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BRIEF COMMUNICATION

Nonlinear Analysis of Building Structures Resting on Soft Soil Considering Soil–Structure Interaction and Structure–Soil–Structure Interaction

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Abstract Over the decades, various researchers have suggested that considering a structure fixed at the base predicts erroneous results in estimating the seismic response of soil–structure systems due to earthquake motions, potentially leading to faulty system designs. The magnitude of these errors may be attributed to variables such as soil type and modeling techniques. Improper modeling techniques are major factors contributing to erroneous responses of soil–structure systems. Selecting and implementing wave-transmitting boundaries are challenging tasks in finite element modeling techniques to simulate the infinite extent of soil and account for radiation damping in soil for solving soil–structure interaction (SSI) problems. This paper studies the effects of SSI and soil–structure–soil interaction (SSSI) on a four-storey steel structure with a raft foundation resting on soft semi-infinite soil. Here, the infinite domain of soil is simulated through an infinite element as a boundary condition after validating the modeling technique with experimental results found in the literature. The new modeling method, using ABAQUS, effectively handles soil–structure interaction (SSI) problems with acceptable accuracy, facilitating simulation of both SSI and SSSI scenarios for a four-storey steel structure. Using an infinite element (CIN3D8) in finite element method (FEM) analysis proves viable for SSI and SSSI simulations. Results show reduced storey drifts but varied floor shear forces across soil types (S1: a uniform soil system and S2: a two-layer soil system) compared to fixed base conditions. In SSSI analysis, higher storey levels experience increased drifts, while lower levels have decreased drifts compared to SSI scenarios. Base shear forces are consistently higher in SSSI analysis across all soil profiles, resulting in overall higher total floor displacements in both SSI and SSSI conditions compared to fixed base conditions.

Keywords Finite element analysis · Soil boundary condition · Soil–structure interaction · Structure–soil–structure interaction

Introduction

It has been observed that the seismic response of the site affects the magnitude of damage to buildings during seismic excitation. The significance of site response has been confirmed through processing earthquake motion data received from loose soil deposits during the Mexico City (1985) and Loma Prieta (1989) earthquakes [28]. Such recorded seismic data from instrumented sites are generally used to validate the numerical models developed for SSI problems. Obtaining results of SSI problems from laboratory tests and in situ tests is very costly and difficult, mainly from the point of view of complex geometries. Due to advancements in computation, it is possible to simulate the complex SSI problems using a robust numerical FEM modeling technique [2]. These numerical methods can be very useful in identifying the response of SSI systems and in designing buildings.

If the response of a structure is affected by soil and the response of soil is affected by the structure, then these mutual interactions of soil and structure are defined as soil–structure interaction (SSI). The mutual effect of the vibration of the structure and soil leads to changes in their vibrational characteristics. Mainly, two types of interactions

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are observed in SSI: kinematic interaction (KI) and inertial interaction (II). The soil response under earthquake motion in the absence of any structure is the free field motion. The KI effect arises when a solid foundation resting on soil is unable to behave in a similar manner to the free field motion of the soil. Stiff foundation, incoherency, and the wave inclination are the main factors of KI effects. The KI effects are mainly quantified by the transfer function, which is frequency dependent. Assuming a massless foundation, the transfer function is the ratio of the foundation response and free field ground motion [34]. The transfer function, in the case of a rigid massless rectangular footing resting on viscoelastic semi-infinite soil, was derived by Luco and Wong [15]. The deformation in soil due to the mass of the structure is termed as inertial interactions. Inertial interaction also affects the response of structures. The inertia force of the structure produces a moment and base shear. Damping factors and modal characteristics of structures are also affected by inertial interaction. A simple lumped mass model is used to study the effect of inertial interaction.

The effect of SSI on the seismic response of buildings has garnered interest among researchers for the last few decades. The main focus of these researchers is on theoretical study, while very little work has been performed on experimental work. More importantly, it is observed that many theoretical results have not been validated with experimental results to attain the desired accuracy to qualify for practical applications. In recent years, America, Australia, Japan, and many others have started to conduct in situ tests and shake table tests for SSI problems [1, 4, 6, 18, 33]. With the development of advanced modeling techniques, shake table tests have gained an increasingly important role for validation purposes in the research of seismic response of SSI problems. However, it is very difficult to conduct this kind of test due to its costly and complex nature. Based on validated modeling techniques using finite element software ABAQUS (2013), 3D FEM modeling on SSI is presented in this paper. This paper presents a detailed modeling technique on dynamic SSI problems that includes validation of the modeling, simulation of the infinite nature of boundary conditions of soil, and study of the response of a four-storey steel building with a raft foundation resting on soft soil.

Modeling of Soil–Structure System Considering SSI

To evaluate the effect of SSI, generally two types of buildings are considered in analysis. One is a fixed base structure, and the second is a flexible base structure. In the case of a fixed base structure, it is assumed that soil stiffness is very high in comparison with the foundation. The second refers to those structures resting on a soft-soil media. This permits oscillation in the foundation of the structure when subjected to earthquake motion. As a result, the response of a fixed-base structure becomes different compared to structures resting on a rigid base. To study the structural response considering SSI, many experimental and analytical studies have been done in the past. System identification methods were suggested [27] for the calculation of dynamic characteristics for flexible-base and fixed-base structures when the response of the foundation and the roof of the structure are available but free field motion at ground level is not available. In this work, input and output data for the evaluation of SSI are calculated.

Numerical Solution Approach and Governing Equation

There are two approaches to quantify the SSI problem, named as the indirect method and the direct method. There are three steps to perform the indirect method as described by Varun (2010). The first step is to find out the input motion at the foundation level, assuming no mass for the structure and foundation; it is termed as foundation input motion (FIM). The second step is to calculate the impedance function for the soil–foundation system. The last step is the analysis of the structural system, which comprises the impedance function for the soil and FIM as input motion at the base. Kramer [13] reported that these steps are superimposed only if the soil and structure behave linearly. Yang et al. [36] studied the SSI problem using the indirect method successfully in the past.

In the case of the direct approach, soil, foundation, and structure are modeled simultaneously in one step [13]. The SSI problem analyzed using this method consists of a structure, foundation, soil, and interface nodes system and seismic displacement (velocity or acceleration) at the bottom of the soil as shown in Fig. 1. This method is more accurate and provides a realistic solution for the nonlinear SSI problem. Many researchers in the past have used the direct method to

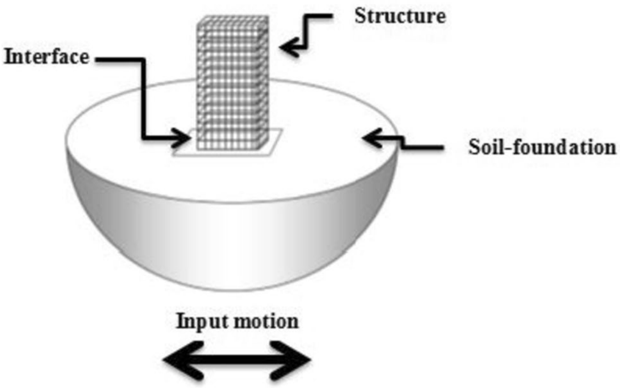


Fig. 1 SSI system in direct method

solve the SSI problems [17, 32]. The dynamic response of the soil deposit and structure is calculated using Eq. (1) in the time domain analysis of SSI simulation.

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = -[M]\ddot{u}_g \tag{1}$$

where $\{\ddot{u}\}$ and $\{\dot{u}\}$ matrices denote the double derivative and single derivative of displacement matrix $\{u\}$ with respect to time. Here, $\ddot{u}_g$ is the input motion at the base of soil. The Rayleigh damping model is used for evaluating the matrix $[C]$ as discussed in detail in the following sections. The $[K]$ of the system is evaluated at each time-step from the constitutive relation formulation for static and dynamic stress–strain behavior of the structure and soil materials. ABAQUS (2013) was used to simulate a numerical study seismic response and SSI in semi-infinite soft soils. The ABAQUS software includes advanced geotechnical and structural material models for dynamic seismic simulations. This FEM analysis consists of two steps: One is static, and the other step is seismic loading. The soil–structure system is analyzed in the first step for gravitational loading, and then, in the second step, seismic loading is applied at the base of the soil. The implicit method of analysis is used in ABAQUS to evaluate the SSI problem in this paper.

Material Modeling and Boundary Conditions

Steel is modeled using constitutive material model data obtained from experimental stress–strain data in uniaxial tension tests to account for the effect of nonlinearity in the beam and column of the structure. To simulate the behavior of concrete, Park et al. [22] are used to model the cyclic behavior of concrete. This model handles the cyclic behavior of concrete well. A nonlinear Mohr–Coulomb constitutive model is used in this SSI system for simulating the nonlinear behavior of the semi-infinite soil medium in earthquake loadings. The Mohr–Coulomb model has been employed successfully in the past [25] for modeling the dynamic SSI problems to study the soil behavior under earthquake loads.

Rayleigh model is used to model the damping behavior of steel, concrete, and soil in this study. This model is expressed with two parameters α and β along with the mass matrix $[M]$ and stiffness matrix $[K]$, which allow evaluating the damping matrix $[C]$ as shown in Eq. (2). This allows calculating the damping ratio (ξ) as shown in Eq. (3), where ω is the frequency of excitation at which the critical damping ratio applies.

$$[C] = \alpha[M] + \beta[K] \tag{2}$$

$$\xi = 0.5[\alpha/\omega + \beta\omega] \tag{3}$$

where ω is selected corresponding to the dominant frequency of the earthquake obtained from the Fourier spectrum, and a 5% critical damping ratio is used in this study.

To evaluate mesh size convergence in analyzing static loading conditions for columns, they are represented as cantilever beams fixed at the base. Deflections are computed at various points along the beam using the finite element method (FEM) after applying a load at the free end. These numerical deflection values are compared with theoretical predictions obtained from Eq. (4). The mesh size that produces deflection values closest to the theoretical predictions is selected for further analysis, determining the optimized element size for the beam and column under study.

$$\mathrm{Y} = \frac{PX^2(3L - X)}{6EI} \tag{4}$$

In Eq. (4), where Y represents the vertical deflection at the considered point, X denotes the position of the point from the fixed end, E represents Young's modulus, I denotes the second moment of area of the beam, L represents the length of the beam, and P signifies the applied load. To check the mesh size performance of columns under dynamic condition, natural frequencies for first three mode of vibration (f_1, f_2 *and* f_3) of cantilever beam obtained under frequency analysis of FEM were also compared with its theoretical values which is calculated using Eq. (5) and mesh size 3 (100 mm) perform well under both condition of convergence test as shown in Fig. 2.

$$f_i = \frac{1}{2\pi}\sqrt{\frac{EI}{\rho A}}\left(\frac{K_i}{L}\right)^2 \tag{5}$$

In Eq. (5), where f_i represents the natural frequencies, E denotes the material's Young's modulus, I is the moment of inertia, ρ represents the material density, A denotes the area of the cross section, L represents the beam length, K_i signifies the factor dependent on the vibration mode ($k_1 = 1.88$, $k_2 = 4.69$, $k_3 = 7.86$). The assumed mechanical and sectional properties required for finite element method (FEM) analysis, as well as for Eqs. (4) and (5), are listed in Table 1.

Similar to steel, the soil response due to earthquake loadings is severely affected by the element size in FEM simulation if it is not suitably selected according to wave propagation in discretized soil. Lysmer and Kuhlemeyer [16] suggested a rule of thumb about selecting an appropriate element size (Δx) and time-step (Δt) for proper wave motion in soil. From the point of view of element size, it was suggested that there should be at least eight to twelve elements in the minimum wavelength (λ_min) of elastic waves propagating in the soil. Considering the above rule in the simulation, the maximum element length is selected considering ten elements in the minimum wavelength of seismic motion. Therefore, the maximum element size in this study is estimated using Eq. (6), assuming the maximum frequency (f_max) of

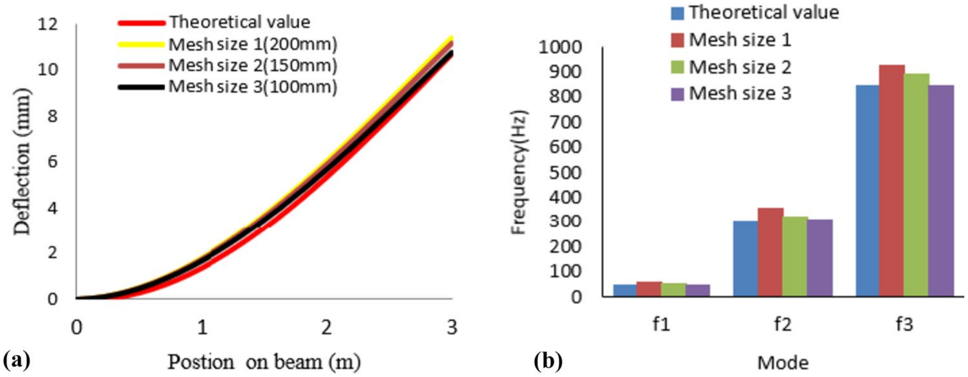


Fig. 2 Mesh convergence for cantilever beam (**a**) under static loading and (**b**) for natural frequency analysis

Table 1 Sectional and mechanical properties of cantilever beam

L (m)	E (N/m^2)	I (m^4)	A (m^2)	P (kg/m^3)
3	2.1×10^{11}	1.5×10^{-4}	6.6×10^{-3}	7856

interest is 10 Hz considered in this calculation. Similarly, Nilsson and Jones [20] suggested that the accuracy and stability of the simulation are affected by the time step in simulation and it provides faulty results if not selected properly. Equation (7) is used to calculate the time step in this simulation as suggested by the authors mentioned above.

$$\Delta x = \frac{\lambda_{\min}}{10} = \frac{v_s}{10 f_{\max}} \tag{6}$$

$$\Delta t = \frac{\Delta x}{v_p} \tag{7}$$

where $v_s$andv_p are longitudinal and shear wave velocity, respectively.

C3D8 and CIN3D58 elements have been used by many researchers in the past to study SSI problems. Nguyen et al. [19] applied C3D8R and CIN3D8 elements to model the near and far fields of soil in the modeling of concrete structures for SSI analysis. Maheshwari et al. [17] used a conventional C3D8 element in their study of soil–pile interaction. Stromblad [30] applied C3D8I and CIN3D8 elements to study the SSI effect on steel piles under seismic excitation. Kant and Samanta [11] found that C3D8 and CIN3D8 soil elements effectively represented free field soil responses. In this study, a solid three-dimensional, eight-node linear brick element (C3D8) is used to model the structural parts of the FEM model. The soil domain of the FEM model is modeled with C3D8 for the finite region of soil, and the infinite element (CIN3D8) is used for modeling the far region.

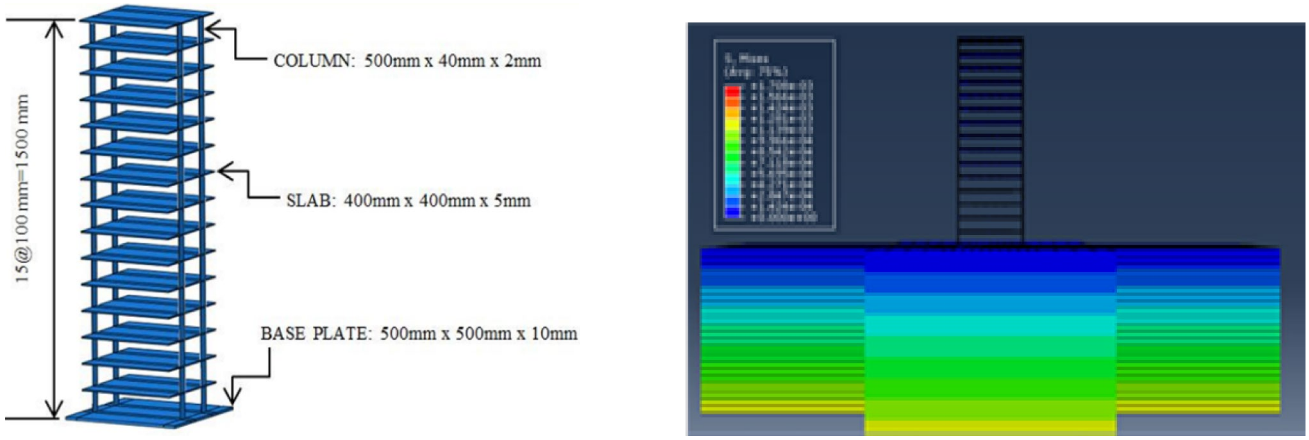
For simplifying the simulations, soil layers are assumed to be homogeneous with no sliding in-between. Layers are extended to infinity, and ground motions are applied below the foundation as per Novák and Beredugo [21]. The soil is assumed to be placed on rigid bedrock, and reflection of outward moving waves is taken care of by infinite element. It is assumed that there is no sliding between the base of the structure and soil mat; therefore, a tie constraint is imposed between them.

Verification of Developed Modeling Technique

In this section, the results of the novel and enhanced SSI model are compared with shake table test results from the literature. Utilizing a direct modeling approach, a robust and advanced 3D FEM SSI model is developed realistically using ABAQUS to simulate the nonlinear complex SSI problem. The present model simulates the behavior of both the structure and soil with equal rigor simultaneously.

Details of the structure are taken from the study of Tabatabaiefar [31] as shown in Fig. 3a. The required mechanical and sectional properties, including the area of cross section for the column (A_c), second moment of area for the column (I_c), area of cross section of the beam (A_b), moment of inertia of the beams (I_b), area of cross section of the slab of the foundation (A_s), second moment of area of the slab of the foundation (I_s), modulus of elasticity of steel (E), material density (ρ), minimum yield stress (f_y), minimum tensile strength (f_u), and damping ratio of the structure (ϕ), are listed in Table 2. Soil parameters are presented in Table 3 which are utilized in the soil–structure model. Roesset et al. [26] stated that defining damping in the SSI system in a useful and meaningful way is the most troublesome aspect of modeling the SSI problem. Only stiffness proportional damping is considered in the soil damping modeling. The sequence of analysis consists of two steps: (i) geostatic step and (ii) seismic loading in both types of buildings, i.e., fixed base and flexible base structures.

Two types of scaled earthquake records, the Kobe earthquake of 1995 (depicted in Fig. 4a) and the El Centro earthquake of 1940 (Fig. 4b), were utilized for ground motion analysis. These acceleration records were originally employed by Tabatabaiefar [31] in shake table experiments. The Kobe earthquake represents a near-field ground motion,



(a) Construction detail of structure

(b) Simulated model in geostatic stress step

Fig. 3 Construction details of the structure along with its modeling in ABAQUS during the geostatic step

Table 2 Sectional and mechanical properties of structure used in modeling

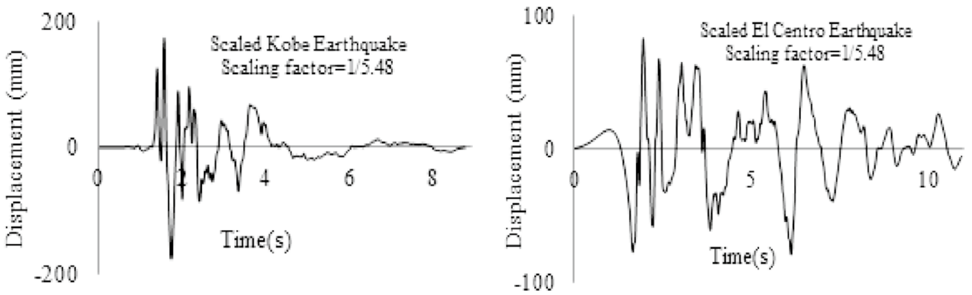
A_c (m^2)	I_c (m^4)	A_b (m^2)	I_b (m^4)	A_s (m^2)	I_s (m^4)	E (MPa)	ρ (kg/m^3)	f_y (MPa)	f_u (MPa)
1.46E−4	5.33E−11	0.002	4.16E−9	0.005	4.16E−8	2E5	7850	280	410

Table 3 Soil parameters used in the numerical simulation of the SSI model

Parameters	Single layer soil system
Young's modulus (MPa)	5.50
Poisson's ratio	0.45
Mass density(Kg/m^3)	1450
Shear wave velocity (m/s)	36.00
Depth of layer (m)	0–2

while the El Centro earthquake represents a far-field ground motion. These two earthquakes were chosen by the International Association for Structural Control and Monitoring [12] for benchmark seismic studies. Table 4 [24] provides detailed characteristics of these earthquake motions. Before applying these seismic inputs in the respective cases, a geostatic analysis was conducted to simulate in situ soil stress conditions, as illustrated in Fig. 2b.

Fig. 4 Scaled record of the Kobe earthquake (1995) and the El Centro (1940)



(a) The Kobe Earthquake (1995)

(b) The El Centro Earthquake (1940)

Table 4 Characteristics of earthquakes motions used as seismic input

Earthquake	Year	PGA (g)	M$_W$	T_s (Duration)	Type	*Distance
Kobe	1995	0.833	6.8	56	Near field	07.40
El Centro	1940	0.339	6.9	56.5	Far field	15.69

*Hypo-central distance (km)

Comparisons of Numerical Results

After conducting nonlinear time history analyses using the 3D FEM analysis model and the two aforementioned scaled ground displacement records, the maximum lateral deflections are determined for both cases based on the displacement history records of each floor. Numerical results are obtained for both fixed base and flexible base scenarios and are compared with available experimental (shake table) and numerical (FLAC 2D) results conducted by Tabatabaiefar [31]. The comparisons of numerical results for the maximum lateral displacements of the two cases are depicted in Fig. 5. An error calculation for the present numerical analysis is performed for both types of seismic records, relative to the experimental results from literature. It is observed that the maximum error in the numerical analysis for both types of seismic inputs is less than 2% for the fixed base analysis of the structure, while for the flexible base analysis, it is approximately 17%. The average error for the fixed base analysis is 1%, and for the flexible base, it is around 8%. As shown in Fig. 5, the FEM simulation results and the experimental results from literature exhibit good agreement. Therefore, the present numerical SSI model can accurately simulate the behavior of real SSI problems. The proposed numerical SSI model holds potential for further numerical analysis of SSI problems. The abbreviations FX, FL, EX, NU, RF, and PS stand for fixed base, flexible base, experimental, numerical, reference study [31], and present study, respectively.

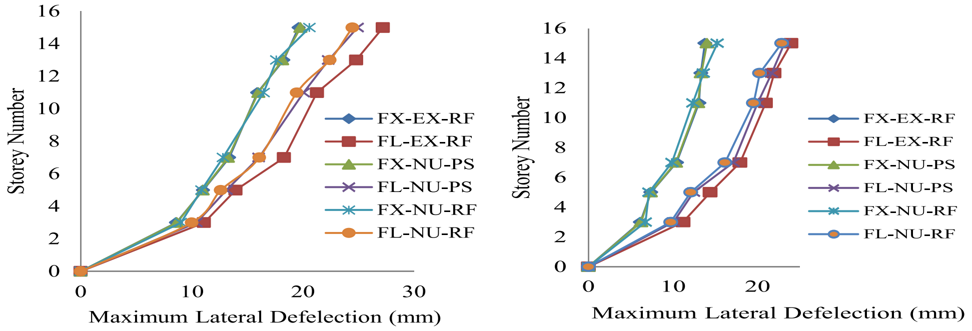
Seismic Response of a Steel Structure Considering SSI

Several researchers have reported the importance of SSI effects on the dynamic response of structures (e.g., Halabian and Naggar [5] and Hosseinzadeh and Nateghi [7]). These studies have included both 2-dimensional and 3-dimensional soil–structure systems using either the indirect approach or the direct method. One common conclusion of these studies is that soil–structure interaction could significantly affect the dynamic response of buildings, with effects that may be either beneficial or detrimental. However, the findings of these studies are still rarely applied in international or national design codes due to doubts regarding the uncertainty and reliability of the results. In this paper, a typical four-storey steel structure (with three bays in both horizontal directions) is analyzed to quantify the effects of SSI on the system's dynamic response. The soil–structure model for the steel structure and soil system is developed according to the modeling technique discussed above while validating the model.

A four-storey residential steel frame building is considered for analyzing the SSI problem. The storey height of the building is 3 m, and the building plan used in this study has three bays of four meters in each direction. The site is located in seismic zone type-IV (high-risk zone) as per IS-1893 [10]. A 3D steel special moment-resisting frame is designed according to IS-1893 [10] standards. The buildings are designed to withstand the following loadings: Dead load (DL) = 7 kN/m^2 and live load (LL) = 2 kN/m^2. The slab is considered a rigid plate with a thickness of 150 mm. ISHB150 is used as the beam section, while IM350 X 300 X 010 and IM350 X 250 X 010 are used as the column sections in this investigation, which are designed using commercially available software STAADPro [29]. The four-storey building is placed on a raft foundation, with the plan of the raft foundation for each building measuring 14 m by 14 m. The thickness of the raft is 0.4 m, and top and bottom reinforcement of the raft foundation are used after designing the raft. Two types of soil profiles are used in the present dynamic analysis to study the effect of uniform soil (S1) and layered (S2) soil. S1 consists of 30 m of thick sand placed on hard bedrock, while S2 consists of 30 m of thick clay soil placed on hard bedrock. Properties of both soil profiles are presented in detail in Table 5.

As for ground motion, the Kobe earthquake of 1995, widely used as a benchmark, is employed. It is a near-field ground motion selected for benchmark seismic studies by the International Association for Structural Control and

Fig. 5 Lateral displacements of fixed/flexible base models for scaled ground motions



(a) Lateral displacements for the Kobe (1995) motion

(b) Lateral displacements for the El Centro (1940) motion

Table 5 Parameters for soil domain

Parameters	1-Layer soil (S1)	2-Layer soil (S2)	
		Upper layer	Lower layer
Young's modulus (MPa)	20	20	40
Poisson's ratio	0.4	0.4	0.4
Mass density (kg/m^3)	1203	1203	1600
Shear wave velocity (m/s)	77	77	94
Depth of layer (m)	0–30	0–15	15–30

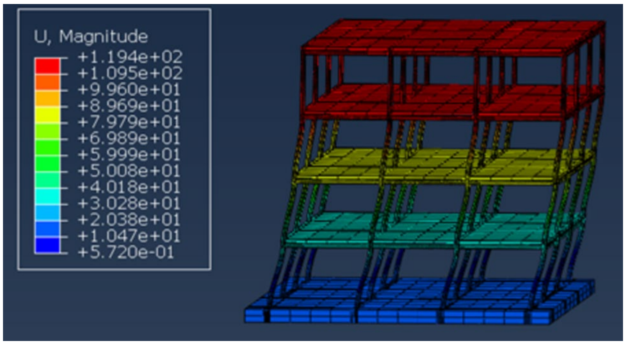


Fig. 6 Deformed shape of 4 storey building under the Kobe earthquake (1995)

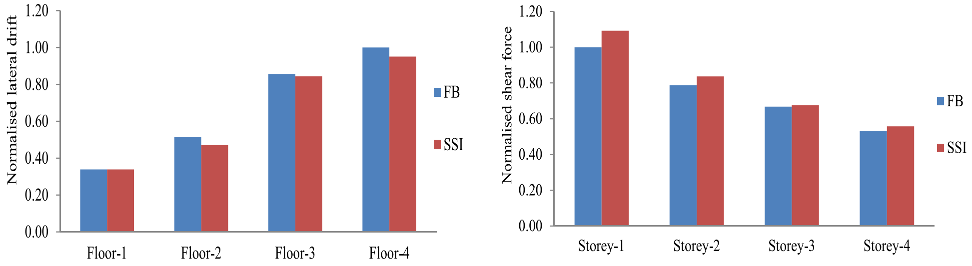
Monitoring [12]. The characteristics of this earthquake motion are listed in Table 3. The structure is modeled using three-dimensional brick elements, as discussed in previous sections. Material properties of steel are considered elasto-plastic. Rayleigh damping, corresponding to a 2% critical damping, accounts for wave dissipation in frame structures. The slab is modeled as rigid by assigning very high stiffness to its elements. The near field of the soil is modeled with regular three-dimensional brick elements (C3D8), while infinite elements (CIN3D8) are used for modeling the far region of the soil to simulate real wave propagation in a semi-infinite domain. Kuhlemeyer and Lysmer [14] suggested taking six times the width of the foundation for the soil domain. The minimum foundation width for a structure is assumed to be 14 m in width. Negligible effects of reflected waves were observed for boundaries located three to four times the equivalent foundation radius in the horizontal direction and two to three times in vertical directions [3]. Similar suggestions are provided for 2D plain strain analysis SSI problems. Ninety meters of soil width were taken following this six-time rule. Thus, the boundary condition was implemented to reduce wave reflection at the boundary. It is also assumed that the soil is placed on hard soil at a depth of 30 m from the free surface of the soil. Therefore, the finalized soil size of the finite model is 90 m × 45 m × 30 m, and the size of the infinite element is taken as 15 m, as suggested by the ABAQUS manual, indicating that infinite elements should be large enough to simulate zero displacements at infinity. The soil and structure are discretized as discussed in the above section for wave propagation in soil. The element size of the soil is 0.5 m in height and 1 m in length in both directions. Soil horizontal BC is simulated by infinite element. Figure 6 shows the deformation of the four-storey steel structure under fixed base conditions for the Kobe earthquake.

Analysis Results for SSI

The maximum storey drift at each floor level is an important parameter, as it directly relates to the nonlinear behavior of the structure, which is used to predict the health of a building. Figures 7a and 8a show the values of the maximum storey drift ratios of the structure. This quantity is normalized to their corresponding maximum fixed base storey drift. It is observed that for all cases, the drifts for the flexible base are always smaller than their corresponding fixed base results. This result contrasts with SSI-based drifts, which are larger than fixed base results. One of the main reasons behind this result is the nonlinear behavior of both soil and structure together. In nonlinear seismic response, the floor shears are not proportional to drift ratios, and as a result, both responses may have different trends. To address base shear variations, the floor shears of the structure are calculated in the nonlinear soil–structure system. These are shown in Figs. 7b and 8b. The floor shears are normalized to their corresponding maximum fixed base shear value. From the above results, it is observed that the shear force for the SSI case is greater in the case of soil type S1 compared to fixed base results, while in the case of soil type S2, this trend is reversed. The storey drift is always less in the case of SSI compared to fixed base results for both types of soil (S1 and S2).

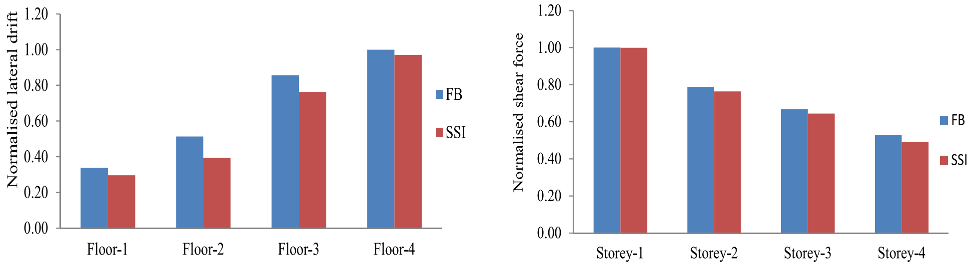
Seismic Response of a Steel Structure Considering SSSI

Structural responses may be affected by structure–soil–structure interaction (SSSI) during strong ground shaking. In this section, the SSSI of steel buildings and its effect on seismic response are examined. Compared to soil–foundation–structure interaction (SFSI) that studies only the structure with soil, SSSI has received very little attention recently. However, SSSI is increasingly being studied due to the construction of building clusters in dense urban areas, as it is very common to build tall structures on soft soil deposition in urban areas.



(a) Storey drift variation (b) Shear force variation

Fig. 7 Variations in storeys drift/shear force in the building under the Kobe earthquake (1995) for soil type S1



(a) Storey drift variation (b) Shear force variation

Fig. 8 Variations in storeys drift/shear force in the building under the Kobe earthquake (1995) for soil type S2

Exchange of vibrational energy may occur through soil between adjacent buildings through soil [23]. The ignorance of these phenomena may lead to faulty designs of buildings especially in the cases of dynamic loadings. In the past various numerical modeling methods like the FEM, boundary element method (BEM), and the coupling of both these methods are used in this filed. However, in the past studies, the dynamic interaction between building structures, through below soil, has not been studied in details. Most past studies focused on the interaction between two or more foundations. Harmonic response of nearby structures on flexible bases was studied by Wang and Schmid [35] using a coupled method of FEM and BEM. They reported that the adjacent buildings response is dependent on the clear distance between the structures. It was also shown to be dependent on the natural frequency of the soil–structure system. Imamura et al. [9] studied the dynamic response of a nuclear structure including SSSI. They reported that a heavy adjacent building can affect the response characteristics of a reactor. Few studies on SSSI show the need for analyzing the effect of SSSI on nearby residential buildings. Researchers either have worked on linear soil or linear structural properties. They mostly analyzed a 2D model to study the SSSI effects. Thus, further research is required for proper understanding of the dynamic interaction between 3D structures.

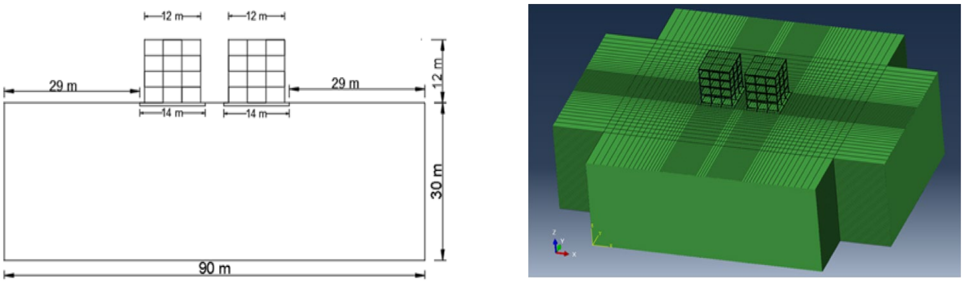
The dynamic analysis of SSSI between two four-storey steel buildings placed on raft foundation is performed using the same modeling technique as discussed in the previous section. In the study of dynamic SSSI between two adjacent buildings, it is required to place two structures at a minimum distance (d) to increase the probability of interaction between the two. On the other hand, the two adjacent buildings should not be so close that there is a severe case of pounding, which will damage the buildings in seismic loadings while investigating the SSSI effects. The International Building Code [8] limits the minimum distance (ΔMT as per IBC 2009 standard) between two adjacent buildings to avoid pounding and also a maximum value is limited to half of the maximum width of the building among adjacent buildings ($a/2$, where a is the maximum building width in plan), and expressed as in Eq. (8).

$$\Delta_{MT} \leq d \leq \frac{a}{2} \tag{8}$$

Δ_{MT} is calculated at critical locations of the SSSI system [8]. The maximum value of d in this study is 6 m, but to ensure the occurrence of SSSI, two four storey buildings are placed at a distance of 4 m as shown in Fig. 9a. The model of SSSI is shown in Fig. 9b.

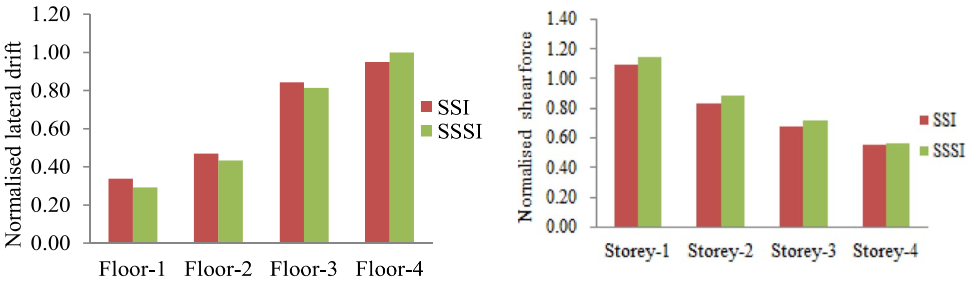
Analysis Results for SSSI

Figures 10a and 11a show the distribution of storey drifts, while Figs. 10b and 11b show the distribution of shear forces with storey heights for both types of soil profiles, S1 and S2, respectively. Here, storey drift and shear forces are presented in normalized form with respect to corresponding maximum fixed base condition values for comparison purposes. It is evident from the results (Figs. 10, 11) that SSSI affects the shear force and drift more for soil profile S1 in comparison with soil profile S2. These results indicate that in the case of



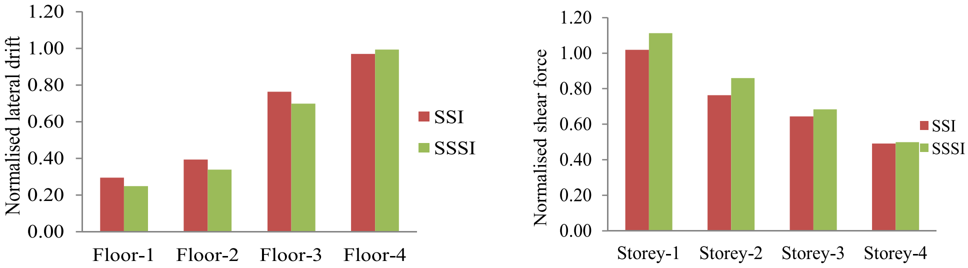
(a) Elevation of buildings (b) Meshed SSSI model

Fig. 9 Elevation of buildings and meshed SSSI model of two 4 storey buildings for dynamic analysis



(a) Storey drift variation (b) Shear force variation

Fig. 10 Variations in storeys drift/shear force in the building under the Kobe earthquake (1995) for soil type S1



(a) Storey drift variation (b) Shear force variation

Fig. 11 Variations in storeys drift/shear force in the building under the Kobe earthquake (1995) for soil type S2

nonlinear analysis, SSSI plays an important role and should be considered while designing buildings.

Conclusions

This paper examines the response of a 4-storey steel structure resting on soft soil with a raft foundation, considering both SSI and SSSI. A novel finite element modeling technique is utilized to study this problem. Numerical FEM models for both simulations are carried out, incorporating infinite elements to represent the far field. The performance of this modeling approach is compared with experimental and numerical results from the literature. It is observed that this new modeling method adequately handles the SSI problem with acceptable accuracy. Furthermore, this modeling approach is extended to simulate SSI and SSSI problems. The validated model is then used to study the seismic response of the 4-storey steel structure, leading to the following conclusions:

- An infinite element (CIN3D8) can be utilized to simulate SSI problems in FEM analysis.
- Storey drifts are lower for both types of soils (S1 and S2) in SSI analysis compared to fixed base results.
- Floor shear forces are higher in soil S1 and lower in soil S2 in SSI analysis compared to fixed base results.
- Storey drifts are higher for higher storey levels for both types of soil (S1 and S2) in SSSI analysis compared to SSI; however, they are consistently lower for lower storey levels.
- Base shear forces are consistently higher in SSSI analysis for both types of soil profiles compared to SSI.
- Total floor displacements are consistently higher in SSI and SSSI conditions compared to the fixed base condition.

The current study presents an ABAQUS model of a four-storey steel frame building situated on soft soil. While the research provides valuable insights, there exist several opportunities for future investigations, addressing those in future research endeavors would contribute to advancing the understanding of soil–structure interaction and seismic response, thereby facilitating the development of more resilient and robust structural designs:

- Analyzing the behavior of high-rise buildings with SSI and SSSI under seismic loading conditions would provide valuable insights into their dynamic response and potential mitigation strategies.
- The current study utilizes a two-layer soil system. Future research could investigate more complex and realistic soil profiles with multiple layers to better capture the diverse soil properties and their influence on structural behavior.
- The effects of two-dimensional earthquake loads using the developed modeling technique would enable a more comprehensive analysis of soil–structure interaction mechanisms and their implications for structural response.

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Declarations

Conflict of interest We declare that we have no known competing financial interests or personal relationships with other people or organizations that could have appeared to influence the work reported in this paper.

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