Najar *et al. J Infrastruct Preserv Resil (2025) 6:5*
https://doi.org/10.1186/s43065-025-00118-2

Journal of Infrastructure Preservation and Resilience

REVIEW **Open Access**

Advancing soil-structure interaction (SSI): a comprehensive review of current practices, challenges, and future directions

Imtiyaz Akbar Najar[1], Raudhah Ahmadi[1*], Akeem Gbenga Amuda[2], Raghad Mourad[3], Neveen El Bendary[4], Idawati Ismail[1], Nabilah Abu Bakar[5] and Shanshan Tang[6]

Abstract

The safety, stability, and long-term performance of reinforced concrete (RC) structures depend significantly on soil-structure interaction (SSI), a critical phenomenon governing the dynamic relationship between soil and structural behaviour. SSI plays a pivotal role in seismic design, influencing the stiffness, damping, and natural frequency of structures, yet its application in practical design remains underutilized due to challenges in modelling and integrating code provisions. This review synthesizes existing knowledge on SSI, emphasizing its impact on buildings, bridges, and foundations under static and dynamic loads. It highlights advancements in analytical, numerical, and experimental modelling methods, such as finite element analysis and discrete element methods, and evaluates their effectiveness in capturing the complex interactions between soil and structural systems. The review identifies key gaps, including a lack of unified guidelines in international codes, inadequate integration of SSI in real-world design processes, and limited exploration of its role in emerging engineering challenges like sustainability and climate resilience. Historical seismic events, such as the Kobe and Loma Prieta earthquakes, are analysed to underscore the detrimental consequences of neglecting SSI considerations. Additionally, the review discusses recent innovations, including the application of machine learning and advanced computational tools, and their potential to enhance the accuracy and efficiency of SSI analysis. This study offers actionable insights for improving design practices, such as adapting SSI frameworks for structures on soft soils and incorporating dynamic interactions in seismic design codes. It concludes with a call for interdisciplinary collaboration and future research into novel SSI applications, including its integration with smart sensing technologies and sustainable infrastructure design. This review bridges the gap between theoretical advancements and practical applications of soil-structure interaction (SSI) by synthesizing current knowledge, identifying critical research gaps, and proposing innovative solutions to enhance structural resilience, sustainability, and seismic safety.

Highlights

➢ The introduction of SSI and the previous studies in seismic design is debated.

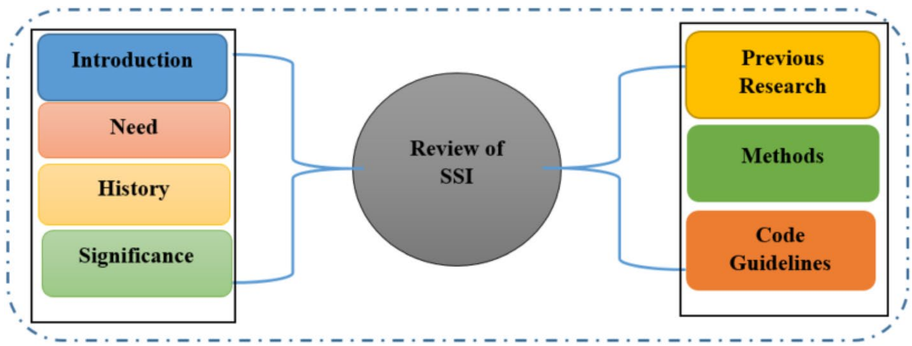
➢ Need, significance and the standard code provisions of SSI of different countries are explained.

➢ Solving methods of SSI are discussed.

Keywords Soil-structure interaction (SSI), Seismic design, Numerical modelling, SSI guidelines, Structural resilience

*Correspondence:
Raudhah Ahmadi
araudhah@unimas.my
Full list of author information is available at the end of the article

Graphical Abstract



Introduction

Understanding the role of soil-structure interaction (SSI)

The safety, stability, and long-term performance of structures, particularly reinforced concrete (RC) buildings, bridges, and foundations, are deeply influenced by the interaction between the built environment and the ground it rests upon [1, 2]. Since earthquakes are unpredictable and unavoidable, and they have significantly impacted human life, infrastructure, and economic development [3, 4]. More of the negative impact has raised concerns about the resilience of structures and their components that are vulnerable to seismic hazards [5, 6]. So in essence, various approaches for mitigating the adverse effects have been developed by researchers worldwide through the consideration of SSI [7–10]. SSI stands for soil-structure interaction (SSI), and it has been an acronym common among researchers [11–13]. Many types of civil infrastructure, like that nuclear power plants [4, 14], hydro dams, subterranean buildings [15], and large-span bridges [8], are severely affected by seismic motions [16–18]. SSI refers to the dynamic interface between the soil and the construction built on it [10, 14, 19]. This interface can considerably impact the behaviour and stability of the structure, particularly in cases where the soil experiences significant changes in load, moisture, and temperature [7–9]. SSI is critical to consider in the design of structures such as buildings, bridges, and foundations, as it can significantly impact the overall performance of these structures [1–4]. To properly understand and predict SSI, engineers use various methods and models, such as Finite Element Analysis (FEA), Finite Element Method (FEM), Discrete Element Method (DEM), Finite Difference Method (FDM), Boundary Element Method (BEM) to consider for the properties of the soil and the structure, and how they interact [20–25]. In this way, engineers can design structures that are safe, stable, and efficient, even under changing soil conditions. It considers the influence of the underlying soil's mechanical and geometrical properties on the structural behaviour of the building and vice versa. It is an essential consideration in the design of foundations, retaining walls, and other structures that are in contact with the soil. The analysis of SSI can be done using analytical, numerical, or experimental methods [12, 26–28]. The numerical study of seismic SSI is a critical stage in the design process that focus on performance-based criteria of the above-mentioned structures. The direct finite element approach by Wolf [29, 30] is frequently used for such analyses. Initially, a one-dimensional (1D) seismic site response analysis is done [22, 26, 31–33], followed by an SSI analysis using a shortened SSI model. To replicate the infinite domain wave radiation effect, the SSI analysis model's shortened border is given an absorbing boundary condition. Ultimately, the seismic response is produced by the equivalent seismic load calculated based on the site's reaction [25, 34, 35].

The majority of civil constructions, particularly bridges (abutments, piles, and retaining structures) are erected on or within the earth [36–38]. When studying such a structure, the results show a significant difference when the analysis is done with ground conditions in mind. Hence, the ground conditions must be considered to achieve analytical findings, such as the behaviour of the actual building [39–41]. SSI is a physical phenomenon that occurs when a structure fails to behave independently and instead interacts with the soil [30], as seen in the Fig. 1. Because earthquakes significantly impact the ground and structures. Therefore, the seismic design must take this phenomenon into account.

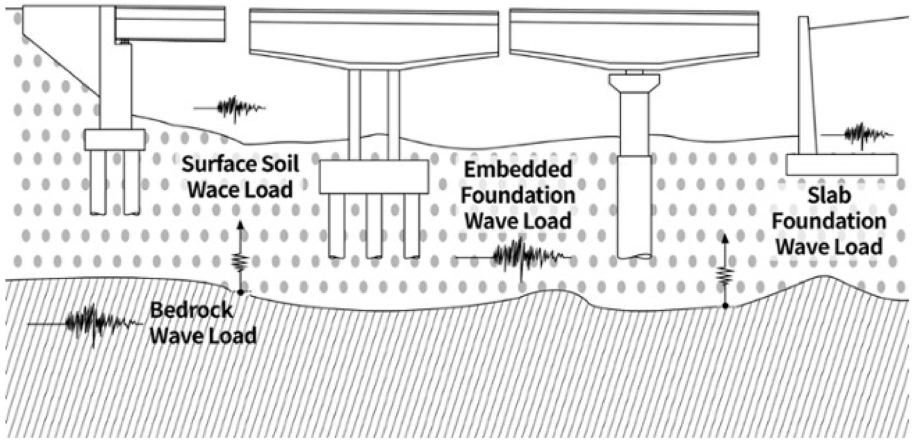


Fig. 1 Interaction of the bridge's structure with the ground [42]

Lessons from historical failure

Numerous pile-supported bridges have collapsed as a result of powerful earthquake shaking globally. One of the primary causes of these tragic collapses is a lack of comprehension and awareness of the influence of SSI [43]. The downfall of the Cypress street viaduct following the Loma Prieta earthquake in 1989 in Oakland, California is one of the well-known instances where SSI played a significant role in a bridge disaster. The unstable sand foundation upon which the structure was constructed caused it to react more severely, which finally caused several of the bridge's sections to collapse structurally [44]. Several bridge piers were harmed during the Northridge earthquake in 1994 as a result of soil-pile-bridge seismic interaction [43, 45]. The Northridge Earthquake of 1994 is depicted in Fig. 2 as causing a bridge column to fail.

The Hanshin Expressway Bridge in Japan throughout the 1995 Kobe earthquake is another instance where SSI significantly contributed to a bridge collapse. A methodical analysis of the Hanshin Expressway Bridge revealed that the behaviour of this structure was significantly influenced by the attributes of the soil [47]. Soft soil refers to soil with a standard penetration of 10 or less ($N \leq 10$). This type of soil can cause the essential period of the soil and structure system to increase, and can also alter the frequency content of an earthquake, which in turn can lead to a more severe structural response [48]. Figure 3 depicts the two bridge constructions' catastrophic collapse as a result of the Loma Prieta and Kobe earthquakes.

Fig. 2 Due to the Californian Northridge shallow crustal earthquake, the Mission Gothic Bridge's column failed [46]

Fig. 3 **A** During the Kobe earthquake in Japan, an approximately 630-meter stretch of the elevated Hanshin Expressway collapsed [49]. **B** Due to the Loma Prieta earthquake, the Cypress Structure, which functioned as the highway connection from Oakland to the Bay Bridge, experienced a structural failure [50]

Challenges in current design practices

Despite its established importance, SSI remains underutilized in practice due to several challenges [51]. These include the complexity of modelling soil's non-linear behaviour [52], the difficulty of simulating infinite domains in computational analyses [53], and the lack of consistent guidelines in international design codes [47, 54]. For instance, while Eurocode 8 and ASCE 7 provide some recommendations for SSI, they fall short of offering universally applicable methodologies [55]. Moreover, the computational expense of detailed SSI models and the fragmented understanding of SSI's impact on structural systems further hinder its widespread adoption.

Two main impacts on the structure may broadly distinguish SSI. The first result is a modification in the dynamic properties of the structure [56]. Because the stiffness of soil is generally lower than that of the structure, the structure's stiffness and natural frequency are reduced. The second effect is an increase in structural damping caused by the addition of radiation damping [25]. These impacts differ based on the mix of soil layers, material qualities, seismic data, and structure frequency [25]. As a result, the reaction due to SSI analysis may be more or less than the typical seismic analysis results under the assumption of ground fixity. Soil response is used to develop design response spectrums, define the dynamic stress-strain relationship of the soil, and quantify the seismic loads acting on the ground structures as a result of an earthquake [32, 57, 58]. The seismic wave characteristics at a bedrock outcrop are nearly identical to those at bedrock. However, subject on the soil parameters, the features of a seismic wave in soft soil or at the ground surface of deep ground might vary greatly [59]. SSI can have a momentous influence on the dynamic behaviour of a structure on (or inside) soft soil. If a structure is built on bedrock and the shear strain is less than 10^{-6}, and the shear wave velocity is more than 1,100 m/sec, the SSI can be neglected [42].

Depiction from above, it can be deduced that the significance of piqued the interest of numerous researchers who have delved into examining the impacts of SSI on diverse structures. They have also worked on formulating several modelling techniques with varying degrees of precision. However, the incorporation of SSI considerations into practical designs has not garnered the focus of structural engineers. This might be attributed to the absence of universal guidelines and the prevalent notion that SSI effects invariably offer advantages to structures. Nevertheless, recent research and historical seismic events suggest that neglecting SSI effects might result in designs that lack safety [60–63].

Objective and scope of the review

The primary objective of this review is to synthesize the current understanding of soil-structure interaction (SSI) and address its critical role in improving the safety, resilience, and sustainability of structures. SSI significantly influences the dynamic behaviour of structures, particularly under seismic loads, yet its integration into practical design remains inconsistent. This review aims to bridge the gap between theoretical advancements and real-world applications by evaluating existing studies, identifying research gaps, and proposing actionable insights for engineering practice.

The scope comprises a comprehensive analysis of SSI's effects on various structures, including buildings, bridges, and foundations, under static and dynamic loads. It examines advancements in analytical, numerical, and experimental modelling methods. Additionally, the review highlights the challenges of incorporating SSI into design practices, including modelling complexities, computational costs, and the lack of standardized guidelines across international seismic codes. Emerging technologies like machine learning, digital twins, and smart sensing technologies are also explored for their potential to revolutionize SSI applications. By addressing these aspects, this review seeks to contribute to the development of resilient, cost-effective, and sustainable infrastructure systems.

Advantages of previous studies

Previous studies on soil-structure interaction (SSI) have significantly advanced the understanding of how soil and structural systems interact, particularly under seismic loading. Analytical and numerical models, such as the FEM and BEM, have enabled engineers to simulate SSI effects with increasing accuracy. These studies provided critical insights into dynamic behaviours, including the alteration of natural frequencies, damping ratios, and base shear, which are essential for resilient design. Experimental approaches, such as shake table tests and centrifuge modelling, validated theoretical models, bridging the gap between research and real-world applications. Historical seismic failures, such as the collapses during the Kobe and Loma Prieta earthquakes, demonstrated the necessity of integrating SSI into design practices, prompting updates in seismic codes like Eurocode 8 and ASCE 7. Moreover, hybrid methods that combine analytical and experimental approaches have provided resource-efficient solutions, while emerging tools such as machine learning and digital twins promise to revolutionize SSI modelling and its role in real-time structural monitoring.

Limitations of previous studies

Despite these advancements, previous studies on SSI are hindered by several limitations. Many rely on idealized assumptions, such as linear soil behaviour and uniform foundation properties, which fail to account for the complexity of real-world conditions like heterogeneous soils and irregular geometries. Computationally intensive methods, though accurate, limit practical application in large-scale projects. Experimental approaches, while valuable, are resource-intensive and constrained to specific scenarios. Furthermore, most research focuses narrowly on seismic events, neglecting multi-hazard scenarios such as tsunamis or extreme winds, which are crucial for comprehensive resilience. SSI's nonlinear behaviour under extreme loads remains underexplored due to the lack of reliable constitutive soil models. Inconsistent and vague guidelines across seismic codes, particularly in regions like Malaysia and New Zealand, further impede its adoption. Additionally, emerging challenges like sustainability, adaptive designs, and SSI's application in renewable energy systems remain inadequately addressed, leaving a critical gap between theoretical advances and practical implementation.

Need of soil-structure interaction (SSI)

The need for considering SSI arises because the behaviour of a structure is not only determined by its own characteristics, but also by the characteristics of the soil on which it is built [60, 64]. The mechanical properties of soil, such as its strength and deformation characteristics, can have a significant impact on the structural behaviour of the building [65]. For example, if a structure is built on soil with a low bearing capacity, it may experience excessive settlements or even failure. Similarly, if a structure is built on soil that is prone to liquefaction or landslides, it may experience instability or even collapse during an earthquake. Furthermore, the structural behaviour of a building can also affect the soil; for example, a foundation or a retaining wall can cause changes in soil stress and deformation. Therefore, considering SSI is important for ensuring the safety, stability, and performance of structures, and preventing structural failures or damage due to soil behaviour [66–69]. Neglecting SSI can lead to overdesign or underdesign of structures, increasing both construction costs and the risk of failure [70]. Historical failures, such as the collapse of the Cypress Street Viaduct during the 1989 Loma Prieta earthquake and the Hanshin Expressway in the 1995 Kobe earthquake, have underscored the catastrophic consequences of disregarding SSI [66]. These cases highlight how soil properties, such as stiffness, damping, and shear strength, significantly influence structural performance during seismic events.

The requirement for SSI may be explained by comparing the structure's deformation based on the stiffness/strength differential between the structural system and the soil [66]. The two conditional constructions mentioned in the ATC-40 (Applied Technology Council) are compared to compare the reaction of the structure to geotechnical circumstances. The comparison of structure responses based on ground conditions is illustrated in Fig. 4.

A) Because the rigidity of a stiff foundation structure is very great, no further deformations occur in the structure [72, 73]. As a result, the shear and moment created by the seismic force are solely resisted by the shear wall's strength. As a result, damage (for example, fractures) forms on the shear wall, but no damage occurs on the frame other than a little displacement [74].
B) Because a flexible foundation cannot withstand structural deformation due to seismic forces, rotation occurs in the shear wall [75]. This rotation generates

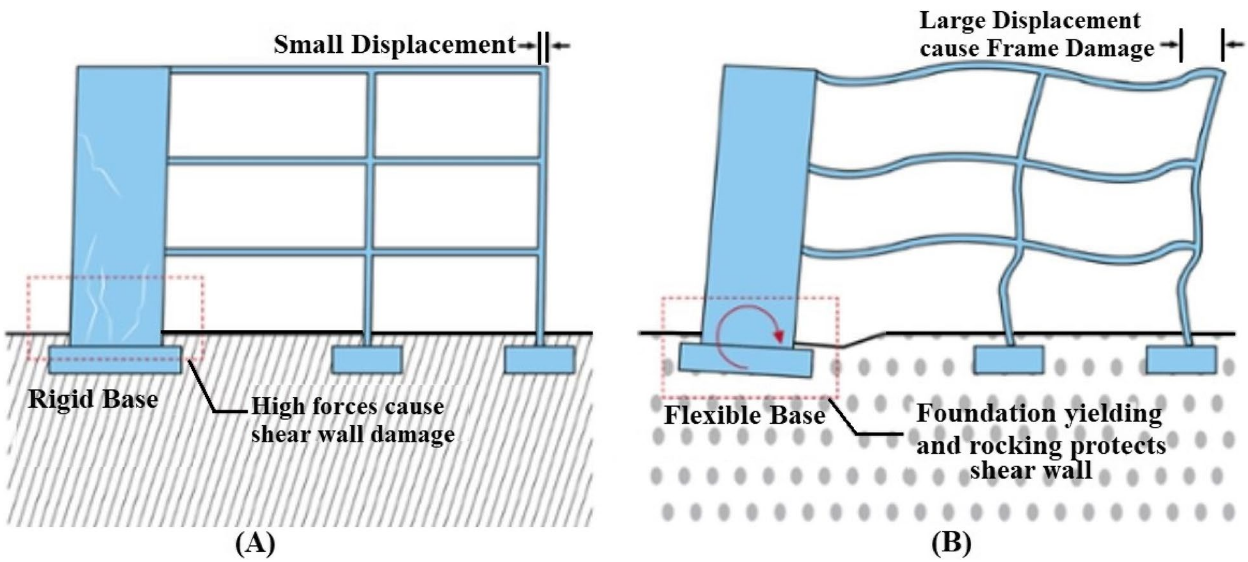


Fig. 4 Comparison of structure responses based on ground conditions (**A**) showing rigid base and (**B**) showing flexible base [71]

frame distortion, resulting in severe deformations and fissures in the frame structure [76]. However, the shear wall's force requirement falls when compared to (A).

As can be observed, the analytical findings for both situations varied largely dependent on the subsoil. The shear wall will be overdesigned if the ground condition is not adequately assessed and understood as a hard foundation, as indicated in (A). The reaction of structure, as in the instance (B), may be calculated as the dissimilarity between the ground motion without the structure and the structure's motion owing to the stiffness of the foundation, as well as an extra displacement in the ground produced by force created by the structure's motion.

The need of SSI highlights the importance of understanding soil-structure interaction (SSI) for accurate structural design and performance analysis. For current practice, focusing on key parameters such as soil stiffness, structural configuration, and seismic loading conditions is essential to achieve resilient designs. These parameters enable engineers to optimize designs for safety and efficiency, particularly in seismic zones. SSI-informed practices reduce overdesign and material waste, ensuring cost-effective solutions. However, challenges such as computational complexity and fragmented design guidelines must be addressed to fully integrate SSI into routine engineering practice. Simplified approaches and unified standards are critical for broader adoption. Simplified yet effective modeling techniques are critical for bridging the gap between research and practical application.

Fundamental concept of soil-structure interaction (SSI)

Soil-structure interaction (SSI) is a complex and dynamic phenomenon that governs the interplay between a structure and the supporting soil medium [17, 77]. Unlike traditional designs that assume fixed-base conditions, SSI considers the mutual influence of structural and soil behaviors, particularly under dynamic loading conditions such as seismic events [69, 78]. This interaction manifests through two primary mechanisms: kinematic interaction and inertial interaction [75, 77], which are discussed as follows:

Kinematic and inertial interaction

Kinematic interaction and inertial interaction are the names given to these mechanical processes [69, 79]. In recent years, substantial innovations in complete seismic risk assessment techniques have been made in earthquake engineering. Indeed, detailed approaches for quantifying non-structural and structural damage, estimating the number of victims, and predicting restoration costs following severe earthquakes have been developed [77, 80]. As a result, strong analysis methods for precisely analyzing structural models and estimating the needs for various levels of shaking have been established [69, 75, 81]. Nonetheless, the majority of these solutions do not include the fundamental requirements. Hence, it is presumed that the structure is closely connected to the foundation medium, and specific soil situations are incorporated by choosing suitable ground motions that align with the features of the underlying soil deposit [71].

Kinematic interaction in soil-structure interaction (SSI)

Kinematic interaction in soil-structure interaction (SSI) arises due to changes in the propagation of seismic waves caused by variations in the density and elasticity of the surrounding media [82]. These changes alter the wave propagation velocity, resulting in the reflection and refraction of incoming seismic waves [83]. Kinematic effects refer to the difference in the structural response when considering free-field motions versus when the structure's presence is accounted for during analysis [79]. Unlike inertial interaction, kinematic effects are independent of the structure's mass and are instead influenced by factors such as the geometry and configuration of the structure, the degree of foundation embedment, the composition of incident free-field waves, and the angle at which these waves strike [77]. However, kinematic interaction can be considered negligible in cases where the structure lacks embedment or when it is subjected to vertically propagating shear waves, as these conditions minimize the influence of wave reflection and refraction on the overall structural response [54, 72].

Inertial interaction in soil-structure interaction (SSI)

Inertial effects in soil-structure interaction (SSI) arise from the dynamic coupling between the structure, its foundation, and the supporting soil medium [82]. The elastic and inertial properties of the soil contribute additional degrees of freedom to the structural system, fundamentally altering its dynamic behaviour [43]. These effects enable the dissipation of seismic energy through two primary mechanisms: radiation damping, where seismic waves propagate outward from the structure, and hysteretic deformation, which involves energy absorption within the soil due to its material behaviour [84]. The significance of inertial effects is closely tied to the relative flexibility of the supporting soil in comparison to the structure. For regular structures founded on stiff soils or rock, inertial effects are typically negligible due to the limited deformation of the soil medium [85, 86]. However, for stiff and massive structures situated on more flexible soils, these effects become pronounced, exerting a considerable influence on the system's overall response. This dynamic interplay underscores the critical role of soil flexibility in governing the inertial behaviour of the soil-structure system [83, 87, 88].

In most seismic vulnerability evaluations, the earth beneath the structures is neglected. In spite of its applicability in construction of structures, its inclusion in seismic studies is unknown [89]. In essence, a previous study suggested that the SSI was favourable as a result of the reduction of internal stresses and drifts caused by the greater flexibility of the soil [62, 90]. As a result, seismic assessments were performed using fixed-base structures to produce conservative results. However, investigations on the impact of the SSI on building capacity evaluation have shown that it does not have a favourable effect on various forms of structures in all varieties of soil [44, 91–94]. It is demonstrated that the SSI influences characteristics of building seismic performance, such as ductility, strength, and energy dissipation. As a result, in some circumstances, omitting the SSI might lead to an overestimation of structural capacity, resulting in inaccurate results [81].

Quantitative insights into SSI effects

Quantitative analyses reveal that SSI can reduce seismic base shear by up to 30% under certain conditions, depending on soil stiffness and structural properties [95]. However, in soft soils, SSI may increase deformation and internal stresses, as seen in studies of tall buildings and bridge piers [63]. Incorporating SSI considerations also prevents overdesign, potentially reducing foundation material requirements by 10–20% [76].

Soil-structure interaction (SSI) history

The history of SSI can be traced back to the early days of civil engineering when engineers first began to understand the significance of the soil's properties in determining the behaviour of structures built on it. Understanding the history of soil-structure interaction (SSI) provides insight into its evolution as a critical field in structural and geotechnical engineering. SSI research emerged from the need to address the complexities of how soil and structures influence each other under static and dynamic loads. Its development has been shaped by groundbreaking theoretical work, technological advancements, and lessons from structural failures.

Early contributions to SSI

In the 19th century, the development of new materials and construction methods, such as reinforced concrete, led to the construction of taller and more complex structures. This increased the prominence of understanding the interplay among the construction and the underlying soil, and the need for better methods of analysis and design. Lord Kelvin initially identified the SSI effect in the 19th century when studying the issue of calculating displacements brought on by rigorous static pressures deforming at any specific location within an infinitely elastic solid [96]. In 1935, Sezawa and Kanai introduced the concept of energy dissipation into the ground, marking an early recognition of DSSI effects. Around the same time, Martel observed the behaviour of the Hollywood Storage Building during the 1933 Long Beach earthquake, documenting the impact of soil properties on structural response. These early efforts provided crucial insights into how ground conditions alter structural behaviour during seismic events.

Mid-20th century advancements

In the early 20th century, the field of soil mechanics was established, which provided a better understanding of the mechanical properties of soil and their influence on the behaviour of structures. This resulted in the creation of techniques for analyzing the behaviour of shallow foundations, such as spread footings and mat foundations. Sir Horace Lamb investigated the characteristics of wave propagation within the earth's subsurface in the early 20th century [96].

In the mid-20th century, the discipline of soil dynamics and mechanics further developed, and the use of numerical methods, such as finite element analysis, became more prevalent. This contributed to an enhanced comprehension of the behaviour of deep foundations, such as piles and drilled shafts, and the ability to analyze more complex SSS. Sezawa & Kanai [97], investigated the decaying vibration of a structure due to the dissipation of its energy into the ground, were the first to consider the influence of SSI on structural response in 1935. Martel first took SSI classes in the US in 1940 [98]. He wrote about his views of the Hollywood Storage Building's operation during the 1933 Long Beach earthquake. Bycroft [99], investigated the behaviour of a stiff circular plate on an elastic bed when it was excited harmonically.

Evaluations of the early-stage advancements in the field of SSI were presented by [96, 100]. Roesset [100], depicted the methods of substructure and direct ways to undertake SSI studies. He also depicted the impacts of embedment, stratified deposits, and piling groups on the latter. On the other hand, Kausel [96], presented a sequential evolution of SSI, starting with the fundamental solutions, also known as Green's functions, which were initially formulated by physicists and mathematicians as far back as the early 1800s. By way of example, he mentioned Boussinesq, Hanson, Mindlin, Reissner, and Steinbrenner as major contributors to static SSI. Reissner laid the foundation for the influential SSI in 1936, and noteworthy contributions from Bycroft, Housner, Luco, Newmark and numerous others helped shape it further. Kausel [96], himself was the driving force for the creation of the substructure approach to SSI challenges [66].

The history of SSI continues to evolve with the advent of advanced numerical and experimental techniques and the increasing complexity of structures and SSS. Today, SSI constitutes a significant subject of study and practice in civil engineering and continues to play a critical role in the design and analysis of structures built on soil.

Integration of experimental and computational techniques

The late 20th century brought the integration of experimental techniques, such as centrifuge modelling and shake table tests, with computational methods [14, 54, 101]. These experiments validated theoretical models and provided data for refining numerical simulations. Pioneers like Gazetas developed impedance curves for various foundation types, offering engineers tools to incorporate SSI into real-world designs.

Wolf's work in the 1980s on direct time-domain SSI analysis addressed challenges in simulating the infinite domain of soil. The introduction of absorbing boundary conditions further improved the accuracy of dynamic SSI models [66, 102, 103]. Software like ABAQUS, ANSYS, and OpenSees became instrumental in applying these techniques, bridging the gap between academic research and industry practices [43, 54, 104].

Modern developments and future directions

In recent decades, SSI research has expanded to address emerging challenges. Advances in non-linear modelling, multi-layered soil analysis, and machine learning have improved the accuracy and efficiency of SSI simulations [17, 53]. Researchers like Kausel have introduced methods to simplify complex interactions using Green's functions and substructuring techniques [105].

Today, SSI is being integrated into interdisciplinary fields, including digital twin technology and real-time structural health monitoring [38, 104, 106]. These innovations aim to provide adaptive solutions for dynamic environmental conditions, such as earthquakes, floods, and extreme weather events. The ongoing development of international guidelines, like Eurocode 8 and ASCE 7, reflects the growing recognition of SSI's importance in ensuring resilient infrastructure.

The history of SSI demonstrates a continuous evolution from theoretical exploration to practical application, driven by technological advancements and lessons from real-world failures. Early pioneers laid the groundwork for understanding soil-structure interaction (SSI), while modern researchers continue to refine models and methods to address new challenges. As infrastructure becomes more complex and climate-related risks increase, the integration of SSI into design practices will remain a cornerstone of resilient and sustainable engineering.

Synthesis of previous studies

With the advent of reliable and quick computational platforms, the discipline of SSI has recently seen numerous and varied improvements. The majority of recent research in the field can be divided into two categories: studies that examine the impacts of SSI on a particular type of structure and those that seek to know the reasoning after these impacts on a broad structural pattern. In most seismic vulnerability evaluations of structures, SSI effects are ignored. Nonetheless, previously it is demonstrated that there is a possibility they could significantly disturb the way they perform under seismic conditions. The previous studies on different structures has been summarised as follows:

Soil-structure interaction (SSI) of tall buildings and skyscrapers

Soil-structure interaction (SSI) significantly influences the seismic response of tall buildings and structures. Studies on sky-pod towers, skyscrapers, high-rise buildings, and tall chimneys demonstrate that SSI effects are particularly pronounced for structures on soft to intermediate soils [107, 108]. Analysis methods incorporating SSI, such as flexible base models with nonlinear soils, provide more realistic representations of structural behaviour during seismic events [1]. SSI generally leads to increased top displacements and decreased base shears in regularly shaped buildings, though this trend may not hold for irregularly shaped structures [17, 109]. The magnitude of SSI effects depends on soil rigidity and seismic excitation characteristics [110]. Advanced modelling techniques, including nonlinear-inelastic approaches, are crucial for accurately assessing the seismic performance of tall buildings with SSI [9]. These findings underscore the importance of considering SSI in the seismic analysis and design of tall structures.

Soil-structure interaction (SSI) of bridges

Using a direct method in the frequency domain, Carbonari et al. [20] calculated the effects of SSI on piers of bridge supported by the group of piles. When calculating the basic frequencies and accompanying damping ratios for an Austrian Railway Bridge with a single span and integral abutments, Bigelow et al. [111] took SSI into account. Li et al. [112] assessed the Sutong cable-stayed bridge's seismic reaction and noted the importance of the direction of the bridge axis in relation to the fault trace. Recent evaluations of bridges that are significant due to their high capital costs or their post-disaster connectedness have produced results that are more accurate to the real world. Therefore it is crucial to take into account how they interact with the underlying soil medium. While Harte et al. [113] used a substructure technique to undertake a dynamic analysis of wind turbines, incorporating SSI.

Soil-structure interaction (SSI) of wind turbines

A study carried out by Fitzgerald & Basu [114], looked into the value of taking SSI into account when controlling wind turbine structures and presented an active structural control. By taking into account working conditions, Zuo et al. [115] expanded their investigations into dynamic SSI (DSSI) experiments involving offshore wind turbines and discovered reactions to be significantly higher. Additionally, the researchers noted that the impact of SSI on tower vibrations are more pronounced than on blade in-plane vibrations. Onshore wind turbine pile-grid foundations were analysed by Michel et al. [116] with the interaction both structure and soil subjected to seismic load in mind. They took into account various pairings of tower and soil characteristics that resulted in diverse dynamic responses, suggesting the need for a comprehensive dynamic strategy for each turbine. When designing deep sea platforms, Chatziioannou et al. [117] took into account the effects of SSI alongside a nonlinear wave structure. The main factors influencing SSI consideration in offshore structures are the significant capital required and peculiar crustal occurrences under the sea. Additionally, Kavitha et al. [118] examined a dockage built on piles while taking into account SSI.

Soil-structure interaction (SSI) of tunnels and nuclear structures

Hatzigeorgiou & Beskos [119], incorporated the finite element approach in the time domain and investigated that the impacts of SSI on the inelastic seismic response of tunnels. For a variety of nuclear plants, time-domain seismic SSI analysis was carried out [120, 121]. By employing LS-DYNA, a technique of non-linear SSI investigation was developed by Bolisetti et al. [122] for nuclear facilities. The impact of SSI on nuclear structures is extremely significant due to their stiffness and weight. The failure of these structures also emphasizes the importance of considering SSI in their structural design. Venanzi et al. [123] expanded on the study of SSI and its effects on tall buildings, stating that it is not only limited to seismic response. Their findings revealed that uniform rotations and displacements at the foundation level may lead to substantial permanent displacements at the top of tall buildings. Over the past decade, the amount of study on how SSI affects structural response has increased substantially. This research has focused on understanding how SSI affects diverse modal characteristics, including frequency, damping, seismic vulnerability, reduction coefficient, seismic fragility, ductility, and acceleration within a general structural layout.

Ayough & Taghia [124], studied steel frames that experienced near-source stimulation and found that SSI could be harmful based on several response parameters. In contrast, Mekki et al. [125] and Tomeo et al. [55] estimated reinforced concrete structures that could resist moment. Bararnia et al. [81] offered a formula for displacement inelastic nature in systems with fixed foundations. This formula takes into account both the kinematic and inertial aspects of SSI. Papadopoulos et al. [126] considered how structures interacted with the underlying medium when computing their modal properties. Cruz & Miranda [127], made an interesting discovery regarding the behaviour of structural damping. They found that effective damping decreases as structures become more slender, which means that thinner structures tend to exhibit reduced damping. On the other hand, for stocky structures (those with more robust proportions), the effective damping increases. This relationship between damping and the structural proportions appears to be linear and is also linked to the modal frequency of the structure [128]. In simpler terms, slender structures tend to have lower damping, while stocky ones exhibit higher damping, and this relationship follows a linear pattern in relation to the modal frequency [129].

Zhang et al. [130] delved into an examination of the damping characteristics within the SSS. They did so by conducting rigorous shake table tests, which allowed them to assess how the structure interacts with the soil under dynamic loading conditions. In a separate study by Nazarimofrad & Zahrai [131], they focused on evaluating the performance of irregularly designed structures equipped with active tuned mass dampers. Importantly, their research considered the impact of SSI during their assessments. This means they took into account how the dynamic behaviour of the structures was influenced by the underlying soil conditions and the use of active tuned mass dampers to mitigate vibrations and enhance structural performance. Both studies represent significant contributions to our understanding of how structures and soils interact under various conditions and the strategies that can be employed to improve their damping and overall performance, Luco [132], explored the impact of SSI on seismic base isolation. Fatahi et al. [133] recommended a seismic clearance requirement equal to at least 1.75% of the structural height based on their study of the effects of seismic pounding on mid-rise buildings supported by piles. Direct methods, as demonstrated by Fatahi et al. [133] are more suitable for analysing SSSI situations in the absence of computational constraints. It should be noted that there has been a decrease in SSI study of earthquake-resistant buildings. Buildings collapsed during earthquakes in Christchurch in 2011 and Mexico City in 1985, as reported by Rosenblueth & Meli [134], and Chouw & Hao, [92].

Boulanger et al. [135] conducted an experiment on the use of p-y analytical methodologies to examine seismic soil-pile-structure interaction issues. The authors compared their findings on seismic soil-pile-structure interaction to those of dynamic centrifuge model testing. They also carried out dynamic p-y analysis and site response analysis by monitoring the dynamic beam on the nonlinear Winkler foundation. Seismic waves travel from the bedrock, traversing through layers of soil during an earthquake, and can lead to loss to structures on the surface. It is crucial to comprehend the local site effects on significant ground motion to minimize earthquake disasters and develop earthquake-resistant construction techniques in the future. Using the Abaqus V.6.8 software, Matinmanesh & Asheghabadi [136], conducted a two-dimensional plane strain finite element study on seismic SSI, which involved three actual ground motion records representing low, moderate, and high-frequency seismic motions. The study investigated the influence of various factors such as subsoil type (dense and loose sand), building height, and earthquake frequency content on acceleration response, soil amplification, and stress propagation at the soil-foundation interaction. The research discovered that both categories of sandy soils enhance seismic wave amplitudes at the interface with the structure because of the influence of SSI.

Sáez et al. [137] carried out research on the impact of inelastic dynamic SSI on the response of moment-resisting frame buildings. They created a modelling technique using a modified 2D in-plane approach, which allowed for quicker finite element analysis In the research, two typical buildings were studied, built on sandy soil in both arid and fully saturated state, and a variety of motions were analyzed to evaluate the impact of inelastic DSSI on structural behaviour. The findings demonstrated that the effect of DSSI on dry soil scenarios was uncertain, whereas it was always beneficial or insignificant when the soil was saturated. According to Sáez et al. motions with extensive inelastic structural behaviour and a mean period close to the first elastic period of the soil deposit are particularly important for inelastic DSSI.

Soil-structure interaction (SSI) of moment-resisting frames (MRFs)

Tomeo et al. [55] examined the influence of SSI on the seismic performance of 2D reinforced concrete (RC) moment-resistant frames (MRFs) using non-linear dynamic analysis. They performed a parametric study in which they varied the SSI modelling technique, the characteristics of the soil, as well as the seismic design criteria for the structures. The mechanical properties of the soil were determined based on Eurocode 8 soil classes. They studied both a substructures method and a direct approach for SSI modelling. Finally, they evaluated structures with 4 and 8 stories designed for vertical loads only or in accordance with the Italian construction regulations (NTC-08). Since SSI effects are expected to be more significant in RC-MRFs constructed on soft soils, they were analyzed. According to Tomeo et al.'s research, the maximum base shear and maximum inter-story drift ratio of SSI have varying effects on seismic demand.

Soil-structure interaction (SSI) of reinforced concrete buildings

Requena-Garcia-Cruz et al. [68] conducted a study on the impact of seismic SSI on the seismic vulnerability of RC buildings. They employed two methods, the Beam on Nonlinear Winker method (BNWM) and direct soil modelling, to quantify the SSI effects and characterize soil behaviour. The study was conducted on a mid-rise RC building in Lisbon built on clay-type soil under undrained conditions. The researchers used 3D FEA to accurately model the nonlinear soil behaviour and the entire system's response. Requena-Garcia-Cruz and colleagues [39] depicted that considering SSI effects can reduce the building's maximum capacity by up to 15% and increase the periods and seismic damage due to soil flexibility. However, the model behaviour and building shape remain the same whether or not SSI is considered.

This review study highlights the critical importance of accurately modelling the soil and foundation systems when considering the impacts of SSI. In order to obtain reliable and trustworthy results when accounting for these interactions, it is imperative to use realistic and representative models for both the structural components and the underlying soil. However, one significant observation is that the majority of the existing studies in this field are heavily based on simplified and idealized representations of both structures and soil conditions. These idealized models might not capture the complexities of real-world scenarios accurately, which can potentially lead to less accurate predictions of SSI effects on structures. Another noteworthy finding is the lack of comprehensive studies and guidelines when it comes to quantifying the effects of SSI, even within established building codes and standards. This gap in knowledge and guidance indicates that there is still much room for research and development in this area to better understand, quantify, and account for the impacts of SSI in structural engineering and construction practices.

Emerging research trends

Recent studies have explored innovative applications of SSI, integrating advanced computational tools and interdisciplinary approaches. Machine learning techniques are increasingly being used to model complex SSI interactions, as shown by [19, 138, 139], who trained neural networks to predict seismic response in layered soils. Additionally, digital twin technology is being applied to monitor real-time SSI effects, offering adaptive solutions for dynamic environmental conditions.

Sustainability-focused studies, such as those by [17, 140, 141], have examined how SSI-informed designs reduce material usage and carbon footprints. Research into multi-hazard scenarios, including earthquakes and tsunamis, is gaining attention, with projects like SAFEL aiming to integrate SSI into disaster-resilient infrastructure frameworks [110, 140].

Research gaps and future directions

Despite significant progress, several gaps remain in SSI research. Many studies focus on idealized conditions, neglecting the complexity of real-world scenarios, such as heterogeneous soils or multi-hazard effects. Additionally, the computational expense of advanced numerical models limits their practical application, particularly in large-scale projects.

Future research should address these gaps by exploring hybrid modelling techniques, integrating experimental, numerical, and machine learning approaches. Studies on SSI in renewable energy infrastructure, such as offshore wind farms and solar installations, represent another promising avenue. Finally, developing standardized SSI guidelines for international codes are crucial for translating research findings into practical engineering solutions.

Significance of soil-structure interaction (SSI)

The role of SSI in enhancing the ability of a structure to withstand earthquakes has been widely acknowledged [64, 66]. The design codes provide options that either neglect SSI or permit a decrease in the overall seismic coefficient due to SSI [26, 87]. The rationale for such choices is that considering SSI leads to increased flexibility, longer natural period, and better damping ratio, which translate to lower base shear demand for the structure than its fixed-base counterpart [59, 127]. Nonetheless, observations from earthquake-damaged sites offer an alternative viewpoint. For example, Yashinsky [102], reported that several pile-supported bridge constructions were damaged in the 1989 Loma Prieta earthquake, while Mylonakis & Gazetas [48], noted the downfall of the Hanshin Expressway Route 3 (Fukae portion) in the 1995 Kobe earthquake. Similarly, Badry & Satyam [142], analyzed the impact of SSI on asymmetrical buildings supported by piled rafts, which were damaged in the 2015 Nepal earthquake. They found that the shape asymmetry of the superstructure could exacerbate the negative effects of SSI. Thus, it is essential to consider the findings of previous studies and carefully evaluate the assumptions made about SSI. Several parametric studies have been conducted to assess the influence of SSI on the seismic response of structures, with most of them finding that the structural geometry, foundation properties, soil modulus, and shear wave velocity profile are critical factors. The studies by Ciampoli & Pinto [85], and Van Nguyen et al. [133, 143] demonstrated that the ratio of aspect and stiffness ratio of the structure-to-soil system and the foundation parameters, such as footing and pile size, play significant roles in determining the seismic reaction of the system.

The importance of SSI lies in its ability to provide a more accurate and realistic representation of the behaviour of structures built on the soil [114, 144]. By considering the effects of the soil's properties on the structural behaviour of the building, and vice versa, SSI allows for more accurate predictions of the performance of the structure under different loading situations [135, 145].

Some of the key significance of SSI are:

1. By considering SSI, engineers can ensure that structures are designed to withstand the forces imposed by the soil and provide sufficient safety and stability for the intended use [66].
2. SSI can be used to optimize the design of a structure, leading to improved performance, such as reduced settlements or increased load-carrying capacity [64].
3. By considering SSI, engineers can design more efficient and cost-effective structures, by reducing the number of materials needed or by avoiding the use of expensive construction methods [111].
4. SSI can be used to design more effective sustainable structures, such as reducing the environmental impact of construction or using local materials [146].
5. SSI is essential to confirm the safety of structures during earthquakes. Proper consideration of SSI can help to minimize the damage and collapse of structures during seismic events [85].

In general, SSI plays a central role in safeguarding the integrity, stability, and functionality of structures. It is essential for the design and analysis of structures constructed on a foundation of soil [75, 93, 147].

So it should be clear that SSI must be considered when designing inelastic structures. Due to the significant financial investment needed, the prominence of connectivity in post-disaster circumstances, and the enormous risks convoluted, SSI needs to be considered during the design stage structures. Nevertheless, SSI concern in the design of different constructions is uncommon despite the substantial amount of study on the topic. This is due to improperly implemented SSI provisions in building codes. A straightforward yet fairly accurate method of SSI problem analysis needs to be developed.

Broader implications of SSI

SSI's significance extends beyond immediate structural performance to address broader challenges in engineering:

- Sustainability: By optimizing material use and enhancing durability, SSI contributes to environmentally sustainable construction practices [110].
- Cost Efficiency: SSI-informed designs prevent overdesign, reducing construction and maintenance expenses over a structure's lifecycle [148].
- Public Safety: SSI enhances resilience, minimizing structural damage and ensuring quicker recovery after disasters [17].
- Standardization: Incorporating SSI into design codes like Eurocode 8 and ASCE 7 ensures consistency in global engineering practices, but further standardization is needed [110, 149].

Emerging trends in SSI

Advancements in technology are reshaping how SSI is analyzed and applied:

- Machine Learning and AI: These tools are improving the accuracy of SSI predictions, enabling efficient modelling of complex soil-structure interaction (SSI) [150].
- Digital Twins: Real-time monitoring systems are integrating SSI into adaptive designs, allowing structures to respond dynamically to environmental changes [130].
- Sustainability Integration: Recent studies highlight SSI's role in reducing embodied carbon by optimizing foundation designs [17].
- Multi-hazard Analysis: Emerging research addresses SSI under combined hazards, such as earthquakes and extreme wind loads, ensuring comprehensive resilience [3].

The significance of SSI lies in its ability to enhance the safety, performance, and cost-efficiency of structures in diverse environments. From mitigating seismic risks to supporting sustainable infrastructure, SSI considerations have become indispensable in modern engineering. As new technologies emerge and global challenges intensify, SSI will continue to play a transformative role in advancing resilient and efficient design practices.

Soil-structure interaction (SSI) solving approaches

Soil-structure interaction (SSI) significantly impacts the behaviour and performance of structures, particularly in seismic regions. SSI effects can alter the dynamic properties and frequency response of structures [140], influencing stresses, displacements, and internal forces in both the building and soil [151]. Solving SSI problems requires understanding the reaction of the soil and the structure, and how they interact with each other.

Because of the infinite domain of the soil, the precision of the SSI analysis results is dependent on how radiation circumstances are handled, the modelling method of soil materials, and the nonlinear modelling method between the soil and the structure. SSI is primarily classified into two approaches. The direct method considers the ground and structure as a whole system and models it as a structure using finite elements or finite differential methods. The Substructure Method, on the other hand, treats the mechanical behaviour of the soil as a single system with independent stiffness and damping.

The first attempts to tackle an SSI problem were largely aimed at achieving an investigative solution. When conducting dynamic response assessments of individual pilings and group of pile within a layered half-space, it's essential to consider the complex behaviour of these foundational elements within the varying soil conditions. The analysis involves investigating how piles, either individually or when grouped together, interact with the surrounding layered soil, Kaynia & Kausel [152], provided a mathematical approach on the basis of Green's formula used in various fields, including physics and engineering, to solve problems related to partial differential equations, boundary value problems, and integral equations that may be applied to the seismic investigation. While these comprehensive solutions are applicable to a broad spectrum of problems,, they are unlikely to gain widespread acceptance due to the complexities and high computing costs required. SSI concerns have been investigated experimentally in a number of cases.

Early SSI assessments relied on analytical estimations of the reactions of footings and foundations sitting on a semi-infinite half-space. The majority of research, such as Kaynia & Kausel, [152]; Luco and Westman, [154]; Veletsos and Verbic, [155]; Veletsos and Wei, [153], designed impedance functions dependent on frequency for inflexible foundations with shapes restricted to rectangles or circles that rested on elastic or viscoelastic half-spaces. Bielak [156]; Jennings and Bielak [157], demonstrated in one of the seismic analysis of buildings studies that the technique to calculate the SSI response of the structure involves the combination of $n+2$ damped linear oscillators that are subject to modified excitations. The building has n resonant frequencies, and the two additional oscillators represent foundation translation and rotation.

In 1974, a groundbreaking research was conducted by Veletsos & Meek [70] where they utilized this discovery to deduce the characteristics of an analogous single-degree-of-freedom (SDOF) oscillator. The said oscillator possesses similar damping ratio and period as that of an SDOF system, which relies on linear elastic soil. Their research was also expanded to find several system factors that may be utilized to evaluate the importance of SSI impacts through thorough numerical simulations on the comparable oscillator. This research also influenced the creation of the first recommendations in FEMA, (1997) to take SSI impacts into account when designing structures. Researchers like e.g., Elsabee et al. [158]; Veletsos & Meek [70], have been able to tackle more intricate foundation structures (such as foundations on layered media and embedded foundations) to determine functions of impedance because of the development of mathematical tools like the boundary element method and the finite element method in the 1970s. Using a variety of analytical and numerical methods over the years, Gazetas [159], created impedance curves that varied depending on the frequency for different types and configurations of foundations, such as embedded foundations and foundations with irregular shapes.

In the past, SSI analyses frequently make use of equivalent springs and dashpots with precomputed impedance functions to represent the soil's flexibility at the foundation. The spring method is another name for this SSI analysis approach. A significant limitation of the spring method was that the damping functions and stiffness of the foundation obtained from previous experiments were not applicable to a wide range of frequencies and were dependent on frequency [100]. The incorporation of more complex foundations with irregular shapes, deeply embedded foundations, and soil profiles featuring non-uniform variations in shear modulus at various depths posed additional challenges. These issues call for more complex solutions, which were subsequently created primarily for the nuclear industry [96, 100]. As a result, two main approaches; the direct technique and the substructuring method, were developed in the quest for more advanced SSI analysis tools. The following sections provide an explanation of these techniques since they are also employed in the SSI analyses reported in this article.

There are several methods for solving SSI problems, each with its own advantages and limitations. Here are a few standard methods:

1. Analytical methods: These methods use mathematical equations to model the behaviour of the soil and structure. Analytical methods include the use of elasticity theory, beam on elastic foundation theory, and Winkler's model for the soil. They include numerous solutions for diverse loading conditions, boundary conditions, and soil profiles [146, 160].
2. Numerical methods: These methods use computer programs to solve the equations that describe the

behaviour of the soil and structure. The FEM and BEM are the two most commonly used numerical methods in SSI analysis. FEM is a powerful tool that can model the behaviour of both the soil and structure in great detail, while BEM is a more efficient method that can handle problems with large deformations and nonlinear material behaviour [78, 161, 162].

3. Experimental methods: These methods use physical testing to measure the behaviour of the soil and structure. The most common experimental methods include centrifuge modelling, laboratory testing, and field testing. These methods are often used to verify the results obtained from analytical or numerical methods, or to study the behaviour of a specific SSS under realistic conditions [75, 86, 128].
4. Hybrid methods: These methods combine the advantages of analytical and numerical methods. For example, a hybrid method can use analytical solutions for simple loading conditions and numerical solutions for more complex loading conditions. Another example is a combination of experimental and numerical methods, where experimental results are used to calibrate the numerical model [107, 163, 164].

The choice of method depends on the specific problem, the available resources, and the level of accuracy required [84]. Analytical methods are generally simple and easy to use, but they may not be able to handle complex loading conditions or nonlinear soil behaviour [146]. Numerical methods such as FEM and BEM are widely used in SSI analysis due to their ability to handle more complex problems and loading conditions, but they can be computationally expensive and may require specialized software and expertise [165]. Experimental methods can provide valuable information about the behaviour of specific SSS, but they can be costly and time-consuming [128]. Hybrid methods can combine the advantages of different methods to provide the most accurate and efficient solution for a specific problem [162, 166].

Substructure method

The SSI is separated into many components (or substructures) in the substructuring approach of SSI analysis, and the response of each substructure is estimated separately [167]. The substructures are interconnected by imposing equal and opposing interaction pressures on each of them. To determine the final reaction of the system, the responses of all the substructures are subsequently superimposed [84]. The advantage of using a proper analysis approach to determine each substructure's reaction is thus made possible by the substructure methodology. The substructure approach is limited to linear studies because it relies on superposition to combine the responses of individual substructures. However, this approach is still commonly used for SSI analysis and there are software packages, such as SASSI and CLASSI, which utilize the substructuring technique in the frequency domain) Lysmer et al. [168].

Figure 5 illustrates the substructure strategy (also called the indirect method). The method aims to use calibrated springs and dashpots to depict the continuum response to summarize the soil response. This method accounts for impacts brought on by the foundation's presence by adjusting the input motion (Foundation Input Motion, or FIM) applied to the structure. Site-response analysis and structural analysis are used to determine the reactions of these substructures [31, 32]. Once the seismic input and the foundation's impedance have been approximated, they can be employed when conducting a dynamic investigation for the building and assessing how it reacts to seismic forces, including the effects of SSI. This can help in designing structures that can better resist seismic forces and reduce potential damage, it is convenient to undertake structural analysis using finite element methods. A scattering analysis is used to calculate the seismic input and should take kinematic interaction into consideration. The calculation of foundation impedance, also known as the interaction analysis or the impedance analysis, should take radiation damping into account. There are four categories of substructuring techniques, classified based on how they resolve the scattering problem and interaction problem. Some of these methods encompass the rigid boundary approach, the pliable boundary approach, the pliable volume method, and the subtraction technique. Each of the three techniques site-response analysis, impedance analysis, and structural response analysis utilizes site-response analysis, impedance analysis, and structural response analysis to compute ground motion, foundation impedance, and structural response.

Direct method

Although the substructuring approach is flexible enough to use multiple analysis methods for various substructures and has low computational requirements, it is only applicable to linear analysis. The direct methodology, which examines the whole SSS as a unified process without relying on superposition, enables a more precise modelling of the nonlinear behaviour of the SSS. Commercial finite element systems including LS-DYNA (LSTC, 2013), ANSYS (ANSYS Inc., 2013), and ABAQUS (Systèmes, 2005), as well as the open source OpenSees software (a finite element tool), can perform SSI utilising the direct technique [170]. Figure 6 displays a FEM for the analysis of SSS employing the direct technique. Since

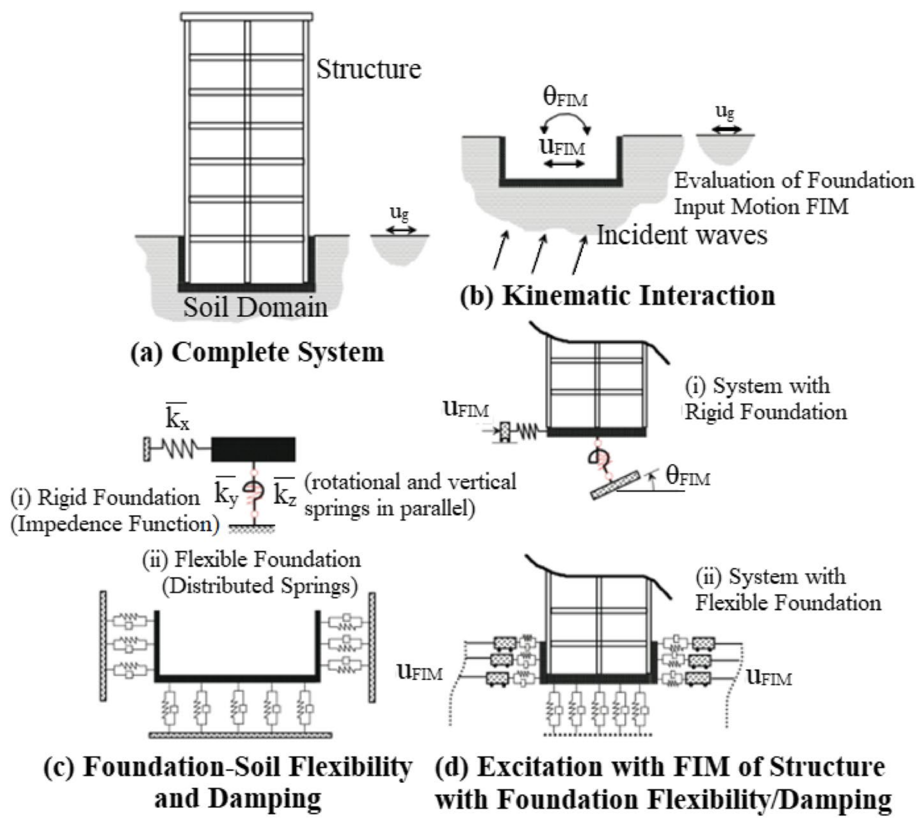


Fig. 5 Schematic diagram of a substructure method to analyse SSI for rigid and flexible foundations [169]

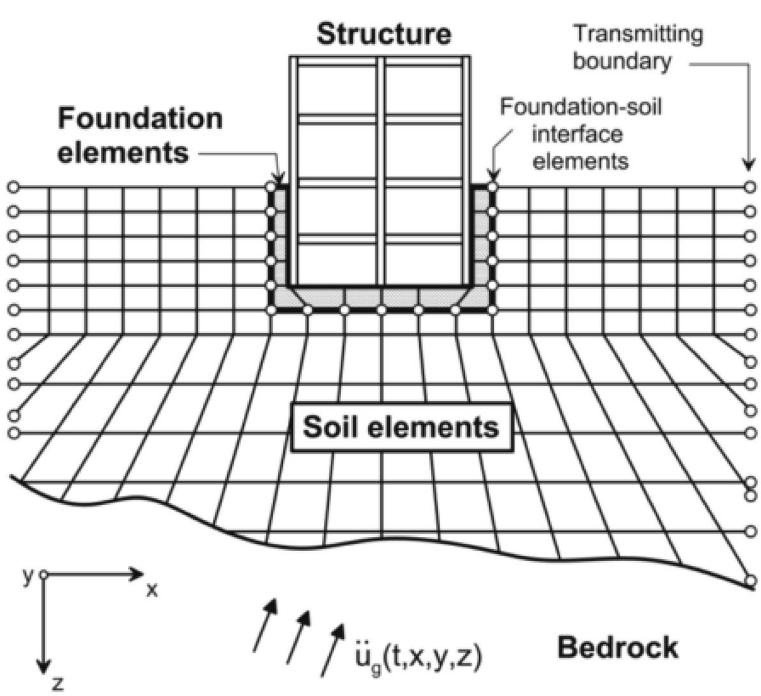


Fig. 6 An example of the direct analysis of SSI using a continuum modelling approach with the FEM [169]

the direct technique of SSI analysis takes more processing power than the substructuring method, it is rarely used in actual practice [43, 66]. Subsequently, performing nonlinear SSI investigation by employing the direct technique remains challenging due to difficulties in defining ground motion, replicating an unbound region, and establishing dependable 3D nonlinear constitutive models for soil [53, 68].

Another significant obstacle in accomplishing nonlinear SSI investigation with the direct approach is simulating an infinite domain [30, 143]. By creating a finite domain that meets the requirements listed below, an infinite soil domain can be replicated [20, 27, 103]. Effective wave damping away from the structure to prevent lateral boundary reflections into the soil domain and ensuring stress equilibrium along the lateral boundaries to incorporate the unconsidered portions of the soil domain that was not incorporated into the finite domain model [78, 171]. The utilization of absorbing boundary models at the lateral boundaries can achieve this by absorbing the incoming waves and diminishing reflections. Commercial finite element programmes have developed and used absorbing boundary models [119, 120, 172]. LS-DYNA incorporates various models for SSI analysis, such as the Perfectly Matched Layer (PML) model introduced by Basu in 2009 and the viscous boundary model developed by Lysmer and Kuhlemeyer [173], in 1969. These models have been proven effective in analyzing SSI in a dynamic environment. Table 1 provides a clear comparison, highlighting the strengths, limitations, and ideal applications of both methods.

Figure 6 provides a schematic representation of the key elements that need to be considered when conducting a study of SSI using a continuum approach (also called the direct method). Using the right constitutive models, this method enables the replicating the non-linear reaction of each component of the model. Table 2 gives the comparison of SSI solving approaches.

The assessment of computational cost in Table 2 is based on extensively accepted benchmarks in SSI modelling. Numerical methods, such as the FEM and BEM, are known for their high computational demands due to their capability to model complex geometries, heterogeneous soil properties, and nonlinear interactions [9, 78, 181, 182]. These models need detailed discretization of the problem domain, which significantly increases the number of calculations and degrees of freedom, particularly in large-scale or dynamic scenarios [27, 166, 183]. High computational cost is further characterized by the necessity of advanced computing resources, such as multi-core processors or GPU clusters, to ensure reasonable processing times [64, 184].

Additionally, numerical methods often involve iterative solvers for nonlinear equations, which demand substantial time to converge, especially in dynamic analyses or when modelling soil-structure interaction (SSI) under extreme conditions [185]. Compared to simpler analytical or hybrid approaches, numerical methods require specialized software, skilled personnel, and significant resource allocation, all of which contribute to the overall computational expense [186].

Guidelines on soil-structure interaction (SSI) based on codes

As stated earlier that soil-structure interaction (SSI) plays a critical role in the seismic design of structures, predominantly in areas with soft soils, deep foundations, or dynamic loading conditions. However, its treatment across international seismic codes, as summarized in the Table 3, reveals significant differences in emphasis and implementation. While some regions, such as Europe

Table 1 Comparative analysis of direct and substructure methods

Aspect	Substructure method	Direct method
Strength	Divides the problem into substructures, allowing for computational efficiency and flexibility	Models the entire soil-structure system as a single entity, enabling precise nonlinear and dynamic analysis
	Suitable for linear analyses and routine design practices with manageable computational requirements	Captures complex geometries, heterogeneous soil properties, and boundary conditions effectively
	Supported by specialized software (e.g., SASSI, CLASSI) that simplifies practical application	Ideal for extreme load scenarios and advanced seismic studies
Limitations	Relies on superposition, limiting effectiveness for nonlinear analyses involving complex soil-structure behaviors	Computationally intensive, requiring significant processing power and time for large-scale models
	May oversimplify soil conditions, reducing accuracy in capturing detailed dynamic responses	Challenges in simulating infinite soil domains, needing advanced boundary techniques like absorbing boundaries
	Requires careful calibration of impedance functions, which can be challenging for heterogeneous or layered soils	Less practical for routine design due to complexity and high cost
Best applications	Routine design projects, especially those involving linear analyses or less complex SSI scenarios	Detailed analysis of nonlinear SSI under extreme loads or advanced seismic conditions

Table 2 Different approaches of solving SSI problems

Approach	Description	Advantages	Limitations	Applications	Reference
Analytical Methods	Simplified, closed-form solutions based on assumptions of linear behaviour and idealized systems	- Quick and computationally efficient - Useful for preliminary analysis and validation	- Limited to simple geometries and linear behaviour - Cannot handle complex soil-structure systems	- Preliminary design - Validation of numerical and experimental models	[38, 174]
Numerical Methods	Computational models like FEM, BEM, and FDM for solving complex SSI problems	- Handles complex geometries and soil behaviours - Accurate for detailed analysis	- High computational cost - Requires extensive input data	- Detailed SSI analysis - Seismic performance studies	[53, 175, 176]
Experimental Methods	Laboratory and field experiments to validate models and understand SSI behaviour	- Provides empirical validation - Captures real-world phenomena like non-linearity	- High cost and scaling challenges - Limited to specific scenarios	- Validation of numerical models - Seismic and dynamic behaviour studies	[130, 177]
Hybrid Methods	Combines analytical, numerical, and experimental methods for enhanced modelling	- Leverages strengths of multiple approaches - Reduces computational effort in complex systems	- May still face scaling and computational challenges	- Multi-hazard scenarios - Layered soils and irregular structures	[162, 178, 179]
Emerging Methods	Advanced tools like AI, machine learning, and digital twins for SSI modelling	- Handles uncertainty effectively - Facilitates real-time monitoring and adaptive designs	- Requires large datasets for training - May need integration with traditional methods	- Real-time SSI monitoring - Predictive analysis in adaptive and sustainable infrastructure	[17, 141, 180]

Table 3 Guidelines on SSI based on codes

Country	Code	Year	Guideline
Europe	EC8, EN 1998-5	2004	According to Eurocode 8, EN 1998-5 [187] when designing structures that are thin or have substantial second-order effects (such as P-δ effects), dynamic SSI must be considered. The use of SSI in the design process is also recommended for buildings supported by piles or with substantial or deep-seated foundations. The standard ground type with extremely high plasticity index and low shear strength is particularly mentioned in EN 1998-1 (EN, 2004), and EN 1998-5 (EN, 2003) requires SSI attention in the design of buildings or any structures to be built on such deposits [188]. Regardless of determining the buildings for which SSI must be employed in design, EN 1998-5 (EN, 2003) does not offer any recommendations for measuring SSI effects
Japan	JSCE, 15	2007	This code [189] advises that dynamic ground interaction must be measured and considered while designing underground constructions, retaining walls, bridge abutments, and foundation constructions. Varies based on the nature and properties of the structure and the ground, SSI effects may be neglected in certain cases, while for others, they should be accurately incorporated into the modelling. It is up to the structural designer to decide whether to model the system with both soil foundation and structure jointly or independently, using a substructure or direct method
United States	(ATC, 1978)	1978,	The Applied Technology Council (ATC) in 1978 created the initial set of SSI provisions as ATC 3–06 [190]. ATC 3–06 [190] recommended a reduction in design base shear in light of the longer natural period and typically stronger damping displayed by SSS compared to their fixed-base counterparts
	[191]	2010	ASCE 7–10 [191] suggested that the amended the designed base shear should remain at or above 70% of the initial value, putting a limit on base shear reduction. However, according to Jarernprasert et al., structures built in accordance with ASCE 7–10 [191] suffer a mean ductility that is higher than the goal ductility for which they were intended. This suggested that these SSI rules needed to be reviewed
	FEMA, (2015)	2015	In the form of (FEMA, 2015), the National Earthquake Hazard Reduction Program (NEHRP) created regulations that established the maximum reduction in base shear in relation to the response modification factor [192]. These regulations were eventually incorporated into ASCE 7–16 [193] and recommended a smaller reduction in design base shear for systems with a higher response modification factor, or those that have a greater capacity for inelastic deformation
	[193]	2016	ASCE 7–16 [193] include a linear dynamic analysis that utilizes either the SSI-modified general design response spectrum or a site-specific response spectrum, taking into consideration the SSI effects. This analysis method is in addition to the conventional lateral force technique. Khosravikia et al. [194] assessed the effects of following ASCE 7–16 [193]/FEMA [192] and ASCE 7–10 [191] in terms of the safety and efficiency of the structural designs that were produced, and they indicated areas in which the current recommendations may be improved
India	IS 1893-1	2016	IS 1893-1 [195] gives a standard for earthquakes resistant design for general provisions and constructions
	IS 1893-2	2014	IS 1893-2 [196] (BIS, 2014) is for liquid retaining structures and does not say anything about the SSI
	IS 1893-3	2014	IS 1893-3 [197] (BIS, 2014) states the criteria for earthquake-resistant design of constructions for retaining walls and bridges mentions the consideration of SSI in the design of bridges
	IS 1893-4	2015	IS 1893-4 [198] (BIS, 2015) states a norms for earthquakes resilient strategy of structures for designing industrial buildings comprising stack-like constructions. If constructions are to be sustained on deep foundations in low shear wave velocity soils i.e. soft soil, SSI must be taken into consideration during design
New Zealand	NZS 1170.5	2004	It makes no recommendations regarding how to apply SSI in field of design. The usage of a structural performance factor is mentioned, which is influenced by various factors such as the material, shape, and age of the seismic-resistant system, as well as the damping properties of the structure and its interaction with the ground. When calculating building deflection, NZS 1170.5 [199] stipulates that foundation deformations must also be taken into account
Australia	AS1170.4	2007	The Australian code [200] depicts the design guidelines for seismic-resistant structures state that soils with SPT-N values lower than 6 are considered to be soft, following the New Zealand design standard. To account for SSI effects and reduce earthquake damage, it is recommended to use structural performance and ductility factors during the design phase
Malaysia	MNA-EC8 -MS EN 1998-1: 2015	2017	Malaysia is following the Eurocode 8 for the design and construction of structures. MS EN 1998-1: 2015 [201] provides the general design of structures for earthquake resistance but SSI has been largely disregarded. It provides the data for the site response analysis and design response spectra but it does not give any proper guidelines in regard of SSI

and Japan, recognize the importance of SSI in certain structural scenarios, they often provide only general recommendations without detailed methods for quantifying SSI effects.

In the United States, guidelines have evolved over time, with updates in ASCE 7–16 introducing more precise provisions, such as adjustments in base shear reduction and dynamic analysis techniques. Despite this progress, inconsistencies remain in aligning design practices with real-world structural behaviour. On the other hand, countries like Malaysia and New Zealand incorporate international standards but fail to address SSI comprehensively, which could lead to oversight in critical site-specific conditions. This disparity underscores the necessity for more consistent and detailed SSI frameworks globally (Table 3).

Discussion and conclusion

It is clear from Table 1 that most of the reputable seismic codes do include requirements for including SSI in design practice, however, there are still no standards for SSI assessment and implementation in design practice. In the event of a discrepancy between the structural and geotechnical engineers, such as a compliance gap and a communication gap, a building's performance may be compromised during seismic activity. Due to the scarcity of appropriate construction sites today and the prevalence of building on landfills and soft soils, this assumes more importance. Hence, where it is anticipated that SSI impacts would be severe require effective coordination between structural and geotechnical experts. For information sharing between them in this situation, NIST [202] recommends checklists that can be used with some project-specific adjustments. In addition, a professional knowledge-sharing system between the different project stakeholders, including the planners, structural consultants, soil mechanics consultants, and building engineers, could potentially be very valuable.

SSI is a phenomenon that involves a number of processes that result in the interdependence of structural displacements and the soil. These processes are classified as inertial or kinematic components of SSI. The current study surveys previous studies on the influence of SSI on structural response. Research has also been performed in recent years to provide novice researchers with a broad overview of the field. This extensive review of the literature yielded few findings. Although some of these observations may be considered common knowledge, they are still essential for gaining a thorough understanding of the phenomenon and determining effective approaches to address it.

It has been found from this state-of-the-art that:

1. Recent attempts to evaluate how SSI might affect a structure's inelastic response have demonstrated the need to consider SSI when designing an inelastic structure. SSI must now be encompassed in guidelines of design recommendations because the majority of structures are now built to demonstrate inelasticity during strong earthquakes. Additionally, Jarernprasert et al. [203] and Aydemir [59], suggest that the criteria for assessing seismic performance could be based on adjusted strength reduction factors and ratios of inelastic displacement.
2. Although the actual response, which varies on frequency, is determined by the seismic accelerogram, it is known that inflexible, big structures built on the soft soils having low shear wave velocity are the most severely damaged [66].
3. Modern studies on SSI concentrate on either examining how it affects a particular structural type or figuring out how it affects a broad structural arrangement. Strength reduction factor, seismic fragility, ductility demand, inelastic displacement ratio, seismic vulnerability, and modal properties are among the parameters of interest. More recent studies have looked at how SSI affects buildings with seismically resistant features such seismic base isolators and tuned mass dampers [131]. The study of SSSI and the related phenomenon of structural pounding is another area of study that is becoming more and more popular.
4. SSI may be advantageous or unfavorable to a structural reaction through an earthquake, depending on the structure-to-soil stiffness differential. This is based on findings from an examination of the collapse of Hanshin Expressway Route 3's condition throughout the Kobe Earthquake in 1995 by Mylonakis and Gazetas [48].
5. The advantages of the substructure technique over the direct approach have been thoroughly covered. There has been a heightened focus on physical modelling techniques, particularly cone models, when considering impedance functions during substructure analysis for inertial interaction. Cone models are advantageous because they provide a better understanding of the physical system, can account for pile foundations in layered deposits, and require less computation than other modelling methods.
6. As a last point, it should be noted that researchers who are new to the topic of SSI would benefit from reading the current work. It is possible to gain a thorough understanding and recognize its importance to the field of design. It may also be helpful in choosing the best solution approach for an SSI problem. Additionally, knowledge of the most recent SSI regulations found in different seismic codes can be acquired. Academicians and researchers may find the current work useful in deciding on a line of study based on current research.

In conclusion, SSI is an imperative consideration in the design and analysis of structures built on the soil. By taking into account the soil's properties on the structural behaviour of the building, and vice versa, SSI allows for more accurate predictions of the reaction of the structure under various loading.

There are several methods that can be used to solve SSI problems, including analytical methods, numerical methods, experimental methods, hybrid methods and empirical methods. The selection of approach will be contingent on the precise problem being considered, the available resources, and level of precision required. Despite the advancements in the field of SSI, there are still many challenges and open questions that need to be addressed. These include the development of more accurate and efficient methods for analyzing SSI, the need for a better understanding of the reaction of SSS under extreme loading conditions, such as earthquakes and fires, and the need for more sustainable and resilient structures. Overall, SSI is an important and active area of research and practice in civil engineering and will continue to play a critical role in the design and analysis of structures built on soil.

The review establishes SSI as a critical component of modern engineering design, emphasizing its role in seismic safety, cost-efficiency, and sustainability. By addressing soil-structure interaction (SSI), engineers can better predict structural responses and develop resilient systems capable of withstanding extreme conditions. While current research has made significant strides, challenges such as improving computational efficiency, addressing soil variability, and integrating SSI into multi-hazard scenarios remain pressing. Future efforts should focus on interdisciplinary collaboration, real-world validation, and the development of standardized practices to bridge gaps between research and application. SSI will continue to play a transformative role in civil engineering, enabling the design of safer, more resilient, and sustainable infrastructure for a rapidly evolving world.

Abbreviations

AS	Australian standard
ASCE	American society of civil engineers
ATC	Applied technology council
BEM	Boundary element method
BNWM	Beam on nonlinear Winkler method
DEM	Discrete element method
DSSI	Dynamic soil-structure interaction
FDM	Finite difference method
FEA	Finite element method
FEM	Finite element method
FEMA	Federal emergency management agency
FIM	Foundation input motion
IS	Indian standard
MNA	Malaysian national annex
MRF	Moment-resisting frame
NIST	National institute of standards and technology
NZS	New Zealand standard
PML	Perfectly matched layer
RC	Reinforced concrete
SDOF	Single degree of freedom
SSI	Soil-structure interaction

Authors' contributions

Imtiyaz Akbar Najar (conceptualization, writing – original draft); Raudhah Ahmadi (supervision, writing – review and editing); Akeem Gbenga Amuda (conceptualization, writing – review and editing); Raghad Mourad (supervision, writing – review and editing); Neveen El Bendary (writing – review and editing); and Idawati Ismail (writing – review and editing); Nabilah Abu Bakar (writing – review and editing); and Shanshan Tang (writing – review and editing)

Funding

Open Access funding provided by Universiti Malaysia Sarawak. PILOT Research Grant of Universiti Malaysia Sarawak (UNIMAS) has supported this study with grant number UNI/F02/PILOT/85624/2023.

Data availability

No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate

Not applicable.

Competing interests

The authors declare no competing interests.

Author details

[1]Department of Civil Engineering, Faculty of Engineering, Universiti Malaysia Sarawak, 94300 Kota Samarahan, Sarawak, Malaysia. [2]Department of Civil Engineering, Nile University of Nigeria, 900108 Abuja, Nigeria. [3]Department of Architecture, College of Architecture, Art and Design, Ajman University, 346, Ajman, United Arab Emirates. [4]Healthy Buildings Research Centre (HBRC), Ajman University, 346, Ajman, United Arab Emirates. [5]Department of Civil Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia. [6]Faculty of Engineering, Anhui Sanlian University, 230601 Hefei, Anhui, China.

Received: 29 November 2024 Revised: 4 January 2025 Accepted: 6 January 2025
Published online: 26 January 2025

References

1. Firoj M, Bahuguna A, Kanth A, Agrahari R (2022) Effect of nonlinear soil – structure interaction and lateral stiffness on seismic performance of mid – rise RC building. J Build Eng 59:105096. https://doi.org/10.1016/j.jobe.2022.105096
2. Firoj M, Maheshwari BK (July, 2022) Effect of CPRF on nonlinear seismic response of an NPP structure considering raft-pile-soil-structure-interaction. Soil Dyn Earthq Eng 158. https://doi.org/10.1016/j.soildyn.2022.107295
3. Liu J et al (June, 2024) Failure mechanisms and seismic fragility analysis of overhead transmission lines incorporating pile-soil-structure interaction. Eng Fail Anal 160. https://doi.org/10.1016/j.engfailanal.2024.108201
4. Bahuguna A, Firoj M (2022) Nonlinear seismic performance of Nuclear structure with soil–structure Interaction. Iran J Sci Technol - Trans Civ Eng 46(4):2975–2988. https://doi.org/10.1007/s40996-021-00728-2
5. Kassem MM, Nazri FM, Noroozinejad Farsangi E (2019) Development of seismic vulnerability index methodology for reinforced concrete buildings based on nonlinear parametric analyses. MethodsX 6:199–211. https://doi.org/10.1016/j.mex.2019.01.006
6. El-Maissi AM, Argyroudis SA, Kassem MM, Mohamed Nazri F (2022) Development of intrinsic seismic vulnerability index (ISVI) for assessing roadway system and its assets framework. MethodsX 9:101818. https://doi.org/10.1016/j.mex.2022.101818
7. Firoj M, Maheshwari BK (2022) A new nonlinear spring-dashpot model of CPRF of NPP structure based on coupled BEM-FEM approach. Earthq Eng Struct Dyn 52(4):932–955

8. Pinto F, Astroza R, Bazáez R, Hernández F, Navarro N (February, 2024) Probabilistic seismic assessment of multispan RC highway bridges considering soil-structure interaction and chloride-induced corrosion. Eng Struct 301. https://doi.org/10.1016/j.engstruct.2023.117257
9. Firoj M, Maheshwari BK (2023) Dynamic impedances of CPRF using coupled BEM-FEM approach: A parametric study and application. EngAnal Bound Elem. 156:8–19. https://doi.org/10.1016/j.enganabound.2023.07.036
10. Tasleem M, Firoj M, Bahuguna A (2022) Effect of open-ground storey on RC frame buildings incorporating soil–structure interaction. Asian J Civ Eng 23(4):471–485. https://doi.org/10.1007/s42107-022-00435-x
11. Gao X, Duan P, Duan S (2021) Simulated seismic response analysis of subway tunnels under complex geological conditions of obliquely incident seismic SV waves. Arab J Geosci 14(11). https://doi.org/10.1007/s12517-021-07376-w
12. Jeong SY, Kang THK, Yoon JK, Klemencic R (2020) Seismic performance evaluation of a tall building: practical modeling of surrounding basement structures. J Build Eng 31:101420. https://doi.org/10.1016/j.jobe.2020.101420
13. Yuan WH, Wang HC, Zhang W, Dai BB, Liu K, Wang Y (2021) Particle finite element method implementation for large deformation analysis using Abaqus. Acta Geotech 16(8):2449–2462. https://doi.org/10.1007/s11440-020-01124-2
14. Maheshwari BK, Firoj M, March (2023) 112518. https://doi.org/10.1016/j.nucengdes.2023.112518
15. Givens MJ, Stewart JP, Haselton CB, Mazzoni S (2012) Assessment of Soil-structure interaction Modeling Strategies for Response History Analysis of Buildings. Proc 15th World Conf Earthq Eng. pp. 1–10
16. Maheshwari BK, Firoj M (June, 2024) Seismic response of combined piled raft foundation using advanced liquefaction model. Soil Dyn Earthq Eng 181. https://doi.org/10.1016/j.soildyn.2024.108694
17. Fang H, Hongjie Fang CQ, Lai Z (2024) Investigation of Seismic Amplification on Soil-Structure Interaction Problems Based on a 3D DRM-RFEM, Framework ASCE-ASME. J Risk Uncertain Eng Syst Part A Civ Eng. 10(1):131–142. Available: http://scioteca.caf.com/bitstream/handle/123456789/1091/RED2017
18. Bahuguna MF (2023) Analytical plasticity-based model for soil-structure interaction of lumped system on heterogenous soil media. Earthq Eng Resil 2(4):493–514
19. Weihang Ouyang S-WL, Li G (2024) Machine learning - based soil – structure interaction analysis of laterally loaded piles through physics - informed neural networks. Acta Geotech 19(1):4765–4790
20. Carbonari S, Morici M, Dezi F, Gara F (2017) Leoni G (2016) Soil-structure interaction effects in single bridge piers founded on inclined pile groups. Soil Dyn Earthq Eng. 92:52–67, 2017. https://doi.org/10.1016/j.soildyn.2016.10.005
21. Emani PK, Maheshwari BK (2009) Dynamic impedances of pile groups with embedded caps in homogeneous elastic soils using CIFECM. Soil Dyn Earthq Eng 29(6):963–973. https://doi.org/10.1016/j.soildyn.2008.11.003
22. Kwag S, Ju BS, Jung W (2018) Beneficial and detrimental effects of Soil-structure interaction (SSI) on probabilistic seismic hazard and risk of Nuclear Power Plant. Adv Civ Eng 2018. https://doi.org/10.1155/2018/2698319
23. Manna B, Baidya DK (2010) Dynamic nonlinear response of pile foundations under vertical vibration-theory versus experiment. Soil Dyn Earthq Eng 30:456–469. https://doi.org/10.1016/j.soildyn.2010.01.002
24. Abell JA, Orbović N, McCallen DB, Jeremic B (2018) Earthquake soil-structure interaction (SSI) of nuclear power plants, differences in response to 3-D, 3 × 1-D, and 1-D excitations. Earthq Eng Struct Dyn 47(6):1478–1495. https://doi.org/10.1002/eqe.3026
25. Zhao M, Gao Z, Wang L, Du X, Huang J, Li Y (2017) Obliquely incident earthquake for soil-structure interaction (SSI) in layered half space. Earthq Struct 13(6):573–588. https://doi.org/10.12989/eas.2017.13.6.573
26. Civelekler E, Okur VD, Afacan KB (2021) A study of the local site effects on the ground response for the city of Eskişehir, Turkey. Bull Eng Geol Environ 80(7):5589–5607. https://doi.org/10.1007/s10064-021-02285-4
27. Zhidong G, Xu Z, Mi Z, Xiuli D, Junjie W, Pengcheng L (2021) Efficient seismic analysis for nonlinear soil-structure interaction (SSI) with a thick soil layer. Earthq Eng Eng Vib 20(3):553–565. https://doi.org/10.1007/s11803-021-2038-3
28. Lou M, Wang H, Chen X, Zhai Y (2011) Structure-soil-structure interaction (SSI): literature review. Soil Dyn Earthq Eng 31(12):1724–1731. https://doi.org/10.1016/j.soildyn.2011.07.008
29. Wolf JP (1986) Dynamic soil-structure interaction (SSI). Earthq Eng Struct Dyn 14(4):177–190. https://doi.org/10.1111/j.1547-5069.1986.tb00574.x
30. Wolf JP (1989) Soil-structure-interaction analysis in time domain. Nucl Eng Des 111(3):381–393. https://doi.org/10.1016/0029-5493(89)90249-5
31. Ahmadi R, Najar IA, Faisal AA (2020) T. Gallin Response spectra for moderate seismic area – application to Miri district of Sarawak, Malaysia, in *The 13th International UNIMAS Engineering Conference 2020 (ENCON* IOP Conf. Series: Materials Science and Engineering. 2020;1–10
32. Najar IA, Ahmadi RB, Jamian MAH, Hamza HB, Ahmad A, Sin CH (2022) Site-Specific Ground Response Analysis using the Geotechnical dataset in Moderate Seismicity Region. Int J Mech 16:37–45. https://doi.org/10.46300/9104.2022.16.5
33. Kuyumcu Z, Ates S (2012) Soil-structure-foundation effects on stochastic response analysis of cable-stayed bridges. Struct Eng Mech 43(5):637–655. https://doi.org/10.12989/sem.2012.43.5.637
34. Huang J, Zhao M, Du X (2017) Non-linear seismic responses of tunnels within normal fault ground under obliquely incident P waves. Tunn Undergr Sp Technol 61:26–39. https://doi.org/10.1016/j.tust.2016.09.006
35. Huang J, Zhao M, Xu C, Du X, Jin L, Zhao X (2018) Seismic stability of jointed rock slopes under obliquely incident earthquake waves. Earthq Eng Eng Vib 17(3):527–539. https://doi.org/10.1007/s11803-018-0460-y
36. Chugh AK, Labuz JF, Olgun CG (2016) Soil structure interactions of retaining walls. Geotech Struct Eng Congr 2016 - Proc Jt Geotech Struct Eng Congr 2016 no December 2017:pp439–454. https://doi.org/10.1061/9780784479742.036
37. Dhar S, Dasgupta K (2019) Seismic soil structure Interaction for Integral Abutment bridges: a review. Transp Infrastruct Geotechnol 6(4):249–267. https://doi.org/10.1007/s40515-019-00081-y
38. Kottary AS, Ahmed DSK (2022) Soil-structure interaction (SSI) and retaining walls: a Review paper. Int J Res Appl Sci Eng Technol 10(6):599–606. https://doi.org/10.22214/ijraset.2022.43804
39. Tsai CC, Liu HW (2017) Site response analysis of vertical ground motion in consideration of soil nonlinearity. Soil Dyn Earthq Eng. 102:124–136. https://doi.org/10.1016/j.soildyn.2017.08.024
40. Amirsardari A, Lumantarna E, Goldsworthy HM, Professor A (2014) Seismic site response analysis for Australia. Aust Earthq Eng Soc
41. Tsipianitis A, Tsompanakis Y, Psarropoulos PN (2020) Impact of Dynamic Soil–Structure Interaction on the Response of Liquid-Storage Tanks. Front Built Environ 6:1–18. https://doi.org/10.3389/fbuil.2020.00140
42. Bridge M (2022) What is soil-structure interaction (SSI)? https://www.midasbridge.com/en/solutions/soil-structure-interaction
43. Mylonakis G, Nikolaou A, Gazetas G (1997) Soil-pile-bridge seismic interaction: Kinematic and inertial effects. Part I: soft soil. Earthq Eng Struct Dyn 26(3):337–359. https://doi.org/10.1002/(SICI)1096-9845(199703)26:3<337::AID-EQE646>3.0.CO;2-D
44. Barbosa AR, Mason HB, Romney KT (2014) SSI-Bridge: Soil-Bridge Interaction during Long-Duration Earthquake Motions
45. Mitchell R, Bruneau D, Williams M, Anderson M, Saatcioglu D, M., and, Sexmith (1995) Performance of bridges in the 1994 Northridge Earthquake. Can J Civ Eng 22(2):415–427
46. Achheim MA (1994) Mission Gothic Bridge, Image-NR917, *National Earthquake Engineering Information Resources (NISEE) e-Library, University of California, Berkeley*
47. Mittal V, Samanta M (2021) A critical review on design philosophies of different design standards on seismic soil–structure Interaction. Lect Notes Civ Eng 120 LNCE:1–13. https://doi.org/10.1007/978-981-33-4005-3_1
48. Mylonakis G, Gazetas G (2000) Seismic soil-structure interaction (SSI): beneficial or detrimental? J Earthq Eng 4(3):277–301. https://doi.org/10.1080/13632460009350372

49. Tsikada Y, Shimbun A (1995) Collapse of Hanshin Expressway, Image--K0013, *National Earthquake Engineering Information Resources (NISEE) e-Library, University of California, Berkeley*
50. Steinbrugge KV (1989) Cypress St. Viaduct, Image- S6130, *National Earthquake Engineering Information Resources (NISEE) e-Library, University of California, Berkeley*
51. Raheem SEA, Hayashikawa T (2013) Soil-structure interaction (SSI) modeling effects on seismic response of cable-stayed bridge tower. Int J Adv Struct Eng 5(1):1–17. https://doi.org/10.1186/2008-6695-5-8
52. a Hashash YM, Groholski DR (2010) Recent advances in non-linear site response analysis, Fifth Interantional Conf. Recent Adv. Geotech. Earthq. Eng. Soil Dyn. Symp. Honor Profr. I.M. Idriss, vol. 29, no. 6, pp. 1–22. Available: http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Remarks+on+site+response+analysis+by+using+Plaxis+dynamic+module#0
53. Scarfone R, Morigi M (2020) Conti R (2019) Assessment of dynamic soil-structure interaction (SSI) effects for tall buildings: A 3D numerical approach. Soil Dyn Earthq Eng. 128:105864, 2020. https://doi.org/10.1016/j.soildyn.2019.105864
54. Awchat G, Monde A, Sirsikar R, Dhanjode G, Tayade S (2022) Soil-structure interaction (SSI): comparative review of International codes and other Literature with Indian Seismic Code. Civ Environ Eng 18(1):87–95. https://doi.org/10.2478/cee-2022-0009
55. Tomeo R, Bilotta A, Pitilakis D, Nigro E (2017) Soil-structure interaction (SSI) effects on the seismic performances of reinforced concrete moment resisting frames. Procedia Eng 199:230–235. https://doi.org/10.1016/j.proeng.2017.09.006
56. Gouasmia A, Belkhiri A, Athmani A (2015) Dynamic soil-structure interaction (SSI) analysis of Reinforced concrete buildings. Int J Civil Environ Struct Constr Archit Eng 9(7):862–868
57. Ahmadi R, Suhaili MHAM, Najar IA, Ladi MA, Bakie NA, Abdullahi AF (2021) Evaluation on the Soil flexibility of the largest HEP dam area in East Malaysia using 1-D Equivalent Linear Analysis. Int J Adv Sci Eng Inf Technol 11(4):1535–1542. https://doi.org/10.18517/ijaseit.11.4.12281
58. Najar IA, Ahmadi RB, Hamza H, Sa'don NBM, Ahmad A (2020) First Order Seismic Microzonation of Miri district of Sarawak Malaysia using AHP-GIS Platform. Test Eng Manag. 83(2):13918–13928. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85084159527&partnerID=40&md5=07f3d42ad483f69135870a6da8d18746
59. Aydemir ME (2013) Soil structure interaction effects on structural parameters for stiffness degrading systems built on soft soil sites. Struct Eng Mech 45(5):655–676. https://doi.org/10.12989/sem.2013.45.5.655
60. Varma M, Sawant VA, Chandaluri VK (2017) Effect of soil structure Interaction on response of G + 3 building. J Struct Eng 44(4):307–318
61. Anwar N, Uthayakumar A, Najam FA (2019) Significance of soil-structure interaction (SSI) in seismic response of buildings. NED Univ J Res 1:43–54 Special Issue on First SACEE'19. https://doi.org/10.35453/nedjr-stmech-2019-0004
62. Kamal M, Inel M, Cayci BT (2021) Seismic behavior of mid-rise reinforced concrete adjacent buildings considering soil-structure interaction (SSI). J Build Eng 51:104296, 2022. https://doi.org/10.1016/j.jobe.2022.104296.
63. Yanik A, Ulus Y (2023) Soil–structure Interaction consideration for base isolated structures under Earthquake Excitation. Buildings 13(4). https://doi.org/10.3390/buildings13040915
64. Riaz MR, Motoyama H, Hori M (2021) Review of soil-structure interaction (SSI) based on continuum mechanics theory and use of high performance computing. Geosci 11(2):1–22. https://doi.org/10.3390/geosciences11020072
65. Yuan B et al (2019) Transparent Synthetic Soil and Its Application in Modeling of Soil-structure interaction (SSI) Using Optical System. Front Earth Sci 7:1–9. https://doi.org/10.3389/feart.2019.00276
66. Anand V, Satish Kumar SR (2018) Seismic soil-structure interaction (SSI): a state-of-the-art review. Structures 16:317–326. https://doi.org/10.1016/j.istruc.2018.10.009
67. Bezih K, Chateauneuf A, Kalla M, Bacconnet C (2015) Effect of soil-structure interaction (SSI) on the reliability of reinforced concrete bridges. Ain Shams Eng J 6(3):755–766. https://doi.org/10.1016/j.asej.2015.01.007
68. Requena-Garcia-Cruz MV, Bento R, Durand-Neyra P, Morales-Esteban A (2022) Analysis of the soil structure-interaction effects on the seismic vulnerability of mid-rise RC buildings in Lisbon. Struct. 38:599–617. https://doi.org/10.1016/j.istruc.2022.02.024
69. Stefanidou SP, Sextos AG, Kotsoglou AN, Lesgidis N (2017) Kappos AJ (2018) Soil-structure interaction (SSI) effects in analysis of seismic fragility of bridges using an intensity-based ground motion selection procedure. Eng Struct. 151:366–380, 2017. https://doi.org/10.1016/j.engstruct.2017.08.033
70. Veletsos AS, Meek JW (1974) Dynamic behaviour of building-foundation systems. Earthq Eng Struct Dyn 3(2):121–138. https://doi.org/10.1002/eqe.4290030203
71. MidasBridge (2020) Midasbridge.pdf, https://www.midasbridge.com/en/solutions/soil-structure-interaction,
72. Turner B, Brandenberg S, Stewart J (2017) Influence of kinematic SSI on foundation input motions for bridges on deep foundations. Pacific Earthq Eng Res Cent. 241
73. Alam AKMT, Bhuiyan MAR (2013) Effect of soil-structure interaction (SSI) on seismic response of a seismically isolated highway bridge pier. J Civ Eng 41(2):179–199
74. Thusoo S, Modi K, Kumar R, Madahar H (2015) Response of buildings with soil-structure interaction (SSI) with varying Soil types. 9(4):353–357
75. Borghei A, Ghayoomi M (2019) The role of kinematic interaction on measured seismic response of soil-foundation-structure systems. Soil Dyn Earthq Eng 125:105674. https://doi.org/10.1016/j.soildyn.2019.05.013
76. Moghaddasi M, MacRae GA, Chase JG, Cubrinovski M, and and, Pampanin S (2015) Seismic design of yielding structures on flexible foundations. Earthq Eng Struct Dyn 44(2):1805–1821. https://doi.org/10.1002/eqe
77. Zogh P, Motamed R, Ryan K (2021) Empirical evaluation of kinematic soil-structure interaction (SSI) effects in structures with large footprints and embedment depths. Soil Dyn Earthq Eng 149:106893. https://doi.org/10.1016/j.soildyn.2021.106893
78. Carbonell JM, Monforte L, Ciantia MO, Arroyo M, Gens A (2022) Geotechnical particle finite element method for modeling of soil-structure interaction (SSI) under large deformation conditions. J Rock Mech Geotech Eng 14(3):967–983. https://doi.org/10.1016/j.jrmge.2021.12.006
79. Stefanidou SP, Sextos AG, Kotsoglou AN, Lesgidis N, Kappos AJ (2017) Soil-structure interaction (SSI) effects in analysis of seismic fragility of bridges using an intensity-based ground motion selection procedure. Eng Struct 151:366–380. https://doi.org/10.1016/j.engstruct.2017.08.033
80. Betti ASN (1993) Kinematic soil-structure interaction (SSI) for long-span. Earthq Eng Struct Dyn 22(3):415–430
81. Bararnia M, Hassani N, Ganjavi B, Ghodrati Amiri G (2018) Estimation of inelastic displacement ratios for soil-structure systems with embedded foundation considering kinematic and inertial interaction effects. Eng Struct. 159:252–264. https://doi.org/10.1016/j.engstruct.2018.01.002
82. Brandenberg SJ, Mylonakis G, Stewart JP (2015) Kinematic Framework for evaluating Seismic Earth pressures on retaining walls. J Geotech Geoenvironmental Eng 141(7). https://doi.org/10.1061/(asce)gt.1943-5606.0001312
83. Torabi H, Rayhani MT (2014) Three dimensional Finite element modeling of seismic soil-structure interaction (SSI) in soft soil. Comput Geotech 60:9–19. https://doi.org/10.1016/j.compgeo.2014.03.014
84. Bapir B, Abrahamczyk L, Wichtmann T, Prada-Sarmiento LF (2023) Soil-structure interaction (SSI): A state-of-the-art review of modeling techniques and studies on seismic response of building structures. Front Built Environ. 9:1–17. https://doi.org/10.3389/fbuil.2023.1120351
85. Ciampoli M, Pinto PE (1995) Effects of Soil-structure interaction (SSI) on Inelastic Seismic Response of Bridge Piers. J Struct Eng. 12(5):806–814. https://doi.org/10.1061/(asce)0733-9445(1995)121:5(806)
86. Bhaumik L, Raychowdhury P (2013) Seismic response analysis of a nuclear reactor structure considering nonlinear soil-structure interaction (SSI). Nucl Eng Des 265:1078–1090. https://doi.org/10.1016/j.nucengdes.2013.09.037
87. Wolf JP, Song C (2002) Some cornerstones of dynamic soil-structure interaction (SSI). Eng Struct 24(1):13–28. https://doi.org/10.1016/S0141-0296(01)00082-7
88. Van Nguyen Q, Fatahi B, Hokmabadi AS (2017) Influence of size and load-bearing mechanism of piles on seismic performance of buildings

considering soil–pile–structure Interaction. Int J Geomech 17(7):1–22. https://doi.org/10.1061/(asce)gm.1943-5622.0000869
89. Pavić G, Hadzima-Nyarko M, Bulajić B, Jurković Ž (2020) Development of seismic vulnerability and exposure models-A case study of Croatia. Sustain 12(3):1–24. https://doi.org/10.3390/su12030973
90. González Acosta JL, Vardon PJ, Hicks MA (February, 2021) Study of landslides and soil-structure interaction (SSI) problems using the implicit material point method. Eng Geol 285. https://doi.org/10.1016/j.enggeo.2021.106043
91. Requena-Garcia-Cruz MV, Morales-Esteban A, Durand-Neyra P, Romero-Sánchez E, Soil-structure interaction (SSI) in the seismic vulnerability analysis of RC buildings. Application to a case study building located in southwestern Spain, (2021). https://doi.org/10.7712/120121.8846.18945
92. Chouw N, Hao H (2012) Pounding damage to buildings and bridges in the 22 February 2011 Christchurch earthquake. Int J Prot Struct 3(2):123–140. https://doi.org/10.1260/2041-4196.3.2.123
93. Tseng WS, Lilhanand K, Hamasaki D, Garcia JA, Srinivasan R (2014) Seismic soil-structure interaction (SSI) with consideration of spatial incoherence of seismic ground motions: a case study. Nucl Eng Des 269:200–206. https://doi.org/10.1016/j.nucengdes.2013.08.030
94. Shye K-Y, Robinson AR (2018) Civil Engineering studies Dynamic Soil-structure interaction (SSI), no. 484
95. Jasim FA, Jasim NA, Al-Hussein AA (2024) Assessment of Soil-structure interaction (SSI) effects on Seismic Behavior of Isolator and Mass Damper equipped buildings. Math Model Eng Probl 11(2):325–339. https://doi.org/10.18280/mmep.110205
96. Kausel E (2010) Early history of soil-structure interaction (SSI). Soil Dyn Earthq Eng 30(9):822–832. https://doi.org/10.1016/j.soildyn.2009.11.001
97. Sezawa K, Kanai K (1935) Decay in the Seismic Vibrations of a Structure by Dissipation of their Energy into the Ground, *Proceedings of the Imperial Academy*, vol. 11, no. 5. pp. 174–176. https://doi.org/10.2183/pjab1912.11.174
98. Martel RR (1940) Effect of foundation on earthquake motion. Civ Eng J 10(1):7–10
99. Bycroft GN (1956) Forced vibrations of a rigid circular plate on a semi-infinite elastic space and on an elastic stratum. Philos Trans R Soc Lond Ser Math Phys Sci 248(948):327–368. https://doi.org/10.1098/rsta.1956.0001
100. Roesset (2013) Soil structure interaction the early stages. J Appl Sci Eng 16(1):1–8
101. Ghosh B, Madabhushi SPG (2004) Dynamic soil structure interaction for layered and inhomogeneous ground: a comparitive study, 13th World Conf. Earthq Eng. 440
102. Yashinsky M (1998) The Loma Prieta, California, Earthquake of October 17, 1989, Highway systems (No. 1552)
103. Rahnema H, Mohasseb S, JavidSharifi B (2016) 2-D soil-structure interaction (SSI) in time domain by the SBFEM and two non-linear soil models. Soil Dyn Earthq Eng 88:152–175. https://doi.org/10.1016/j.soildyn.2016.01.008
104. Li M, Lu X, Lu X, Ye L (2014) Influence of soil-structure interaction (SSI) on seismic collapse resistance of super-tall buildings. J Rock Mech Geotech Eng 6(5):477–485. https://doi.org/10.1016/j.jrmge.2014.04.006
105. Causse M, Cotton F, Cornou C, Bard PY (2008) Calibrating median and uncertainty estimates for a practical use of empirical Green's functions technique. Bull Seismol Soc Am 98(1):344–353. https://doi.org/10.1785/0120070075
106. Abdelmonem MAES, Osman EA (2014) Seismic Response Analysis Considering Soil-structure interaction (SSI) of High-Rise Buildings
107. Karapetrou ST, Fotopoulou SD, Pitilakis KD (2015) Seismic vulnerability assessment of high-rise non-ductile RC buildings considering soil-structure interaction (SSI) effects. Soil Dyn Earthq Eng 73:42–57. https://doi.org/10.1016/j.soildyn.2015.02.016
108. Galvín P, Romero A (2014) A MATLAB toolbox for soil-structure interaction (SSI) analysis with finite and boundary elements. Soil Dyn Earthq Eng 57:10–14. https://doi.org/10.1016/j.soildyn.2013.10.009
109. Abd Rahim SM, Mohd Zahid MZA, Wan Omar WMS, Bin Ab MA, Rahim, Faisal A (2016) Assessment of reinforced concrete building with soil structure interaction effect under vertical earthquake. Mater Sci Forum 857:331–336. https://doi.org/10.4028/www.scientific.net/MSF.857.331
110. Akbar Firoozi A, Asghar Firoozi A (2024) Soil-structure interaction (SSI): understanding and mitigating challenges. in Challenges in Foundation Engineering - Case studies and Best practices. no. February, p 33. https://doi.org/10.5772/intechopen.112422.
111. Bigelow H, Pak D, Hoffmeister B, Feldmann M, Seidl G, Petraschek T (2017) Soil-structure interaction (SSI) at railway bridges with integral abutments. Procedia Eng 199:2318–2323. https://doi.org/10.1016/j.proeng.2017.09.204
112. Li S, Zhang F, quan Wang J, Alam MS, Zhang J (2017) Seismic responses of super-span cable-stayed bridges induced by ground motions in different sites relative to fault rupture considering soil-structure interaction (SSI). Soil Dyn Earthq Eng 101:295–310. https://doi.org/10.1016/j.soildyn.2017.07.016
113. Harte M, Basu B, Nielsen SRK (2012) Dynamic analysis of wind turbines including soil-structure interaction (SSI). Eng Struct 45:509–518. https://doi.org/10.1016/j.engstruct.2012.06.041
114. Fitzgerald B, Basu B (2016) Structural control of wind turbines with soil structure interaction included. Eng Struct 111:131–151. https://doi.org/10.1016/j.engstruct.2015.12.019
115. Zuo H, Bi K, Hao H (2017) Dynamic analyses of operating offshore wind turbines including soil-structure interaction (SSI), *Eng. Struct.*, vol. 157, no. November pp. 42–62, 2018. https://doi.org/10.1016/j.engstruct.2017.12.001
116. Michel P, Butenweg C, Klinkel S (2018) Pile-grid foundations of onshore wind turbines considering soil-structure-interaction under seismic loading, *Soil Dyn. Earthq. Eng.*, vol. 109, no. March, pp. 299–311. https://doi.org/10.1016/j.soildyn.2018.03.009
117. Chatziioannou K, Katsardi V, Koukouselis A, Mistakidis E (2017) The effect of nonlinear wave-structure and soil-structure interaction (SSI)s in the design of an offshore structure. Mar Struct 52:126–152. https://doi.org/10.1016/j.marstruc.2016.11.003
118. Kavitha P, Venkatesh MM, Sundaravadivelu R (2015) Soil Structure Interaction Analysis of a Dry Dock. Aquat Procedia 4(Icwrcoe):287–294. https://doi.org/10.1016/j.aqpro.2015.02.039
119. Hatzigeorgiou George GD D. and, Beskos DE (2010) Soil-structure interaction (SSI) effects on seismic inelastic analysis of 3-D tunnels. Soil Dyn Earthq Eng 30(9):851–861. https://doi.org/10.1016/j.soildyn.2010.03.010
120. Coleman JL, Bolisetti C, Whittaker AS (2016) Time-domain soil-structure interaction (SSI) analysis of nuclear facilities. Nucl Eng Des 298:264–270. https://doi.org/10.1016/j.nucengdes.2015.08.015
121. Farahani RV, Dessalegn TM, Vaidya NR, Bazan-Zurita E (2016) Seismic soil-structure interaction (SSI) analysis of a nuclear power plant building founded on soil and in degraded concrete stiffness condition. Nucl Eng Des 297:320–326. https://doi.org/10.1016/j.nucengdes.2015.12.002
122. Bolisetti C, Whittaker AS, Coleman JL (2017) Linear and nonlinear soil-structure interaction (SSI) analysis of buildings and safety-related nuclear structures, *Soil Dyn. Earthq. Eng.*, vol. 107, no. October pp. 218–233, 2018. https://doi.org/10.1016/j.soildyn.2018.01.026
123. Venanzi I, Salciarini D, Tamagnini C (2014) The effect of soil-foundation-structure interaction on the wind-induced response of tall buildings. Eng Struct 79:117–130. https://doi.org/10.1016/j.engstruct.2014.08.002
124. Ayough P, Taghia SAHS (2017) Response of steel moment and braced frames subjected to near-source pulse-like ground motions by including soil-structure interaction (SSI) effects. Soil Dyn Earthq Eng 101:53–66. https://doi.org/10.1016/j.soildyn.2017.07.013
125. Mekki M, Elachachi SM, Breysse D, Zoutat M (2016) Seismic behavior of R.C. structures including soil-structure interaction (SSI) and soil variability effects. Eng Struct 126:15–26. https://doi.org/10.1016/j.engstruct.2016.07.034
126. Papadopoulos M, Van Beeumen R, François S, Degrande G, Lombaert G (2017) Computing the modal characteristics of structures considering soil-structure interaction (SSI) effects. Procedia Eng 199:2414–2419. https://doi.org/10.1016/j.proeng.2017.09.296
127. Cruz C, Miranda E (2017) Evaluation of soil-structure interaction (SSI) effects on the damping ratios of buildings subjected to earthquakes. Soil Dyn Earthq Eng 100:183–195. https://doi.org/10.1016/j.soildyn.2017.05.034
128. Aldaikh H, Alexander NA, Ibraim E, Oddbjornsson O (2015) Two dimensional numerical and experimental models for the study of structure-soil-structure interaction (SSI) involving three buildings. Comput Struct 150:79–91. https://doi.org/10.1016/j.compstruc.2015.01.003
129. Niu Y et al (2023) Dynamic displacement estimation and modal analysis of long-span bridges integrating multi-GNSS and acceleration

measurements. J Infrastruct Preserv Resil 4(1). https://doi.org/10.1186/s43065-023-00077-6
130. Zhang Z, Wei H, Qin X (2017) Experimental study on damping characteristics of soil-structure interaction (SSI) system based on shaking table test. Soil Dyn Earthq Eng. 98: 183–190. https://doi.org/10.1016/j.soildyn.2017.04.002
131. Nazarimofrad E, Zahrai SM (2018) Fuzzy control of asymmetric plan buildings with active tuned mass damper considering soil-structure interaction (SSI). Soil Dyn Earthq Eng. 115:838–852. https://doi.org/10.1016/j.soildyn.2017.09.020
132. Luco JE (2014) Effects of soil-structure interaction (SSI) on seismic base isolation. Soil Dyn Earthq Eng 66:167–177. https://doi.org/10.1016/j.soildyn.2014.05.007
133. Fatahi B, Van Nguyen Q, Xu R, Sun W (2018) Three-Dimensional response of neighboring buildings sitting on Pile foundations to Seismic pounding. Int J Geomech 18(4). https://doi.org/10.1061/(asce)gm.1943-5622.0001093
134. Rosenblueth E, Meli R (1986) The 1985 earthquake: causes and effects in Mexico City. Concr Int 8(1):23–24
135. Boulanger RW, Curras CJ, Kutter BL, Wilson DW, Abghari A (1999) Seismic soil-pile-structure Interaction experiments and analyses. J Geotech Geoenvironmental Eng 125(9):750–759. https://doi.org/10.1061/(asce)1090-0241(1999)125:9(750)
136. Matinmanesh H, Asheghabadi MS (2011) Seismic analysis on soil-structure interaction (SSI) of buildings over sandy soil. Procedia Eng 14:1737–1743. https://doi.org/10.1016/j.proeng.2011.07.218
137. Sáez E, Lopez-Caballero F, Modaressi-Farahmand-Razavi A (2013) Inelastic dynamic soil-structure interaction (SSI) effects on moment-resisting frame buildings. Eng Struct 51:166–177. https://doi.org/10.1016/j.engstruct.2013.01.020
138. Sbartai B, Goudjil K (2012) Response of soil-structure interaction (SSI) system using Artificial Neural Network (ANN), World Sci. Proc. Ser. Comput. Eng. Inf. Sci. 7; Uncertain. Model. Knowl. Eng. Decis. Mak. - Proc. 10th Int. FLINS Conf. 7: 1017–1022. https://doi.org/10.1142/9789814417747_0163
139. Boudghene Stambouli A, Zendagui D, Bard PY, Derras B (2017) Deriving amplification factors from simple site parameters using generalized regression neural networks: implications for relevant site proxies. Earth Planet Sp 69(1). https://doi.org/10.1186/s40623-017-0686-3
140. Krishnan R, Sivakumar VL (2024) The effect of soil-structure interaction (SSI) on Structural Stability and sustainability of RC structures. Civ Environ Eng Rep 34(1):47–67. https://doi.org/10.59440/ceer/184254
141. Won J, Shin J (2021) Machine learning-based approach for seismic damage prediction method of building structures considering soil-structure interaction (SSI). Sustain 13(8). https://doi.org/10.3390/su13084334
142. Badry P, Satyam N (2017) Seismic soil structure interaction analysis for asymmetrical buildings supported on piled raft for the 2015 Nepal earthquake. J Asian Earth Sci 133:102–113. https://doi.org/10.1016/j.jseaes.2016.03.014
143. Van Nguyen Q, Fatahi B, Hokmabadi AS (2016) The effects of foundation size on the seismic performance of buildings considering the soil-foundation-structure interaction. Struct Eng Mech 58(6):1045–1075. https://doi.org/10.12989/sem.2016.58.6.1045
144. Lv H, Chen SL (2022) Analysis of nonlinear soil-structure interaction (SSI) using partitioned method. Soil Dyn Earthq Eng 162:107470. https://doi.org/10.1016/j.soildyn.2022.107470
145. Swami JM, Panchal PBJ (2018) Review Paper on effects of Soil-structure interaction (SSI) on Bridge structures. Int J Sci Res Dev 6(02):2449–2451
146. Amorosi A, Boldini D, di Lernia A (2017) Dynamic soil-structure interaction (SSI): a three-dimensional numerical approach and its application to the Lotung case study. Comput Geotech 90:34–54. https://doi.org/10.1016/j.compgeo.2017.05.016
147. Oz I, Senel SM, Palanci M, Kalkan A (2020) Effect of soil-structure interaction (SSI) on the seismic response of existing low and mid-rise RC buildings. Appl Sci 10(23):1–21. https://doi.org/10.3390/app10238357
148. Imran H, Al-Jeznawi D, Al-Janabi MAQ, Bernardo LFA (2023) Assessment of soil–structure Interaction approaches in mechanically stabilized Earth retaining walls: a review. CivilEng 4(3):982–999. https://doi.org/10.3390/civileng4030053
149. Bapir B, Abrahamczyk L (2024) Assesment of Simplified Soil-structure interaction (SSI) Models for Seismic Analysis of RC Buildings, in 18th World Conference on Earthquake Engineering. p. 13
150. Ramaiah P, Kumar S (2018) Dynamic analysis of soil structure interaction (SSI) using ANFIS model with oba machine learning approach. Int J Civ Eng Technol 9(11):496–512
151. Edgers L, Sanayei M, Alonge JL (2005) Modeling the effects of soil-structure interaction (SSI) on a tall building bearing on a mat foundation. Civ Eng Pract 20(2):51–68
152. Kaynia AM, Kausel E (1991) Dynamics of piles and pile groups in layered soil media. Soil Dyn Earthq Eng. 10(8):386–401. https://doi.org/10.1016/0267-7261(91)90053-3
153. Veletsos YT, A.S. and, Wei (1971) Lateral and rocking vibration of footings. J ASCE Soil Mech Found Div 97(SM9):1227–1249
154. Luco RA, J. E., and, Westman (1971) Dynamic response of circular footings. J Eng Mech Div 97(EM5):1381–1395
155. Veletsos B, A. S., and, Verbic (1973) Vibration of viscoelastic foundations. Earthq Eng Struct Dyn 2(1):87–104. https://doi.org/10.1061/ajgeb6.0000020
156. Bielak J, (1974) Dynamic behaviour of structures with embedded foundations. Earthq Eng Struct Dyn 3(3):259-274. https://doi.org/10.1002/eqe.4290030305
157. Jennings, PC, Bielak J (1973) Dynamics of building-soil interaction. Bull seismol soc Am 63(1):9-48. https://doi.org/10.1785/BSSA0630010009
158. Elsabee JM, Kausel F, E., and, Roesset (1977) Dynamic Stiffness of Embedded Foundations, in Seconf Annual Engineering Division Specialty Conference ASCE North Carolina State University Rayleigh, Noth Carolina, pp. 40–43
159. George Gazetas, Foundation Vibrations, in *Foundation Engineering Handbook*, vol. 22, no. 2, (1991) pp. 553–565. https://doi.org/10.1680/iicep.1962.11089
160. Li P Lu X Chen B & Chen, Y (2004, August). Computer simulation on dynamic soil-structure interaction system. In 13th World conference on earthquake engineering (No. 3233). Vancouver, Canada.
161. Liao HJ, Liu J, Zhao YG, Xiao ZH (2014) Analysis of Soil-structure interaction (SSI) with Finite Element Method. Key Eng Mater., vol. 340–341, no. July pp. 1279–1284, 2007. https://doi.org/10.4028/www.scientific.net/kem.340-341.1279
162. Mirhashemian P, Khaji N, Shakib H, Soil-structure interaction (SSI) analysis using a hybrid spectral element/finite element (SE/FE) approach, *JSEE-Journal Seismol.* …, vol. 11, no. 2, 2009
163. Pitilakis KD, Karapetrou ST, Fotopoulou SD (2014) Consideration of aging and SSI effects on seismic vulnerability assessment of RC buildings. Bull Earthq Eng 12(4):1755–1776. https://doi.org/10.1007/s10518-013-9575-8
164. Todorovska MI (2002) Full-scale experimental studies of soil-structure interaction. ISET J Earthq Tech 39(3):139-165.
165. Bezih K, Chateauneuf A, Demagh R (2020) Effect of long-term soil deformations on RC structures including soil-structure interaction (SSI). Civ Eng J 6(12):2290–2311. https://doi.org/10.28991/cej-2020-03091618
166. Vasilev G, Parvanova S, Dineva P, Wuttke F (2015) Soil-structure interaction (SSI) using BEM-FEM coupling through ANSYS software package. Soil Dyn Earthq Eng 70:104–117. https://doi.org/10.1016/j.soildyn.2014.12.007
167. Kramer SL (1996) Geotechnical Earthquake Engineering. Prentice Hall, Upper Saddle River, New Jersey, USA
168. Lysmer, J., Ostadan, F., & Chin, C. (1999). SASSI2000-A system for analysis of soil-structure interaction. University of California, Berkeley, California.
169. Tadesse ZL, Padavala HK, Koteswara VRP (2022) Seismic response assessment of building structures with underground stories: a state-of-the-art review. Innov Infrastruct Solut 7(6):336–351. https://doi.org/10.1007/s41062-022-00942-5
170. Mazzoni, S., McKenna, F., Scott, M. H., & Fenves, G. L. (2009). Computer Program OpenSees: Open System for Earthquake Engineering Simulation, Pacific Earthquake Engineering Research Center (PEER). University of California, Berkeley, California.
171. Sharma N, Dasgupta K, Dey A (2020) Optimum lateral extent of soil domain for dynamic SSI analysis of RC framed buildings on pile foundations. Front Struct Civ Eng 14(1):62–81. https://doi.org/10.1007/s11709-019-0570-2

172. Ferro AN (2013) Nonlinear dynamic soil-structure interaction (SSI) in Earthquake Engineering, p. 138
173. Lysmer RL, J., and, Kuhlemeyer (1969) Finite dynamic model for infinite media. J Eng Mech Div 95(EN4):859–877
174. Pang L, Jiang C, Zhang C (2023) An analytical method for predicting the soil-structure interaction (SSI) of axially loaded piles in sands incorporating the two-surface plasticity model. Eng Struct 295(11):116841. https://doi.org/10.1016/j.engstruct.2023.116841
175. Yesane PM, Ghugal YM, Wankhade RL (2016) Study on Soil-structure interaction (SSI): A Review Study on Soil-structure interaction (SSI) : A Review, no. February. https://doi.org/10.17950/ijer/v5i3/047
176. Davenne L, Ragueneau F, Mazars J, Ibrahimbegovic A (2003) Efficient approaches to finite element analysis in earthquake engineering. Comput Struct 81(12):1223–1239. https://doi.org/10.1016/S0045-7949(03)00038-5
177. Lu, Y. (2016). Seismic soil-structure interaction in performance-based design (Doctoral dissertation, University of Nottingham).
178. Markou G, Sabouni R, Suleiman F, El-Chouli R (2015) Full-scale modeling of the soil-structure interaction (SSI) Problem through the use of Hybrid models (HYMOD). Int J Curr Eng Technol 5(2):885–892
179. Gupta JP, (1982) Three-dimensional hybrid modelling of soil- structure interaction. Earthq Eng Struct Dyn 10(10):69–87
180. Jong SC, Ong DEL, Oh E (March, 2021) State-of-the-art review of geotechnical-driven artificial intelligence techniques in underground soil-structure interaction (SSI). Tunn Undergr Sp Technol 113. https://doi.org/10.1016/j.tust.2021.103946
181. Moreno-Mateos MA, Steinmann P (2024) Configurational force method enables fracture assessment in soft materials. J Mech Phys Solids 186:105602. https://doi.org/10.1016/j.jmps.2024.105602
182. Boudaa S, Khalfallah S, Hamioud S (2019) Dynamic analysis of soil structure interaction by the spectral element method. Innov Infrastruct Solut 4(1):1–8. https://doi.org/10.1007/s41062-019-0227-y
183. Chen S, Lv H, Zhou G (2022) Partitioned analysis of soil-structure interaction (SSI) for Nuclear Island buildings. Earthq Eng Struct Dyn 51(10):2220–2247. https://doi.org/10.1002/eqe.3661
184. Du Mi X, Zhao Q, Ding (2024) Shengtao. Cao, Zhishan. Li, large-scale seismic soil–structure interaction analysis via efficient finite element modeling and multi-GPU parallel explicit algorithm. Comput Civ Infrastruct Eng 10(2):1886–1908
185. Sen Yang Y, Wang W, Lin JZ (2017) Direct-iterative hybrid solution in nonlinear dynamic structural analysis. Comput Civ Infrastruct Eng 32(5):397–411. https://doi.org/10.1111/mice.12259
186. David T, Stevens J, Krauthammer (1991) Analysis of blast-loaded, buried RC arch response. I: numerical approach. J Struct Eng 117(1):197–212
187. EN 1998-5 (2004) Eurocode 8–design of structures for earthquake resistance, part 5: foundations, retaining structures and geotechnical aspects. EN 1998-5, European Committee for Standardization, Brussels.
188. EN 1998-1 (2004) Eurocode 8: Design of structures for earthquake resistance- Part 1: General rules, seismic actions and rules for buildings. EN 1998-1, European Committee for Standardization, Brussels.
189. JSCE 15 (2007) Standard specifications for concrete structures- design. JSCE 15, Japan Society of Civil Engineers, Tokyo.https://doi.org/10.3151/coj1975.46.7_3
190. ATC (1978) Tentative provisions for the development of seismic regulations for buildings. ATC 3–06, Applied Technology Council, California.
191. ASCE. (2010) Minimum design loads for buildings and other structures. Standard ASCE/SEI 7-10, American Society of Civil Engineers, Virginia.
192. FEMA (2015) NEHRP recommended seismic provisions for new buildings and other structures. FEMA P-1050, Federal Emergency Management Agency, Washington, DC, USA.
193. ASCE (2016) Minimum design loads for buildings and other structures. ASCE/SEI 7-16, American Society of Civil Engineers, Virginia.
194. Khosravikia F, Mahsuli M, Ghannad MA (2017) Probabilistic evaluation of 2015 NEHRP soil-structure interaction (SSI) provisions. J Eng Mech 143(9):1–11. https://doi.org/10.1061/(asce)em.1943-7889.0001274
195. IS 1893-1 (2016) Criteria for earthquake resistant design of structures-Part 1: general provisions and buildings. IS 1893- 1, Bureau of Indian Standards, New Delhi
196. IS 1893-2 (2014) Criteria for earthquake resistant design of structures-Part 2: liquid retaining tanks. IS 1893-2, Bureau of Indian Standards, New Delhi.
197. IS 1893-3 (2014) Criteria for earthquake resistant for design of structures part 3: bridges and retaining walls. Bureau of Indian Standards, New Delhi.
198. IS 1893-4 (2015) Criteria for earthquake resistant design of structures-Part 4: industrial structures including stack-like structures. IS 1893-4, Bureau of Indian Standards, New Delhi.
199. NZS 1170.5 (2004) Structural design actions- Part 5: earthquake actions-New Zealand. NZS 1170.5, Standards New Zealand, Wellington.
200. AS (2007) Structural design actions–Part 4 earthquake actions in Australia. AS/NZS 1170.4: 2007.
201. MNA-EC8 (2015) NA-2017 to MS EN1998-1, Eurocode 8: Design of structures for earthquake resistance – Part 1: general rules, seismic actions and rules for buildings. Department of Standards. Malaysia
202. NIST (2012) Soil-structure interaction for building structures. NIST GCR 12-917-21, NEHRP Consultants Maryland.
203. Jarernprasert S, Bazan-Zurita E, Bielak J (2013) Seismic soil-structure interaction (SSI) response of inelastic structures. Soil Dyn Earthq Eng 47:132–143. https://doi.org/10.1016/j.soildyn.2012.08.008

Publisher's Note