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Soil-Structure Interaction Effects on the Seismic Performance of Reinforced Concrete Buildings: A Critical Review

Sanket Vijay Wadekar[1], G. V. Joshi[2]

[1]PG Student, Department of Civil Engineering (Structural Engineering), G.H. Raisoni College of Engineering and Management, Pune, India
Email: *sanketwadekar14[at]gmail.com*

[2]Professor, Department of Civil Engineering (Structural Engineering), G.H. Raisoni College of Engineering and Management, Pune, India
Email: *girish.joshi[at]raisoni.net*

Abstract: ***Soil–structure interaction (SSI) changes the effective dynamic system of reinforced concrete (RC/RCC) buildings by coupling superstructure response with foundation translation, foundation rocking, soil deformability and site-dependent ground-motion amplification. This paper presents a critical review of recent SSI research on RCC buildings, with emphasis on soil stiffness, structural height and irregularity, foundation representation, analysis procedure, and the sensitivity of natural period, displacement, inter-storey drift, base shear, torsional response and damage measures. The reviewed evidence shows a consistent tendency for decreasing soil stiffness to increase effective period, foundation movement, lateral displacement and drift. In contrast, base-shear trends are not universally monotonic because period elongation can either reduce or amplify spectral demand depending on the soil profile, structural period, foundation system and frequency content of earthquake excitation. Irregular and high-rise systems are especially sensitive because translational, rocking and torsional modes interact, while direct continuum and nonlinear soil–foundation models reveal response features that fixed-base idealisations cannot capture. The review further identifies growing use of nonlinear time-history, fragility and reliability approaches, but highlights persistent limitations associated with simplified soil models, inconsistent benchmark configurations, limited validation and insufficient treatment of uncertainty. Future work should prioritise standardised benchmark models, layered and nonlinear soil behaviour, foundation-system effects, hazard-consistent ground-motion selection, torsional response of irregular buildings, and experimental or field validation. The review concludes that SSI should be treated as a response-modifying mechanism whose effect can be beneficial or detrimental depending on the coupled soil–foundation–structure system.***

Keywords: Soil–Structure Interaction, Reinforced Concrete Buildings, Seismic Response, Soft Soil, Storey Drift, Torsional Irregularity, Response Spectrum Analysis, Foundation Flexibility

1. Introduction

Reinforced concrete buildings are commonly analysed by idealising the column or wall bases as perfectly fixed. That assumption is convenient because it decouples the superstructure from the supporting ground, yet the physical earthquake problem is a coupled soil–foundation–structure system. During shaking, the soil modifies the motion reaching the foundation, the foundation translates and rotates, and the vibrating structure feeds forces back into the soil. Consequently, the dynamic characteristics and demand of an RCC building may differ from those obtained from a rigid-base model. These effects are particularly important when comparing hard, medium and soft soil conditions and when deformation-sensitive response measures such as displacement, drift and torsion govern design.

The engineering significance of SSI is broader than the familiar observation that soft soil is “more flexible.” Soil stiffness and damping, foundation dimensions and embedment, structural height, plan regularity, lateral-load-resisting system and earthquake frequency content interact. A reduction in support stiffness generally lengthens the system period and increases foundation translation and rocking. Period lengthening can reduce force demand if the elongated period moves to a lower spectral-acceleration region, but it can increase displacement and drift or even amplify force demand when site and earthquake frequency characteristics are unfavourable. Recent studies therefore reject a single universal statement that SSI is always beneficial or always detrimental [3], [10], [12].

The problem becomes more important for tall or irregular buildings. Plan asymmetry couples translational and torsional modes, while flexible support can amplify edge displacement, diaphragm rotation and inter-storey drift. High-rise buildings also possess longer natural periods and may be sensitive to long-period ground motion and soil amplification. Studies on irregular RC buildings, dual frame–wall systems and high-rise buildings repeatedly show that soil condition can modify not only peak response but also the distribution of damage and internal forces [4], [8], [16], [19].

This review synthesises recent research with four objectives: (i) to explain the physical mechanisms through which SSI modifies RCC seismic response; (ii) to compare how modelling approach, soil condition, structural system and ground motion influence reported outcomes; (iii) to evaluate the consistency of commonly reported response trends; and (iv) to identify research and code-development needs. The synthesis is based entirely on published literature; no original ETABS or experimental results are presented in this review paper.

2. Review Scope and Synthesis Method

The review is structured as a critical synthesis rather than a formal systematic review. The literature corpus comprises

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peer-reviewed studies on reinforced-concrete buildings, soil classification, soil–structure interaction, foundation flexibility and seismic response, with emphasis on recent research represented in the underlying study literature. Duplicate bibliographic records were consolidated, and priority was given to journal papers that explicitly model a building–foundation–soil problem and report at least one structural response quantity. Bibliographic details and DOI information for the retained journal papers were cross-checked against publisher or journal records.

The retained evidence was organised using five review dimensions: (1) soil and foundation representation, including fixed base, Winkler springs, impedance/cone models and continuum finite-element models; (2) structural characteristics, including building height, frame, frame–shear-wall, braced and irregular systems; (3) analysis procedure, including response spectrum, nonlinear time-history, incremental dynamic, pushover, fragility and reliability analysis; (4) response measures, particularly natural period, displacement, drift, base shear, torsional response and damage state; and (5) the reported direction of SSI influence. This coding permits comparison across studies without implying that their numerical results are directly interchangeable.

A reproducible database search log, complete search strings and screening history were not available; therefore, this paper does not claim to be a PRISMA-based systematic review and no artificial database counts are reported. The review instead focuses on technical mechanisms, consistency and contradiction among published findings, modelling limitations, engineering implications and research gaps. This distinction improves transparency while retaining the depth expected from a critical review.

3. Mechanisms Governing SSI in RCC Buildings

3.1 Period elongation and system flexibility

When foundation compliance is introduced, the effective lateral and rotational stiffness of the complete system decreases. This generally increases the natural period relative to a fixed-base representation. Wani et al. [17] and Timilsina et al. [14] both demonstrate this effect in RC framed buildings, while Khan et al. [3] report an approximately 8% increase in fundamental period for a 10-storey combined bracing–shear-wall building under SSI. Period elongation is therefore one of the most repeatable SSI observations in the reviewed literature.

Period change is not itself a performance measure. Its design consequence depends on the response spectrum and on earthquake frequency content. If the longer period lies on a descending portion of the acceleration spectrum, base shear may reduce even though displacement increases. If period elongation moves the system toward a region of higher spectral demand, both force and deformation can increase. Zhang and Far [12] explicitly frame SSI as potentially beneficial or detrimental for this reason, and Yang et al. [10] show similar dependence under far-field long-period motions.

3.2 Foundation translation, rocking and energy dissipation

Foundation flexibility introduces translational and rotational degrees of freedom that do not exist in a fixed-base model. Rocking can increase roof and edge displacements, alter storey-drift distribution and redistribute force between frames and walls. At the same time, radiation and material damping in the soil can dissipate energy. The balance between added flexibility and additional damping determines whether a given response quantity rises or falls.

Santoso and Saito [9] show that even base-isolated RC buildings can exhibit significant foundation rotation on medium and soft soils, particularly for taller, slender structures. Visuvasam and Chandrasekaran [21] similarly demonstrate that pile–raft response is affected by soil density, pile spacing and building height. These results indicate that "soil type" alone is not a complete SSI descriptor; foundation type, impedance, embedment and rocking resistance need to be represented when they are significant.

3.3 Site amplification, soil layering and input motion

The soil is both a support medium and a filter of earthquake motion. Layer thickness, impedance contrast and shear-wave velocity can amplify or attenuate different frequency components before they reach the foundation. Kumar and Ghosh [4] and Shiuly et al. [5] show that homogeneous and layered soils can produce substantially different vulnerability trends, especially when the location of a soft layer changes. Local soil classification therefore affects both the boundary condition and the excitation reaching the structure. Ground-motion type adds another layer of interaction. Near-field motions can contain velocity pulses and high energy over relatively short durations, whereas long-period motions may strongly excite tall flexible systems. Khan et al. [3] reported that SSI increased base shear and displacement for selected short-period motions but produced small reductions for a long-period record. This contrast is a central reason that SSI conclusions should be stated by response quantity and excitation type rather than as a single global effect.

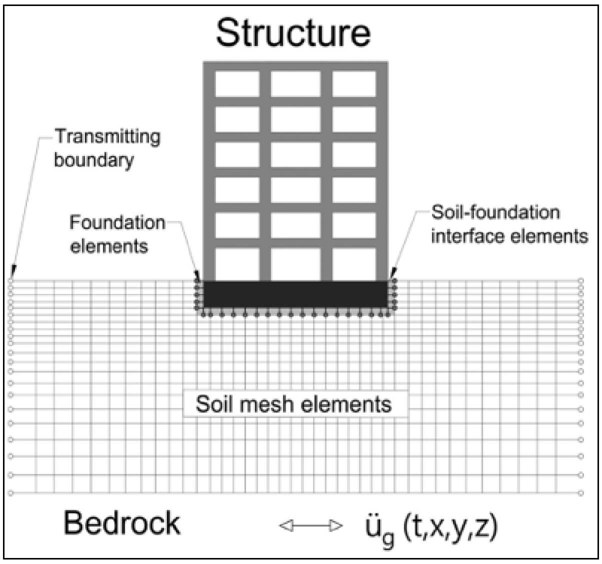

Figure 1: Schematic Representation of the Direct Soil–Structure Interaction (SSI) Modelling Approach

4. Evidence from Recent Literature

4.1 Soil stiffness and deformation demand

Across the reviewed studies, displacement and inter-storey drift show the most consistent sensitivity to soil flexibility. Debnath et al. [1] found that soft clay conditions produced greater deformation and seismic vulnerability than dense sand in a five-storey RC frame. Öz et al. [20], using a large set of existing low- and mid-rise RC buildings, observed that soft-soil SSI notably increased drift demand, particularly in more vulnerable older buildings. Timilsina et al. [14] reported pronounced increases in period, displacement and drift on very soft soil, including large displacement amplification for the taller model under the Kobe record. These studies span different modelling frameworks but converge on the same serviceability concern. Local-soil-class studies likewise show that weaker site conditions can increase target displacement and seismic vulnerability [6].

The physical explanation is straightforward: lower support stiffness increases the total lateral deformation of the soil–foundation–structure system. However, the magnitude of amplification is strongly model-dependent. Simplified springs may capture first-order flexibility but not nonlinear soil yielding, gapping, uplift or spatial variation. Detailed continuum models can represent these mechanisms but require more geotechnical data and careful boundary treatment. A rigorous review must therefore compare not only response values but also the fidelity of the soil and foundation model used to obtain them.

4.2 Building height and lateral-load-resisting system

Building height changes the relative importance of structural and foundation flexibility. Al Agha et al. [19] showed that high-rise dual frame–shear-wall buildings on soft soil are sensitive to raft size and complete soil–foundation representation. The difference between fixed and flexible base becomes more pronounced when the soil is weak and the raft is relatively small. In contrast, larger foundations can make the flexible-base response approach the rigid-base condition. Nonlinear analyses that vary structural plan and foundation type further demonstrate that SSI effects are inseparable from the selected structural and foundation configuration [11].

Structural systems designed to increase lateral stiffness do not eliminate SSI. Verma and Debbarma [15] showed that shear-wall buildings still experience period lengthening and increased deformation with decreasing soil stiffness. Khan et al. [3] similarly demonstrated meaningful SSI effects in a building with both bracing and shear walls. The implication is that a stiff superstructure can reduce drift, but the support system remains part of the global dynamic model. Foundation flexibility can also modify how lateral forces are shared among walls, frames and coupling elements.

4.3 Plan irregularity and torsional response

Plan-irregular buildings deserve special attention because soil flexibility can interact with pre-existing eccentricity between centres of mass and rigidity. Dhakal and Chaulagain [16] reported that flexible support increased translational deformation and amplified torsional effects in irregular RC buildings. Poudel and Chaulagain [8] reached a similar conclusion using nonlinear SSI analysis. Kumar and Ghosh [4] further show that irregularity, height and soil amplification interact in fragility response rather than acting as independent variables.

Torsional demand is important because a global average drift can remain acceptable while edge columns, walls or non-structural components experience larger local deformation. Plan-irregular studies show that flexible soil can amplify an existing torsional tendency by adding foundation translation and rotation to structural eccentricity. Consequently, SSI assessment for irregular buildings should include diaphragm rotation, edge displacement and directional torsional measures rather than relying only on centre-of-mass displacement or a single global drift value.

4.4 Analysis method and foundation representation

Response-spectrum analysis remains attractive for design-oriented comparison because it captures modal response efficiently and is compatible with code-based spectra such as IS 1893 (Part 1):2016 [22]. Several reviewed studies use response-spectrum procedures to compare soil classes and support conditions. Its principal limitation is that it generally represents the structure and soil through linear or equivalent-linear behaviour. Nonlinear time-history analysis can represent material yielding, cyclic soil response and motion-specific effects, but requires suitable records, calibrated material models and considerably greater modelling judgement.

The literature displays a hierarchy of SSI representations. Fixed-base models provide a reference but suppress soil flexibility. Winkler springs introduce translational stiffness economically but may neglect coupling among foundation degrees of freedom. Coupled spring/impedance models improve representation of translation and rocking. Direct finite-element models such as those used in PLAXIS, ABAQUS or OpenSees can model soil continuum and foundation behaviour in greater detail [1], [7], [19]. Higher fidelity does not automatically guarantee accuracy; calibration, mesh size, constitutive model, damping and boundary conditions remain decisive. Nevertheless, model choice should reflect the engineering question rather than computational convenience alone. Three-dimensional studies of deformable soil in mixed structural systems similarly confirm that soil representation can materially alter lateral response [13].

4.5 Ground-motion dependence, fragility and collapse

Recent research increasingly evaluates damage probability rather than only elastic peak response. Yousefi and Tehrani [2] used nonlinear and collapse-oriented procedures to show that soil–foundation–structure interaction can increase plastic rotation and reduce collapse margin, with stronger effects in some lower-rise configurations and weaker soils. Kumar and Ghosh [4] and Shiuly et al. [5] combine nonlinear response with fragility or reliability measures and show that soil profile and near-field motion can materially change vulnerability. Vulnerability studies of mid-rise RC building stocks also show that incorporating SSI can materially change predicted damage and exceedance probabilities [18].

This shift is important because a decrease in base shear does not necessarily mean improved seismic performance. A flexible system may attract lower force while undergoing larger displacement, increased P–Delta effects and more severe non-structural damage. Conversely, force amplification may occur without unacceptable drift. Performance-based SSI assessment therefore needs multiple demand measures and explicit limit states rather than a single force-based indicator.

5. Comparative Synthesis of Representative Studies

Table 1: Mechanism-oriented synthesis of representative RCC soil–structure interaction studies

Study	System / Method	Key SSI observation
[1] Debnath et al., 2026	5-storey RC; PLAXIS 3D; dense sand vs soft clay; near/far-field	Soft soil increased displacement, drift and vulnerability; ground-motion characteristics strongly affected response.
[2] Yousefi & Tehrani, 2026	RC dual frame–wall; nonlinear TH, IDA and pushover	SFSI increased plastic rotations and could reduce collapse-resistance margin, particularly under weaker soil conditions.
[3] Khan et al., 2026	10-storey RC; wall + bracing; Winkler SSI; nonlinear TH	Period increased; short-period motions amplified shear/displacement, while selected long-period response slightly reduced.
[4] Kumar & Ghosh, 2025	Irregular L-plan RC; multiple heights/soil profiles; fragility	Near-field excitation and soil amplification increased vulnerability; soil profile and height interacted with torsion.
[5] Shiuly et al., 2025	G+1/G+4/G+9; layered soils; nonlinear TH; reliability	Soft-layer position changed displacement and fragility; shallow soft layer was particularly critical for taller models.
[7] Amritha & Prasanth, 2025	RC with masonry openings; PLAXIS 3D SFSI	Fixed-base models underestimated deformation/damage on soft soil, especially with larger infill openings.
[8] Poudel & Chaulagain, 2024	Irregular RC; nonlinear SSI	Flexible soil increased displacement, drift and torsional response; fixed base could underestimate vulnerability.
[10] Yang et al., 2024	RC frame–wall; long-period ground motions	SSI lengthened period and modified force distribution; response direction depended on soil/structure/motion period relation.
[12] Zhang & Far, 2024	High-rise; parametric SSI assessment	SSI can be beneficial for some force responses but detrimental for deformation; no universal sign of effect.
[14] Timilsina et al., 2023	3–10 storey RC; direct FE soil modelling	Very soft soil increased period, lateral displacement and drift; effects increased with height and flexibility.
[17] Wani et al., 2022	G+10 RC on mat; fixed vs Winkler/coupled SSI	Foundation flexibility modified period, base shear and drift, confirming sensitivity to support idealisation.
[20] Öz et al., 2020	40 existing low/mid-rise RC buildings; nonlinear TH	Soft soil notably amplified drift in vulnerable buildings; stiff/moderate soil response was closer to fixed base.

6. Critical Discussion

6.1 What is consistent across studies?

Three observations are comparatively robust. First, decreasing soil stiffness generally increases effective period and foundation movement. Second, displacement and inter-storey drift are more consistently amplified than force measures. Third, irregularity, height and foundation flexibility interact, so the significance of SSI grows when the structural system is already deformation-sensitive. These patterns appear in direct finite-element studies, spring-based studies and damage-oriented investigations [1], [8], [14], [17], [20].

These consistent findings explain why displacement-based checks should accompany base-shear checks. A design may exhibit a lower seismic force after period elongation while simultaneously experiencing larger drift, diaphragm displacement, façade demand or P–Delta sensitivity. For performance-based assessment, the critical response measure is therefore not predetermined; it emerges from the combined soil–foundation–structure model.

6.2 Why do published base-shear trends differ?

Base shear is the response quantity for which apparently contradictory results most often occur. Some studies report reduction because flexible support lengthens period and reduces spectral acceleration. Others report increases because the soil spectrum, motion frequency content or site amplification places the elongated system in a higher-demand region. Khan et al. [3] show both trends under different records in the same structural system. Yang et al. [10] and Zhang and Far [12] similarly demonstrate response dependence on the relation among soil period, structural period and excitation.

There is therefore no contradiction when the mechanisms are stated correctly. “SSI reduces base shear” and “soft soil increases base shear” can both be true for different spectra, records and modelling assumptions. A review paper should not average such outcomes without preserving the underlying excitation and spectral context. This is particularly relevant to code-based response-spectrum studies, where the selected soil spectrum can directly change the design horizontal coefficient.

6.3 Limits of simplified soil modelling

Simplified springs are valuable for practical parametric studies, but they can hide coupling, frequency dependence and nonlinear behaviour. A single modulus of subgrade reaction cannot fully represent rotational impedance, radiation damping, uplift, gapping or strain-dependent stiffness. Continuum models can represent more mechanisms, yet they require additional assumptions about soil boundaries, constitutive laws and damping. The appropriate model is therefore a hierarchy: simple models for screening and design sensitivity, calibrated impedance models for routine SSI where data permit, and direct nonlinear models for critical or unusual sites.

Validation remains a weak point in much of the numerical literature. Several studies compare trends with established theory but relatively few use field measurements, centrifuge data or instrumented earthquake records for full soil–foundation–building validation. This limits confidence in absolute numerical amplification factors even when the qualitative trend is credible.

7. Research Gaps and Future Directions

The reviewed literature converges on the need for controlled comparisons in which soil behaviour is changed without simultaneously changing the superstructure, seismic hazard and analysis method. The following priorities would materially improve the quality, reproducibility and transferability of future SSI research:

1) Standardised benchmark buildings and foundations should be developed so that different SSI formulations can be compared using identical geometry, material properties, mass, damping and input motions.
2) Layered and nonlinear soils require wider study. Equivalent soil classes are convenient, but real sites contain impedance contrasts, strain-dependent stiffness, damping variation and potential cyclic degradation.
3) Irregular RCC buildings need combined translational–torsional evaluation. Edge displacement, diaphragm rotation, torsional ratios and local wall/frame demand should be reported together with centre-of-mass drift.
4) Foundation system effects should be separated explicitly. Rafts, isolated footings, pile–rafts, embedded basements and base-isolated foundations have different translational and rocking impedances.
5) Ground-motion selection should include near-field pulse-like records, far-field records and long-period motions, with spectral matching or hazard-consistent selection documented clearly.
6) Probabilistic fragility, collapse and uncertainty analysis should be expanded. Soil parameter uncertainty can be as important as nominal soil class, especially when site data are sparse.
7) Model verification should move beyond numerical consistency toward experimental, field or instrumented-building validation wherever possible.
8) Code-oriented research should identify when simplified fixed-base analysis is adequate and when SSI must be explicitly included, with criteria tied to structure-to-soil stiffness, foundation geometry and performance objective.

8. Engineering Implications

For design practice, the main implication is that soil condition should be treated as part of the structural system rather than only as a foundation bearing-capacity input. At minimum, designers of medium- and high-rise RCC buildings on soft or uncertain sites should assess the sensitivity of period, drift and displacement to foundation flexibility. Where plan irregularity is present, directional torsion and diaphragm response should be checked explicitly.

Force and deformation measures should be interpreted together. A reduction in base shear after including SSI is not sufficient evidence of improved performance, and an increase in base shear does not automatically imply unacceptable response if drift and detailing remain adequate. The relevant question is whether the combined system satisfies strength, drift, stability and damage-control requirements under a physically defensible soil and motion model.

Response-spectrum analysis remains suitable for comparative code-level design, but important soft-soil or irregular projects may justify nonlinear time-history or direct SSI analysis. The level of modelling should increase with consequence, uncertainty and the likelihood that foundation translation or rocking contributes materially to global response.

9. Conclusions

1) Soil–structure interaction modifies the seismic response of RCC buildings through coupled changes in support stiffness, foundation translation and rocking, damping and site-dependent input motion.
2) The most consistent effect of softer support is increased system period, lateral displacement and inter-storey drift. These deformation measures are generally more robust indicators of adverse SSI than base shear alone.
3) Base-shear response is spectrum- and motion-dependent. SSI can increase or reduce force demand depending on period elongation, soil amplification and earthquake frequency content; therefore, universal beneficial/detrimental labels are technically inappropriate.
4) Irregular and tall RCC buildings require special attention because flexible support can couple with torsional modes, diaphragm rotation and P–Delta effects. Directional response and edge demand should be included in evaluation.
5) Foundation modelling controls the credibility of the result. Fixed-base, Winkler, impedance and continuum approaches represent different levels of physics and should be selected according to the design question and available geotechnical data.
6) Future research should emphasise controlled benchmark models, layered and nonlinear soil behaviour, uncertainty and fragility, foundation-system effects, hazard-consistent ground motions, torsional response and experimental or field validation.

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