

# A Review on Seismic Performance Assessment of RC Buildings Considering Combined Effects of Soil Structure Interaction and Soil Liquefaction

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**Abstract** - The seismic performance of reinforced concrete (RC) buildings is strongly influenced by the characteristics of the supporting soil and foundation system. Conventional seismic analysis generally assumes fixed-base conditions, neglecting the interaction between the soil, foundation, and superstructure. However, during earthquake events, soil flexibility significantly modifies the dynamic response of structures through Soil-Structure Interaction (SSI). In addition, soil liquefaction occurring in loose saturated soils causes substantial reduction in soil stiffness and strength, leading to excessive settlement, tilting, and structural damage. Although considerable research has been carried out on SSI and liquefaction independently, studies investigating their combined influence on RC buildings remain limited. This paper presents a comprehensive review of recent research related to SSI, soil liquefaction, foundation flexibility, and seismic response of RC structures. The findings from previous studies are summarized and analyzed to identify existing knowledge gaps. The review highlights the need for integrated assessment of SSI and liquefaction effects for realistic seismic performance evaluation. Based on the identified research gaps, a framework for future investigation of RC buildings subjected to combined SSI and liquefaction effects is proposed.

**Key Words:** Soil Structure Interaction, Soil Liquefaction, Reinforced Concrete Buildings, Seismic Performance, Foundation Flexibility, Response Spectrum Analysis, Earthquake Engineering.

## 1. INTRODUCTION

Earthquakes continue to be one of the most destructive natural hazards affecting buildings and infrastructure worldwide. Traditionally, seismic analysis and design of buildings are performed by assuming that the structure is supported on a rigid foundation with fixed-base conditions. This assumption simplifies the analysis but often fails to

represent actual field conditions, particularly when buildings are founded on soft or medium soils.

During earthquake excitation, the soil, foundation, and superstructure interact continuously, altering the dynamic characteristics of the building. This phenomenon is known as Soil-Structure Interaction (SSI). SSI affects the natural period, damping characteristics, base shear, displacement response, and overall seismic behavior of structures.

Another important geotechnical hazard associated with earthquakes is soil liquefaction. Liquefaction occurs when loose saturated soil experiences an increase in pore water pressure during cyclic loading, resulting in a significant loss of shear strength and stiffness. Buildings founded on liquefiable soils may experience excessive settlement, tilting, lateral spreading, and foundation instability.

Recent earthquake events such as Niigata (1964), Kobe (1995), and Bhuj (2001) demonstrated that soil conditions play a crucial role in determining structural damage. These observations have increased the importance of incorporating both SSI and liquefaction effects in seismic assessment procedures.

## 2. SOIL STRUCTURE INTERACTION IN SEISMIC ANALYSIS

Soil Structure Interaction refers to the mutual response between a structure and the supporting soil during loading conditions. Unlike fixed-base structures, SSI models account for soil deformability and foundation flexibility.

The primary effects of SSI include:

- Increase in natural time period.
- Modification of damping characteristics.
- Reduction in base shear demand.
- Increase in lateral displacement.
- Increase in inter-storey drift.
- Redistribution of internal forces.

SSI effects become more significant for:

- Tall buildings.
- Flexible structures.
- Soft and medium soils.
- Raft and pile foundations.
- Structures subjected to strong seismic excitation.

The inclusion of SSI enables a more realistic representation of actual structural behavior and provides improved prediction of earthquake.

## 2.1 Mechanism of Soil Structure Interaction

Soil Structure Interaction (SSI) refers to the mutual interaction between the structure, foundation system, and supporting soil during dynamic loading conditions such as earthquakes. In conventional seismic design, the base of the structure is assumed to be fixed, implying that no deformation occurs in the foundation soil. However, in reality, the supporting soil undergoes deformation and participates in the overall dynamic response of the structural system.

During earthquake excitation, seismic waves propagate through the soil medium before reaching the foundation. The flexibility of the soil modifies the motion transmitted to the structure and influences the structural response. As a result, the natural frequency, damping characteristics, displacement, and internal force distribution of the structure may differ significantly from those predicted using fixed-base assumptions.

SSI is generally classified into two components: inertial interaction and kinematic interaction. Inertial interaction occurs due to the transfer of structural inertia forces to the soil through the foundation system, whereas kinematic interaction results from the modification of free-field ground motion caused by the presence of the foundation. Both mechanisms contribute to changes in structural behaviour and must be considered for realistic seismic performance evaluation.

The influence of SSI becomes more pronounced for structures founded on soft soils, high-rise buildings, heavy structures, and buildings supported on raft or pile foundations. Therefore, incorporating SSI in seismic analysis can provide a more accurate prediction of the actual behaviour of structures during earthquakes.

## 3. SOIL LIQUEFACTION AND ITS INFLUENCE ON STRUCTURAL PERFORMANCE

Liquefaction occurs when saturated granular soils lose their effective stress due to the generation of excess pore water pressure during earthquake shaking.

The major consequences of liquefaction include:

- Reduction in soil stiffness.
- Reduction in bearing capacity.
- Excessive settlement.
- Foundation rotation and tilting.
- Lateral spreading.
- Increased structural displacement.
- Uneven load transfer.

Liquefaction not only affects the soil but also changes the interaction mechanism between the soil and the structure. As soil stiffness decreases, the flexibility of the foundation increases, leading to significant changes in seismic response. Therefore, seismic assessment of buildings in liquefaction-prone regions requires simultaneous consideration of soil behavior and structural response.

## 3.1 Mechanism of Soil Liquefaction

Soil liquefaction is one of the most destructive geotechnical hazards associated with earthquakes. It generally occurs in loose, saturated, cohesionless soils such as sand and silty sand when subjected to intense cyclic loading. During earthquake shaking, the repeated application of shear stresses causes a rapid increase in pore water pressure within the soil mass. As the pore water pressure increases, the effective stress decreases, resulting in a substantial loss of shear strength and stiffness.

When the effective stress approaches zero, the soil behaves temporarily like a viscous fluid rather than a solid material. Under such conditions, foundations lose support and may undergo excessive settlement, differential settlement, tilting, and lateral displacement. Severe liquefaction can lead to structural instability and even collapse.

The occurrence of liquefaction depends on several factors including soil density, groundwater level, grain size distribution, confining pressure, and earthquake magnitude. Areas with shallow groundwater tables and loose sandy deposits are particularly susceptible to liquefaction during strong ground shaking.

Historical earthquakes such as the 1964 Niigata Earthquake in Japan, the 1989 Loma Prieta Earthquake in the United States, and the 2011 Christchurch Earthquake in New Zealand demonstrated the devastating effects of liquefaction on buildings and infrastructure. These events highlighted the importance of evaluating liquefaction potential and incorporating its effects into seismic design and assessment procedures.

#### 4. SEISMIC PERFORMANCE PARAMETERS USED FOR ASSESSMENT

The seismic performance of reinforced concrete buildings is generally evaluated using several structural response parameters obtained from analytical studies. These parameters provide information regarding the behaviour, safety, and serviceability of the structure under earthquake loading.

##### Fundamental Time Period

The fundamental time period represents the time required by a structure to complete one cycle of free vibration. SSI generally increases the flexibility of the overall system, resulting in a higher fundamental time period. Liquefaction-induced reduction in soil stiffness further contributes to this increase.

##### Base Shear

Base shear is the total horizontal seismic force acting at the base of the structure. It is one of the most important design parameters specified in IS 1893:2016. Variations in soil stiffness due to SSI and liquefaction significantly affect the magnitude of base shear experienced by the building.

##### Storey Displacement

Storey displacement indicates the lateral movement of each floor level during earthquake excitation. Excessive displacement may lead to structural and non-structural damage. Structures supported on flexible or liquefied soils generally exhibit larger lateral displacements compared to fixed-base structures.

##### Storey Drift

Storey drift is defined as the relative displacement between two consecutive floors divided by the storey height. It is a critical parameter for evaluating structural safety and serviceability. Increased drift can result in damage to partitions, cladding systems, and structural members.

##### Overturning Moment

Overturning moment represents the tendency of a structure to rotate about its base due to seismic forces. It provides an indication of the stability of the building under earthquake loading and is influenced by soil flexibility and foundation behaviour.

These parameters are commonly used in seismic performance assessment studies to compare the behaviour of fixed-base structures with SSI and liquefaction-based models.

#### 5. REVIEW OF PREVIOUS RESEARCH

Several researchers have investigated the influence of SSI and liquefaction on seismic performance.

Wang et al. (2025) studied RC buildings supported on piled raft foundations considering SSI and pounding effects. Their findings showed that foundation flexibility significantly affects displacement demand and damage distribution.

Hidayati et al. (2025) reported that soil flexibility and varying ground motions considerably alter seismic performance and should be incorporated in seismic assessment.

Qutayeb et al. (2025) compared fixed-base and SSI models and observed increased natural periods and lateral displacements when SSI was considered.

Naoui (2024) demonstrated that SSI significantly modifies seismic demand and energy dissipation characteristics of RC buildings.

Serdar et al. (2025) concluded that SSI increases the probability of structural damage and that soil properties become increasingly important at higher performance levels. Kurniawandy et al. (2025) reported that flexible foundation conditions generally increase displacement while reducing base shear compared to fixed-base assumptions.

Bapir et al. (2023) presented a comprehensive review of SSI studies and highlighted the need for nonlinear soil modeling and combined hazard investigations.

Faisal Mehraj Wani et al. (2022) investigated various SSI modeling approaches and concluded that neglecting SSI may result in inaccurate estimation of seismic demand, especially on soft soils.

Recent studies on liquefaction have shown that reduction in soil stiffness significantly amplifies displacement demand and alters force distribution throughout the structure. However, most investigations focus either on SSI or liquefaction independently.

#### 6. SUMMARY OF LITERATURE FINDINGS

Based on the reviewed studies, the following observations are made:

1. SSI generally increases structural flexibility and natural period.
2. Lateral displacement and inter-storey drift increase when SSI is considered.
3. Base shear generally decreases due to increased flexibility.

4. Soft and medium soils exhibit more pronounced SSI effects.
5. Foundation type significantly affects seismic response.
6. Liquefaction induces substantial degradation in soil stiffness and bearing capacity.
7. Structural vulnerability increases when liquefaction effects are present.
8. Fixed-base assumptions may underestimate seismic demands under realistic soil conditions.

## 7. RESEARCH GAPS

The following research gaps have been identified:

1. Most studies investigate SSI and liquefaction independently rather than simultaneously.
2. Limited research exists on the combined effect of SSI and liquefaction on RC buildings.
3. Many investigations assume linear elastic soil behavior and neglect soil degradation during liquefaction.
4. Comparative studies involving fixed-base, SSI-only, liquefaction-only, and combined SSI-liquefaction conditions are scarce.
5. The influence of different foundation systems under liquefaction conditions remains insufficiently explored.
6. Current seismic design codes provide limited guidance regarding combined SSI and liquefaction effects.

## 8. PROPOSED RESEARCH FRAMEWORK

To address the identified gaps, future investigations should consider:

- Development of detailed RC building models.
- Inclusion of realistic soil spring systems.
- Simulation of soil liquefaction through stiffness reduction methods.
- Comparative evaluation of fixed-base, SSI-only, and SSI with liquefaction models.
- Assessment of seismic response parameters such as:
  - Fundamental time period
  - Base shear
  - Storey displacement
  - Inter-storey drift
  - Storey shear
  - Overturning moment

The proposed framework will enable a more realistic evaluation of structural performance during earthquakes.

## 8. CONCLUSIONS

This review paper highlights the importance of considering both Soil Structure Interaction and soil liquefaction in seismic performance assessment of RC buildings. Existing literature demonstrates that SSI substantially modifies structural response, while liquefaction significantly reduces soil stiffness and foundation stability. Despite extensive research on both topics individually, limited studies have investigated their combined effects. The identified research gaps indicate the need for integrated analytical approaches capable of representing actual soil-foundation-structure behavior during earthquakes. Future studies incorporating both SSI and liquefaction are expected to provide more reliable predictions of seismic performance and contribute to safer structural design practices in earthquake-prone regions.

## REFERENCES

- [1] Wang Y., Zhang H., Zhou L. (2025). Seismic Resilience Assessment of RC Superstructures on Long-Short Combined Piled Raft Foundations.
- [2] Hidayati R. et al. (2025). Comprehensive Soil-Structure Interaction Analysis for Multi-Storey Buildings.
- [3] Qutayeb S. et al. (2025). Soil-Structure Interaction Study of Mid-Rise RC Buildings.
- [4] Naoui T. (2024). Dynamic Modeling of Soil-Structure Interaction for RC Buildings.
- [5] Serdar M. et al. (2025). Damage Probability Assessment of RC Buildings Considering SSI.
- [6] Bapir B. et al. (2023). State-of-the-Art Review of Soil-Structure Interaction.
- [7] Wani F.M. et al. (2022). Influence of SSI on Dynamic Response of RC Structures.
- [8] Kassas K. et al. (2022). Structure-Soil-Structure Interaction on Liquefiable Soils.
- [9] Razzouk Y. et al. (2023). Advanced Numerical Modeling of SSI Effects.
- [10] Najar I.A. et al. (2025). Comprehensive Review of SSI Research and Practice.