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Examining Soil-Structure Interaction in Irregular RC and Steel Frames: A Comprehensive Assessment

Himanshu Yadav, Mukesh Pandey and Aditya Sharma
ITM University Gwalior-474026 M.P., India 2020-2022

Abstract

When a structure experiences seismic activity, the displacement caused by the structureand the ground becomes intertwined, leading to noticeable alterations in the structure's behavior. Understanding this mutual dependence gives rise to a phenomenon known as soil-structure interaction (SSI), which has often been overlooked in the design process despite its critical importance; neglecting it can result in unsafe designs. The concept of soil-structure interaction was introduced, and various research approaches were explored. Drawing from numerous sources, a methodical overview of the historical development and current state of research on soil-structure interaction, specifically considering neighbouring structures, was formulated as a point of referencefor researchers. While this study is in its developmental phase, owing to the intricate nature of both soil and structural models and the tendency to oversimplify, it warrants further pursuit due to its significance. An effort was made to comprehensively encapsulate the terminologies within this field of study. The existing challenges and the potential trajectories for future research in this domain were thoroughly scrutinized.

Keywords seismic, Soil-Structure Interaction, static loading, seismic loading, nonlinear, finite element analysis, space frame, isolated footing, raft footing.

Introduction

The extent of socio-economic devastation caused by earthquakes hinges greatly on the characteristics of the potent ground motion they generate. Earthquake ground motions arise predominantly from three factors: source characteristics, wave propagation paths, and local site conditions. A significant aspect of Structural Engineering, known as Soil-Structure Interaction (SSI), has gained prominence with the rise of massive constructions on soft terrains such as nuclear power plants, concrete, and earth dams. The attention to SSI issues is also imperative for structures like buildings, bridges, tunnels, and subterranean constructions[4].

Over time, as humanity and its habitats evolved, the construction landscape transformed. Parallel to human evolution, societal and economic progress, along with population growth, led to a surge in building construction, particularly high-rise buildings[2], due to increased population density and housing needs. However, earthquakes occurring in these densely populated zones inflict substantial damage on structures, lives, and economies. This structural damage is a direct outcome of inadequate scientific design.

Earthquakes release energy through the movement of the Earth's crust, and structures respond to this energy by undergoing changes. This discussion focuses on the simulation methods employed for soil-structure interaction and their execution[3]. The estimation of earthquake motions at a structure's location constitutes a pivotal phase in seismic design and retrofitting. Classical structural analysis methods assume that motion at the foundation level equals ground motion without constraints. This assumption holds true only for structures built on solid rock or extremely rigid soils. For structures on soft soils, foundation motion typically diverges from free field motion, often accompanied by a rocking element attributed to the horizontal foundation motion's flexibility. In the realm of rigid-base structures, analysis traditionally assumes that input motion at the base aligns with free field ground motion. However, in cases of flexible-base structures, besides the supplementary rocking element in horizontal motion, a portion of the structure's vibration energy transfers to the soil layer and dissipates due to wave propagation radiation damping and soil material hysteresis damping. Conventional methods typically neglect this energy dissipation for rigid base structures.

The influence of soil on structural response depends on soil and structure properties, as well as the excitation's characteristics. The bidirectional influence between soil response and structural motion constitutes Soil-Structure Interaction (SSI). Incorporating SSI effects empowers designers to accurately evaluate inertial forces and real displacements of the soil-foundation-structure system under the impact of free field motion[1, 3].

Kinematic and Inertial Effects

Structures situated on soil exhibit two distinct forms of interaction effects: kinematic and inertial effects. Kinematic interaction effects arise due to alterations in wave propagation mediums stemming from changes in media density and elasticity. These changes influence wave propagation velocity, causing the reflection and refraction of incoming seismic waves. Kinematic effects in soil-structure interaction (SSI) pertain to alterations in a structure's response when considering its presence in contrast to when analyzing responses with only free-field motions. These effects are independent of the structure's mass but are impacted by factors such as structural geometry, foundation embedment, incident free-field wave composition, and wave angle of incidence. Kinematic interaction becomes negligible for structures without embedment that are stimulated by vertically propagating shear waves.

On the other hand, inertial effects result from the collective dynamic behavior of the structure, foundation, and supportive soil medium. The elastic and inertial properties of the soil medium introduce additional degrees of freedom to the structure, facilitating the dissipation of incoming seismic wave energy through wave radiation away from the structure and the hysteric deformation of the supporting soil medium. Inertial effects hinge on the relative flexibility of the supportive soil medium in comparison to the structure. This implies that the significance of inertial effects is marginal for regular structures founded on rigid soils or rock formations. However, these effects could be substantial for structures that are both rigid and massive in nature.

Soil–structure interaction under static loading:

Numerous investigations have been dedicated to comprehending the impact of soil-structure interaction under static loads. However, these explorations have often approached the subject in a simplistically limited manner, showcasing revisions in force quantities attributed to such interactions. The focus has largely been on elucidating the modifications introduced by this interaction. Relatively few studies have ventured into examining the soil-structure interaction effects within the realm of three-dimensional space frames.

These investigations have surfaced intriguing findings, suggesting that relying solely on a two-dimensional plane frame analysis might lead to substantial misestimations of the actual interaction effect within a space frame. Insights from these studies underscore that a two-dimensional approach can potentially yield significant overestimations or underestimations of the genuine interaction effect present in a space frame structure. These outcomes undeniably spotlight the critical role of accounting for interaction effects, as they wield the power to meaningfully reshape design force quantities.

While these studies may carry quantitative approximations, they undeniably emphasize the urgency of delving into soil-structure interaction. By doing so, designers can glean more accurate estimations of force quantities within structural members. This is particularly pertinent when considering the intricate three-dimensional behaviors inherent in these structural configurations. In essence, these studies beckon the engineering community to recognize the value of investigating soil-structure interaction to unveil realistic force distributions, thereby bolstering the integrity of structural design and analysis.

Soil-structure interaction (SSI) effects, often overlooked in seismic vulnerability analyses of buildings, have been proven to significantly impact their seismic performance. European seismic codes recognize the necessity of incorporating SSI effects in the analysis of certain structures, particularly those with notable second-order (p-Δ) effects or mid/high-rise buildings. These characteristics are shared by reinforced concrete (RC) buildings in Portugal, which constitute a substantial portion of the nation's building stock. Additionally, a significant percentage (50%) of these buildings were constructed prior to the enforcement of stringent seismic codes, lacking adequate seismic design considerations.

Achieving accurate outcomes when accounting for SSI effects necessitates the proper modeling of soil and foundations. However, existing studies often hinge on idealized structural and soil configurations. Furthermore, a deficiency exists in both research and guidance, even within codes, concerning the quantification of SSI effects. This paper aims to address this gap by quantifying SSI effects in seismic vulnerability analyses of RC buildings through two approaches: the Beam on Nonlinear Winkler Method (BNWM) and direct soil modeling.

The primary goal is to propose a practical method for incorporating SSI effects and comprehensively characterizing soil behavior. The method was applied to a case study involving a mid-rise RC building in Lisbon. The characterization focused on a clay-type soil commonly found in the region, conducted under undrained conditions. To capture the intricacies of the soil's nonlinear constitutive behavior, 3D finite element procedures were employed. These procedures aimed to accurately represent the behavior of the complete system, encompassing soil, foundation, and structure.

Comparisons were drawn in terms of seismic safety verification and fragility assessment. The findings revealed that while the modal behavior and deformations of the building remained consistent with or without SSI effects, the flexibility of the soil was influential. Increased soil flexibility led to longer periods and elevated seismic damage. For the examined case study, considering SSI effects could reduce the models' maximum capacity by up to 15%.

In essence, this study underscores the significance of quantifying SSI effects for seismic vulnerability analyses of RC buildings, providing practical methodologies for their inclusion. It also highlights the importance of factoring in soil flexibility when assessing seismic performance, particularly for buildings constructed in seismic-prone areas.

Soil-structure interaction (SSI) can exert a significant influence on the seismic vulnerability of structures through diverse mechanisms contingent upon the interplay of soil properties and structural attributes. In this study, a probabilistic-based methodology is employed to examine the ramifications of SSI on the fragility assessment of two designated benchmark buildings: one featuring Reinforced Concrete with Infill Masonry Walls (RCIMW) and the other comprising Reinforced Concrete (RC) elements.

Analytical fragility curves are developed via nonlinear 3D numerical simulations implemented with Open Sees. This simulation framework incorporates hysteresis models and advanced plasticity representations to accurately capture the nonlinear behaviors exhibited by both soil conditions and structural configurations. The study delves into the impacts of soil deformability and structural flexibility on the nonlinear response of the entire system encompassing soil, foundation, and structure.

The focus of the investigation revolves around four distinct limit states, categorized as slight, moderate, extensive, and collapse states. These limit states are defined based on the magnitude of maximum inter-story drifts. By meticulously analyzing these diverse scenarios, the study endeavors to shed light on the intricate relationships between SSI, structural response, and seismic vulnerability.

Ultimately, the study contributes to a comprehensive understanding of how SSI can shape the fragility assessment of structures under seismic conditions. The integration of probabilistic approaches and advanced numerical simulations serves to provide a robust framework for evaluating the multifaceted influences of SSI on different structural configurations. The findings are anticipated to offer valuable insights for enhancing seismic design strategies and improving the resilience of structures in earthquake-prone regions.

The intricate and challenging issue of Dynamic Soil-Structure Interaction (SSI), which involves the interplay of structure, foundation, and soil, becomes particularly crucial when soil nonlinearity becomes a significant factor. This paper aims to elucidate how different SSI models impact the assessment of seismic fragility functions. Initially, the linear substructure approach is employed, implementing two distinct models. The first model, a one-dimensional representation, incorporates a translational elastic spring and a dashpot between the foundation node and the ground. The stiffness and viscous damping of this element are deduced from the real and imaginary components of the dynamic impedance at the structure's first natural frequency. The second model, a more sophisticated Lumped-Parameter Model (LPM), factors in the frequency- dependence of the impedance.

To explore the fragility functions' sensitivity to the linearity assumption, an additional approach involving soil nonlinearities is introduced. In this approach, a nonlinear footing macro-element captures near-field behavior by condensing the entire soil-foundation system into a singular nonlinear element at the base of the superstructure. Additionally, the consideration of energy dissipation through radiation damping is incorporated. The superstructure response is simulated across all approaches using a simple nonlinear single-degree-of-freedom (SDOF) system.

The paper conducts a comparative analysis of these approaches in terms of their impact on characterizing fragility functions for unreinforced masonry buildings (URM) resting on shallow foundations. By examining these distinct methodologies, the study seeks to offer insights into how different SSI models influence the assessment of seismic vulnerability for specific structural configurations. Through this exploration, the paper contributes to advancing our understanding of the complexities inherent in dynamic soil-structure interaction and its ramifications on structural fragility assessment.

This study is dedicated to exploring the seismic behavior of outrigger-braced buildings while taking into account soil-structure interaction, specifically to determine the optimal positioning of the outrigger and belt truss system. The investigation centers on a central outrigger-braced frame within a steel tall building. This frame is situated atop a layered soil deposit, forming a coupled soil-structure system that is subsequently subjected to seismic forces. The analytical approach involves the utilization of the direct method in OpenSees. Both elastic and inelastic analyses are conducted, and a comparison is drawn between the findings of the current study and those associated with a fixed-base system.

The primary objective is to identify the most suitable location for the outrigger-belt truss system. This determination is guided by evaluating factors such as maximum roof displacement, base moment, and base shear, while accounting for the presence of soil-structure interaction. Notably, the outcomes underscore how soil-structure interaction influences the optimal placement of the outrigger-belt truss system. The elastic analysis performed on both scenarios, one with a fixed base and the other incorporating soil-structure interaction, reveals a compelling trend. Specifically, situating the belt truss at higher stories leads to reduced roof displacement.

By delving into these dynamics, the study contributes to a deeper understanding of how soil-structure interaction shapes the behavior of outrigger-braced buildings. Furthermore, it provides insights into the strategic placement of the outrigger and belt truss system for optimizing seismic performance. Through its comprehensive analytical approach and comparisons, the study offers valuable information for enhancing the design and resilience of tall buildings subjected to seismic forces.

The study delved into the essential criteria for designing structures to withstand earthquakes. It encompassed spectrum analysis for different soil types, namely hard, medium, and soft soils, while also investigating soil-structure interaction across various foundation systems. The analysis was conducted on a 3D frame model using SAP 2000 V14 software, treating the soil and structure as a unified continuum model.

A significant aspect of the study was the exploration of the response of buildings subjected to seismic forces, particularly those employing raft foundations. The structural analysis was carried out using the response spectrum method within the SAP 2000 software.

The study's central focus was the analysis of energy transfer mechanisms between the substructure and superstructure during earthquakes. This factor is of critical importance for designing earthquake-resistant structures and retrofitting existing ones. Given the evolving challenges posed by seismic events, the paper emphasized that the need for research into soil-structure interaction problems is becoming increasingly crucial.

By tackling these aspects, the study contributed to the understanding of seismic design principles, the effects of different soil types, and the significance of soil-structure interaction. The findings underscored the significance of comprehensively addressing energy transfer mechanisms and soil-structure interaction in the pursuit of earthquake-resistant structures, further emphasizing the urgency for ongoing research in this field.

The study focused on investigating the dynamic behavior of building frames situated over raft footings when subjected to seismic forces, while also accounting for the effects of soil- structure interaction. The analysis was conducted using finite element method (FEM) software SAP2000 Ver14.

In the context of soil-structure interaction analysis, the study treated the foundation and soil as an integrated and compatible entity. The soil was modeled using specific soil models for the analysis. To account for the influence of soil, a true soil model in the form of an elastic continuum was employed. This model assumed homogeneity, isotropy, and elasticity in a half-space configuration. The model required inputs for dynamic shear modulus and Poisson's ratio.

Several parameters were explored in the study, including the number of stories, types of soil, and height ratio, with a focus on seismic zone-V. The building responses were evaluated for both bare frames and frames incorporating soil flexibility. Result parameters encompassed attributes such as lateral natural period, seismic base shear, and lateral displacement (story drift).

Through this investigation, the study contributed to a better understanding of the complex interplay between building frames, raft footings, and soil-structure interaction under seismic forces. The findings elucidated the influence of various parameters on structural responses and underscored the importance of considering soil- structure interaction effects in seismic design practices. By addressing these intricacies, the study provided insights that can guide more accurate and reliable earthquake-resistant design strategies for building structures situated on raft footings in seismic-prone regions.

The study examined the behavior of both bare frames and infilled frames, considering the presence of soil underneath. The investigation encompassed three distinct types of soils: soft, medium stiff, and hard. The infilled panels in the frames were constructed from brick masonry exclusively. A significant aspect of the study was the analysis of seismic behavior, accounting for the behavior of columns at the foundation level as fixed, even though real-world conditions do not guarantee complete fixity due to the properties of the soil. This aspect gives rise to what is known as "Soil-Structure Interaction" (SSI). Settlement and rotation of the foundation, along with shear forces and bending moments, can cause alterations in the superstructure.

These cases encompassed a variety of combinations, including the presence or absence of infill panels and the influence of soil. The analysis was performed using ANSYS 14.5 software. The results encompassed findings from both scenarios - with Soil-Structure Interaction (SSI) effects considered and without SSI effects.

By conducting these analyses, the study aimed to provide insights into the impact of soil-structure interaction on the seismic behavior of building frames with and without infill panels. The variations in structural responses dueto the presence or absence of soil and infill panels were explored. Such findings are vital for refining seismic design strategies, particularly when accounting for complex interactions between structural elements and the surrounding soil.

The study conducted an analysis of the performance of reinforced concrete (RC) frame buildings with and without infill walls. RC framed structures are commonly employed in construction due to their ease of assembly and rapid construction progress. The introduction of infill panels in these frames enhances both stiffness and strength. In essence, infill panels act as compression struts between columns and beams, effectively transferring compression forces from one node to another within the structure.

The study's focus was to investigate the behavior of RC frame buildings under seismic conditions, with a particular emphasis on the influence of infill walls. The seismic event that was considered was the Bhuj earthquake. The study revealed that the presence of infill walls can play a significant role in the structural performance of buildings during seismic events.

To assess the response of these structures in terms of seismic resistance, the study employed the concept of equivalent diagonal struts. This analytical approach allows for a comprehensive evaluation of the effect of infill walls on the seismic behavior of RC buildings. The study used computerized model analysis to obtain results for both scenarios - with infill structures and without.

Various parameters were considered in the analysis, including base shear, lateral floor displacement, story drift, and beam and column reactions. By comparing the results obtained from the analyses of buildings with and without infill walls, the study aimed to provide insights into how these structural elements impact the seismic performance of RC frame structures. This knowledge is essential for refining design practices and strategies thataccount for infill panels and their implications on structural behavior during seismic events.

The study investigated the seismic behavior of superstructures while considering the interaction between the substructure and the superstructure. Specifically, the dynamic responses of structures were compared between fixed base conditions and dynamic base conditions. To address this, the Finite Element Method was employed, utilizing SAP 2000 V14 software to model soil-structure interaction in framed structures supported by raft foundations.

The results were obtained through a comprehensive analysis that considered various parameters. These parameters included time period, lateral displacement, storey drift, and bending moments in both the X-X and Y-Y directions. The study employed time history analysis to delve into these responses, including base shear and roof top displacement of building frames situated over raft foundations and soil media.

The study revealed that the effect of soil-structure interaction significantly impacts several structural parameters. Notably, it was found that soil-structure interaction tends to increase the time period of vibration, as well as bending moments in both the X-X and Y-Y directions. Moreover, lateral displacement was also influenced by soil-structure interaction, showcasing its impact on the overall structural response.

A key insight from the study was that as the flexibility of the soil increased, there was a corresponding increase in bending moments. This underscores the complex interplay between the soil and the structural response and emphasizes the importance of considering soil-structure interaction effects when evaluating seismic performance.

By conducting this investigation and analyzing the outcomes, the study contributed to a better understanding of how soil-structure interaction influences the behavior of structures during seismic events. The findings have implications for seismic design practices, further emphasizing the necessity of accounting for these interactions in order to design structures that can better withstand and respond to seismic forces.

The study explored the conventional design approach for dynamic loading, which typically assumes that buildings are fixed at their bases. However, in reality, the soil medium that supports these buildings is capable of undergoing deformation, allowing for movement to some extent. This flexibility in the foundation can result in a reduction in the overall stiffness of the structural system, potentially leading to an increase in the natural periods of vibration of the system. This intricate mutual behavior between the soil and the structure, which regulates the overall response, is termed "soil-structure interaction."

The study emphasized that the effects of soil-structure interaction need to be considered when designing structures subjected to dynamic loading. The interaction between the soil and the structure can significantly influence the behavior of the building during seismic events, as well as other dynamic forces.

One method to account for the soil-structure interaction effect is by introducing spring elements with specified stiffness values. These springs emulate the interaction between the soil and the structure and can be used to model the dynamic response more accurately.

The study highlighted that changes in the natural periods of vibration due to the effects of soil-structure interaction are an important consideration in the design process. These changes can impact the overall dynamic behavior of the structure and should be accounted for to ensure accurate and reliable design outcomes.

In summary, the study underscored the significance of acknowledging the interplay between soil and structure in dynamic loading scenarios, emphasizing the need to incorporate soil-structure interaction effects to achieve more realistic and robust designs for buildings subjected to dynamic forces.

To validate the newly proposed approach, the paper compares its results with those obtained from the established frequency-domain code SASSI, which is used for linear SSI analysis in scenarios involving low- intensity earthquakes. Additionally, the paper introduces the use of the finite-element code LS-DYNA for nonlinear analysis and contrasts its outcomes with those derived from equivalent-linear analysis within SASSI. The key distinction between equivalent-linear and nonlinear responses is that the latter captures effects such as gapping, sliding, and uplift that occur near the soil-structure boundary during intense shaking events.

In summary, the paper highlights the need for more comprehensive analysis techniques when dealing with extreme seismic conditions that induce nonlinear soil-structure interactions. The presented nonlinear, time- domain SSI analysis approach aims to provide a more accurate representation of these interactions, even in cases where traditional linear methods fall short. By showcasing the differences in results between linear and nonlinear analyses, the paper underscores the significance of accurately capturing the complex behaviors that can arise in soil-structure interactions during intense seismic events.

Conclusion

The review of current practices in soil-structure interaction (SSI) analysis reveals that researchers have predominantly treated the soil mass as homogeneous, isotropic, and exhibiting both linear and nonlinear behavior in interaction analyses. While some studies have ventured into considering the soil mass as elasto- plastic, visco-elastic, and visco-plastic in these analyses, they remain relatively limited in number.

The finite element method has proven to be an invaluable tool for exploring SSI effects in a thorough manner. This technique is particularly effective in accounting for material nonlinearity, non-homogeneity, and interface modeling between soil and foundation. When dealing with nonlinear soil-structure interaction analysis, the incremental iterative technique has emerged as a suitable and widely applicable approach.

For practical purposes, it's recommended to use the Winkler hypothesis at a minimum, as it provides a more realistic representation compared to fixed base idealizations of structures. Soil-structure interaction can lead to a notable increase in the seismic base shear of low-rise building frames that rest on isolated footings.

In order to accurately predict the response of a structure, the influence of soil-structure interaction needs to be accounted for under both static and dynamic loading conditions. The presence of SSI significantly alters the forces within the superstructure, foundation, and soil mass. To achieve precise estimates of design force quantities, considering the interaction effect is crucial. Load redistribution plays a substantial role in modifying total and differential settlements, with nonlinear analyses often revealing more significant settlements.

Researchers have explored a range of foundation types in analyzing interaction behavior, including raft foundations, isolated footings, grid foundations, and pile foundations, among others.

In summary, the study of soil-structure interaction is an evolving field that has employed a variety of techniques to capture the complex behaviors and interactions between structures and the surrounding soil. The importance of accounting for these effects is underscored by the significant alterations they can introduce to the response of structures and their foundations.

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