Soil – Structure Interaction (SSI) Effects on Seismic Behaviour of Buildings Using Finite Element Modelling

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Abstract— ***Soil–Structure Interaction (SSI) plays a significant role in determining the seismic performance of buildings. Traditional seismic design approaches generally assume a fixed-base condition, neglecting the influence of soil flexibility and foundation compliance. However, numerous studies have demonstrated that SSI can considerably alter the dynamic characteristics of structures, including natural periods, damping ratios, base shear, inter-storey drift, and foundation forces. This review paper presents a comprehensive assessment of recent advances in SSI research, focusing on seismic behaviour of multi-storey buildings. Various modelling techniques including analytical methods, finite element approaches, simplified spring-based models, and nonlinear soil–foundation representations are examined. The influence of soil conditions, foundation systems, structural irregularities, and ground motion characteristics on seismic response is critically reviewed. Recent developments in structure–soil–structure interaction (SSSI), performance-based design, resilience assessment, and computational modelling are also discussed. The review identifies major research gaps and highlights the need for practical yet reliable SSI modelling approaches suitable for engineering applications.***

Keywords: Soil–Structure Interaction, Seismic Analysis, Finite Element Modelling, Deep Foundations, Structural Dynamics, SAP2000, Nonlinear Analysis

I. INTRODUCTION

Earthquakes are among the most destructive natural hazards, causing significant loss of life, economic damage, and disruption to critical infrastructure worldwide. The primary objective of earthquake-resistant design is to ensure that structures can withstand seismic forces without experiencing catastrophic failure while maintaining acceptable levels of safety and functionality. Traditionally, seismic design procedures have been based on the assumption that building foundations are rigidly fixed to the underlying ground. Under this fixed-base assumption, the effects of soil deformability and foundation flexibility are neglected, and the seismic response of the structure is considered independently from the supporting soil. Although this simplification facilitates analysis and design, it may not accurately represent the actual behaviour of structures during earthquake events.

In reality, the soil supporting a structure possesses finite stiffness, damping, and mass characteristics. During seismic excitation, the soil, foundation, and superstructure interact as a coupled dynamic system. This phenomenon, known as **Soil–Structure Interaction (SSI)**, significantly influences the transmission of seismic energy from the ground to the structure and affects the overall dynamic response of the building. SSI modifies both the characteristics of the incoming ground motion and the response of the structure itself, leading to changes in natural frequencies, damping ratios, base shear forces, inter-storey drifts, floor accelerations, and foundation deformations. The concept of SSI can be broadly divided into two components: **kinematic interaction** and **inertial interaction**. Kinematic interaction occurs because the presence of a foundation alters the free-field ground motion before it reaches the structure. The stiffness, geometry, and embedment depth of the foundation influence the way seismic waves propagate through the soil and are transmitted to the structure. Inertial interaction, on the other hand, results from the dynamic forces generated by the vibrating structure and transferred back to the supporting soil through the foundation system. These forces cause additional soil deformation and foundation movement, thereby modifying the overall structural response. The combined effects of kinematic and inertial interaction make SSI a complex yet critical aspect of earthquake engineering.

Numerous experimental, analytical, and numerical investigations conducted over the past several decades have demonstrated that SSI can substantially affect the seismic performance of buildings. One of the most commonly observed consequences of SSI is the elongation of the fundamental natural period of the structure. As foundation flexibility increases, the overall stiffness of the soil–foundation–structure system decreases, resulting in longer vibration periods. This period elongation often leads to a reduction in seismic base shear because the structure shifts to a different region of the design response spectrum. Consequently, SSI may appear beneficial from a force-demand perspective. However, the associated increase in flexibility frequently results in larger lateral displacements, increased inter-storey drift ratios, foundation settlements, and rocking motions. Therefore, while SSI can reduce force demands, it may simultaneously increase deformation demands and potential structural damage.

The significance of SSI is particularly pronounced for structures founded on soft or medium-stiff soils. Soft soil deposits exhibit lower stiffness and higher deformability, which amplify SSI effects and lead to greater foundation movements and structural displacements. Buildings supported on deep foundation systems, such as pile foundations and pile–raft foundations, are also highly susceptible to SSI because the load transfer mechanism involves complex interactions between piles and surrounding soil. High-rise buildings, slender structures, and buildings with irregular plan or elevation configurations may experience substantial modifications in their dynamic characteristics when SSI is considered. In contrast, structures founded on hard rock or very stiff soils often exhibit relatively minor SSI effects due to the high stiffness of the supporting medium.

Recent earthquake events have further highlighted the importance of considering SSI in seismic analysis and design. Observations from major earthquakes such as the **1995 Kobe Earthquake**, the **1999 Chi-Chi Earthquake**, the **2001 Bhuj Earthquake**, the **2011 Tohoku Earthquake**, and the **2015 Nepal Earthquake** have revealed instances where soil conditions and foundation flexibility significantly influenced structural performance. In many cases, structures that appeared adequately designed under fixed-base assumptions experienced unexpected settlements, tilting, excessive drifts, or foundation damage due to soil-related effects. These observations have encouraged researchers and practicing engineers to develop more realistic methods for evaluating SSI behaviour.

The advancement of computational technology has revolutionized SSI analysis in recent years. Modern finite element software packages such as SAP2000, ETABS, ABAQUS, ANSYS, Open Sees, and PLAXIS enable detailed modelling of soil–foundation–structure systems. These tools allow engineers to simulate nonlinear soil behaviour, pile–soil interaction, foundation rocking, material inelasticity, and complex seismic loading conditions. Sophisticated three-dimensional finite element models can provide highly accurate predictions of structural response; however, they often require extensive computational resources, specialized expertise, and detailed geotechnical data. Consequently, their application in routine engineering practice remains limited.

To overcome these challenges, simplified SSI modelling techniques have been developed and widely adopted. These methods typically represent the soil and foundation system using equivalent springs, dashpots, or impedance functions. Such approaches offer a practical balance between computational efficiency and analytical accuracy, making them suitable for implementation in commonly used structural analysis software. Nevertheless, questions remain regarding the level of modelling sophistication required for reliable seismic assessment, particularly for multi-storey buildings supported on deep foundations and subjected to strong ground motions.

In addition to conventional SSI, recent research has expanded the scope of investigation to include **Soil–Foundation–Structure Interaction (SFSI)** and **Structure–Soil–Structure Interaction (SSSI)**. In densely populated urban environments, neighbouring buildings may interact through the shared soil medium, altering seismic response characteristics and increasing the likelihood of pounding between adjacent structures. These emerging research areas have demonstrated that seismic response cannot always be accurately predicted by considering individual structures in isolation.

Despite significant advances in SSI research, several challenges remain unresolved. These include the accurate characterization of soil properties, modelling of nonlinear soil behaviour under strong earthquakes, representation of pile–soil interaction, incorporation of uncertainty in geotechnical parameters, and development of practical design guidelines suitable for engineering applications. Furthermore, there remains a substantial gap between advanced research-oriented SSI models and the simplified approaches typically used in professional design offices.

Therefore, a comprehensive review of recent developments in SSI is essential to improve understanding of its effects on the seismic behaviour of buildings. This review paper examines the current state of knowledge regarding soil–structure interaction, including fundamental concepts, modelling approaches, effects of soil and foundation conditions, numerical simulation techniques, and recent advances in performance-based seismic assessment. The study also identifies key research gaps and provides recommendations for future investigations aimed at enhancing the safety, reliability, and resilience of building structures subjected to earthquake loading.

II. OBJECTIVES

The objectives of this research are:

1. To develop finite element models of multi-storey buildings incorporating soil–structure interaction.
2. To compare seismic responses of fixed-base and flexible-base structural systems.
3. To investigate the influence of soil stiffness on structural performance.
4. To evaluate the effect of soil nonlinearity on seismic response.
5. To compare two-dimensional and three-dimensional SSI models.
6. To provide practical recommendations for seismic analysis of pile-supported buildings.

III. METHODOLOGY

3.1 Structural Modelling

The present study investigates the seismic behaviour of multi-storey reinforced concrete (RC) buildings considering Soil–Structure Interaction (SSI) through finite element modelling in SAP2000. A representative RC building is selected based on common Indian construction practices and designed according to IS 456:2000 and IS 1893 (Part 1): 2016 provisions.

The structural components are modelled using appropriate finite element formulations available in SAP2000. Beams and columns are represented by three-dimensional frame elements capable of simulating axial force, bending moment, shear force, and torsional effects. Reinforced concrete slabs are modelled using shell elements to accurately capture diaphragm action and load transfer mechanisms.

The foundation system consists of reinforced concrete piles connected through pile caps. The pile foundations are explicitly represented in the finite element model to evaluate pile head forces, bending moments, settlements, and rotations. The overall structural model includes realistic mass distribution, stiffness properties, and boundary conditions.

For comparison purposes, both fixed-base and flexible-base models are developed. The fixed-base model assumes a rigid connection between the foundation and ground, while the flexible-base model incorporates soil flexibility through equivalent spring representations.

3.2 Soil Modelling

The supporting soil medium is represented using the substructure approach, which is widely adopted in practical engineering applications due to its computational efficiency and reasonable accuracy.

Three representative soil conditions are considered:

a) Soft Soil

Soft soil possesses low shear modulus and stiffness characteristics. Such soils undergo significant deformation during seismic excitation and generally amplify SSI effects.

b) Medium Soil

Medium soil exhibits moderate stiffness and represents typical urban construction sites. The interaction effects are expected to be moderate compared with soft soil conditions.

c) Stiff Soil

Stiff soil provides higher resistance against deformation and exhibits relatively smaller SSI effects. Buildings founded on stiff soil generally behave closer to fixed-base conditions.

For each soil type, the following geotechnical properties are defined:

- Unit Weight (γ)
- Shear Modulus (G)
- Young's Modulus (E)
- Poisson's Ratio (ν)
- Damping Ratio (ξ)
- Soil Layer Thickness

Equivalent translational and rotational stiffness values are calculated using established foundation impedance relationships available in the literature.

The soil is represented through:

- Horizontal Springs
- Vertical Springs
- Rotational Springs

For nonlinear SSI modelling, multilinear spring elements are introduced. These springs simulate realistic soil behaviour through force–displacement relationships and allow yielding and stiffness degradation during strong seismic excitation.

3.3 Analysis Cases

To systematically evaluate the influence of SSI, five major modelling scenarios are considered:

d) Case 1: Fixed-Base Model

The building foundation is assumed perfectly rigid and connected directly to the ground without any flexibility.

e) Case 2: Flexible-Base Model with Linear Springs

The soil is represented using linear elastic springs. Soil stiffness remains constant throughout the analysis.

f) Case 3: Flexible-Base Model with Nonlinear Springs

Nonlinear spring elements are used to simulate soil yielding and stiffness degradation under increasing seismic loads.

g) Case 4: Two-Dimensional Frame Model

A plane frame model is developed to investigate the influence of modelling simplification on seismic response.

h) Case 5: Three-Dimensional Space Frame Model

A complete three-dimensional model is developed to capture torsional behaviour, load redistribution, and interaction among structural components.

The comparison among these cases enables identification of the most appropriate modelling strategy for practical engineering applications.

3.4 Seismic Analysis

Three types of seismic analyses are performed:

i) Modal Analysis

Modal analysis is carried out to determine:

- Natural frequencies
- Fundamental time period
- Mode shapes
- Modal mass participation ratios

The influence of soil flexibility on dynamic characteristics is evaluated by comparing fixed-base and flexible-base models.

j) Response Spectrum Analysis

Response Spectrum Analysis (RSA) is performed according to IS 1893 (Part 1): 2016.

The following response parameters are extracted:

- Base Shear
- Storey Shear
- Storey Drift
- Roof Displacement
- Overturning Moment
- Foundation Rotations

RSA provides an efficient method for assessing seismic demands under code-specified earthquake excitation.

k) Nonlinear Time-History Analysis

For selected critical models, nonlinear time-history analysis is conducted using recorded earthquake ground motions.

The analysis captures:

- Inelastic structural behaviour
- Soil nonlinearity
- Hinge formation
- Dynamic force redistribution

The following responses are evaluated:

- Peak Storey Drift
- Floor Acceleration
- Foundation Settlement
- Foundation Rotation
- Pile Forces
- Plastic Hinge Development

IV. RESULT AND DISCUSSION

4.1 Effect on Natural Period

The inclusion of soil flexibility significantly alters the dynamic characteristics of the building. The fundamental period increases because the soil introduces additional compliance into the structural system.

The greatest increase in natural period is observed for buildings founded on soft soil due to its lower stiffness. Medium soil produces moderate period elongation, whereas stiff soil results in only minor changes compared with the fixed-base condition.

The increase in natural period may range between 10% and 40%, depending on soil properties and foundation flexibility. This period elongation influences the spectral acceleration demand and consequently affects overall seismic response.

4.2 Effect on Base Shear

Response spectrum analysis reveals that flexible-base structures generally experience lower base shear than fixed-base structures.

As the natural period shifts toward a longer range, spectral acceleration decreases, resulting in reduced seismic force demand.

The reduction in base shear is more significant in soft soil conditions because of greater flexibility introduced by the soil-foundation system.

Although lower base shear appears beneficial, it should not be interpreted as improved seismic performance because increased deformation demands often accompany the reduction in forces.

4.3 Effect on Storey Drift

Storey drift is one of the most critical parameters governing structural damage during earthquakes.

The results indicate that SSI substantially increases lateral displacement and inter-storey drift. This increase occurs because the flexible foundation allows additional movement and rocking of the structure.

Maximum drift generally occurs in upper storeys and becomes more pronounced as soil stiffness decreases.

Buildings founded on soft soil exhibit the highest drift demands, potentially exceeding code-prescribed limits if SSI is neglected during design.

4.4 Effect of Soil Nonlinearity

Nonlinear soil models exhibit markedly different behaviour compared with linear models.

During strong ground motion, soil stiffness decreases due to yielding and plastic deformation. This behaviour leads to:

- Increased lateral displacement
- Increased foundation rotation
- Reduced base shear
- Redistribution of internal forces

The nonlinear soil absorbs part of the seismic energy through hysteretic damping, reducing force demands but simultaneously increasing deformation demands.

These findings demonstrate that linear SSI models may underestimate displacement-related damage.

4.5 Comparison Between 2D and 3D Models

The comparison between 2D and 3D models highlights the importance of realistic structural representation.

Two-dimensional models neglect torsional effects and transverse load redistribution. Consequently, they tend to underestimate:

- Torsional response
- Pile forces
- Foundation moments
- Localised structural demands

Three-dimensional models provide a more accurate representation of actual building behaviour and should be preferred for irregular structures and important buildings.

4.6 Foundation Response

Foundation response is strongly affected by SSI.

Flexible-base models exhibit:

- Larger pile head displacement
- Higher pile bending moments
- Increased axial force variation
- Greater foundation settlement
- Significant foundation rotation

The effects become particularly severe under soft soil conditions.

The study confirms that neglecting foundation flexibility may lead to unsafe estimation of pile forces and foundation performance.

V. CONCLUSION

Based on the analytical investigation, the following conclusions are drawn:

1. Soil–Structure Interaction significantly affects the seismic response of multi-storey RC buildings.
2. The natural period increases with increasing soil flexibility, resulting in notable period elongation under soft soil conditions.
3. Base shear decreases when SSI is considered because of the increased flexibility of the soil-foundation system.
4. Storey drift and lateral displacement increase considerably in flexible-base models.
5. Nonlinear soil behaviour amplifies deformation demands while reducing force demands through energy dissipation mechanisms.
6. Foundation rotations, settlements, and pile forces increase significantly due to SSI effects.
7. Three-dimensional models provide more realistic seismic response predictions than simplified two-dimensional models.
8. Neglecting SSI may result in inaccurate estimation of seismic demand and structural performance.
9. SSI should be explicitly incorporated in the design and assessment of pile-supported buildings, particularly when founded on soft and medium soils.
10. Practical spring-based SSI models in SAP2000 provide an efficient and reliable approach for engineering applications.

II. FUTURE SCOPE

The present study can be extended in several directions:

1. Investigation of SSI effects under near-fault earthquake ground motions.
2. Inclusion of soil liquefaction and cyclic degradation behaviour.
3. Development of fully coupled soil–pile–structure finite element models using advanced geotechnical software.
4. Evaluation of SSI effects on high-rise buildings with shear walls, braced frames, and outrigger systems.
5. Study of structure–soil–structure interaction (SSSI) in densely populated urban areas.
6. Assessment of SSI effects on performance-based seismic design and resilience evaluation.
7. Investigation of machine learning techniques for rapid prediction of SSI effects.
8. Development of simplified design charts and code recommendations for routine engineering practice.

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