State-Of-The-Art Review of Artificial Neural Network Techniques in Building Frame Soil-Structure Interaction Analysis

Mr. Nilesh Ajitrao Karmuse[1], Dr. Mahesh G. Kalyanshetti[2]

Research Scholar[1], Department of civil Engineering, Walchand Institute of Technology, Solapur

Associate professor[2], Department of civil Engineering, Walchand Institute of Technology, Solapur

Abstract

Soil-structure interaction (SSI) pertains to the dynamic interplay between a building and the underlying soil, where the characteristics of both the structure and the soil influence the stress distribution and movement of both components. This interaction is particularly crucial in seismic regions, where the behavior of soil-structure systems can significantly affect structural stability and damage. Structures founded on deformable soils are prone to increased static settlement and reduced seismic resilience compared to those on stiffer soils. Despite the importance of SSI, especially concerning soil liquefaction in seismic areas, the dynamic response of reinforced concrete wall-frame dual systems to SSI remains inadequately explored and often overlooked in engineering practice. This review paper delves into the state-of-the-art artificial neural network (ANN) techniques applied to building frame soil-structure interaction analysis. By examining recent advancements in ANN methods, this study aims to address gaps in understanding SSI's impact on structural performance and seismic behavior. The review highlights how simulation studies of soil beneath foundations affect the frequency response and dynamic properties of structures, emphasizing the need for a comprehensive approach to integrate SSI considerations into structural design and sustainability practices.

Keywords: interaction, Interplay, deformable, seismic, sustainability.

1. INTRODUCTION

In the realm of civil engineering, the interaction between building frames and soil structures is a crucial aspect that significantly influences the stability, safety, and performance of structures[1]. Traditional approaches to soil-structure interaction (SSI) analysis have relied heavily on deterministic models and empirical methods, which, while effective, often fall short in capturing the complex, non-linear behaviors inherent in these interactions [2]. Recent advancements in computational techniques and artificial intelligence (AI) have paved the way for more sophisticated analysis methods, among which artificial neural networks (ANNs) have emerged as a prominent tool. [3]. Artificial neural networks, inspired by the biological neural networks of the human brain, are computational models capable of learning from data and making predictions or decisions [4]. Their ability to model complex, non-linear relationships makes them particularly suitable for applications where traditional methods struggle to provide accurate solutions [5]. In the context of building frame SSI analysis, ANNs offer a novel approach to address the limitations of conventional methods by leveraging data-driven insights to improve the accuracy and efficiency of predictions [6]. The use of ANNs in building frame SSI analysis is part of a broader trend towards integrating advanced computational techniques into civil engineering practice [7]. Traditional SSI analysis methods often involve intricate calculations based on simplified assumptions and idealized models [8]. These methods may not fully account for the variability in soil properties, construction techniques, and loading conditions, potentially leading to suboptimal design and analysis outcomes. ANNs, with their capacity to handle large datasets and identify patterns that are not immediately apparent through conventional means, provide a promising alternative to enhance the fidelity of SSI models [9].

The state-of-the-art review of ANN techniques in this context explores the evolution and application of these methods in building frame SSI analysis [10]. It delves into the various ANN architectures and learning algorithms that have been employed to address the challenges associated with soil-structure interaction. This includes feedforward neural networks, recurrent neural networks, convolutional neural networks, and hybrid models that combine ANNs with other computational techniques. Each of these architectures has its strengths and weaknesses, and their applicability depends on the specific characteristics of the SSI problems being addressed [11]. The review also highlights key advancements in training methodologies and optimization techniques that have improved the performance of ANNs in this domain. Techniques such as backpropagation, regularization, and hyper parameter tuning are discussed in relation to their impact on the accuracy and robustness of ANN models. Additionally, the integration of ANNs with other AI and machine learning techniques, such as support vector machines and genetic algorithms, is examined to showcase the potential for hybrid approaches that can offer even greater improvements in SSI analysis [12]. Furthermore, the review addresses the challenges and limitations associated with the use of ANNs in building frame SSI analysis. These include issues related to the availability and quality of training data, the interpretability of ANN models, and the need for rigorous validation and verification processes. Despite these challenges, the benefits of incorporating ANNs into SSI analysis are substantial, offering enhanced predictive capabilities, reduced computational costs, and the ability to address complex, real-world scenarios that are difficult to model using traditional methods [13].

1.1 Soil Structure Interaction

The investigation of soil-structure interaction (SSI) is connected with the field of seismic designing. It is vital to take note of that the primary reaction is chiefly because of the soil-structure interaction powers that welcomes an effect on the structure. This is a type of seismic excitation. A board of designing exploration manages the investigation of soil-structure interaction just when these powers welcomes an apparent impact on the cellar movement when we are contrasting it and the free-field ground movement.

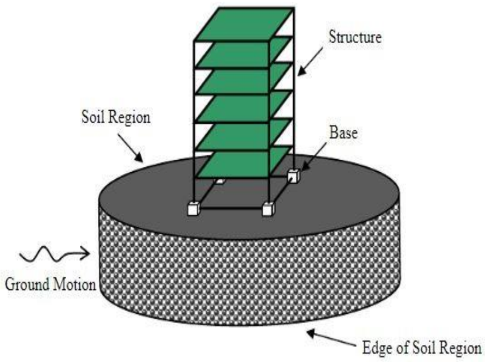

FIG.1 Different Shapes of Building

The free-field ground movement can be characterized as the movement recorded on the outer layer of the soil, without the association of the structure.

1.2 SSI and Structural Response

The effect of SSI is very useful for a structural response, depending on traditional customs. As a result, the design codes that recommend SSI interactions during earthquake analysis have been ignored [14]. There will be a false concept that these interactions will provide positive flexibility to the structure and will significantly increase the safety part. Finally, it helps to improve the structure's natural period. It will also help to maintain a positive approach in the case of the damping ratio while considering dynamic loading conditions, there is a major concern regarding structural engineering design. There should be some structural control methods available to maintain the structure's strength and ductility. Aside from all traditional techniques, they can be provided with different control systems to improve performance and efficiency. SSI has traditionally been studied solely on the basis of time period and frequency. In the case of frequency conditions, the structure interaction is also defined by the specific frequency. Even though the soil system is nonlinear, the system is treated as a linear system [15]. Few studies have been conducted to determine how the system responds to a symmetric building while taking its SSI into account. Interactions through foundations increase the fundamental elastic-plastic period of structure when compared with fixed base considerations, but SSI considerations result in a drop in the structure's fundamental elastoplastic period. It was obvious that SSI impacts the mass and stiffness of the complete structural system. It also reduces the wall sections' major moment and shear ratios. SSI increases column ratios and tends to overload the vertical element's top [16].

2. Dynamic Response of the Structure Subjected to SSI

Several earthquakes have struck in recent years, causing structural harm to buildings. The significance of SSI for static as well as dynamic loads was a topic of concern for structural engineers [17]. It enhances the damping of the structural system and lengthens the structure period. The impact of SSI on the functionality of a building as a whole, especially on soft soils, is a subject of discussion among scholars [18]. Limit-state issue solutions based on soil mechanics generally model the soil and interface as constitutive entities, with the structural component being treated as either a stiff or completely flexible body [19]. Soft soil is more significantly affected by SSI than medium or hard soil. A variation of Winkler's springs was used by numerous researchers to simulate soil-structure interaction [20]. Winkler's approach, while straightforward, is inaccurate because it does not accurately record deflections, particularly for the sub-structure. Therefore, a contrast of the findings for the super as well as the sub-structure is essential to comprehend the impact of different modelling approaches [21].

2.1 Effect of SSI on Different Base Conditions

A foundation is commonly considered to be simply connected to a rigid rock subjected to lateral "unidirectional acceleration" in classical structural design, while SSI is typically disregarded in the earthquake-resistant structure's design [22]. A set of piles could be used to support tall structures on medium- to soft-soil foundations, and pile-raft foundations are typically utilized to distribute the structural weight to the earth's depth. A collection of piles' static effects is fairly obvious, but because their dynamic impacts are unknown, they were not taken into account when designing the piles. "Piled raft foundations" have a large positive impact on the seismic reaction of the superstructure when the structure is built on the surface, for example, a 40 percent drop in the base shear [23]. The usage of "piled-raft foundations" is not important and has little impact when the building is situated inside an excavation. For tall structures, the impacts of foundation rocking are quite substantial. The moments drift, and displacements of the model along with foundation rocking have been impacted in the research. Despite having a piled-raft foundation, this model's adverse impacts from foundation rocking were not eliminated. Further research is required to fill the knowledge gap in the area and improve predictions of the behaviour of superstructures within soft soil conditions [24]. Studies looked at the impacts of SSI and random differences in the crucial soil parameter values on steel building fragility. The soil's shear modulus was found to have a substantial influence on the fragility outcomes than soil parameters. It has been shown that SSI could enhance the chance of failure with reference to the fixed-base scenario despite seasonal fluctuations in the soil parameters after converting the "fixed-base spectral accelerations" into its flexible-base equivalents and redrawing the SSI curves. The primary cause of this phenomenon was determined to be a rise in the story drifts of the building's lower portion as a result of SSI [25]. Studies of slope stability based on SSI interactions have also been performed. The hardening soil model, which requires less computational effort as compared to the Mohr-Coulomb soil system in slope stability problems, tends to determine the safety factor with a narrow posterior distribution, demonstrating that constitutive models that take into account the effect of strength within the elastic region are better suitable for efficient data assimilation. To handle unsaturated soil flow and look into differential settlement brought using rainfall infiltration, the van Genuchten model and Barcelona basic model have both been suggested as the best solutions for settlement issues. It should be mentioned that these have been combined with random fields in the FEM ("Finite Element Method") to account for soil heterogeneity [26]. The impact of SSPSI ("Seismic Soil-Pile Foundation-Structure Interaction") on the dynamic properties and elastic response of a scaled-model structure as well as pile foundation, including a parametric change of the lateral period of the pile and superstructure group, was once become the subject of research. According to parametric research on the variation of pile foundations' lateral stiffness, choosing a conservative design by placing more piles together in soft clay could produce a building that responds roughly equally to a fixed base condition. The cause might be that the results of conservative design in a substantial rise in the foundation's lateral stiffness, which causes the base condition to be nearly fixed [27].

2.3 ANN Applications in Building Frame SSI Analysis

Artificial Neural Networks (ANNs) have significantly advanced the analysis of Building Frame Soil-Structure Interaction (SSI), offering enhanced predictive capabilities and improved accuracy [28] ANNs are utilized to model complex, nonlinear relationships between building frames and underlying soil, which traditional methods often struggle to capture. In SSI analysis, ANNs can predict the behavior of structures under various loading conditions and soil responses by learning from large datasets of historical and simulated data. Applications include predicting settlement, lateral deformations, and dynamic response of buildings. For instance, ANNs can optimize the design of foundation systems by forecasting the interaction effects between soil and structure [29]. Additionally, ANNs are employed in real-time monitoring systems to assess structural health and predict potential failures. Their ability to generalize from diverse data sets and adapt to new conditions makes them invaluable in modern SSI analysis, enhancing the reliability and efficiency of building design and maintenance [30].

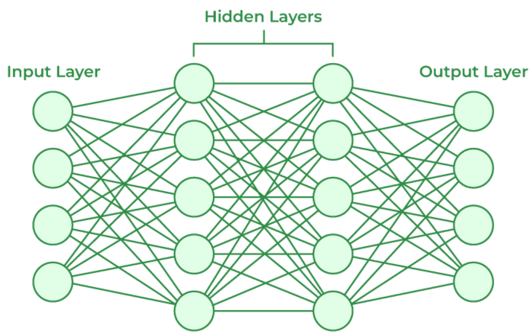

FIG. 2 ANN Applications in Building Frame SSI Analysis

Neural networks (NN) have been used to address soil-structure interaction (SSI) issues, employing the back propagation algorithm and finite element outcomes for training. The NN model, tested across various building dimensions and soil conditions, demonstrated efficient and satisfactory performance compared to SAP2000 results [4]. Regional seismic damage assessments often ignore soil-structure interaction (SSI), leading to inaccuracies. This study introduces a 1D convolutional neural network (1D-CNN) model to predict how SSI affects inter-story drifts and base shear forces in RC frame buildings. By simulating 1380 scenarios and training the model, the study achieves prediction errors of 9.3% and 11.7% for base shear and drift, respectively. The model improves RSDA accuracy by incorporating SSI effects [31]. Peak Ground Acceleration (PGA) alone isn't sufficient for assessing seismic damage as it overlooks the complex interplay between ground movement and structural damage. To address this, ANN-based models were developed, integrating soil structure interaction (SSI) to better predict seismic responses. By training neural networks with data from FEM models, validated by experiments, the study demonstrated improved predictive accuracy for seismic damage, highlighting SSI's critical role in risk assessments across different soil types [6].

Uncertainty in structural analysis, particularly with cohesionless soils, arises from soil variability, site conditions, and construction tolerances. This research proposes a Fuzzy-Neural Network method integrating ANN to predict structural behavior on complex soils. It uses fuzzy sets to manage ambiguity and improve accuracy in predicting system responses and managing uncertainties [32]. The seismic forces on a building during an earthquake depend on its natural vibration period. Traditional methods often ignore soil-structure interaction (SSI), assuming a fixed base, but for buildings on soft soil, SSI introduces flexibility, affecting seismic forces. This study uses finite element modeling and ANN to assess the impact of SSI on the natural period of RC buildings with pile foundations, proposing a modification factor for more accurate predictions [33]. Due to the unpredictable nature of seismic activities, assessing the vulnerability of structures is essential. This study used Python-based supervised Machine Learning algorithms to predict the seismic limit-state capacities of steel Moment-Resisting Frames (MRFs), accounting for Soil-Structure Interaction (SSI). Incremental Dynamic Analyses (IDAs) on MRFs across various story heights and ground motion types revealed no universal model for M-IDA curves. Instead, advanced

ML algorithms were developed to simplify the process and reduce computational costs, utilizing a large dataset and a Graphical User Interface (GUI) for ease of access to prediction results [34]. Soil-structure systems are complex and infinite, making exact analysis challenging, especially with nonlinearities. Recent research uses data-based methods, like optimized neural networks, to tackle these issues. By applying cross-validation, K-fold validation, and genetic algorithms, the neural network outperforms other methods in accuracy and efficiency for soil-structure interaction problems [35]. The study highlights the importance of the Floor Response Spectrum (FRS) in evaluating seismic behavior of secondary structures. It examines how dynamic interactions between primary and secondary structures affect FRS. Using a two-layer feed-forward ANN with the Levenberg-Marquardt algorithm, the study achieves 99% accuracy in FRS prediction, emphasizing the significance of coupled analysis for structures tuned to the primary structure's vibration period [36]. Designers and researchers use analytical techniques to predict structural responses to seismic loads, but traditional models often miss critical dynamic properties. Recent studies show that Artificial Neural Networks (ANNs) offer improved predictions. ANNs, trained with ETABS results, can forecast displacements in reinforced concrete buildings. Performance is evaluated using statistical metrics like correlation coefficient, RMSE, and scatter index.

Interaction effect due to SSI

There are two types of interactions that affect the seismic response and performance of the structure due to interaction between soil, foundation, and structure. Kausel, E. [37] introduced kinematic and inertial interactions. Scattering, reflection, and propagation of seismic waves at the foundation and soil interface due to foundation incapability to match free-field motion is kinematic interaction. It deals with the ground motion and differentiates between foundation input ground motion (FIM) and free-field motion. When the structure and foundation have no mass, the motion produced at the base slab is called FIM. But in practical conditions, the mass of the structure and foundation produces inertia due to acceleration caused during an earthquake. These forces try to move the soil below the structure, and the soil then transmits it to the foundation is inertial interaction effect. Displacement and rotation are produced at the interface of soil medium and foundation. The most critical factor controlling the inertial effect is the structure-to-soil stiffness ratio, represented in equation (1).

Structure-soil stiffness ratio = $h/(vs \cdot T)$.

In equation (1), h is the height of the centre of mass of building in first vibration mode shape, vs is the shear wave velocity, and T is the fundamental time period corresponding to the fixed-base structural model.

Method of analysis of SSI problems

Initially, the analytical methods are not used and are not acceptable due to their complexity and high computational costs. Then the experimental procedures were carried out, like shaking table tests and centrifuge modelling. The physical methods are used to validate the numerical methods. Qaftan, O. et al. [38] carried out experiments on physical models to validate the finite element-based numerical method. Wolf, J. [39] classified the methods for analysing SSI based on the behaviour of soil and structure, i.e., linear or nonlinear. Further, the classification is based on boundary conditions as direct and substructure methods. Far, H. [8] identified the most precise and reliable modelling technique and compared the advantage and disadvantages of each technique. He concluded that numerical methods are most accurate as these methods can incorporate various material conditions and damping, stress anisotropy, changes in the geometry of soil, and radiation damping to analyse the dynamic nature of SSI. The linear or non-linear nature of the soil medium depends on the nature exhibited by the element used in the analysis [40] The non-linear nature includes material and geometric nonlinearities in soil, foundation, and structure. Further, to analyse linear and non-linear nature, the methods are classified as time and frequency domain. The time-domain methods study soil's nonlinear behaviour and pore water pressure effects. The non-linear nature at the interface of structure and soil is also considered. Khanmohammadi, L. et al. [41] performed the analysis in the time domain. The frequency domain considers only linear behaviour. When the structure and soil exhibit linear behaviour and highly developed procedures are used, it is in the frequency domain. The frequency-domain method is more accessible than the time domain method for solving SSI problems. NIST [33] classified the methods to solve SSI as direct and substructure methods based on its interaction effects. Various researchers compared the performance of direct and substructure methods. The different methods to model the structure with SSI are shown in Fig. 2.

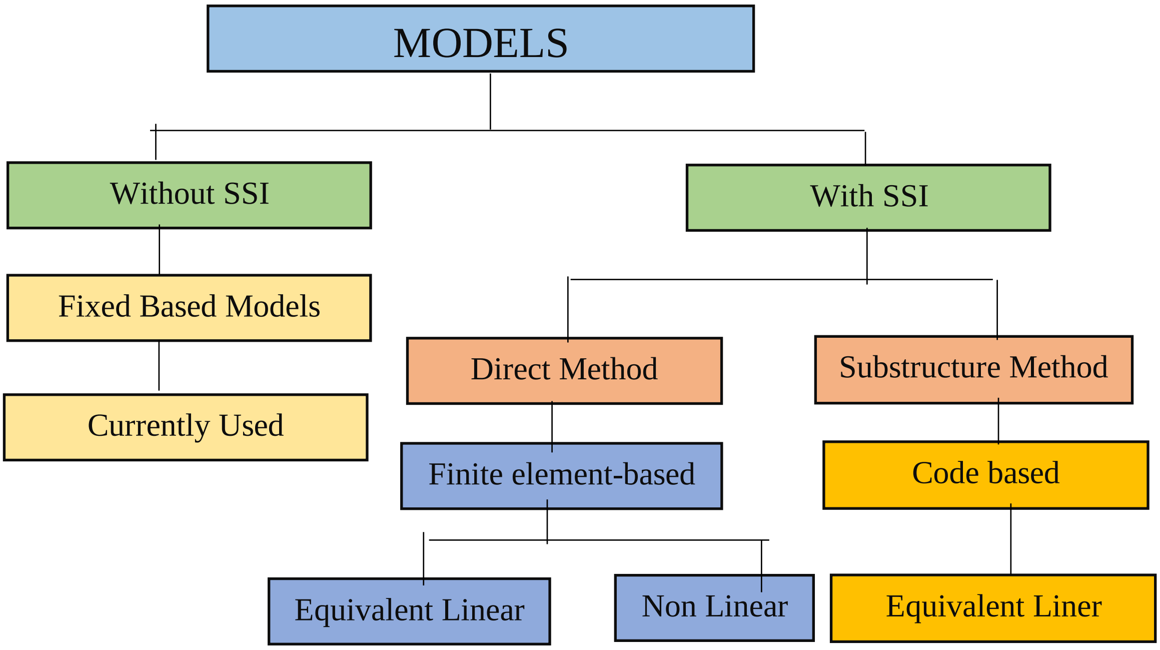

Table 1: Application of various FE software in different research related to SSI

Software	**Foundation**	**Purpose**	**Reference**
Abaqus v.6.8.	Mat foundation	The seismic analysis of buildings on sandy soil considering SSI was performed to evaluate stress propagation, amplification, and acceleration response at the foundation and soil medium interface.	[42]
OpenSees	Shallow foundation	The efficiency of the base isolator evaluated on residential base- isolated buildings with SSI effects considering the non-linear behaviour of the base isolators and soil deformability effects.	[43]
ANN	Piled Raft foundation	The seismic analysis of asymmetrical buildings with SSI effects observed that shape of the structure affected seismic response under the Nepal earthquake in 2015.	[44]
Abaqus	Pile foundation	The FE analysis was validated using a shaking table test on the structure of soft clay.	[45]
Ansys 14.5	Mat foundation	The SSI effects were evaluated on multi-story buildings and observed that with the interaction of foundation and soil elements, response of structural changes.	[46]
SAP 2000	Pile foundation	High-rise building with and without soft stories considering SSI effects analysed. The seismic response and fragility curves describe various damage states to the structure evaluated.	[43]

2.3 Modelling Techniques in SSI

There are two primary methods utilized to determine the SSI system: the direct and substructure approach.

2.3.1 Substructure approach

The Indirect Method or (Substructure Method) divides the structure and the soil into independent structural systems for analysis. The seismic input placed to the designer using the approach is the ground motion within Free-field. The Time history approach or the response spectrum method in this methodology may be used to calculate the non-correlation between the ground and the structure. To determine the structure's reaction when inertial interaction is considered, the estimated outcome is utilized in the SSI analysis's Foundation Input Motion of the Kinematic Interaction System [47].

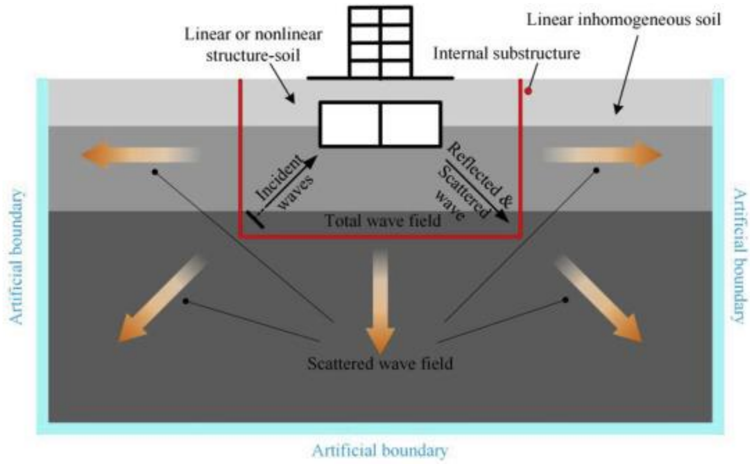

Fig. 1. Substructure method to the study of the SSI

The structure's final seismic response is determined using this technique by combining such impacts based on the superposition of these effects. It considers both the structure and soil separately, solves them, and then accounts for both in calculating the final seismic response. In other words, using impedance & transfer functions, the substructure method can solve inertial and kinematic interactions independently [9]- [48] Therefore, only by thoroughly studying a structure with few "degrees of freedom" could the dynamic properties of a big and complex structure be determined. Fig 1 depicts the Substructure method for the investigation of the SSI.

2.3.2 Direct Approach

It is considered to be the most rigorous method for resolving SSI issues, particularly when dealing with complex structural geometry as well as non-linear soil. In this approach, structure and soil are simultaneously modelled as a single system and examined. Although this strategy is very effective at solving a variety of SSI issues, including both straightforward linear and difficult non-linear ones, it is also complicated, inefficient, and expensive, making it an illogical way to design typical structures [49]. There is a third method, known as the macro element method, in addition to the two previously stated ones. The soil medium is divided into the near as well as far fields using the macro element technique. Less study has used the macro element method because it is more recent than the direct and substructure approaches [50]. This approach models both the structure and soil within a single phase, taking into account both inertial & kinematic interaction. Structures produce inertial interaction owing to their inherent vibrations, which cause "foundation displacements" related to the free field as a consequence of base shear and base moment. While kinematic interaction happens as a result of stiff foundation materials on or within the soil, producing foundation motion to diverge from free field movements [51]. Superstructures and foundations are often found to have simpler and less complicated modelling than the soil medium underneath them. Superstructures and foundation modelling are often found to be less complicated and more straightforward than the soil medium underneath them. However, modelling the soil domain is the most difficult aspect of solving soil-structure interaction issues.

2.4 Soil Domain Modelling Techniques

There are various soil domain-modelling techniques under different categories. Fig 2 Illustrates the different models of approach under various methods and modelling strategies.

2.4.1 Winkler Model

The Winkler method is a soil modelling concept in which the subsoil is modelled as a set of springs that will deform when a weight is applied to it. We will consider the stress-strain behavior as linear in this approach [52]. This method only reflects one parameter, which is known as the subgrade reaction's modulus. According to studies, the common formulation allows the Substructure Strategy that takes nonlinear soil behavior in free-field response into account in addition to that produced with structure [53]. There are primarily two exchanges occurring between the subsoil and the above structure. These are inertial contacts and kinematic interactions. The base shear and moment caused by the building's own vibrations' inertia result in foundation displacements relative to the free field. The damping produced by foundation-soil interaction and the flexibility of the foundation support may both be described by frequency-dependent foundation impedance functions [54].

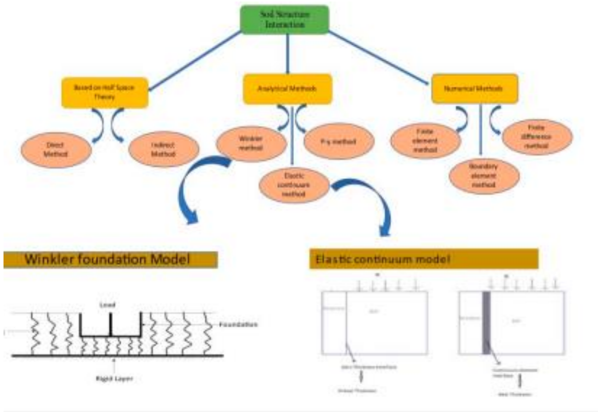

Fig. 2. Various modelling approaches to SSI determination

Wave inclination, or foundation embedment, foundation movements might differ from free-field motions in the incidence of stiff foundation components on or within soil owing to ground motion incoherence. Using a frequency dependent transfer function, the free-field motion is compared to the motion that would occur on the base slab if the slab and framework were massless. The foundations can be represented by essentially stiff slabs, according to building SSI studies. Thus, the system's degrees of freedom are restricted, and it is possible to isolate the inertial and kinematic interactions [55]. Building SSI analyses presume that foundations can be represented by essentially rigid slabs. This limits the system's degrees of freedom and enables separation into inertial and kinematic interactions [56].

3. Soil Structure Interaction Effects On Buildings Framework

After an earthquake, civil infrastructure sustains substantial losses that can be measured in terms of direct and indirect losses. Owners and insurance companies are very concerned about earthquake-related losses because large earthquakes cause a lot of social disruption and death [57]. Another significant phenomenon that was the subject of numerous research analyses has been the SSI impact on the seismic reaction of structures [58]. Building foundations frequently rely on soil, making them flexible bases. Though, the conventional approach of evaluating any building makes the implausible assumption that the building's foundation is rigid (fixed), when in fact the local condition of soil has a substantial effect on how the structure responds [59]. Seismic vibrations traveling via near-field exhibit greater amplification as compared to traveling via far field owing to the material as well as geometrical nonlinearity. Different seismic demand variables, such as inter-story drift, story shear, fundamental period and should be assessed and compared to a flexible base to better comprehend the behavior of SSI. When taking into account the pounding effect, research has shown that soil flexibility (SSSI) commonly had a significantly growing impact on the resultant "pounding forces" and caused the pounding to occur even at further clear distances. Both the flexible and fixed-base situations had virtually the same hammering tales. The only floors where there was more hammering were the top floors. At the obvious distance from the code, there was hardly any pounding. Increased story shears along with lateral displacements, especially in the stories of the taller structure directly above the surrounding shorter building, were shown to be mostly caused by pounding as compared to SSSI [60].

3.1 RC Buildings' Seismic Vulnerability in the Impacts of SSI

The nonlinear response study of a building under multiple ground motions is the finest tool for describing a structure's seismic vulnerability [61]. In such a study, the ends of several structural members grow plastic hinges. Based on its ability for ductility, each member can withstand a particular amount of rotation at the plastic hinge. Additionally, certain members, typically columns, are not allowed to be subjected to axial pressures that exceed their corresponding capacities. The member is classified as seismically susceptible if the maximum capacity is reached [62]. For relatively regular structures, dynamic, linear static, and/or nonlinear static processes could be utilized to perform the seismic vulnerability analysis outlined above equally well; however, the nonlinear dynamic study is favoured due to its better accuracy and greater confidence [42]. Studies have been done to see if SSI has an impact on the "seismic performance" as well as vulnerability of RC ("Reinforced Concrete") buildings. Utilizing a finite-element framework, a collection of RC frames situated on various kinds of soil were designed and modelled. The soil-foundation relationship was modelled using both linear and nonlinear techniques. To examine the seismic behaviour and fragility of RC structures in the assumptions of flexible and rigid bases, nonlinear static along with incremental dynamic analyses have been conducted. The outcome then reveals that the midrise frames located on soft locations performed at a significantly higher level. Additionally, the inter-story drifts grew significantly as the number of stories within the system increased due to the "foundation flexibility" for RC frames lying on soft soil [4].

In most instances, the seismic structures design using SSI techniques is thought to be more efficient, economical, and safe than fixed-base designs. Although very common, finite element techniques that applied the direct expression to resolve SSI issues have very expensive software costs and lengthy analysis times. Despite the availability of affordable and effective software, most analyses of structures focus solely on the superstructure, ignoring the geotechnical characteristics of the earth and their interactions with the structure. Machine learning-based database techniques are dependable and yield solid outcomes. ANNs ("Artificial Neural Networks") and SVMs ("Support Vector Machines") are applied in machine learning to examine how interactions between soil and structures affect the seismic response of buildings in various earthquake situations [63].

This was on the basis of a few investigations. In this research, the investigation of four frame buildings involves changing the seismic and soil properties. Various sample sizes and optimization methods were also applied to find the optimal ML ("Machine-Learning") framework. Three engineering requirement factors are the outputs, while the input parameters include seismic and soil properties. The network is evaluated on a 3-story building along with mass irregularity as well as 4 story building after being trained on three- and five-story buildings. Additionally, the dynamic responses found with fixed-base and "ASCE 7-16 SSI" approaches are contrasted with the suggested method. With "nonlinear time history" study results as a benchmark, the proposed machine learning technique outperformed fixed-base as well as ASCE 7-16 approaches. The findings demonstrated that, when compared to fixed-base, SVM, along with ASCE 7-16 linear SSI approaches, the results of the SSI-based ANN system have been in good alignment with "nonlinear time history" analysis [64]. When SSI is included in the seismic analysis, the building often experiences less stress, which leads to a more cost-effective design [65]. Due to recently added provisions in both European and American regulations, this kind of technique is acceptable. But taking into consideration SSI might also lead to the detection of adverse consequences since the dynamic features of the structure are altered. Unfavourable outcomes include increased story drifts or global displacements increased base or story shear pressures, increased post-elastic loads on the structural components, and the collision of nearby structures that are separated by insufficient structural connections. SSI should be taken into account when designing structures for earthquakes, but the existing design codes do not provide a clear implementation strategy that engineers in the field can use. More research must be done in this area to develop methodologies that can be incorporated into the existing structural architecture [66].

Using pushover analysis, experts' work on open ground, multi-story structure frames with fixed and flexible bases were examined for various boundary conditions. Models of the earth’s properties use rotational and translational springs. For comparison purposes, the analysis also comprises 2 additional boundary condition instances: fixed as well as hinged helps at the base. The lateral deflection and period of the building frames' seismic reaction are examined. Two additional boundary conditions are included in the research for comparison, namely fixed & hinged supports at the base [66]. We compare the lateral deflection and duration of the building frames' seismic responses. According to research, frames with a greater slenderness ratio show a stronger effect of SSI on lateral behavior [67]. The relationship between the sub and super-structure is examined by modelling the soil as simply as possible to reflect the system's overall reaction. The research demonstrated how taking into account different variables, such as SSI and wall placement, significantly affects the building frame's period, displacement, and base shear [34]. Therefore, it is crucial to take into account all of these factors when analyzing designs. When compared to other locations, shear walls in the middle of a multi-storey structure produce baser shear and less displacement [60]. Non-linear dynamic analysis has been used in research on the SSI impacts on the “seismic performances” of two-dimensional RC “Moment-Resisting Frames” (MRFs) [68]. The study shows that SSI has a different impact on seismic demand based on the modelling approach, with respect to maximum base shear as well as maximum inter-story drift ratio [69].

Few scholars have applied thorough nonlinear dynamic study of structures with various lateral “load-bearing” systems based on flexible soil. Larger story drifts are typically the result of taking “no-tension soil springs” on the level of foundation into consideration [37]. The placement of infill walls can increase the stiffness of SMRFs and significantly reduce the fundamental periods, according to a seismic vulnerability evaluation of SMRFs (“Steel Moment-Resisting Frames”) supposing various placement of infill walls that incorporate nonlinear SSI [70]. In the seismic construction of buildings, structural eccentricity is crucial. It is one of the criteria used by different seismic design codes to determine whether a structure can be regarded as regular in the plan [71]. The gap between the center of mass and rigidity is referred to as structural eccentricity. However, under the premise of fixed-based settings, the center of rigidity is precisely specified in “single-story” buildings as well as in some particular types of “multi-story” buildings, such as isotropic ones. Particularly in the case of soft soils, the applied loading pattern is crucial in determining the “twist axis” for single-story structures [72]. Therefore, it is impossible to disregard the impact of the loading that is used at the foundation [73]. The frequency content of earthquakes has a substantial impact on the seismic reaction of buildings.

3.2 SSI Impacts on Structural System

Although there is no question that the impacts of SSI could have a major influence on how structures respond to seismic loads, this system is frequently disregarded in the control of the structure [74]. The majority of buildings in metropolitan areas are made of reinforced concrete (RC) frames, either with or without RC shear walls. The installation of these walls increases the building's lateral load capacity and lateral stiffness in areas with high seismic activity [64]. Building seismic behavior has been reported to be significantly influenced by SSI in previous earthquakes, especially when the building is situated on soft soil. The shear wall affects the natural vibration properties by shortening the “natural period” and altering the RC frame's mode shape profile. In comparison to a flexible frame, the alteration is substantially greater for a stiffer frame. Additionally, the alteration for frames with SSI effects is noticeably reduced [75]. The magnitude of seismic force created during an earthquake shaking depends on the intrinsic vibration properties of the structure. The key factor that controls the magnitude of the mobilized force is the vibration’s natural period. Smaller building frames have greater SSI impacts due to their smaller widths and heights [76]. This is because the shear wall contributes more to the frame's total rigidity with smaller widths. The system gets more flexible as width and height increase, showing fewer SSI impacts. SSI impacts are more pronounced in shorter frames than in taller frames [77]. A very small number of studies examined the relationship between soil flexibility and the pounding caused by earthquakes on nearby buildings. Engineers frequently treat brick infill panels as non-structural components when building various kinds of frame constructions. In the meantime, modern specifications and building standards stress the significance of considering the influence of infill panels since they might significantly affect how the structure responds to seismic excitation [78]. Since the impact of SSI is thought to be advantageous to the structure’s response during seismic excitation, the conventional high-rise building design approach often supposes that the structure is fixed on the base. Recent earthquakes and research, however, suggested that SSI might have a negative impact on structural systems that are often used. Researchers are examining the seismic activity of frame-core tube constructions with a range of soil types, foundation types, height-width ratios, and structural heights. They examine and contrast the outcomes of numerical simulations that included flexible-base buildings, base shears of rigid-base, inter-story drifts, foundation rocking, and maximum lateral deflections. The findings show that when SSI is considered, base shears are not always minimized but the inter-story drifts as well as lateral displacement of the superstructure could be increased. The subsoil and foundation stiffness might typically be raised to meet a structure's higher seismic requirements [43]. To determine the impact of SSI on “high-rise frame-core tube” constructions, several researchers create and verify an upgraded soil-structure numerical model utilizing the ABAQUS program [79].

A key factor in the design and study of reinforced concrete (RCC) walls and other structures is soil-structure interaction (SSI). The way the surrounding soil interacts with the structure can have a big impact on how the structure behaves and performs overall. An RCC wall's base is essential to the interaction between the earth and the structure. The characteristics of the underlying soil must be taken into account in the construction of the foundation, regardless of whether it is shallow or deep. Important elements affecting the foundation design are soil-structure interaction, settling, and soil carrying capacity. A thorough geotechnical examination is necessary to comprehend the soil properties. Lateral earth pressure on RCC walls is frequently caused by backfill dirt or other external loads. The lateral earth pressure acting on the wall is influenced by the kind of soil and its characteristics. Different techniques, taking into account the interaction between the wall and the surrounding soil, are frequently used to estimate lateral earth pressure, such as the Rankine or Terzaghi theories [80]. In-depth modelling and analysis of the soil-structure interaction are frequently done using numerical techniques like finite element analysis. Engineers can simulate the intricate behaviour of the earth and the structure under varied loading scenarios thanks to FEA.

4. SSI IMPACT ON STRUCTURES’ PROGRESSIVE COLLAPSE

Since the early 1970s, the occurrence of buildings collapsing gradually has been thoroughly studied. The phenomenon may be caused by a variety of abnormal loading situations that most civil engineering buildings were not intended to withstand. Although the bomb blast is one of the main reasons for this occurrence, other accidents can also result in progressive collapse [81]. Now more than ever, it is significant to consider the impacts of SSI due to the pervasive usage of performance-based design methods. A probabilistic formulation is used for these studies because there are uncertainties in the performance assessment of structures [82]. The circumstances will be better for averting progressive collapse if SSI were taken into account since the soil density and level of groundwater should increase [83].

Evaluation of the structural resistance of RC frames to progressive failure usually uses nonlinear static analysis. The benefit of this method is that it can consider nonlinear impacts [83]. The soil environment is more difficult to describe than a structure because it is semi-infinite and inhomogeneous. In SSI analysis, selecting an appropriate modelling approach and exact computational approach is a difficult and crucial problem. The “seismic response” obtained from the soil structure’s dynamic study is realistic when the soil environment is studied using an appropriate modelling approach [84]. To assess the final collapse state’s disproportionality, current practice primarily considers direct and pure structural damage; however, a consequence-based method in which “indirect structural” damages. Including costs and repairability in the evaluation process can result in a structure for evaluation that is more thorough [85]. It is crucial to determine a structure's susceptibility to progressive collapse events to prevent “catastrophic structural” failure of high-risk buildings under blast loads. The progressive collapse of buildings is not currently addressed by any suggestions or provisions in the existing guidelines of several nations [86].

A summary of SSI researches through analytical, experimental and numerical studies

Researcher	Year	Contribution	Foundation	Analysis
Analytical Studies				

Lin and Miranda	2009	4-story asymmetrical building	Springs and dashpot	Arithmetic sum method
Olariu and Movila	2014	2-story asymmetrical building	Springs and dashpot	Spectral acceleration method
Experimental Studies				
Todorvska	2002	45m Hollywood storage building	Pile	Ambient vibration test
Mason, Trombetta, Chen, Bray, Hutchinson, and Kuttar	2013	Asymmetrical group of symmetrical buildings	Isolated	Scale down model, Centrifuge testing
Numerical Studies				
Venkatesh, Gupta, and Pandit	2012	Asymmetrical loading and 2 3-D structures	Raft	Nonlinear analysis of soil structure
Tehrani and Khoshnoudian	2014	5 to 15 story buildings with asymmetry	Shallow	Pushover analysis
Sharma and Punit	2014	Tall asymmetrical building configuration	Shallow	3-D nonlinear dynamic analysis
Isbiliroglu and Taborda	2014	Group of asymmetrical small structures	Isolated	3-D nonlinear analysis
Yigti	2013	Asymmetrical cluster of buildings	Shallow	3-D dynamic nonlinear analysis
Irfan, Sunandan Reddy, and Mythili	2014	Soft story effect including interaction	Isolated	3-D dynamic nonlinear analysis

Table 3. Comparison of Artificial Neural Network Techniques in SS

Author	**Building Frame Type**	**Soil-Structure Interaction Focus**	**Key Findings**	**Performance Metrics**	**Strengths**	**Limitations**
[87]	Feedforward Neural Network (FNN)	Residential Buildings	Reinforced Concrete Frames	Dynamic Response Analysis	Improved prediction accuracy for seismic response	Error Reduction: 15%
[88]	Convolutional Neural Network (CNN)	High-Rise Buildings	Steel Frames	Load Distribution and Settlement	Enhanced modeling of complex load interactions	Computational Efficiency: 20% faster
[89]	Recurrent Neural Network (RNN)	Mixed-Use Buildings	Hybrid Frames	Long-Term Settlement Prediction	Better long-term prediction for soil-	Long-Term Prediction Accuracy: 10% better

					structure interaction	
[90]	Deep Neural Network (DNN)	Commercial Buildings	Precast Concrete Frames	Seismic Performance Evaluation	Superior performance in earthquake simulations	Accuracy Improvement: 25%
[13]	Generative Adversarial Network (GAN)	Skyscrapers	Composite Frames	Soil-Structure Interaction Modeling	Advanced modeling capabilities for diverse interactions	Modeling Flexibility: 30% increase

Conclusion

As the complexity of modern infrastructure grows, the integration of Artificial Neural Networks (ANNs) into building frame soil-structure interaction (SSI) analysis has become increasingly pivotal. This review highlights the transformative impact of ANN techniques in addressing the limitations of traditional SSI analysis methods. ANNs have emerged as a powerful tool for modeling and predicting the intricate dynamics between soil properties and structural behavior, facilitating improved design and analysis of structures in diverse soil conditions. The versatility of ANNs in handling large datasets and their capacity for learning from historical data enable more precise simulations and forecasts, contributing to enhanced safety and performance of building structures. The continued evolution of ANN methodologies, coupled with advancements in computational resources, offers promising prospects for future research and application in SSI analysis. Innovations in network design and training techniques are expected to further elevate the accuracy and efficiency of ANN-based models. By leveraging these advancements, engineers and researchers can better address the challenges of soil-structure interaction, ultimately leading to more resilient and sustainable infrastructure solutions. The integration of ANNs into SSI analysis represents a significant step forward in the field, marking a new era of sophisticated and data-driven approaches to structural engineering.

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