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Soil-Structure Interaction and Foundation System optimization for Enhanced Seismic Performance of Multistorey RC Building

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Abstract: Structural failures during earthquakes often occur due to inadequate analysis and design practices. Typically, foundations are designed based on superstructure loads, site conditions, and seismic zoning. Conventional analysis assumes no interaction between the structure and the supporting soil, with structural engineers assuming fixed supports and geotechnical engineers designing foundations independently. In reality, the interaction between soil and structure plays a crucial role, as both deform under load and must act compatibly. This study reviews the dynamic behaviour of framed structures supported on various foundation types, emphasizing the importance of SSI. Analytical, numerical, and experimental approaches from recent literature are discussed, highlighting current challenges and future research needs in SSI modelling.
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***Keywords* - Soil-Structure Interaction, Finite element analysis, response spectrum method, Numerical Modeling.**

I. INTRODUCTION

Earthquakes have caused significant structural damage in India, especially in regions along the Asia-Pacific plate. Traditional design methods often ignore the interaction between the structure, foundation, and soil. However, during seismic events, both the structure and the soil deform, making Soil–Structure Interaction (SSI) a critical factor in accurate analysis and design. SSI involves both kinematic and inertial interactions, influenced by soil properties, foundation type, and structural characteristics. In pile foundations, group effects such as pile–soil–pile interaction, spacing, and configuration play a key role in seismic response. Understanding these interactions is essential for designing safe, resilient structures on soft and loose soils.

II. CORRESPONDING LITERATURE

The Soil–structure interaction (SSI) under dynamic loading conditions presents a complex challenge in structural engineering. This study offers a detailed review of literature focusing on the seismic performance of buildings supported by pile foundations, with an emphasis on the influence of SSI. Various parametric studies have demonstrated the critical role of SSI in structural design, identifying factors such as superstructure geometry, foundation configuration, soil stiffness, and shear wave velocity profiles as key determinants of seismic response.

Koushik Bhattacharya et al. (2003)[3] studied the impact of soil compressibility on the lateral stiffness and natural periods of structures, showing that increased soil flexibility leads to longer natural periods and affects seismic response. The study emphasized the importance of soil structure interaction (SSI) in determining lateral period, base shear, and torsional effects in raft-supported buildings. Various parameters were analyzed, including soil properties, structural configuration, and ground motion. The findings highlight the need to consider soil flexibility in seismic design, especially for low-rise buildings.

Halkude S.A. et al. (2014)[4] highlighted that conventional raft foundation design often neglects soil flexibility, which can influence structural performance. Their study investigates the impact of soil-structure interaction (SSI) on building frames resting on raft foundations by comparing fixed and flexible base conditions. Symmetrical space frames (2×2×2, 2×2×5, and 2×2×8 storeys) on three soil types hard, medium, and soft are analyzed using response spectra per IS 1893:2002. Two SSI modeling approaches are considered: the Winkler (spring) model and the elastic continuum (FEM) model, developed in SAP-2000. The study evaluates natural time period, base shear, roof displacement, and member forces. Results show that SSI significantly affects structural response, with the elastic continuum approach offering more accurate representation of soil flexibility.

Shehata E. Abdel Raheem et al. (2015)[5] emphasized the critical role of soil conditions in structural damage during earthquakes, highlighting the importance of understanding energy transfer from soil to buildings. Their study focuses on the seismic behavior of multi-story buildings considering soil–structure interaction (SSI), noting that conventional design often neglects foundation flexibility and soil compressibility, potentially leading to unsafe designs. The research evaluates the impact of SSI on buildings supported by raft foundations using three seismic analysis methods: equivalent static load, response spectrum, and nonlinear time history analysis with a set of nine earthquake records. Findings underline that SSI can adversely affect seismic response and must be accounted for in design.

Husain Khalaf Jarallah (2015)[6] investigated the impact of soil-structure interaction (SSI) on the seismic performance of a framed building supported on a raft foundation. The study models soil flexibility using equivalent springs and conducts nonlinear static pushover analysis of an eight-storey RC hospital building in Delhi using the Capacity Spectrum Method (ATC-40). Performance levels are evaluated as per NEHRP and FEMA-356 guidelines under both fixed and flexible base conditions for Design Basis and Maximum Considered Earthquakes. Findings reveal that SSI significantly influences roof displacement, storey drift, base shear, damping, and crack patterns, while its effect on torsional behavior is minimal. Overall, SSI makes the building more vulnerable, emphasizing the need to include soil flexibility in seismic evaluation.

Dhritiman Mondal (2019)[7] explored the effects of dynamic soil-structure interaction (SSI), focusing on how foundation flexibility and embedment influence the seismic behavior of buildings. The study compares surface and embedded ten-storey building models resting on raft foundations using finite element analysis in ANSYS and STAAD Pro V8i. While prior research has focused on large-scale structures like nuclear plants and bridges, this study highlights the need for advanced SSI analysis in high-rise buildings. Various load cases dead, live, and lateral are considered, and structural responses such as storey displacement, column bending moments, and time periods are evaluated. Results emphasize the influence of SSI and foundation embedment on dynamic response.

Aslan S. Hokmabadi et al. (2014)[9] investigated the effects of seismic soil–pile–structure interaction (SSPSI) through shaking table tests and numerical simulations. The study compares three scenarios: fixed-base structures, structures on shallow foundations, and those on floating pile foundations in soft soil. A laminar soil container was used to minimize boundary effects in physical tests, and a fully nonlinear 3D model in FLAC3D was employed for time-history analysis. Results indicate that SSPSI increases lateral deflections and inter-storey drifts compared to fixed-base assumptions. However, floating pile foundations reduce lateral displacements relative to shallow foundations by limiting foundation rocking. The close agreement between experimental and numerical results validates the modeling approach and underscores the importance of considering SSPSI in seismic design, especially on soft soils.

Krishna Chaitanya et al. (2019)[14] reviewed the importance of accurately considering soil-structure interaction (SSI) in the analysis and design of engineering structures. They noted that standard assumptions of fixed or pinned supports often overlook the influence of soil type, which can significantly affect structural response. The study emphasized that support conditions vary with soil characteristics (loose, medium, or hard), impacting the accuracy of dynamic analysis, especially under seismic or lateral loading. The review underscores the growing recognition of SSI's role in modern structural engineering and highlights the need for detailed SSI evaluation for reliable design outcomes.

In their study E. Ravi et al. (2019)[17] examined that the Clayey soils which are expansive will swell and can cause lifting of buildings or other structures through the ingress of high moisture. Conversely, during evaporation, it will shrink and can result in building settlement. The vertical cylindrical cells reinforced with geogrid are referred as geopiles in which expansive soil is compacted at 95% optimum moisture content in rigid tank. This research work presents the heave behavior of expansive clay through the provision of geogrid encased with different materials, viz. fine sand, coarse and gravel. We studied that the heave behavior of expansive clay is by using single, two and four geopiles of same diameter filled with above said materials. The results indicated that heave decreased with increasing diameter particles size of the fill materials. The comparisons between unreinforced clay and reinforced clay using geogrid were analyzed.

During seismic activity in (2015)[24], M Roopa, et al. have found that the response of structures is influenced by Soil Structure Interaction (SSI) which is the process where the response of soil particles to earthquake ground motion affects the motion of structure and the response of structure affects the motion of soil mass. In design offices the base of multi-storey buildings are taken as fixed and analyzed for earthquake response using provisions of IS 1893-2002 with the aid of response spectrum given for soft, medium and hard soils in foundation. But in reality, the type of soil present in and around the foundation structure also participates in the seismic response and the assumption of fixed base becomes conservative. Soil structure interaction usually carried out for soft, medium and hard soil. This study is mainly concentrated on in situ clayey soil conditions. The RC building considered to analyse SSI is an apartment of G+12 Storey with an elevation of 40.15m and with the plan shape of 28.2m×16.1m proposed at Mambakkam, South Chennai, Tamil Nadu state, India. The study has used the finite element tools ETABS 9.7.4 for modeling and SAP2000 ver17 for SSI analysis.

Venkatesh M. B. et al. (2017)[27] investigated the seismic performance of medium-rise RCC buildings considering soil-structure interaction (SSI). An eight-storey RC building model was analyzed using STAAD Pro, with soil flexibility incorporated via equivalent soil springs connected to the raft foundation. The study compared fixed-base and flexible-base models under response spectrum analysis, applying seismic loads per IS 1893-2002 for soil types I, II, and III across Zones III, IV, and V. The results highlighted the significance of SSI in accurately assessing dynamic responses and emphasized the need for realistic modelling of building–foundation–soil interaction under earthquake loading conditions.

The research by Saad Kondkari, et al. (2025)[(30)] , aims to provide a comprehensive overview in current state of structure-soil-structure interaction issues in tall building frames supported by different types of foundations. Their analysis emphasizes the impact of adjacent structures and highlights the need for further academic research in this area. This literature review provides a comprehensive overview of the significant contributions made by various researchers in the field of soil-structure interaction, highlighting the critical importance of considering SSI effects in building design and analysis to ensure their safety and performance under various loading conditions.

2.1 Pile Foundation

Pulikanti Sushma et al. (2010)[11] conducted a numerical study on dynamic soil-structure interaction (SSI) of high-rise buildings in a viscoelastic half-space using the direct FEM based approach in ANSYS 10. The analysis focused on pile supported structures and considered interactions between adjacent buildings. Several scenarios were examined: groups of identical and different structures, variations in building height (5, 10 and 15 storey), and different structural shapes. Each case compared SSI responses with fixed base assumptions. Results highlighted that both soil structure and structure to structure interactions significantly influence the seismic behavior of high-rise buildings, especially when supported on piles.

Pallavi Ravishankar et al. (2015)[12] addressed the complexity and high computational cost of soil-structure interaction (SSI) analysis by proposing an optimized approach using the *equivalent pier method* for deep foundations. The study analyzed an 11-

storey L-shaped building on pile foundations under dynamic loading, incorporating SSI effects. The method simplified modeling of asymmetrical pile groups and reduced computational effort while maintaining accuracy. The research also examined wave propagation and SSI behavior across different soil types (cohesive, cohesionless, and mixed), showing that kinematic interaction is more influenced by soil bearing capacity than by stiffness. The findings highlight the potential of the equivalent pier method for efficient and reliable SSI analysis.

J. Visuvasam et al. (2019)[15] emphasized the importance of considering soil properties and soil–pile–structure interaction (SPSI) in the design of industrial buildings, especially in coastal regions with loose soils. The study investigated the seismic behavior of reinforced concrete frames (5, 10 and 15 storey) on pile foundations using PLAXIS 3D, adopting a direct analysis approach. Parameters such as soil density (30%, 50%, 70%) and pile spacing (2D, 4D, 6D) were analyzed. Results showed that SPSI significantly affects pile lateral displacements, raft rocking, storey displacements, and inter-storey drifts, with noticeable differences compared to fixed-base assumptions. The study highlights the need for realistic modeling of SPSI in seismic design.

S. A. Rasal et al. (2017)[18] conducted a 3D finite element study on the soil–structure interaction (SSI) behavior of a three-storey building frame supported by a pile group foundation embedded in cohesive soil. The structural components (beams, columns, slab, pile, and cap) were modeled using 20-node isoparametric elements, while the pile soil interface was represented using 16-node surface elements. Various continuum elements (8-node, 9-node, and 12-node) were used for refined soil modeling. The study assumed linear elastic behavior for both the structure and soil, focusing on immediate soil response and total stress. A parametric analysis was conducted by varying pile spacing to assess its effect on structural response. Results showed that SSI significantly influenced frame displacements and column bending moments, underscoring the importance of considering SSI in design.

Mahmoud N. Hussien et al. (2010)[21] investigated the impact of soil–pile separation on the lateral performance of pile foundations through full-scale tests involving single and 3×5 pile groups under static and dynamic lateral loads. The coupled soil pile system was modeled using 2D finite elements, with soil behavior represented by a hyperbolic multiple shear mechanism and nonlinear hysteretic springs for soil pile interaction. A separation–contact interface model was used to simulate soil pile separation. Results showed that neglecting soil pile separation significantly overestimates lateral load capacity by 43% for single piles and 73% for trailing piles in groups under static loads, and similarly distorts dynamic load deflection behavior. The study highlights the critical role of accounting for separation effects in accurate pile group analysis.

P. A. Dode et al. (2015)[22] examined the effect of soil-structure interaction on a four storeyed, two bay frame resting on pile and embedded in the cohesive soil is examined in this paper. For the purpose of the analysis, simplified idealizations made in the theory of finite elements are used. The slab provided for all storeys are idealized as three-dimensional four nodded shell elements. Beams and columns of the superstructure frame are idealized as three-dimensional two nodded beam elements. Pile of the sub-structure is idealized as three-dimensional two nodded beam elements. The finite element-based software program ANSYS is used for the purpose of analysis. The effect of different pile diameters on the response of superstructure is evaluated. The responses of the superstructure considered include storey displacements at respective storeys.

Radhika J. et al. (2024)[(28,31)] have investigated the dynamic soil-pile structure interaction (SSPSI) of a 15-story symmetric building frame resting on different pile configurations and provided with damping layers for studying the performance of such building under earthquake. Damping layers with increasing damping around the soil medium is introduced to absorb seismic energy, reduce resonance effects, and enhance the structures resilience. The results show that the addition of the damping layers and different types of piles greatly reduces the stress that earthquakes put on the structure by releasing vibrational energy.

2.2 Piled-Raft Foundation

S.A. Rasal et al. (2019)[1] investigated the effect of soil-structure interaction on a three-storey (G+2) building frame supported on a piled-raft foundation. The building frame comprises two bays, and its columns are supported by a piled-raft foundation embedded in cohesive soil. Simplified idealizations in the theory of finite elements were used for the analysis. The slab was modelled as two-dimensional plate elements, while beams and columns of the superstructure frame and the pile of the sub-structure were modelled as one-dimensional beam-column elements. The soil mass was represented by equivalent springs. The study evaluated the impact of different raft thicknesses with a uniform pile diameter on the superstructure's response, specifically focusing on frame displacement.

Shukla S.J. et al. (2013)[8] studied the seismic behavior of 25-storey buildings supported by piled raft foundations on various subsoil types. A piled raft foundation combines shallow (raft) and deep (piles) foundation elements, allowing load sharing between both components. Unlike conventional designs where piles or raft carry the entire load, this system reduces settlement and tilt while enhancing performance. The complex soil-structure interaction (SSI) during earthquakes is modeled using the Finite Element Method with realistic soil behavior. The study highlights the critical role of SSI modeling in ensuring stability and performance of high-rise structures with piled raft foundations.

Ashutosh Kumar et al. (2017)[25] investigated the application of a piled-raft foundation for a raw materials storage building in South Bà Rịa–Vũng Tàu Province, Vietnam. The system consisted of a large raft (81 m × 55.5 m) connected to 581 precast hollow concrete piles, each 20 m long. A detailed soil–structure interaction (SSI) analysis was conducted using finite element modeling, validated with field pile load test data. The study considered various loading scenarios, from fully loaded to empty compartments. Results showed the raft contributed significantly, sharing 23–31% of the vertical load. Key outcomes—such as vertical and differential settlement, raft tilt, and pile axial forces—were used for final design and offer valuable reference for similar engineering applications.

R. R. Chaudhari et al. (2013)[26] examined the performance of piled-raft foundations for high-rise buildings, emphasizing their advantages over conventional pile or mat foundations. The study focused on the impact of pile length configurations under vertical loading using finite element analysis in ANSYS 11. It highlighted how structural stiffness, typically neglected in settlement estimations, can significantly influence foundation displacements and internal forces. Even minor differential settlements can alter the force distribution in structural members. The findings confirm that soil–structure interaction (SSI) plays a crucial role in accurately predicting structural behavior, and must be accounted for in design to ensure realistic performance assessments.

2.3 Linear and Non-Linear Analyses

Ibrahim Oz et al. (2020)[2] conducted reconnaissance research after devastating earthquakes, which showed that buildings constructed on unstable soils demonstrate notably poor seismic performance. This emphasizes the detrimental effects of the interaction between soil and structures on seismic performance. In order to examine these impacts, a total of 40 pre-existing structures in Turkey were chosen, and nonlinear models were constructed to account for several types of soil conditions, including fixed-base, stiff, moderate, and soft soils. Buildings were classified into two categories: old, referring to those designed prior to the implementation of the 1998 Turkish Earthquake Code, and modern, referring to those designed after the code was put into effect. The substructure approach was used to model soil conditions, which were classified based on shear wave velocities. In order to determine the inelastic deformation needs, a nonlinear time history analysis was conducted utilizing 20 actual acceleration recordings from significant earthquakes. The study discovered that the interaction between soil and structures, especially in soft soils, has a substantial effect on the seismic response of old buildings. The most dramatic rise in drift demands is observed at the lower levels. The findings indicated that the influence of soil-structure interaction on the seismic behavior of new structures is less significant than that of ancient buildings. Moreover, the responses of buildings with fixed-base, stiff, and moderate soil conditions were similar; however, buildings on soft soils saw more noticeable effects.

Riccardo Scarfone et al. (2020)[10] conducted 3D nonlinear time-domain analyses to investigate soil–structure interaction (SSI) effects in a 20-storey building using an elastoplastic soil model. The study evaluates three foundation systems shallow, deep embedded, and pile foundations across two soil profiles. It isolates site amplification, kinematic, and inertial interactions, and emphasizes the influence of foundation deformability and soil stratigraphy. Results show that increased foundation flexibility reduces seismic base shear and increases foundation rotation, without significantly increasing structural displacements. The study also highlights limitations of traditional substructure approaches, particularly for deep foundations in soft soils, and demonstrates that embedded pile elements offer a computationally efficient method for simulating complex SSI behavior.

Raychowdhury and Singh (2012)[13] investigated the effects of nonlinear soil-structure interaction (SSI) on the seismic performance of low-rise steel moment-resisting frames (SMRF). Their study highlighted how soil nonlinearity introduces additional flexibility and energy dissipation at the soil–foundation interface, potentially altering seismic response. A Winkler-based approach was used to model the soil as a system of nonlinear springs. A 3-storey SMRF was analyzed using both static pushover and nonlinear dynamic methods. The findings demonstrated that nonlinear SSI significantly influences structural performance, yet is often neglected in practice due to modeling complexities.

Christos Mourlas and colleagues published a study in (2019)[16] the nonlinear dynamic analysis of full-scale reinforced concrete structures, incorporating 3D comprehensive modeling that accounts for the soil-structure-interaction (SSI) phenomenon, is a very important area of research for both researchers and engineers. The main numerical challenges encountered during the nonlinear dynamic analysis of SSI models are the occurrence of numerical instabilities when cracks open and close, as well as the high computational demand, even for small numerical models. Researchers utilize numerical models, such as the beam-column element, to discretize the superstructure and piles of a foundation system in order to analyze soil-structure interaction (SSI) models. Researchers extensively record the constraints of this method, particularly when simulating shear walls and joints using one-dimensional models. Furthermore, the beam-column element has an impact on the interaction between the 3D soil domain and the piling foundation. This research utilizes a computationally efficient and reliable 3D modeling method to simulate RC structures.

In (2006)[19] Hossein Tahghighi et al. states that the nonlinear p–y element was provided which can simply model the behavior of a pile group foundation subjected to lateral loading. Its elasto-plastic side soil is expressed as a Winkler-type distributed model. Despite the simplification involved in modeling such a complex phenomenon the proposed nonlinear soil model can reproduce the system behavior as computed by more rigorous 3D finite element methods. The numerical results are also compared with those from available physical model data to confirm that our simulations can predict the behavior of pile groups with good accuracy.

Behzad Fatahi et al. (2012)[20] evaluated the accuracy of equivalent linear versus fully nonlinear methods for dynamic soil structure interaction (SSI) analysis. Three building models (5, 10, and 15-storey) were analyzed on soft soils (shear wave velocity < 600 m/s) under seismic loading. The study compared results for fixed-base models, equivalent linear SSI models, and fully nonlinear SSI models. Findings revealed that the equivalent linear method significantly underestimates lateral deflections and inter-storey drifts in mid-rise buildings compared to the nonlinear approach. The authors concluded that relying solely on equivalent linear analysis may compromise structural safety for buildings on soft soils, highlighting the importance of fully nonlinear modeling for accurate SSI representation.

S. A. Rasal et al. (2018)[23] conducted a 3D finite element study to analyze the soil–structure interaction (SSI) behavior of a three-storey building frame supported by a 2×2 pile group embedded in cohesive soil. Superstructure and foundation elements were modeled using 20-node isoparametric continuum elements, while the pile–soil interface was modeled using 16-node surface elements. Soil was assumed to behave nonlinearly, whereas the structural components were treated as linear elastic. A substructure approach was used, comparing non-interaction and interaction analyses by evaluating equivalent stiffness of the foundation. Parametric studies were carried out by varying pile spacing and embedment depth ratios. Results demonstrated that SSI significantly affects structural response—particularly displacements, internal forces, and moments—depending on pile configuration and soil behavior.

III. SUMMARY

Numerous studies have investigated the impact of soil–structure and soil–pile–structure interaction on the seismic behavior of buildings. Researchers like Rasal *et al.* and Fatahi *et al.* highlighted the importance of incorporating realistic soil models and interaction effects in dynamic analysis. Finite element modeling has been widely used to simulate 3D building–foundation systems, with variations in pile configuration, spacing, and soil type showing significant influence on structural response. Comparative studies between fixed-base, linear SSI, and nonlinear SSI models reveal that simplified methods often underestimate seismic demands, particularly in soft soils. Full-scale tests and advanced modeling approaches have confirmed that ignoring factors like soil–pile separation or raft contribution can lead to unsafe design assumptions. Overall, these findings emphasize the critical role of SSI in achieving accurate predictions of displacement, internal forces, and overall seismic performance, especially for mid- to high-rise structures on pile or piled-raft foundations.

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