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The Influence of Soil Flexibility on Structural Seismic Behavior

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Abstract: The dynamic behavior of buildings during earthquakes is deeply influenced by the interaction between the structure and the supporting soil. This work investigates the influence of soil-structure interaction (SSI) on the seismic behavior of 3-, 6-, and 9-story reinforced concrete moment-resisting frames designed in accordance with the Algerian seismic code RPA99 (Version 2003). The numerical analyses are carried out using the FLAC2D software, where the soil is modeled as a homogeneous profile with elastic perfectly plastic behavior, and the structural components remain within the linear elastic domain. Two scenarios are compared: a fixed-base model and a flexible-base model that accounts for SSI effects. The frames are subjected to three recorded ground motions. The comparison is made in terms of spectral acceleration, top lateral displacements, and base shear. The results indicate that SSI modifies the dynamic response of structures and can induce resonance effects that amplify structural response, highlighting the necessity of considering these phenomena in seismic design.

Keywords: Soil-structure interaction, Numerical analysis, Reinforced concrete frames, Resonance effects.

Introduction

Soil-structure interaction (SSI) plays a crucial role in seismic analysis, as the flexibility of supporting soil significantly influences the way dynamic forces are transmitted and dissipated. Unlike a rigid base, which imposes uniform motion on the structure without deformation, a flexible soil absorbs part of the seismic energy and alters the structural response. This interaction leads to modifications in natural frequencies, damping, and internal force distribution, thereby affecting the overall seismic behavior of buildings. One of the most notable effects of SSI is the elongation of the fundamental period due to the overall softening induced by soil deformability (Ramadan et al., 2012; Scarfone et al., 2020). This elongation directly impacts seismic response by altering the internal force distribution and increasing lateral displacements. In fact, lateral displacements in structures with SSI tend to be larger than those in fixed-base structures, as they result from the combined effects of soil deformations and structural oscillations (Tabatabaiefar & Fatahi, 2014; Outayeb et al., 2023). This increase can have adverse consequences, particularly in terms of occupant comfort and additional stresses on non-structural elements. Furthermore, SSI affects base shear forces, as soil flexibility modifies the way seismic energy is absorbed and redistributed. In some cases, this results in a reduction of base shear compared to fixed-base conditions, but the extent of this variation depends on multiple factors (Hokmabadi et al., 2014; Yeganeh et al., 2015).

Beyond these effects, a particularly critical aspect of SSI is the potential resonance between the structure and the supporting soil. This phenomenon occurs when the modified fundamental period of the structure aligns with a frequency range of the seismic motion, leading to excessive amplification on internal forces (Scholl, 1989; Mylonakis & Gazetas, 2000; Torabi & Rayhani, 2014). The severity of resonance depends on soil stiffness, structural height, and seismic input characteristics, potentially increasing the vulnerability of the building.

Given these considerations, incorporating SSI into seismic analysis is essential for refining numerical models and improving the accuracy of structural response assessments under earthquake loading. In this context, this present study investigates SSI effects on reinforced concrete moment-resisting frames, considering 3-, 6-, and 9-story structures designed according to the Algerian seismic code RPA99/Version 2003. The frames are supported by a homogeneous soil modeled with an elastic perfectly plastic behavior, while the structural elements are assumed to remain within the linear elastic range. Numerical simulations are conducted using FLAC2D, employing the global method to compare fixed-base and flexible-base conditions. The models are subjected to three recorded seismic events, and the effects of SSI are evaluated in terms of spectral acceleration, top lateral displacements, and base shear.

Development of a 2D Numerical Model

For comparative investigation of fixed and flexible base support conditions of the structures, a set of three structural models, consisting of 3, 6, and 9-story RC building frames, is adopted herein, representing conventional types of low and mid-rise moment-resisting building frames. The building site was assumed to have a 30-meter-thick deposit of very flexible homogeneous soil with a shear wave velocity V_s constant with depth and less than 200 m/s, underlain by the bedrock.

RC Frame Structures

The model buildings considered are located in the Algiers area and have a plan that represents an ordinary architectural plan. Figure 1 shows the plan view of the repetitive story of the three buildings.

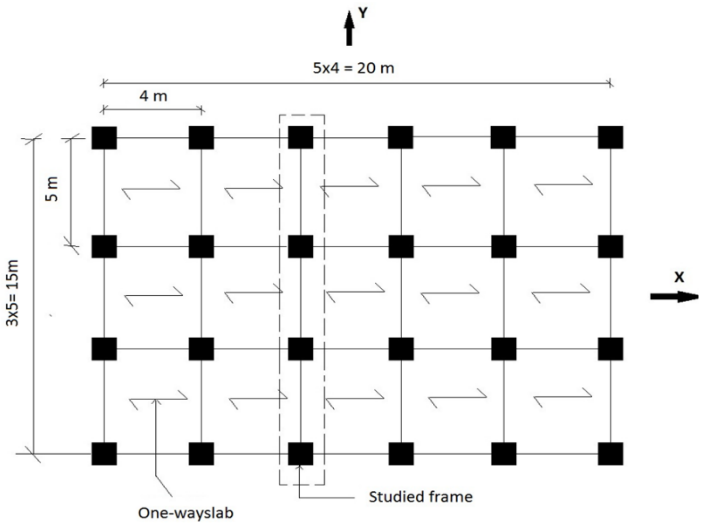

Figure 1. Typical floor plan for model buildings of 3-, 6-, and 9- story

Structural components and dimensions of the studied frames are presented in Table 1. All structures are regular in elevation and in plan to remove secondary effects due to irregularity when analyzing the dynamic behavior of building frames with the effect of soil-structure interaction. Columns and beams of frames are considered to be made of reinforced concrete with the same material properties. The structural design was performed in accordance with the criteria specified by the Reinforced Concrete Code BAEL 91 and Algerian Seismic Design Code Provisions RPA 99/version 2003 under the design seismic action of PGA = 0.25 g, which corresponds to a high seismicity zone (Zone III), soil type S3 (soft soil), a quality factor of 1, and a viscous damping ratio of 5%.

A seismic behavior factor of 5 was adopted for frames without masonry infill. The gravity loads assigned to the buildings were the own weight of structural components, including the reinforced concrete beams, columns, and slabs, and the live loads they support. Therefore, the imposed load in weight calculation is a uniform story live load of LL = 2.5 kN/m^2 and a roof live load of LL = 1.0 kN/m^2. Also, a story dead load of LD = 5.1 kN/m^2 and a roof dead load of LD = 5.8 kN/m^2 are adopted. A characteristic cylinder strength of 25 MPa for concrete and a yield strength of 500 MPa for steel are utilized. Structures are assumed to be built over shallow foundations that are 0.5 m thick and 15 m length and assumed to be located close to the ground; the effect of the embedment depth of the foundation has been ignored in soil-structure interaction.

Table 1. Structural components and dimensions of the studied frames.

Number of Stories	Total Height (m)	Bay Spacing (m)	Beam Cross-Section (cm × cm)	Column Cross-Section (cm × cm) per Story
3 stories	9	5	30 × 40	40 × 40 (all stories)
6 stories	18	5	30 × 40	50 × 50 (1st–2nd stories) 45 × 45 (3rd–4th stories) 45 × 45 (5th–6th stories)
9 stories	27	5	30 × 45 (1st–4th stories) 30 × 40 (5th–9th stories)	60 × 60 (1st–2nd stories) 55 × 55 (3rd–4th stories) 50 × 50 (5th–6th stories) 45 × 45 (7th–8th stories) 40 × 40 (9th stories)

The structural frame was modeled using standard 1D beam elements, with soil-structure interaction (SSI) incorporated in FLAC2D by connecting beam elements to the soil grid points via the GRID keyword. The superstructure, supported by an elastic concrete foundation, was installed after achieving equilibrium. As reported by Rayhani and Naggar (2006) and Yue and Wang (2012), both the frame and foundation remained elastic under static and dynamic conditions. While slabs were not explicitly modeled, their weight and live load were accounted for by distributing their reactions onto the supporting girders. To reflect these loads in both static and dynamic analyses, the mass density of beams was adjusted accordingly.

To ensure a realistic representation of energy dissipation, Rayleigh damping was introduced in the numerical model. The α and β coefficients determined based on the dominant modal frequencies extracted from a modal analysis in SAP2000. The fundamental and secondary periods of the 3-, 6-, and 9-story frames were identified respectively as 0.42 s and 0.12 s for the 3-story frame, 0.77 s and 0.25 s for the 6-story frame, and 1.00s and 0.35 s for the 9-story frame. Using these values, the minimum critical damping ratio (ξ_{min}) and the minimum center frequency (f_{min}) were computed for each structural frame according to the following equations:

$$\xi_{min} = \left(\alpha\beta^{1/2}\right) \tag{1}$$

$$f_{min} = \frac{1}{2\pi}\left(\frac{\alpha}{\beta}\right)^{1/2} \tag{2}$$

The results yielded $\xi_{min} = 4.1\%$ and $f_{min} = 4.4\,Hz$ for the 3-story frame, $\xi_{min} = 4.4\%$ and $f_{min} = 2.15\,Hz$ for the 6-story frame, and $\xi_{min} = 4.4\%$ and $f_{min} = 1.6\,Hz$ for the 9-story frame. These parameters were implemented in FLAC2D to accurately capture damping effects in the numerical simulations.

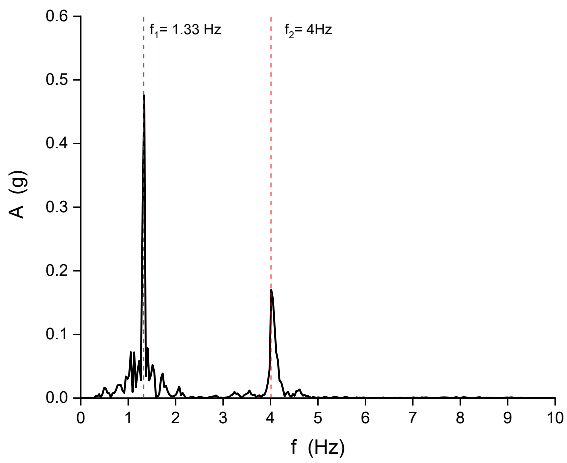

Figure 2. Fourier amplitude spectra of the top accelerations of the 6-story frame

The effectiveness of this approach is confirmed by the Fourier amplitude spectra presented in Figure 2, where the first two natural frequencies of the fixed-base 6-story frame ($f_1 = 1.30\ Hz$ and $f_2 = 4\ Hz$) are clearly identified. Furthermore, the computed natural frequencies exhibit excellent agreement with those obtained from a numerical analysis performed in SAP2000 on an identical 2D model of the fixed-base structure.

Soil Profile

The soil we are concerned with is basically a very simple one. A horizontal soil layer, bounded by the free surface and below by a semi-infinite elastic medium representing the bedrock, is postulated. The soil deposit is located at El Biar, in Algeria with the geotechnical characteristics based on the available in-situ tests and illustrated in Table 2 (Saci 2011). With a constant shear velocity V_s of 180 m/s, this soil is classified as a very flexible soil according to the Algerian seismic code RPA2003.

Table 2. Details of soil parameters

Mass density (kg/m^3)	Shear velocity (m/s)	Shear modulus (MPa)	Bulk modulus (MPa)	Friction angle	Cohesion (KPa)
1520	180	49.2	90.1	10°	60

To properly account for wave propagation effects in soil-structure interaction (SSI) modeling, the soil domain was set to five times the structure's width, minimizing boundary effects as recommended by Rayhani and Naggar (2009). The soil deposit, discretized into 2250 quadrilateral elements (75 m × 30 m), was meshed following Kuhlemeyer and Lysmer's (1969) criterion to ensure accurate wave transmission. A rigid bedrock boundary was assumed for the underlying layer, as suggested by Kocak and Mengi (2000), ensuring realistic seismic wave reflections.

To characterize the mechanical response of the soil under seismic loading, an elastic-perfectly plastic model with a Mohr-Coulomb failure criterion and a non-associated flow rule ($\psi = 0$) was adopted. Given the limited availability of site-specific soil data, this approach was chosen for its balance between simplicity and effectiveness in SSI studies. To account for nonlinear soil behavior, a hysteretic damping model based on Masing rules (1926) was implemented. This model was calibrated using the backbone curves proposed by Sun et al. (1988) for clayey soils, with the fitting parameters $a = 1.017, b = -0.479$, and $x_0 = -1.249$, defining the relationship between shear modulus reduction (G/G_0) and cyclic shear strain. These relationships, along with the variation of the material damping ratio as a function of cyclic shear strain, are illustrated in Figure 3, where Figure 3a depicts the evolution of G/G_max, while Figure 3b presents the corresponding damping ratio curves.

Beyond hysteretic damping, Rayleigh damping was applied to mitigate high-frequency numerical noise and capture small-strain frequency-dependent behavior. A viscous damping ratio of 0.2% was assigned at $f = 1.5\ Hz$, ensuring a realistic dynamic response of the soil model.

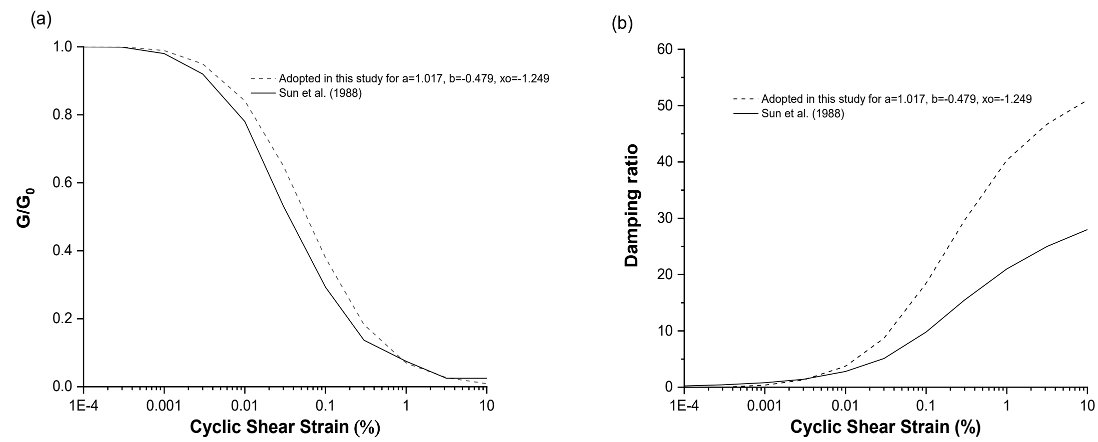

Figure 3. (a) Relationships between G/G_{max} and the cyclic shear strain and (b) Relationships between the material damping ratio and the cyclic shear strain

Ground Motion Excitations

The ground motion time histories adopted in this study are representative of the maximum probable earthquakes expected to occur at the site of interest during the lifetimes of the systems considered. Three well-known earthquakes are taken from the Canadian Association for Earthquake Engineering (CAEE) (Naumoski, 1988) as real-world input data. The names and seismic parameters of the earthquakes are presented in Table 3, and the corresponding elastic acceleration response spectra are shown in Figure 5. Once the selected ground input motions are scaled to a peak ground acceleration of the design spectrum of the Algerian seismic code (RPA 2003) as a PGA=0.25g according to the PGA scaling method (Choopool & Boonyapinyo 2011), they are low-pass filtered to remove frequencies higher than 15 Hz, aiming at limiting the element dimension adopted in the mesh, and baseline corrected using a standard polynomial detrending algorithm.

Table 3. Ground motions used in time-history analysis

Earthquake	Date	Site	Comp	Mag.(Ms)	Max. Acc. A (g)	Max. Vel. V (m/s)	A/V ratio*
San Fernando-1 California	09/02/1971	Lake Hughes	Station 4 S21W	6.4	0.146	0.085	1.72
Imperial Valley California	18/05/1940	El Centro	S00E	6.6	0.348	0.334	1.04
San Fernando-2 California	09/02/1971	3470 Wilshire Blvd L A	S90W	6.4	0.114	0.186	0.61

*A/V>1.2: high frequency content; 0.8<A/V<1.2: intermediate frequency content; A/V<0.8: low frequency content (Naumoski, 1988).

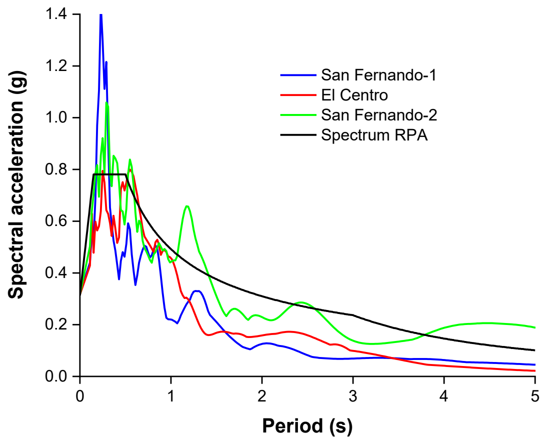

Figure 4. Acceleration response spectrum for the selected earthquakes and the RPA99/Version 2003 elastic design spectrum

Dynamic Analysis and Boundary Conditions

To carry out all the analyses, an initial static stage is performed, during which the construction of the structure is simulated and the system is brought to an initial equilibrium state under only gravity loads. During the static stages, the boundary conditions are the usual ones, i.e., nodes on the lateral sides are permitted to move only along the vertical direction, whereas entire fixities are imposed on the nodes at the base of the model.

The static stage is followed by the dynamic stage, which is achieved when the seismic input is applied to the base of the model at the level of the bedrock. As stated by Wegner and Zhang (2005), the generally considered seismic wave model is that of volume waves propagating vertically from assumed rigid horizontal bedrock. Subsequently, dynamic loading is applied at the base of the model as an acceleration excitation, assuming horizontally polarized shear waves propagating vertically. For lateral boundaries of the soil medium, the procedure of quiet (viscous) boundaries developed by Lysmer and Kuhlemeyer (1969) and available in the FLAC2D library is activated in order to represent the effect of the truncated soil by using viscous spring dashpot dampers at the boundaries, which can fully absorb waves and prevent outward propagating waves from returning into the boundary of the model. The independent dashpots in the normal and shear directions are coupled to the free-field columns at the sides of the model to reproduce the free-field motion that would exist in the absence of the structure.

Results and Discussions

The acceleration response spectra shown in Figure 5 illustrate the effects of soil-structure interaction (SSI) on the amplification of accelerations at the top of the 3-, 6-, and 9-story reinforced concrete frames. For each structure, the comparison between the fixed-base models and those incorporating soil flexibility highlights an overall reduction in peak accelerations when SSI is considered. This attenuation is primarily due to the soil's hysteretic behavior and energy dissipation in a plastic soil medium. The reduction is more pronounced for low-rise structures, particularly the 3-story frame, where the interaction with the soil induces significant energy dissipation. However, spectral ordinates are higher for the 6-story structure, particularly at the second natural period $T_2 = 0.25\ s$. This period is close to the second natural period of the soil, calculated as follows:

$$f_n = (2n - 1)\ \frac{V_S}{4H}$$

where Vs is the shear wave velocity, H is the height of the soil deposit, and n represents the corresponding mode number. This proximity between structural and soil natural frequencies may lead to a resonance phenomenon. Furthermore, the spectral curves exhibit a shift of peak values towards longer periods in the presence of SSI, indicating an increase in the fundamental period of the structure due to soil flexibility. This effect is more pronounced for taller buildings, as they are more sensitive to softening effects induced by soil deformability. In contrast, the fixed-base models display higher spectral peaks concentrated over shorter periods, reflecting a globally stiffer behavior. The impact of SSI is therefore twofold: on the one hand, it reduces peak accelerations, which can be beneficial for the protection of internal equipment; on the other hand, it alters the dynamic response of the structure, making it more flexible, which can influence seismic design considerations.

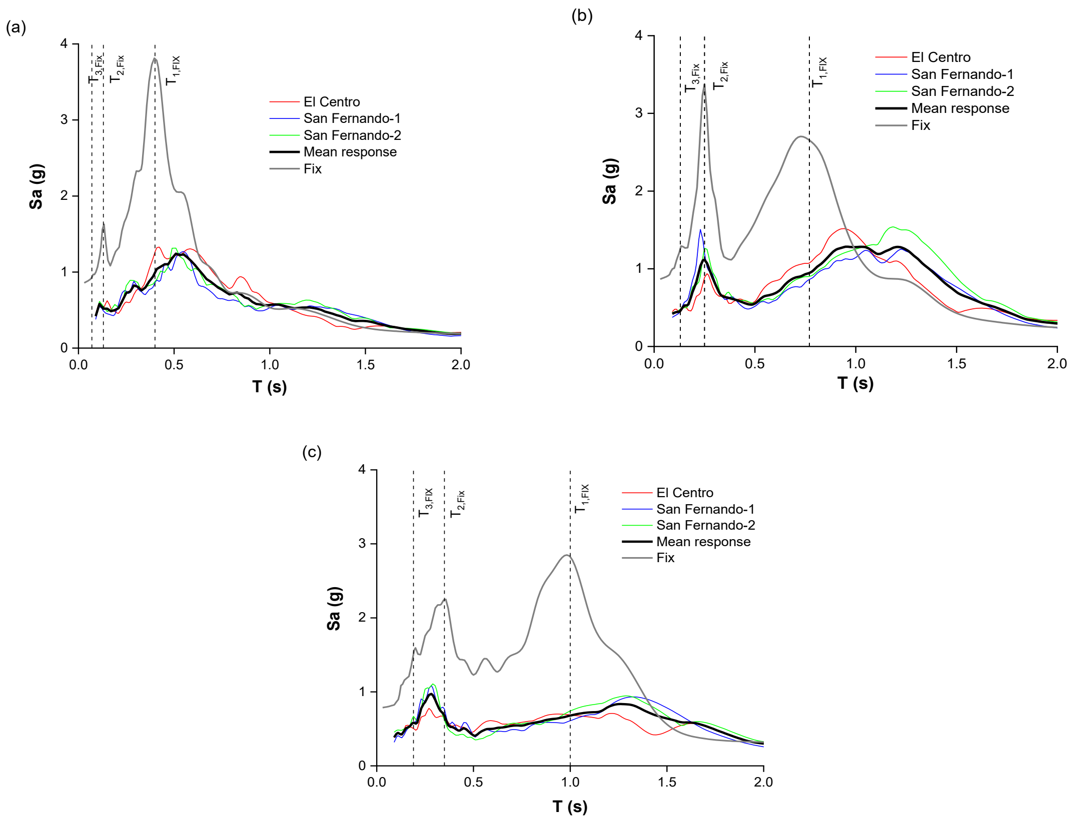

Figure 5. Acceleration response spectra at the roof of the frames: (a) 3-story frame, (b) 6-story frame, and (c) 9-story frame for fixed and flexible base models

The results in Figure 6 highlight the influence of soil-structure interaction (SSI) on the dynamic behavior of reinforced concrete frames with 3, 6, and 9 stories. The pie chart shows that the ratio of top lateral displacements between the SSI and fixed-base configurations is highest for the 3-story frame (45.34 %), followed by the 6-story frame (32.89 %) and the 9-story frame (21.97 %). This indicates that SSI amplifies displacements more significantly in low-rise structures, where soil flexibility plays a dominant role.

In parallel, the bar chart reveals that the maximum base shear force is consistently lower in the SSI case compared to the fixed-base case. This reduction is attributed to energy dissipation induced by soil deformability, which acts as a natural damper, as well as the hysteretic behavior of the soil, which contributes to additional energy dissipation through loading-unloading cycles. However, for the 6-story frame, the base shear force remains relatively higher than for the 3- and 9-story structures in the SSI case. This phenomenon can be attributed to resonance effects, resulting from the proximity between the fundamental period of the structure and that of the soil, thereby amplifying the dynamic response. These findings emphasize the importance of incorporating soil flexibility in seismic assessments to better capture dynamic effects and adapt seismic design accordingly.

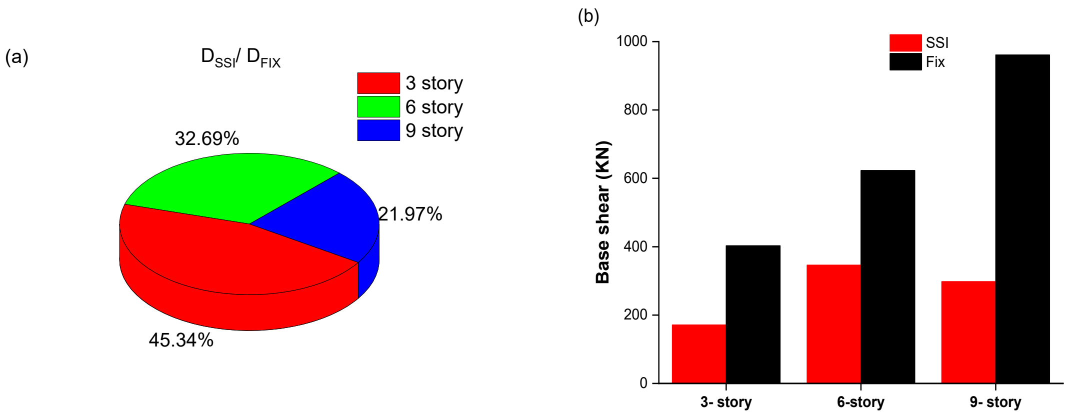

Figure 6. (a) Ratio of top lateral displacement between soil-structure interaction and fixed-base configurations, and (b) maximum base shear for 3-, 6-, and 9-story frames

Conclusion

This study examines the effects of soil-structure interaction (SSI) on the dynamic response of reinforced concrete moment-resisting frames of 3, 6, and 9 stories, designed according to the Algerian seismic code RPA99/Version 2003. The numerical analyses, conducted using FLAC2D, compare fixed-base and flexible-base conditions under three recorded seismic events, with SSI effects evaluated in terms of spectral acceleration, top lateral displacements, and base shear. The results indicate that:

- Peak spectral accelerations are reduced, with a more significant effect observed in low-rise structures. However, resonance effects in the 6-story frame, influenced by soil-structure interaction (SSI), lead to higher spectral ordinates at certain periods.
- Soil-structure interaction results in an elongation of the fundamental period, particularly for taller buildings, emphasizing the need to incorporate soil flexibility into seismic design for more accurate dynamic predictions.
- Lateral displacements are amplified due to SSI, with the 3-story frame experiencing the most pronounced increase, underlining the effect of soil deformability on structural deformations.
- SSI leads to a systematic reduction in base shear through energy dissipation from soil deformability and hysteretic effects. However, for the 6-story frame, resonance effects mitigate the reduction, amplifying the overall structural response.

SSI alters the dynamic response by increasing structural flexibility and modifying frequency content. The combined effects of soil deformability and energy dissipation mechanisms must be considered in seismic design to accurately assess structural performance.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM Journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

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