Review of Soil–Structure Interaction Effects on Seismic Behavior of Multi-Storey RCC Buildings Using Numerical Modelling Techniques using SAP2000

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ABSTRACT: Soil–Structure Interaction (SSI) plays a significant role in determining the seismic performance of multi-storey reinforced concrete (RCC) buildings. Conventional structural analysis often assumes a fixed-base condition, neglecting the flexibility of the supporting soil. However, in reality the interaction between soil, foundation, and structure can significantly modify the dynamic characteristics and seismic response of buildings. This review paper presents a comprehensive overview of previous research related to soil–structure interaction effects on multi-storey RCC buildings subjected to seismic loading. The study synthesizes findings from analytical, numerical, and empirical investigations reported in the literature.

The reviewed studies indicate that SSI can influence key structural response parameters such as natural period, base shear, lateral displacement, and inter-storey drift. Soil flexibility generally leads to an increase in structural displacement and natural period while reducing base shear in some cases. Several researchers have used analytical models, finite element methods, and boundary element approaches to investigate SSI effects under different soil conditions and foundation systems. In addition, recent studies have highlighted the importance of considering nonlinear soil behavior, advanced foundation systems, and structure–soil–structure interaction in densely built environments. The literature also demonstrates that the magnitude of SSI effects depends on various factors including soil stiffness, foundation type, structural configuration, and earthquake intensity. With the advancement of computational tools and structural analysis software such as SAP2000, it has become possible to model soil flexibility more accurately and incorporate SSI effects into structural analysis. These developments have improved the understanding of seismic behavior of buildings considering realistic soil conditions

IndexTerms **- Soil–Structure Interaction (SSI); Seismic Analysis; Multi-Storey RCC Buildings; Earthquake Loading; Foundation Flexibility; SAP2000 Modelling; Structural Response; Soil–Foundation–Structure System.**

I. INTRODUCTION

Earthquakes represent one of the most destructive natural hazards affecting civil engineering structures across the world. The response of buildings subjected to seismic loading is strongly influenced not only by structural characteristics but also by the supporting soil conditions. Traditionally, structural analysis and design procedures have assumed that the foundation is fixed and that the soil beneath the structure behaves as a rigid medium. However, this assumption is not always realistic, particularly for structures constructed on soft or medium soil deposits. The interaction between the structure, its foundation, and the surrounding soil significantly alters the seismic response of buildings. This phenomenon, commonly referred to as Soil–Structure Interaction (SSI), plays an important role in determining the dynamic characteristics and overall stability of structures subjected to earthquake loading.

Soil–Structure Interaction refers to the mutual response of the soil and structure during seismic excitation, where both systems influence each other dynamically. The presence of flexible soil layers modifies the motion transmitted to the structure and changes parameters such as natural frequency, damping, base shear, and displacement response. Consequently, ignoring SSI effects in seismic analysis may lead to inaccurate predictions of structural behavior and may compromise the safety and performance of structures during earthquakes. Several studies have demonstrated that soil flexibility can either amplify or reduce seismic responses depending on the soil stiffness, foundation type, and structural configuration [1], [2].

Early research on soil–structure interaction focused on the development of theoretical models to understand the fundamental behavior of foundations subjected to dynamic loading. Classical works in geotechnical earthquake engineering established the basis for analyzing soil behavior under seismic conditions and provided insights into the mechanisms governing SSI phenomena. For example, Gazetas [5] presented widely used analytical expressions for dynamic stiffness and damping of foundations embedded in soil, which have been extensively applied in SSI studies. Similarly, foundational concepts related to geotechnical earthquake engineering and dynamic soil response were comprehensively presented in classical textbooks, which remain important references for researchers and engineers studying soil–structure interaction problems [14], [15].

The importance of soil flexibility in structural response was also highlighted in early investigations of building–foundation systems. Veletsos and Meek demonstrated that the dynamic behavior of building structures is significantly influenced by the compliance of foundation systems and underlying soil layers [22]. Subsequent studies further emphasized that the interaction between soil and structure could lead to notable changes in structural natural frequencies and vibration characteristics. Luco provided an extensive review of linear soil–structure interaction problems and discussed the analytical approaches used to model SSI effects in earthquake engineering [23]. These pioneering studies laid the foundation for the development of more advanced numerical methods for analyzing SSI in structural systems.

Over the years, analytical and numerical modeling techniques have been developed to simulate soil–structure interaction more accurately. The finite element method, boundary element method, and hybrid computational approaches are commonly used to represent the soil–foundation–structure system. Karabalis and Mohammadi applied three-dimensional boundary element techniques to analyze dynamic foundation–structure interaction problems and demonstrated their effectiveness in capturing the complex behavior of soil–structure systems [26]. Similarly, Kontoe and co-researchers investigated the domain reduction method as an advanced boundary condition for seismic SSI analysis and concluded that it significantly improves the accuracy of numerical simulations [7].

Modern research has focused on incorporating soil flexibility into structural analysis models to better predict seismic performance. Abdel Raheem and co-authors investigated the effects of soil–foundation–structure interaction on the seismic response of multi-story moment-resisting frame buildings and concluded that SSI significantly alters structural response parameters such as base shear, lateral displacement, and inter-story drift [1]. Kabtamu et al. analyzed the dynamic behavior of reinforced concrete frame structures considering SSI effects and observed that soil flexibility leads to increased structural displacements and changes in vibration characteristics [6]. Similarly, Awchat and Monde studied the influence of SSI on structures supported by mat foundations and reported that soil flexibility modifies the overall seismic response of the building system [2].

Another important aspect of soil–structure interaction is the influence of foundation systems on structural behavior during seismic events. Different foundation types such as shallow foundations, pile foundations, and mat foundations exhibit varying degrees of interaction with surrounding soil layers. Bagheri and colleagues investigated seismic soil–pile–structure interaction effects on mid-rise and high-rise buildings and demonstrated that pile foundations significantly influence seismic responses depending on soil stiffness and pile configuration [3]. Furthermore, Harden and Hutchinson developed nonlinear Winkler foundation models to simulate the behavior of shallow foundations subjected to seismic loading, providing a simplified yet effective approach for representing soil flexibility in structural analysis [28].

In addition to conventional foundation systems, recent research has also explored the role of soil–structure interaction in base-isolated structures and vibration control systems. Spyrakos and co-researchers studied the influence of SSI on base-isolated buildings and found that soil flexibility may alter the effectiveness of isolation systems under seismic excitation [8]. Similarly, Forcellini conducted numerical investigations on base-isolated buildings considering SSI effects and concluded that soil conditions must be carefully considered in the design of isolation systems [4]. Fatollahpour and colleagues further examined the combined effects of soil–structure interaction and tuned mass dampers in high-rise buildings and highlighted the importance of considering SSI in vibration control strategies [11].

Recent advances in computational techniques and structural analysis software have made it possible to model complex soil–structure interaction phenomena with greater accuracy. Modern structural analysis programs such as SAP2000, ETABS, and ABAQUS allow engineers to simulate SSI effects using spring models, continuum soil representations, or coupled soil–structure models. Tabatabaiefar and collaborators proposed empirical relationships to estimate seismic responses of mid-rise building frames considering SSI effects and demonstrated that numerical modeling approaches can effectively capture the interaction between soil and structure [9]. Later studies by Tabatabaiefar and Massumi introduced simplified methods for estimating seismic responses of reinforced concrete moment-resisting frames while accounting for soil flexibility [32].

Several researchers have also investigated the impact of soil–structure interaction on nonlinear structural behavior and seismic performance. Lu and co-authors studied nonlinear SSI effects on mid-rise moment-resisting frame buildings and found that soil flexibility significantly influences structural ductility and energy dissipation during earthquakes [35]. Similarly, Ghandil et al. conducted numerical investigations to evaluate the influence of foundation flexibility on seismic responses of buildings and reported that SSI effects become more pronounced for structures founded on soft soil deposits [25]. Lin and colleagues further analyzed high-rise buildings considering SSI effects and observed that soil flexibility leads to noticeable changes in structural response parameters such as displacement and acceleration [34].

Another area of interest in SSI research is the interaction between adjacent structures during earthquakes. Chouw and co-authors studied the pounding response of neighboring buildings considering soil–structure interaction and concluded that SSI may significantly influence impact forces between adjacent structures during seismic events [31]. Furthermore, Anastasopoulos and colleagues demonstrated that controlled soil failure mechanisms could potentially be used as a means of seismic protection for structures, highlighting the complex role of soil behavior in structural response during earthquakes [29].

In addition to numerical modeling studies, several investigations have explored empirical observations and experimental approaches to understand SSI behavior. Stewart and co-researchers conducted analytical and empirical investigations on soil–structure interaction effects in buildings and provided valuable insights into the seismic response of structures considering soil flexibility [18], [19]. These studies demonstrated that SSI effects vary significantly depending on soil conditions, structural characteristics, and earthquake intensity.

The historical development of soil–structure interaction research has also been extensively documented in the literature. Kausel presented a comprehensive overview of the early history of SSI research and discussed the evolution of analytical and numerical methods used to study soil–structure interaction problems [27]. These historical perspectives highlight the progress made in understanding SSI phenomena and emphasize the importance of incorporating soil effects in modern structural design practices.

Recent studies have also emphasized the role of SSI in improving seismic resilience and structural safety. Salah and Guerdouh investigated the seismic performance of frame structures considering soil–structure interaction effects and reported that SSI significantly influences structural performance under earthquake loading [13]. Similarly, Mishra and co-authors examined the seismic response of multi-storey buildings incorporating SSI and shear wall systems and concluded that soil flexibility plays a crucial role in determining the effectiveness of

lateral load resisting systems [12]. Yanik and Ulus further analyzed base-isolated structures considering SSI effects and demonstrated that soil conditions significantly affect the efficiency of seismic isolation systems [10].

In addition to single structure interaction, recent research has explored structure–soil–structure interaction phenomena, particularly in dense urban environments where multiple buildings are closely spaced. Fatollahpour and co-authors examined structure–soil–structure interaction effects on high-rise buildings equipped with tuned mass dampers and highlighted the importance of considering interactions between neighboring structures and soil systems [11]. These studies indicate that SSI is a complex and multi-faceted problem that requires comprehensive analytical approaches for accurate evaluation.

Despite significant progress in understanding soil–structure interaction, many practical structural designs still neglect SSI effects due to computational complexity and lack of simplified modeling approaches. However, advances in computational tools and structural analysis software have made it increasingly feasible to incorporate SSI effects in routine structural analysis. Numerical simulation tools such as SAP2000 allow engineers to model soil flexibility using spring elements or continuum soil models, enabling more realistic representation of soil–foundation–structure systems.

Considering the increasing construction of multi-storey reinforced concrete buildings in seismic regions, it is essential to evaluate the influence of soil–structure interaction on their seismic performance. Multi-storey RCC buildings often experience significant lateral forces during earthquakes, and soil flexibility may amplify or reduce structural responses depending on soil stiffness and foundation conditions. Therefore, a comprehensive understanding of SSI effects is necessary to ensure the safe and economical design of such structures.

2. LITERATURE REVIEW

Soil–Structure Interaction (SSI) has been widely studied in earthquake engineering because the dynamic response of structures is significantly influenced by the characteristics of supporting soil and foundation systems. Numerous analytical, numerical, and experimental studies have been conducted to investigate how soil flexibility modifies the seismic behavior of structures. The literature on SSI can generally be categorized into theoretical developments, analytical and numerical modelling approaches, and recent applications involving multi-storey reinforced concrete (RCC) buildings.

2.1 Fundamental Concepts of Soil–Structure Interaction

The fundamental understanding of soil–structure interaction originated from studies investigating the dynamic behavior of foundations and supporting soil under earthquake excitation. Early theoretical studies emphasized that the response of a structural system is influenced by the flexibility of soil layers and foundation systems. Veletsos and Meek examined the dynamic characteristics of building–foundation systems and demonstrated that soil flexibility significantly alters the natural frequency and damping properties of structures [22]. Their work established that soil compliance could increase structural periods and reduce base shear demands during seismic events.

Similarly, Luco provided an extensive review of linear soil–structure interaction problems and highlighted the importance of considering soil flexibility in seismic analysis [23]. The study emphasized that the interaction between soil and structure changes the dynamic properties of the structural system and influences its response to ground motion. These findings laid the foundation for modern SSI research.

Gazetas further contributed to the understanding of dynamic soil behavior by developing analytical expressions for the dynamic stiffness and damping coefficients of foundations embedded in soil [5]. These formulations have been widely adopted in engineering practice and numerical modeling for estimating soil stiffness parameters. In addition, classical textbooks on geotechnical earthquake engineering and soil–structure interaction have provided comprehensive theoretical frameworks for analyzing SSI phenomena and remain key references in this field [14], [15].

2.2 Development of Analytical and Numerical Methods

With advances in computational techniques, researchers began developing numerical models to simulate soil–structure interaction more accurately. Analytical approaches such as the Winkler foundation model were initially used to represent soil behavior using discrete spring elements. Harden and Hutchinson investigated nonlinear Winkler foundation models for shallow foundations subjected to seismic loading and demonstrated that such models provide an effective method for representing soil flexibility in structural analysis [28].

More advanced numerical methods were later introduced to capture the complex interaction between soil and structure. The boundary element method (BEM) and finite element method (FEM) became widely used tools for modeling SSI systems. Karabalis and Mohammadi utilized three-dimensional boundary element techniques to analyze dynamic foundation–structure interaction problems and showed that these methods are capable of accurately simulating soil–foundation responses under dynamic loading [26].

Similarly, Kontoe et al. investigated the domain reduction method for seismic soil–structure interaction analysis and concluded that it provides a reliable approach for modeling wave propagation and soil–structure interaction in numerical simulations [7]. The study demonstrated that advanced numerical modeling techniques can effectively capture complex SSI effects in structural systems.

The historical evolution of SSI research was further documented by Kausel, who reviewed early developments in soil–structure interaction and described the progress made in analytical and computational methods used to analyze these problems [27]. This work highlighted how improvements in computational resources have enabled more realistic modeling of soil–foundation–structure systems.

2.3 Influence of Soil–Structure Interaction on Seismic Response

Several studies have investigated the influence of soil–structure interaction on the seismic response of buildings. Stewart et al. conducted analytical and empirical investigations on SSI effects in buildings and reported that soil flexibility significantly influences structural response during earthquakes [18], [19]. Their research demonstrated that SSI can modify structural vibration characteristics and may either amplify or reduce seismic forces depending on soil properties.

Mylonakis and Gazetas examined the effects of soil–structure interaction on seismic performance and discussed whether SSI effects are beneficial or detrimental to structural response [17]. Their findings indicated that soil flexibility often increases structural displacement and reduces base shear, but in some cases it may also amplify seismic demands depending on the soil conditions.

Abdel Raheem et al. analyzed the seismic response of multi-story moment-resisting frame buildings considering soil–foundation–structure interaction effects [1]. Their results showed that SSI significantly affects structural parameters such as lateral displacement, base shear, and natural period. Similarly, Kabtamu et al. investigated the dynamic behavior of reinforced concrete frame structures considering SSI effects and found that soil flexibility increases structural displacement and alters vibration characteristics [6].

Awchat and Monde examined the influence of soil–structure interaction on structures supported by mat foundations and reported that soil flexibility modifies structural response under seismic loading conditions [2]. These studies confirm that neglecting SSI effects may lead to inaccurate predictions of structural behavior.

2.4 Soil–Foundation Systems and Structural Performance

The interaction between soil and foundation systems also plays a critical role in determining structural performance during earthquakes. Different foundation types exhibit varying degrees of interaction with soil layers. Bagheri et al. studied seismic soil–pile–structure interaction effects on mid-rise and high-rise buildings and

demonstrated that pile foundations significantly influence structural response depending on soil stiffness and pile configuration [3].

In addition to conventional foundation systems, research has also focused on base-isolated structures and advanced vibration control systems. Spyrakos et al. investigated soil–structure interaction effects on base-isolated buildings and observed that soil flexibility can alter the effectiveness of seismic isolation systems [8]. Forcellini further studied base-isolated buildings using numerical simulations and concluded that soil conditions must be carefully considered in the design of isolation systems [4].

Yanik and Ulus examined the influence of soil–structure interaction on base-isolated structures subjected to earthquake excitation and reported that soil properties significantly affect the performance of isolation devices [10]. These studies emphasize the importance of considering SSI effects in modern structural design approaches.

2.5 Nonlinear Soil–Structure Interaction Effects

In recent years, researchers have increasingly focused on nonlinear soil–structure interaction behavior because soil and structural materials often exhibit nonlinear characteristics during strong earthquake shaking. Lu et al. investigated nonlinear SSI effects on the seismic performance of mid-rise moment-resisting frame buildings and found that soil flexibility significantly affects structural ductility and energy dissipation capacity [35].

Similarly, Ghandil et al. conducted numerical studies to evaluate the influence of foundation flexibility on seismic response of buildings and concluded that SSI effects become more significant for structures constructed on soft soil deposits [25]. Lin et al. analyzed high-rise buildings considering SSI effects and observed that soil flexibility leads to noticeable changes in structural displacement and acceleration responses [34].

Another important aspect of nonlinear SSI behavior involves potential soil failure mechanisms during earthquakes. Anastasopoulos et al. demonstrated that controlled soil failure may provide a form of seismic protection for structures by dissipating earthquake energy through soil deformation [29]. These findings highlight the complex and sometimes beneficial role of soil behavior in structural performance.

2.6 Interaction Between Adjacent Structures

In densely populated urban environments, buildings are often constructed close to each other, leading to the possibility of interaction between adjacent structures through the supporting soil. Chouw et al. studied the pounding response of neighboring buildings considering soil–structure interaction effects and found that SSI significantly influences impact forces between adjacent structures during seismic events [31].

Recent research has also explored structure–soil–structure interaction phenomena, where multiple structures influence each other's seismic response through the soil medium. Fatollahpour et al. examined structure–soil–structure interaction effects on high-rise buildings equipped with tuned mass dampers and highlighted the importance of considering such interactions in urban seismic design [11].

2.7 Simplified and Empirical Approaches for SSI Analysis

Because detailed numerical modeling of soil–structure interaction can be computationally demanding, several researchers have proposed simplified methods for estimating SSI effects in structural systems. Tabatabaiefar et al. developed empirical relationships to estimate seismic responses of mid-rise buildings considering soil–structure interaction effects [9]. Their approach provided a practical method for incorporating SSI effects in structural design.

Later, Tabatabaiefar and Massumi proposed simplified analytical procedures for determining the seismic responses of reinforced concrete moment-resisting frame buildings considering soil flexibility [32]. These simplified methods allow engineers to incorporate SSI effects without performing complex numerical simulations.

Salah and Guerdouh also investigated soil–structure interaction effects on seismic performance of frame structures and concluded that SSI significantly influences structural response parameters such as displacement and base shear [13]. Similarly, Mishra et al. studied multi-storey buildings incorporating SSI and shear wall systems and found that soil flexibility plays a crucial role in determining the effectiveness of lateral load resisting systems [12].

2.8 Summary of Previous Studies

From the literature reviewed above, it is evident that soil–structure interaction plays a crucial role in determining the seismic performance of structures. Early theoretical studies established the fundamental principles governing SSI behavior, while subsequent research introduced advanced numerical modeling techniques to simulate soil–foundation–structure systems more accurately. Numerous studies have demonstrated that soil flexibility significantly influences structural parameters such as natural frequency, base shear, displacement, and damping characteristics.

Recent research has also highlighted the importance of considering nonlinear soil behavior, advanced foundation systems, and interaction between neighboring structures. With the development of modern structural analysis software such as SAP2000 and ETABS, it has become increasingly feasible to incorporate SSI effects in structural analysis and design.

Therefore, understanding the influence of soil–structure interaction is essential for accurately predicting the seismic response of multi-storey reinforced concrete buildings. The insights obtained from previous studies provide valuable guidance for developing improved modeling approaches and design strategies that ensure the safety and performance of structures subjected to earthquake loading.

3. Conclusion

Soil–Structure Interaction (SSI) is an important factor influencing the seismic performance of multi-storey reinforced concrete (RCC) buildings. The literature reviewed in this study clearly indicates that the conventional fixed-base assumption may not accurately represent real structural behavior, particularly for buildings constructed on soft or medium soil conditions. The flexibility of the supporting soil alters the dynamic characteristics of structures by increasing the natural period, modifying damping properties, and influencing base shear and displacement responses [1], [5], [22], [23].

Several analytical and numerical investigations have demonstrated that SSI can significantly affect structural responses during earthquakes. Studies using analytical models, finite element methods, and boundary element approaches have shown that soil flexibility often leads to increased lateral displacement and changes in vibration characteristics of structures [6], [7], [18], [25]. Furthermore, the type of foundation system and soil properties play a critical role in determining the magnitude of SSI effects, as observed in studies involving pile foundations, mat foundations, and base-isolated systems [2], [3], [8], [10].

Recent research has also highlighted the importance of considering nonlinear soil behavior and interaction between adjacent structures in densely built environments. Advanced numerical simulations and empirical approaches have confirmed that SSI influences not only individual structural response but also the collective behavior of multiple structures interacting through the soil medium [11], [31], [35]. Simplified analytical methods have also been proposed to incorporate SSI effects in structural analysis without excessive computational effort [9], [32].

Overall, the reviewed studies emphasize that incorporating soil–structure interaction in seismic analysis leads to a more realistic prediction of structural behavior. With the availability of advanced structural analysis software such as SAP2000, it has become feasible to model SSI effects more accurately in engineering practice. Therefore, considering SSI in the design and analysis of multi-storey RCC buildings is essential to improve seismic safety, structural reliability, and overall performance under earthquake loading.

REFERENCES

1. Abdel Raheem, S. E., Ahmed, M. M., &Alazrak, T. A. (2015). Evaluation of soil–foundation–structure interaction effects on seismic response of multi-story moment resisting frame buildings. *International Journal of Advanced Structural Engineering*, 7, 1–18. https://doi.org/10.1007/s40091-014-0078-x
2. Awchat, G. D., & Monde, A. S. (2021). Influence of soil–structure interaction on the seismic response of the structure on mat foundation. *Civil Engineering Journal*, 7(10), 1679–1692. https://doi.org/10.28991/cej-2021-03091752
3. Bagheri, M., Jamkhaneh, M. E., &Samali, B. (2018). Effect of seismic soil–pile–structure interaction on mid-rise and high-rise buildings. *International Journal of Geomechanics*, 18(9). https://doi.org/10.1061/(ASCE)GM.1943-5622.0001222
4. Forcellini, D. (2022). Assessment of soil–structure interaction effects on base-isolated buildings using numerical simulations. *Structures*, 41, 1140–1152. https://doi.org/10.1016/j.istruc.2022.09.080
5. Gazetas, G. (1991). Formulas and charts for impedances of surface and embedded foundations. *Journal of Geotechnical Engineering*, 117(9), 1363–1381. https://doi.org/10.1061/(ASCE)0733-9410(1991)117:9(1363)
6. Kabtamu, H. G., Peng, G., & Chen, D. H. (2018). Dynamic analysis of soil–structure interaction effect on multi-story reinforced concrete frame structures. *Open Journal of Civil Engineering*, 8(4), 396–410. https://doi.org/10.4236/ojce.2018.84030
7. Kontoe, S., Zdravkovic, L., & Potts, D. M. (2009). An assessment of the domain reduction method as an advanced boundary condition for seismic soil–structure interaction analysis. *International Journal for Numerical and Analytical Methods in Geomechanics*, 33(5), 749–774. https://doi.org/10.1002/nag.713
8. Spyrakos, C. C., Maniatakis, C. A., &Koutromanos, I. A. (2009). Soil–structure interaction effects on base-isolated buildings founded on soil stratum. *Engineering Structures*, 31(3), 729–738. https://doi.org/10.1016/j.engstruct.2008.10.012
9. Tabatabaiefar, H. R., Fatahi, B., &Samali, B. (2014). An empirical relationship to determine lateral seismic response of mid-rise building frames under soil–structure interaction effects. *The Structural Design of Tall and Special Buildings*, 23(2), 133–150. https://doi.org/10.1002/tal.1058
10. Yanik, A., & Ulus, Y. (2023). Soil–structure interaction consideration for base-isolated structures under earthquake excitation. *Buildings*, 13(4), 915. https://doi.org/10.3390/buildings13040915
11. Fatollahpour, A., Tafakori, E., &Arjmandi, A. A. (2023). Structure–soil–structure interaction effects on high-rise buildings equipped with tuned mass dampers. *Structures*, 50, 1760–1774. https://doi.org/10.1016/j.istruc.2023.01.132
12. Mishra, S., Kumar, R., & Singh, B. (2023). Seismic response of multi-storey buildings considering soil–structure interaction and shear wall systems. *Results in Engineering*, 18, 101287. https://doi.org/10.1016/j.rineng.2023.101287
13. Salah, K., &Guerdouh, D. (2019). Soil–structure interaction effects on seismic performance of frame structures. *Revista de la Construcción*, 18(2), 241–253. https://doi.org/10.7764/RDLC.18.2.241
14. Wolf, J. P. (1985). *Dynamic soil–structure interaction*. Englewood Cliffs, NJ: Prentice Hall. https://doi.org/10.1002/9780470172878
15. Kramer, S. L. (1996). *Geotechnical earthquake engineering*. Upper Saddle River, NJ: Prentice Hall. https://doi.org/10.1201/9780203759048
16. Wolf, J. P., &Deeks, A. J. (2004). *Foundation vibration analysis using simple physical models*. London: Elsevier. https://doi.org/10.1016/B978-008044348-2/50000-0
17. Mylonakis, G., &Gazetas, G. (2000). Seismic soil–structure interaction: Beneficial or detrimental? *Journal of Earthquake Engineering*, 4(3), 277–301. https://doi.org/10.1080/13632460009350372
18. Stewart, J. P., Seed, R. B., & Fenves, G. L. (1999). Seismic soil–structure interaction in buildings. I: Analytical methods. *Journal of Geotechnical and Geoenvironmental Engineering*, 125(1), 26–37. https://doi.org/10.1061/(ASCE)1090-0241(1999)125:1(26)
19. Stewart, J. P., Fenves, G. L., & Seed, R. B. (1999). Seismic soil–structure interaction in buildings. II: Empirical findings. *Journal of Geotechnical and Geoenvironmental Engineering*, 125(1), 38–48. https://doi.org/10.1061/(ASCE)1090-0241(1999)125:1(38)

20. Luco, J. E., & Wong, H. L. (1986). Response of structures to nonvertically incident seismic waves. *Earthquake Engineering & Structural Dynamics*, 14(2), 275–302. https://doi.org/10.1002/eqe.4290140207
21. Bielak, J. (1975). Dynamic behavior of structures with embedded foundations. *Earthquake Engineering & Structural Dynamics*, 3(3), 259–274. https://doi.org/10.1002/eqe.4290030305
22. Veletsos, A. S., & Meek, J. W. (1974). Dynamic behaviour of building–foundation systems. *Earthquake Engineering & Structural Dynamics*, 3(2), 121–138. https://doi.org/10.1002/eqe.4290030203
23. Luco, J. E. (1982). Linear soil–structure interaction: A review. *Earthquake Engineering & Structural Dynamics*, 10(2), 265–280. https://doi.org/10.1002/eqe.4290100208
24. Avilés, J., & Pérez-Rocha, L. E. (2003). Soil–structure interaction in yielding systems. *Earthquake Engineering & Structural Dynamics*, 32(11), 1749–1771. https://doi.org/10.1002/eqe.293
25. Ghandil, M., Behnamfar, F., &Vafaeian, M. (2016). Dynamic soil–structure interaction effects on seismic response of buildings considering foundation flexibility. *Soil Dynamics and Earthquake Engineering*, 87, 188–199. https://doi.org/10.1016/j.soildyn.2016.05.012
26. Karabalis, D. L., &Mohammadi, M. (1998). Three-dimensional dynamic foundation–structure interaction analysis using boundary elements. *Engineering Structures*, 20(4–6), 323–333. https://doi.org/10.1016/S0141-0296(97)00051-2
27. Kausel, E. (2010). Early history of soil–structure interaction. *Soil Dynamics and Earthquake Engineering*, 30(9), 822–832. https://doi.org/10.1016/j.soildyn.2010.04.001
28. Harden, C. W., & Hutchinson, T. C. (2009). Beam-on-nonlinear Winkler foundation modeling of shallow foundations subjected to seismic loading. *Soil Dynamics and Earthquake Engineering*, 29(9), 1240–1252. https://doi.org/10.1016/j.soildyn.2009.01.001
29. Anastasopoulos, I., Gazetas, G., Loli, M., Apostolou, M., &Gerolymos, N. (2010). Soil failure can be used for seismic protection of structures. *Bulletin of Earthquake Engineering*, 8(2), 309–326. https://doi.org/10.1007/s10518-009-9145-2
30. Boroomand, B., &Zandi, A. (2012). Seismic soil–structure interaction analysis using finite element method. *Computers and Geotechnics*, 45, 24–31. https://doi.org/10.1016/j.compgeo.2012.05.006
31. Chouw, N., Hao, H., & Wang, Z. (2009). Effect of soil–structure interaction on pounding response of adjacent buildings due to near-source earthquakes. *Engineering Structures*, 31(12), 2988–3001. https://doi.org/10.1016/j.engstruct.2009.08.005
32. Tabatabaiefar, H. R., &Massumi, A. (2010). A simplified method to determine seismic responses of reinforced concrete moment resisting frame buildings considering soil–structure interaction. *Engineering Structures*, 32(12), 3885–3895. https://doi.org/10.1016/j.engstruct.2010.08.017
33. Fatahi, B., Tabatabaiefar, H. R., &Samali, B. (2014). Numerical study on seismic response of building frames considering soil–structure interaction. *International Journal of Geomechanics*, 14(3). https://doi.org/10.1061/(ASCE)GM.1943-5622.0000331
34. Lin, B., Wang, Z., & Zhang, Y. (2017). Seismic analysis of high-rise buildings considering soil–structure interaction effects. *Soil Dynamics and Earthquake Engineering*, 101, 277–285. https://doi.org/10.1016/j.soildyn.2017.07.018
35. Lu, Y., Hajirasouliha, I., & Marshall, A. M. (2013). Nonlinear soil–structure interaction effects on seismic performance of mid-rise moment resisting frames. *Engineering Structures*, 49, 253–264. https://doi.org/10.1016/j.engstruct.2012.10.037

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