A Review on 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.

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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. LITERATURE REVIEW

2.1 Bharti et al. (2025)

Bharti et al. presented a critical review of seismic Soil–Structure Interaction (SSI) analysis techniques and their application in earthquake engineering. The study evaluated analytical, numerical, and experimental approaches used in SSI investigations. The authors highlighted that neglecting SSI may result in inaccurate estimation of seismic demands, particularly for structures resting on soft soils. The review emphasized the importance of incorporating nonlinear soil behavior and advanced numerical modeling techniques. The study identified the need for practical SSI design methodologies suitable for routine engineering applications.

2.2 Bharti and Garg (2024)

Bharti and Garg conducted a comprehensive review of both Soil–Structure Interaction (SSI) and Structure–Soil–Structure Interaction (SSSI) effects on building seismic behavior. The study summarized recent advancements in numerical modeling and seismic assessment techniques. Results indicated that neighboring structures can significantly influence each other's seismic response through shared soil media. The authors emphasized the necessity of considering SSSI in densely populated urban areas and recommended further research on multi-building interaction effects.

2.3 Najar et al. (2025)

Najar et al. reviewed current practices, challenges, and future directions in SSI research. The paper examined various numerical and experimental methods used for analyzing soil–foundation–structure systems. Findings indicated that soil nonlinearity, uncertainty in soil properties, and computational complexity remain major challenges. The authors suggested the integration of artificial intelligence and machine learning techniques for improved SSI prediction and assessment.

2.4 Savvides (2024)

Savvides performed a parametric study on dynamic SSI effects using nonlinear finite element modeling. The research focused on shear-vulnerable structures subjected to seismic loading. Results demonstrated that SSI significantly alters structural response parameters including displacement and acceleration demands. The study concluded that nonlinear soil behavior should be incorporated into seismic analysis for realistic performance evaluation.

2.5 Poudel and Chaulagain (2024)

Poudel and Chaulagain investigated nonlinear SSI effects on irregular reinforced concrete buildings using numerical simulations. Various irregularity configurations and soil conditions were considered. The study revealed that SSI increased inter-storey drifts and modified damage distribution patterns. Results emphasized the importance of considering soil flexibility in the seismic assessment of irregular buildings.

2.6 Zhan et al. (2024)

Zhan et al. presented a state-of-the-art review on SSI effects in large-span spatial structures. The authors examined recent developments in analytical methods, numerical modeling, and experimental investigations. The review highlighted that SSI significantly influences vibration characteristics and seismic performance of large-span systems. Future research was recommended in the area of nonlinear SSI and performance-based seismic design.

2.7 Zhao et al. (2024)

Zhao et al. developed an efficient finite element framework for large-scale SSI analysis using multi-GPU parallel computing algorithms. The study improved computational efficiency while maintaining analysis accuracy. Results demonstrated significant reductions in computational time compared to conventional methods. The proposed approach enables high-resolution SSI simulations for complex engineering structures.

2.8 Nguyen and Ngo (2025)

Nguyen and Ngo reviewed recent developments in Soil–Foundation–Structure Interaction (SFSI) and Structure–Soil–Structure Interaction (SSSI). The study focused primarily on numerical simulation techniques. Findings showed that both SFSI and SSSI can significantly affect structural response under seismic loading. The authors emphasized the need for unified modeling approaches capable of capturing complex interaction mechanisms.

2.9 Krishnan and Sivakumar (2024)

Krishnan and Sivakumar evaluated the influence of SSI on the structural stability and sustainability of reinforced concrete buildings. Various soil conditions and structural configurations were investigated. Results indicated that SSI affects both safety and serviceability performance. The study recommended incorporating SSI considerations into sustainable structural design frameworks.

2.10 Kadhim and Abdulridha (2025)

Kadhim and Abdulridha conducted numerical simulations to evaluate SSI effects on reinforced concrete buildings. Different soil conditions and seismic intensities were analyzed. Results demonstrated significant changes in displacement, base shear, and internal force distribution when SSI was considered. The study highlighted the limitations of fixed-base assumptions in seismic analysis.

2.11 KC et al. (2025)

KC et al. reviewed ground-motion modifications caused by soil, structures, and topography within the SSI framework. The study discussed multi-scale interaction mechanisms affecting seismic wave propagation. Findings revealed that local soil conditions and topographical features significantly influence seismic response. The authors recommended integrating geological and structural factors into future SSI studies.

2.12 Özmen and Sayin (2025)

Özmen and Sayin compared different SSI modeling strategies for the seismic analysis of a historic masonry church. Various foundation and soil modeling techniques were evaluated. Results showed substantial differences in seismic response depending on the selected SSI model. The study emphasized the importance of appropriate modeling strategies for heritage structures.

2.13 Kant and Samanta (2024)

Kant and Samanta investigated nonlinear SSI and SSSI effects on buildings resting on soft soil. Numerical analyses demonstrated that interaction effects significantly influence displacement demands and structural forces. The study revealed that neighboring structures can amplify seismic response under certain conditions. Results highlighted the necessity of considering both SSI and SSSI in urban seismic assessments.

2.14 Wang et al. (2024)

Wang et al. studied seismic structure–soil–structure interaction in groups of reinforced concrete frame buildings resting on medium clay soil. The research considered code-specified earthquake excitations. Findings indicated that interaction among adjacent structures altered vibration characteristics and seismic demands. The study concluded that SSSI should be incorporated into seismic design procedures for building clusters.

2.15 Patrício et al. (2024)

Patrício et al. investigated settlement behavior of concrete-walled buildings using finite element-based SSI analysis. The study focused on the influence of soil properties and foundation conditions on structural settlement. Results showed that SSI significantly affects settlement distribution and structural performance. The authors recommended coupled soil–structure analyses for accurate settlement prediction.

2.16 Requena-Garcia-Cruz et al. (2025)

Requena-Garcia-Cruz et al. investigated the contribution of Soil–Structure Interaction (SSI) to the seismic behaviour of the historic Mosque-Cathedral of Córdoba. The study employed advanced numerical modeling techniques to assess the influence of soil flexibility on structural response. Results indicated that SSI significantly affects dynamic characteristics, displacement patterns, and stress distribution in heritage structures. The authors concluded that SSI must be incorporated in seismic assessment and retrofitting strategies for historical monuments.

2.17 Hafshejani et al. (2025)

Hafshejani et al. examined the seismic response of neighboring irregular structures founded at different embedment depths considering SSI effects. Numerical analyses revealed that embedment depth strongly influences seismic interaction between adjacent buildings. The study found that SSI can amplify displacement demands and alter structural vibration modes. The authors recommended considering foundation depth variations in urban seismic design.

2.18 Nuriga et al. (2025)

Nuriga et al. performed a comparative investigation of SSI effects across various soil conditions. The study evaluated seismic performance parameters including displacement, acceleration, and base shear under different ground profiles. Results showed that buildings resting on soft soils experienced significantly greater deformation demands compared to those on stiff soils. The research emphasized the importance of site-specific soil characterization in seismic analysis.

2.19 Bapir and Abrahamczyk (2024)

Bapir and Abrahamczyk assessed simplified SSI models commonly used in seismic analysis of reinforced concrete buildings. The study compared simplified spring-based approaches with advanced numerical simulations. Findings demonstrated that simplified models can provide acceptable accuracy for preliminary design, although discrepancies increase for highly nonlinear soil conditions. The study recommended calibration of simplified models using detailed numerical analyses.

2.20 Hasan et al. (2025)

Hasan et al. investigated seismic Soil–Pile–Structure Interaction (SPSI) effects on tall buildings supported by pile-mat foundations. A detailed numerical model was developed to evaluate pile behaviour and structural response under earthquake loading. Results indicated that pile flexibility significantly influences building displacements, foundation rotations, and internal force distributions. The study highlighted the necessity of considering SPSI in the design of high-rise structures.

2.21 Ebadi-Jamkhaneh (2024)

Ebadi-Jamkhaneh assessed pounding risk between adjacent high-rise reinforced concrete structures considering SSI effects. The study employed nonlinear dynamic analyses to evaluate collision potential under seismic loading. Results demonstrated that SSI can substantially modify relative displacements between neighboring buildings, thereby influencing pounding probability. The research emphasized the importance of SSI in urban seismic risk assessment.

2.22 Abdulaziz et al. (2024)

Abdulaziz et al. investigated the seismic behaviour of adjacent structures considering foundation embedment levels, dead loads, and SSI effects. The study revealed that both embedment depth and dead load significantly affect dynamic response characteristics. Results showed that SSI can either amplify or reduce seismic demands depending on structural configuration. The authors recommended integrated analysis approaches for adjacent building systems.

2.23 Camayang et al. (2026)

Camayang et al. presented a systematic review of SSI in seismic response and structural performance. The review synthesized recent developments in analytical, experimental, and numerical investigations. Findings confirmed that SSI plays a critical role in determining structural safety, serviceability, and resilience. The authors identified research gaps related to nonlinear modelling, uncertainty quantification, and performance-based design.

2.24 Jang et al. (2025)

Jang et al. examined the influence of structural dynamic characteristics on SSI behaviour under high-frequency seismic excitation. The study demonstrated that structural frequency content strongly affects interaction mechanisms and response amplification. Results indicated that conventional assumptions may underestimate seismic demands for structures subjected to high-frequency ground motions. The research highlighted the importance of frequency-dependent SSI analysis.

2.25 Tallah et al. (2024)

Tallah et al. developed dynamic SSI models for evaluating the seismic performance of reinforced concrete buildings. Various soil conditions and foundation properties were considered. The study showed that soil flexibility modifies vibration characteristics and displacement responses. Results emphasized the importance of incorporating realistic soil models in seismic performance evaluation.

2.26 Pan et al. (2024)

Pan et al. investigated seismic response and vulnerability assessment of column-supported silos considering SSI effects. Numerical analyses demonstrated that SSI significantly influences structural acceleration, displacement, and damage indices. The study concluded that SSI should be incorporated in the seismic design of industrial storage facilities. Vulnerability assessment results highlighted the potential risks associated with neglecting SSI.

2.27 Zajac et al. (2024)

Zajac et al. evaluated the influence of subsoil conditions and construction material properties on soil–structure interaction under mining-induced ground motions. The study found that soil stiffness and material characteristics significantly affect structural response. Results revealed that SSI can alter damage patterns and vibration amplitudes. The authors recommended considering local geotechnical conditions in structural assessments.

2.28 Yang et al. (2024)

Yang et al. performed a three-dimensional numerical analysis of steel frame-core wall structures with basements considering SSI effects. The study demonstrated that SSI significantly modifies seismic force distribution, displacement patterns, and structural acceleration responses. Results showed that basement structures play an important role in interaction mechanisms. The authors emphasized the necessity of three-dimensional modelling for accurate SSI assessment.

2.29 Castelli et al. (2024)

Castelli et al. conducted nonlinear three-dimensional finite element analyses of coupled soil–structure systems using a deterministic approach. The study captured complex interaction mechanisms between soil and structures under seismic loading. Results indicated that nonlinear soil behaviour substantially influences structural response predictions. The research demonstrated the effectiveness of advanced finite element techniques for SSI analysis.

2.30 Bapir (2025)

Bapir investigated the influence of dynamic SSI on the seismic resilience of reinforced concrete structures through a multi-model analysis framework. Various numerical approaches were compared to evaluate resilience indicators. Results showed that SSI significantly affects post-earthquake functionality and recovery potential. The study highlighted the importance of incorporating SSI into resilience-based seismic design methodologies.

2.31 Liu et al. (2024)

Liu et al. examined nonlinear Structure–Soil–Structure Interaction (SSSI) effects between conventional and base-isolated nuclear power plants. The study employed advanced numerical simulations to investigate seismic response under strong ground motions. Results demonstrated that neighboring structures can significantly influence the effectiveness of seismic isolation systems. The authors recommended incorporating SSSI effects in critical infrastructure design.

2.32 Doğan and Erkan (2024)

Doğan and Erkan evaluated nonlinear seismic responses of high-rise reinforced concrete buildings with different foundation systems and structural plans considering SSI effects. Results showed that foundation type, soil condition, and structural configuration strongly influence seismic performance. The study demonstrated that SSI can significantly alter displacement and force demands. The authors emphasized the need for foundation-specific seismic design approaches.

2.33 Zhang and Far (2025)

Zhang and Far investigated the influence of ground conditions and foundation types on the seismic response of high-rise buildings within a dynamic SSI framework. The study revealed that both soil properties and foundation systems play critical roles in determining structural performance. Results indicated substantial variations in displacement and acceleration responses across different soil-foundation combinations. The research highlighted the importance of integrated geotechnical and structural design.

2.34 Blasone et al. (2025)

Blasone et al. proposed methods for incorporating SSI effects into simplified numerical models used for fragility assessment of reinforced concrete structures. The study demonstrated that neglecting SSI may lead to inaccurate fragility estimates and seismic risk evaluations. Results indicated that simplified SSI models can improve prediction accuracy while maintaining computational efficiency. The authors recommended integrating SSI into probabilistic seismic risk assessment frameworks.

2.35 Amarantidou et al. (2025)

Amarantidou et al. conducted seismic assessment and strengthening studies on a load-bearing masonry structure considering SSI effects. Numerical analyses demonstrated that soil flexibility significantly influences structural response and retrofitting effectiveness. Results showed that strengthening measures designed without SSI consideration may not achieve the intended performance objectives. The study emphasized the importance of SSI-informed rehabilitation strategies for masonry structures.

III. RESEARCH GAP

Despite substantial advancements in Soil–Structure Interaction (SSI) research over the past few decades, several important challenges and knowledge gaps remain unresolved. The growing availability of advanced computational tools and numerical modelling techniques has significantly improved understanding of SSI mechanisms; however, many practical and theoretical limitations continue to restrict the widespread implementation of SSI in engineering practice.

1) Limited Studies on Pile-Supported Multi-Storey Buildings Using Practical Software

A significant portion of existing SSI research has focused on shallow foundation systems or idealized structural models. Although several studies have investigated pile-supported structures, relatively few have examined the seismic behaviour of multi-storey buildings supported by deep foundations using commonly adopted structural analysis software such as SAP2000, ETABS, and STAAD Pro. Most available studies rely on highly specialized finite element platforms that require advanced expertise and extensive computational resources. Consequently, there remains a gap between research-oriented SSI modelling techniques and practical engineering applications. More investigations are required to develop simplified yet reliable modelling approaches that can be easily implemented by practicing engineers.

2) Insufficient Comparison Between Two-Dimensional and Three-Dimensional SSI Models

Numerous studies have employed either two-dimensional (2D) or three-dimensional (3D) numerical models for SSI analysis. However, direct comparisons between these modelling approaches remain limited. While 2D models are computationally efficient and widely used for preliminary analysis, they may not adequately capture torsional behaviour, foundation eccentricities, spatial soil variability, and complex structural configurations. Conversely, 3D models provide more realistic representations but require significantly greater computational effort. A comprehensive understanding of the accuracy, limitations, and applicability of each modelling approach is still lacking. Further research is necessary to establish guidelines regarding when 2D analyses are sufficient and when 3D modelling becomes essential.

3) Limited Understanding of Nonlinear Soil and Structural Behaviour

Many existing SSI investigations are based on linear elastic assumptions for both soil and structural materials. Although such assumptions simplify analysis, they do not accurately represent actual conditions during strong earthquake events. Soil nonlinearity, plastic deformation, stiffness degradation, cyclic loading effects, and structural yielding can substantially influence seismic response. The coupled nonlinear behaviour of soil, foundation, and superstructure remains one of the most challenging aspects of SSI analysis. Additional experimental and numerical studies are required to improve understanding of nonlinear interaction mechanisms and develop robust constitutive models for realistic seismic simulations.

4) Lack of Standardized Guidelines for SSI Modelling Complexity

One of the major obstacles preventing widespread implementation of SSI in routine engineering design is the absence of clear guidelines regarding appropriate modelling complexity. Engineers often face uncertainty when selecting between simplified spring-based models, substructure approaches, and fully coupled finite element analyses. Existing design codes provide limited recommendations concerning SSI modelling requirements for different structural systems and soil conditions. Therefore, there is a need for practical design frameworks that balance computational efficiency with analytical accuracy and provide clear guidance for engineers.

5) Limited Integration of SSI in Performance-Based Seismic Design

Modern earthquake engineering increasingly emphasizes performance-based design approaches that evaluate structural performance under different hazard levels. However, many performance-based seismic assessment methodologies continue to neglect SSI effects or incorporate them only through simplified assumptions. The influence of SSI on structural resilience, damage progression, repair costs, downtime, and post-earthquake functionality remains insufficiently explored. Further studies are required to integrate SSI considerations into performance-based design and resilience assessment frameworks.

6) Uncertainty in Soil Characterization and Geotechnical Parameters

Accurate SSI analysis depends heavily on the proper characterization of soil properties. However, soil parameters such as stiffness, damping ratio, shear wave velocity, and nonlinear constitutive behaviour often exhibit significant spatial variability and uncertainty. These uncertainties can considerably affect seismic response predictions. Existing research has not adequately addressed the influence of geotechnical uncertainty on SSI outcomes. Therefore, probabilistic approaches capable of incorporating parameter variability should be further developed.

7) Limited Experimental Validation of Numerical Models

Although numerous sophisticated numerical SSI models have been proposed, experimental validation remains relatively scarce due to the high cost and complexity of large-scale testing. Most studies rely exclusively on numerical simulations without extensive comparison to physical observations. Additional centrifuge tests, shaking-table experiments, and field monitoring programs are necessary to validate numerical predictions and improve confidence in SSI modelling techniques.

IV. FUTURE RESEARCH DIRECTIONS

Considering the identified research gaps, several promising directions can be pursued to enhance understanding and practical implementation of Soil–Structure Interaction in earthquake engineering.

1) Application of Artificial Intelligence and Machine Learning

Recent developments in artificial intelligence (AI) and machine learning (ML) offer significant opportunities for advancing SSI research. Data-driven models can be trained using large datasets generated from numerical simulations, laboratory experiments, and field observations to predict SSI effects rapidly and accurately. Machine learning algorithms may help identify complex relationships between soil properties, foundation characteristics, and structural response while reducing computational requirements.

2) Performance-Based Seismic Assessment Incorporating SSI

Future studies should focus on integrating SSI into performance-based seismic assessment frameworks. Such approaches would enable engineers to evaluate structural performance in terms of damage states, repair costs, downtime, and resilience rather than solely relying on force-based design criteria. This integration would provide a more realistic representation of structural behaviour during and after earthquakes.

3) SSI Under Near-Fault Ground Motions

Most existing SSI studies have focused on conventional earthquake records. However, near-fault ground motions often contain strong velocity pulses and permanent ground displacements that can significantly influence structural response. Further research is needed to investigate how SSI modifies the effects of near-fault seismic excitations and whether existing design methodologies remain adequate under such conditions.

4) Coupled SSI and Liquefaction Analysis

Liquefaction represents one of the most severe geotechnical hazards associated with earthquakes. Current SSI studies often neglect the effects of soil liquefaction or consider them separately. Future investigations should develop integrated numerical frameworks capable of simultaneously capturing

SSI and liquefaction phenomena. Such models would improve seismic risk assessment for structures located in liquefaction-prone regions.

5) Probabilistic SSI Modelling and Reliability Analysis

Future research should increasingly adopt probabilistic approaches that account for uncertainties in soil properties, structural characteristics, earthquake loading, and modelling assumptions. Reliability-based SSI frameworks can provide more realistic estimates of structural safety and support risk-informed decision-making processes.

6) Digital Twin Technology and Real-Time Monitoring

The emergence of digital twin technology presents a promising avenue for SSI research. By combining sensor networks, structural health monitoring systems, and real-time numerical simulations, digital twins can continuously evaluate the condition and performance of soil–foundation–structure systems. Such technologies could significantly improve post-earthquake assessment and infrastructure management.

7) Multi-Hazard SSI Assessment

Future studies should extend SSI investigations beyond earthquake loading to include other hazards such as wind, flooding, landslides, mining-induced vibrations, and blast loading. Multi-hazard assessment frameworks would provide a more comprehensive understanding of infrastructure resilience under complex loading environments.

V. CONCLUSION

This review paper comprehensively examined recent developments in Soil–Structure Interaction (SSI) and its influence on the seismic behaviour of building structures. Based on the reviewed literature, it is evident that SSI plays a critical role in modifying the dynamic characteristics and seismic response of structures and therefore should not be neglected, particularly for buildings founded on soft soils, medium-stiff soils, or deep foundation systems.

The reviewed studies consistently demonstrate that SSI affects several key response parameters, including natural periods, damping characteristics, base shear, storey drifts, floor accelerations, foundation settlements, and rocking behaviour. One of the most widely reported effects of SSI is the elongation of the fundamental vibration period due to foundation flexibility and soil deformability. This period shift often results in reduced base shear demands; however, it may simultaneously increase displacement-related responses such as inter-storey drift, lateral displacement, and foundation rotation. Consequently, SSI may provide both beneficial and adverse effects depending on soil conditions, foundation systems, structural configurations, and earthquake characteristics.

The literature further indicates that SSI effects become increasingly significant for high-rise buildings, irregular structures, pile-supported systems, and structures subjected to strong seismic excitations. Buildings founded on soft soils generally experience greater amplification of SSI effects due to reduced soil stiffness and increased deformability. Similarly, pile-supported structures exhibit complex soil–pile–structure interaction mechanisms that require detailed consideration during seismic analysis and design.

Recent advancements in finite element modelling, computational techniques, and high-performance computing have significantly improved the ability to simulate complex SSI phenomena. Sophisticated three-dimensional numerical models can now capture nonlinear soil behaviour, foundation rocking, soil–pile interaction, and structural inelasticity with high levels of accuracy. Nevertheless, the practical implementation of such advanced methodologies remains challenging because of computational demands, modelling complexity, and uncertainties associated with soil characterization.

Simplified SSI modelling approaches, including equivalent spring-dashpot systems and substructure methods, continue to provide an effective compromise between computational efficiency and analytical accuracy. However, further efforts are required to establish standardized guidelines for selecting appropriate modelling strategies and incorporating SSI into routine engineering practice.

Overall, the findings of this review highlight the necessity of considering SSI as an integral component of seismic analysis and design. Future research should focus on developing practical, reliable, and computationally efficient SSI methodologies that bridge the gap between advanced research models and everyday engineering applications. Furthermore, emerging technologies such as machine learning, digital twins, probabilistic assessment techniques, and performance-based design frameworks offer significant opportunities for advancing the field of Soil–Structure Interaction and enhancing the seismic resilience of modern infrastructure.

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