predicted higher base shear than IS 1893:2002. El Janous and El Ghoulbzouri [5] (2024) combined SSI with vertical setback irregularity in SAP2000 pushover analysis, finding better performance on rock and hard soils and more deformation and hinging on soft and very soft soils. Ghosh and Debbarma [7] (2019) studied a G+4 building on slopes of 0°–45° in Zone V with ETABS and SAP2000 using equivalent static, response spectrum, time history and pushover methods. SSI increased the period and displacement, and steeper slopes increased vulnerability.

2.2 Comparison across SSI studies

The studies agree that softer soil increases period, displacement and drift while lowering base shear [1], [5], [6], [9], which matches the direction of the present results. They differ in analysis method (pushover [1], [5], response spectrum [6], finite element [9], mixed methods [7]), software and the structural feature varied (infill, setback, shear wall, slope, plan shape). Most use soil classes (hard, medium, soft) instead of a single flexible-base case, and none combines plan shape with heights up to G+15. Only [6] considers L- and T-shaped plans.

2.3 Plan irregularity, infill and open ground storey

Tasleem et al. [2] (2022) examined 4- to 10-storey open-ground-storey frames with and without infill struts on medium soil, using nonlinear time history and pushover analyses. Omitting infill struts caused very large period increases relative to the IS 1893:2016 formula, and drift exceeded 0.004 in the bare-frame models. Mai et al. [11] (2024) used SAP2000 pushover analysis on 4-, 5- and 7-storey regular and irregular frames and found that infill raised stiffness and base-shear capacity, reduced displacement and period, and increased the response reduction factor R by about 38%–75%, while irregular buildings were more vulnerable. These studies show that building configuration and non-structural elements modify SSI-related trends, but neither of them addresses L- and T-shaped plans under flexible bases.

2.4 Concrete cracking and stiffness degradation

Ahmed et al. [3] (2008) analysed 4- and 11-storey buildings in STAAD.Pro with gross and cracked sections on medium soil in Zone II and found larger deflection and drift in cracked sections, markedly so for the taller building. Prajapati and Amin [8] (2019) designed 2- to 12-storey Zone V buildings with gross, cracked and modified cracked sections and assessed them by pushover and nonlinear time history analyses. Cracked-section buildings exceeded drift limits unless columns were enlarged, and the effect grew with height. Prasanth and Ghosh [12] (2021) compared gross and cracked G+10 models by pushover analysis (0.10g–1.70g) and found lower resilience, earlier collapse-prevention state and higher expected loss for the cracked model. Pham et al. [10] (2026) examined 3-, 10- and 20-storey frames in SAP2000, finding that beam stiffness governs low-rise response and column stiffness mid- and high-rise response, with marked growth in displacement and period below about 50% effective stiffness. The consistent finding is that cracking amplifies deformation more strongly in taller buildings. Study [3] used STAAD.Pro, the software of the present study, but treated a fixed base only.

2.5 Seismic design and embodied carbon

Yardimci and Bayraktarlı [4] (2026) compared 2- to 8-storey fixed-base RC buildings in ETABS with and without seismic design, using a BIM-integrated LCA. Embodied carbon, steel quantity and cost rose with height and were substantially higher with seismic design, with columns the main contributor in seismic cases and slabs in non-seismic cases. This is the only embodied-carbon study among the reviewed references, and it excludes SSI.

2.6 Research gap addressed

Taken together, the studies establish that SSI, cracking, irregularity and infill each change seismic response, and that seismic design affects embodied carbon. What is missing from this set is an integrated comparison of rectangular, L- and T-shaped frames at four heights (G+3 to G+15) under fixed and flexible bases in STAAD.Pro, linked to environmental performance. The present study addresses the structural part of this gap and introduces the environmental dimension as context (Section 1).

3. CASE STUDY (DIGITAL MODEL)

3.1 Scope and modelling platform

The case study consists of three-dimensional RC frame digital models created in STAAD.Pro. These are structural analysis models; no BIM model is claimed, and BIM is referred to only in the general discussion of LCA. STAAD.Pro is the analysis software used in this study.

3.2 Building configurations and heights

Three plan configurations were studied: rectangular, L-shaped and T-shaped. Each was modelled at four heights: G+3, G+7, G+11 and G+15, giving 12 geometries. Each geometry was analysed with fixed and flexible bases, giving 24 models. Response directions are labelled x (longer direction) and z (shorter direction).

3.3 Base conditions and representation of soil flexibility

Fixed-base models restrain the base nodes completely, representing a rigid foundation. In flexible-base models, soil is represented by translational and rotational springs at the supports, in keeping with the SSI concept described in Section 1. Soil classification follows IS 1893 (Part 1):2016, and the results presented for comparison include the fixed-base and flexible-base conditions as well as soft, medium and hard soil conditions.

3.4 Model parameters

The principal modelling parameters are summarised in Table 1. Seismic analysis follows IS 1893 (Part 1):2016.

Table 1. Summary of model parameters.

Parameter	Description
Plan shapes	Rectangular, L-shaped, T-shaped
Building heights	G+3, G+7, G+11, G+15
Base conditions	Fixed base; flexible base (translational and rotational springs)
Analysis software	STAAD.Pro
Seismic code	IS 1893 (Part 1):2016
Analysis methods	Seismic coefficient method; response spectrum analysis
Response directions	x (longer direction); z (shorter direction)
Response parameters	Storey shear (kN); storey displacement (mm); storey stiffness (kN/mm); storey drift ratio; natural time period (s)

3.5 Output parameters

Models are compared using five responses extracted separately along the x and z directions, except the time period, which is a global quantity: storey shear (kN), storey displacement (mm), storey stiffness (kN/mm), storey drift ratio (dimensionless) and natural time period (s).

4. METHODOLOGY

4.1 Overall procedure

The procedure, summarised in Fig. 1, comprises seven steps.

1. **Define the study.** Select plan shapes (rectangular, L, T) and heights (G+3, G+7, G+11, G+15).
2. **Develop digital models.** Create 12 three-dimensional frame geometries in STAAD.Pro.
3. **Assign base conditions.** For each geometry, define a fixed-base model and a flexible-base model in which soil is represented by translational and rotational springs.
4. **Apply seismic loading.** Apply loading according to IS 1893 (Part 1):2016.
5. **Run analyses.** Perform seismic coefficient analysis and response spectrum analysis for all 24 models.
6. **Extract responses.** Obtain storey shear, displacement, stiffness, drift ratio and natural period in the x and z directions.
7. **Compare.** Compare responses between fixed and flexible bases, among plan shapes, and across heights, and compute percentage changes.

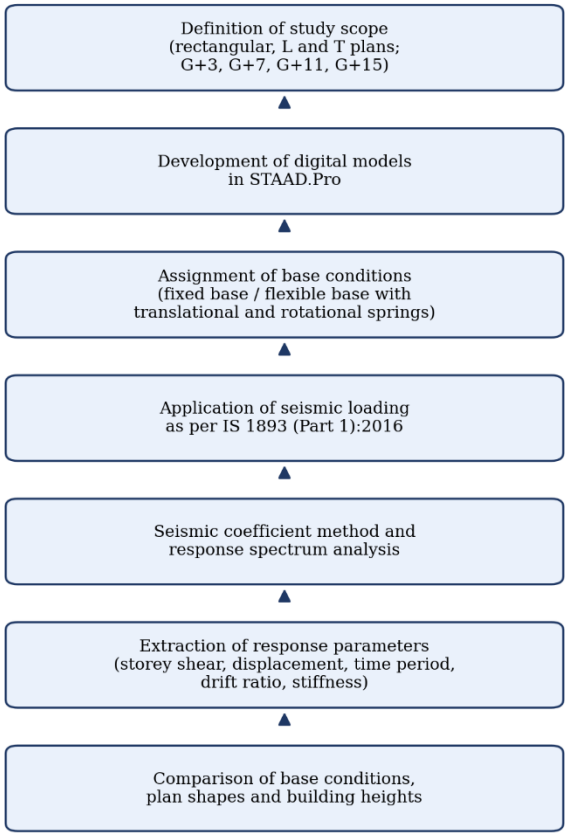


Fig. 1. Methodology flowchart.

4.2 Modelling of shapes and heights

The three plan shapes were each extended to four heights, so that plan irregularity and height can be examined independently and jointly. The rectangular plan is the regular reference, and the L and T plans are re-entrant corner (irregular) layouts. The L shape is unsymmetrical about both axes, and its larger displacement and period are attributed to this asymmetry.

4.3 Fixed-base and flexible-base assumptions

The fixed-base case assumes a rigid foundation. The flexible-base case assumes a linear soil model in which translational and rotational springs reproduce foundation movement, and soil flexibility depends on shear modulus, shear wave velocity, Poisson's ratio and stiffness.

4.4 Seismic analysis methods

Two methods were used. The seismic coefficient method estimates base shear and distributes it over the storeys by code formulae, and is generally limited to regular low- to medium-rise structures dominated by the first mode. Response spectrum analysis obtains modal responses from the design spectrum and combines them to estimate total response. Pushover and time history methods are described only as general background and were not used.

4.5 Extraction and comparison of response parameters

Responses were read at each storey level from STAAD.Pro and plotted as storey-wise graphs for the x and z directions, for flexible and fixed bases (storey shear, displacement, drift ratio and stiffness), and as comparisons between configurations for the time period. The comparison covers: (i) flexible versus fixed base for each shape and height; (ii) the governing shape for each response; and (iii) the change with height. Percentage differences between flexible-base and fixed-base responses were calculated to quantify the effect of SSI.

4.6 Life cycle assessment and embodied carbon

LCA and embodied carbon are considered in this paper at the conceptual level only. A cradle-to-gate web-based platform such as One Click LCA could be used to quantify the embodied carbon of the modelled buildings, but no material quantities, system boundary, functional unit or impact results are reported here, and the analysis presented does not include an LCA calculation.

5. RESULTS AND DISCUSSION

This section presents the base shear and displacement of the L-shaped and rectangular buildings under soft, medium and hard soil conditions. Base shear is expressed in kN and displacement in mm, in line with the output parameters defined in Section 3.5. Differences between the two building shapes are calculated from the tabulated values and are expressed relative to the rectangular building.

5.1 Base Shear Analysis under Different Soil Conditions

Table 2 and Fig. 2 give the base shear of the L-shaped and rectangular buildings for soft, medium and hard soils.

Table 2. Comparison of base shear (kN) of L-shaped and rectangular buildings under soft, medium and hard soil conditions. Difference is the L-shaped value relative to the rectangular value.

Soil	L-shaped (kN)	Rectangular (kN)	Difference (%)
Soft	9348.46	8984.16	+4.05
Medium	7417.09	7254.10	+2.25
Hard	5414.76	5308.98	+1.99

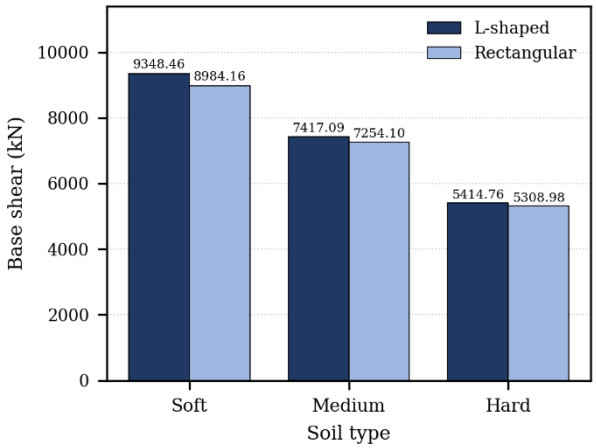


Fig. 2. Base shear (kN) versus soil type for the L-shaped and rectangular buildings.

For both building shapes, base shear is highest on soft soil and lowest on hard soil. For the L-shaped building, base shear is 9348.46 kN on soft soil, 7417.09 kN on medium soil and 5414.76 kN on hard soil; the corresponding values for the rectangular building are 8984.16 kN, 7254.10 kN and 5308.98 kN. Moving from hard to medium soil increases base shear by about 37% for both shapes (36.98% for the L-shaped and 36.64% for the rectangular building). Moving from medium to soft soil increases it by a further 26.04% for the L-shaped and 23.85% for the rectangular building. Overall, base shear on soft soil is about 72.65% higher than on hard soil for the L-shaped building and about 69.23% higher for the rectangular building.

The L-shaped building records a higher base shear than the rectangular building under all three soil conditions. The difference is 4.05% on soft soil, 2.25% on medium soil and 1.99% on hard soil, so the gap between the two shapes is largest on soft soil and smallest on hard soil.

5.2 Displacement Analysis under Different Soil Conditions

Table 3 and Fig. 3 give the displacement of the two buildings for soft, medium and hard soils.

Table 3. Comparison of displacement (mm) of L-shaped and rectangular buildings under soft, medium and hard soil conditions. Difference is the L-shaped value relative to the rectangular value.

Soil	L-shaped (mm)	Rectangular (mm)	Difference (%)
Soft	301.625	332.292	−9.23
Medium	221.075	228.636	−3.31
Hard	159.363	159.339	+0.02

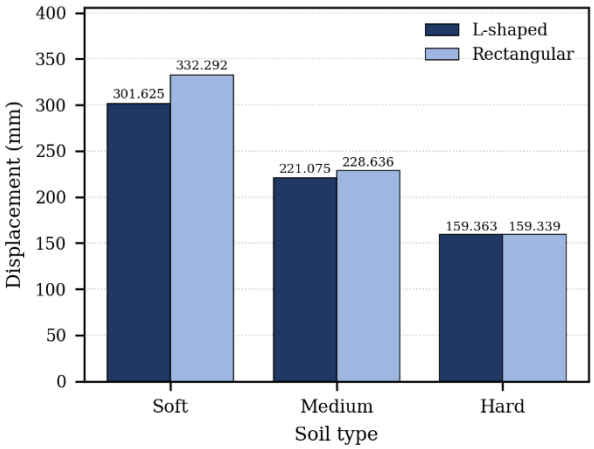


Fig. 3. Displacement (mm) versus soil type for the L-shaped and rectangular buildings.

Displacement increases as the soil becomes softer for both building shapes. For the L-shaped building, displacement is 159.363 mm on hard soil, 221.075 mm on medium soil and 301.625 mm on soft soil; the corresponding values for the rectangular building are 159.339 mm, 228.636 mm and 332.292 mm. Relative to hard soil, displacement on medium soil is higher by 38.72% for the L-shaped and 43.49% for the rectangular building, and displacement on soft soil is higher by 89.27% and 108.54%, respectively. Increases from medium to soft soil are 36.44% for the L-shaped building and 45.34% for the rectangular building.

On hard soil, the displacements of the two buildings are almost identical (159.363 mm and 159.339 mm; a difference of 0.02%). On medium and soft soils, the rectangular building shows larger displacement than the L-shaped building, by about 3.4% and 10.2% respectively (the L-shaped values being 3.31% and 9.23% lower when expressed relative to the rectangular building, as in Table 3).

5.3 Comparative Discussion and Engineering Interpretation

The results show that soil condition has a much larger influence on both response parameters than building shape. Within each building, base shear differs by about 70% and displacement by about 90% to 109% between hard and soft soil, whereas the difference between the two shapes does not exceed about 4% in base shear and about 10% in displacement under any single soil condition. Both responses therefore follow the same ordering with soil type (soft > medium > hard) for both shapes.

The two responses show different shape-related trends. The L-shaped building has the higher base shear under all soil conditions, but the lower displacement on medium and soft soils. The two shapes have practically the same displacement on hard soil. The shape-related differences in both parameters grow as the soil becomes softer, which indicates that the influence of building configuration on seismic response is more noticeable when soil flexibility is greater.

From an engineering viewpoint, the larger displacements on softer soil indicate greater deformation demand on the buildings, which is consistent with the lengthening of the natural period and the increase in displacement with soil flexibility discussed in Sections 1 and 2.1. The base shear trend with soil type, in which soft soil gives the highest value, differs from the lower base shear observed for flexible-base models relative to fixed-base models in this study, and from the reduction in base shear with softer soil reported in [1], [5], [6], [9]. The present data show that base shear and displacement respond to soil type and building shape in different ways; they do not isolate the mechanisms responsible, and the observed differences should therefore be read as differences in computed seismic response between the cases analysed, not as evidence for a specific cause.

6. CONCLUSION

This study compared the base shear and displacement of L-shaped and rectangular RC buildings under soft, medium and hard soil conditions. The main findings are as follows.

- Base shear increased as soil became softer for both shapes. The L-shaped building recorded 9348.46, 7417.09 and 5414.76 kN on soft, medium and hard soil, and the rectangular building 8984.16, 7254.10 and 5308.98 kN.
- Displacement also increased with soil softness for both shapes. The L-shaped building recorded 301.625, 221.075 and 159.363 mm on soft, medium and hard soil, and the rectangular building 332.292, 228.636 and 159.339 mm.
- Soil type had a greater effect than building shape: between hard and soft soil, base shear rose by about 73% (L-shaped) and 69% (rectangular), and displacement by about 89% (L-shaped) and 109% (rectangular).
- The L-shaped building had slightly higher base shear than the rectangular building under all soil conditions (by 1.99% to 4.05%), whereas the rectangular building had larger displacement on medium and soft soils; displacements were nearly equal on hard soil.

These results indicate that both soil flexibility and building configuration affect seismic response, and that design assessments based on a single soil condition or a single plan shape may not represent the range of response.

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