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# THE EFFECT OF SOIL-STRUCTURE INTERACTION ON NON-LINEAR STRUCTURAL ANALYSIS

*Alex Kurniawandy[1], Biefanza Rama[1], Ibnu Harahap[1] and Muhardi[1]

[1]Civil Engineering Department, Faculty of Engineering, Universitas Riau, Indonesia

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**ABSTRACT:** Soil–structure interaction (SSI) plays a crucial role in influencing the seismic response of buildings, particularly those supported by deep foundations on soft soil deposits. Although previous studies have reported that SSI may reduce seismic forces while increasing structural deformation, comparative evaluations considering different building heights under identical soil conditions remain limited. This study investigates the influence of SSI on 5-story and 10-story buildings, comparing mid- and high-rise buildings with significant differences in structural periods, reinforced concrete moment-resisting frame structures using response spectrum and nonlinear pushover analyses. The pile foundation is modeled using distributed spring elements along the pile depth to represent soil stiffness. The results indicate that incorporating SSI increases the natural period of the structures and reduces the seismic base shear by 10% for the 5-story model and 9% for the 10-story model. However, displacement increases by 40% and 26%, while inter-story drift rises by 32% and 38% for the 5-story and 10-story structures, respectively. Nonlinear analysis further shows reduced plastic hinge formation and improved structural performance index under SSI conditions. These findings highlight the importance of incorporating SSI into seismic design, where drift increases even as base shear decreases. This makes performance-based structural assessment even more realistic.

*Keywords: Soil-structure interaction, Restraint stiffness, Dynamic response, Seismic load*

## 1. INTRODUCTION

The interaction between a structure and the supporting soil is a critical factor influencing the overall structural response under static, dynamic, and seismic loading conditions. Soil–structure interaction (SSI) alters the stiffness, damping, and natural vibration characteristics of a structural system, thereby significantly affecting its seismic behavior and safety performance. Neglecting SSI in structural analysis may lead to inaccurate predictions of seismic forces, displacements, and damage mechanisms, particularly for buildings founded on soft soil deposits.

The rapid development of high-rise buildings has increased the demand for more accurate seismic assessment methods that account for SSI effects. Building height is one of the key parameters influencing SSI behavior, as structures with different numbers of stories exhibit distinct dynamic characteristics and interaction mechanisms with the underlying soil. Taller buildings generally have longer natural periods and greater sensitivity to soil flexibility, which may amplify displacement demands during earthquake events.

Numerous studies have investigated the effects of SSI on structural response. Previous research has shown that incorporating SSI into structural models can reduce seismic base shear forces while simultaneously increasing lateral displacements and inter-story drifts, especially for structures founded on soft soils [1-4]. These findings highlight the importance of accounting for SSI in seismic design to avoid unconservative assumptions about structural demand. However, most existing studies focus on single building configurations or limited height variations, and comparative evaluations of SSI effects on buildings with different story heights under consistent soil and foundation conditions remain underexplored.

Furthermore, many previous investigations primarily rely on linear elastic analysis, which may not adequately capture the inelastic behavior and failure mechanisms of structures subjected to strong ground motions. Nonlinear analysis methods, such as pushover analysis, provide valuable insight into structural ductility, plastic hinge development, and overall performance levels under seismic loading. Nevertheless, the combined evaluation of SSI effects using both linear dynamic and nonlinear static approaches for buildings of different heights is still limited in the current literature [5-8].

Therefore, this study aims to investigate and compare the influence of soil–structure interaction on 5-story and 10-story buildings, where mid- and high-rise buildings with significant differences in structural periods, reinforced concrete structures, are compared using response spectrum and nonlinear pushover analyses. Although research on SSI has been conducted extensively, few studies have directly compared reinforced concrete frames in mid-rise and high-rise buildings under identical soil and pile conditions, using both linear and nonlinear performance-based analysis. This research aims to enhance the understanding of how soil-structure interaction (SSI) affects structural behavior by analyzing important response variables such as displacement, inter-story drift, base shear, and performance level. The findings of this study are expected to contribute to improved seismic analysis practices and to support the development of more realistic, performance-based design guidelines for high-rise buildings that consider soil–structure interaction.

The remainder of this paper is organized as follows. Section 2 discusses the research significance of this study. Section 3 describes the methodology used in this study, including the structural model, the SSI modeling approach, and the analysis procedures. Section 4 presents the results and discussion, focusing on the influence of SSI on structural response and the formation of plastic hinges. Finally, Section 5 summarizes the main findings and conclusions of this study.

## 2. RESEARCH SIGNIFICANCE

Structural analysis considering earthquake loads rarely accounts for the actual foundation conditions at the structure's base. Analysis is often performed by modeling the structure's fixed restraints. This study provides significant insights into the dynamic response of reinforced concrete buildings, including soil-structure interaction (SSI), especially under seismic loads. By comparing 5-story and 10-story structures, we may observe how SSI affects structural behavior, base shear reduction, and performance level. These findings are expected to contribute to improved design practices and structural assessment methods for mid- and high-rise buildings in seismic zones, particularly those built on soft soil.

## 3. METHODOLOGY

This study aims to evaluate the influence of soil–structure interaction (SSI) on the dynamic response of reinforced concrete buildings. Structural models were developed with varying assumptions about structural configuration, foundation conditions, and soil stiffness to examine variations in structural response across different interaction scenarios.

Two structural models were analyzed: a 5-story building and a 10-story building. The selection of these models was based on their fundamental natural periods. The 5-story structure represents a relatively short-period system (less than 1.0 s), corresponding to the peak acceleration region of the response spectrum. In contrast, the 10-story structure represents a more flexible system with a natural period exceeding 1.0 s, where spectral acceleration values decrease significantly. This classification enables a comparative assessment of SSI effects on structures with different dynamic characteristics.

Table 1. Dimensions of structural beam elements

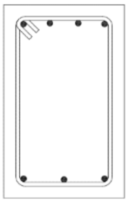
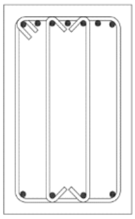
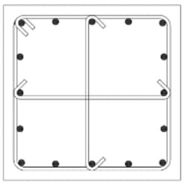
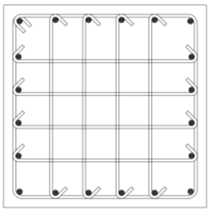
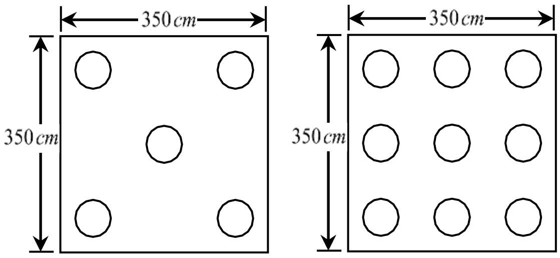
| 5-Story | 10-Story |
|---|---|
| Beam | Beam |
| 400 x 650 mm | 450 x 700 mm |
|  |  |
| Longitudinal rebar: | Longitudinal rebar: |
| Top 4 D19 | Top 7 D19 |
| Bottom 3 D19 | Bottom 4 D19 |
| Transversal rebar: | Transversal rebar: |
| D13 – 100/150 | 4.D13 – 100 |
| | 2.D13 - 100 |

Table 2. Dimensions of Structural Column Elements

| 5-Story | 10-Story |
|---|---|
| Column | Column |
| 700 x 700 mm | 900 x 900 mm |
|  |  |
| Longitudinal rebar: | Longitudinal rebar: |
| 16.D25 | 20.D25 |
| Transversal rebar: | Transversal rebar: |
| 3.D13 - 100 | 6.D13 - 100 |

The structure is made of reinforced concrete in accordance with SNI 2847:2019, has a symmetrical layout, and uses a moment-resisting frame structural system. The foundation used is a pile foundation, as shown in Fig. 1. The pile has a diameter of 600 mm and a depth of 20 m. The geometry data for the structural elements are shown in Tables 1 and 2.



(a). 5-story pile arrangement

(b). 10-story pile arrangement

Fig. 1 Pile arrangement configuration

Structural modeling is done by combining the upper structure and foundation. The foundation was modeled using spring elements at 1-meter intervals along the pile depth to represent the surrounding soil stiffness, as shown in Fig. 2. Discretizing the spring element every 1 m is intended to model a soil reaction distribution that more closely approximates actual conditions and to ensure that soil forces are not concentrated at only a few points, thereby producing a continuous reaction along the structural element and resulting in a smoother deflection curve. The horizontal and vertical soil stiffness values are calculated using the modulus of subgrade reaction, as expressed in equation (1).

$$K_s = \frac{0.65}{D} \times \sqrt[12]{\frac{E_s D^4}{E_p I_p}} \times \frac{E_s}{1-\mu_s{}^2} \qquad (1)$$

Here, $K_s$ denotes the modulus of subgrade reaction (kN/m$^3$), and $D$ is the diameter of the pile. $E_s$ is denoted as soil modulus (kN/m$^2$ ), and $E_p$ is pile modulus (kN/m$^2$). $\mu_s$ is Poisson's ratio. The pile is divided into discrete segments of length (L), and soil springs were assigned to the nodes. Then, to calculate the stiffness of the horizontal soil, the following formula [9] is utilized:

$$K_{sh} = K_s \times D \times L \qquad (2)$$

Vertical end-bearing stiffness ($K_{sv}$) can be computed using the following (3) expression.

$$K_{sv} = \frac{\pi}{4} D^2 \times K_s \qquad (3)$$

The vertical stiffness of the skin friction resistance is calculated using the following equation [10].

$$K_{vf} = 1.8 \times E_s \times \mu \times \lambda^{(0.5 - \lambda/h)} \times \alpha \qquad (4)$$

Where $\eta$ is the ratio of the length of the pile and the diameter ($L/D$). $\lambda$ is the ratio of the modulus of soil and modulus of pile ($E$ /$E_{sp}$). α is the influence of vertical stiffness distribution along the length of the piles. The total skin friction resistance provided by the pile (α) is calculated as follows:

$$\alpha = \frac{Z \cdot \Delta}{L^2} \qquad (5)$$

Where $Z$ is the spring depth position (m), $\Delta z$ is the distance between springs (m), and $L$ is the foundation depth (m).

The earthquake load analysis in this study uses the response spectrum analysis (RSA) method, with response spectrum design in accordance with Indonesian earthquake regulation SNI 1726: 2019. The building is located in Pekanbaru with a short-period earthquake acceleration ($S_s$) of 0.38g and a 1-second period acceleration ($S_1$) of 0.29g.

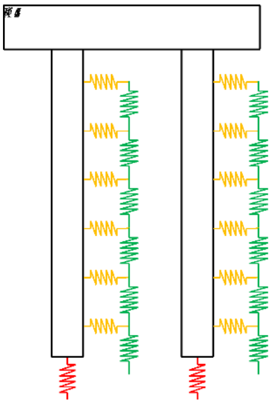
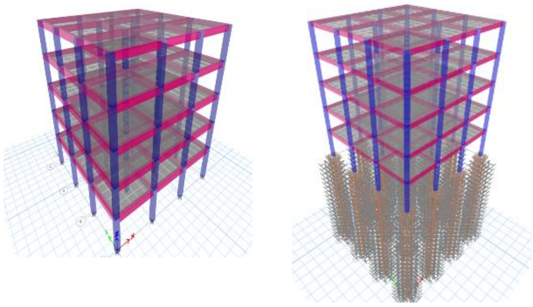


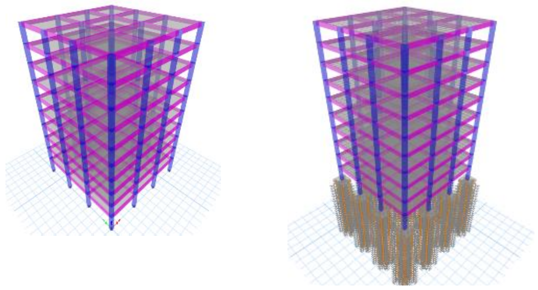
Fig. 2. Modeling a spring on a foundation

Figure 3 is the numerical model reviewed in this study. The modeling used 5- and 10-story structures with 2 different support conditions.



(a) 5-story with a fixed base

(b) 5-story with SSI



(c) 10-story with a fixed base

(d) 10-story with SSI

Fig. 3 Numerical model

## 4. RESULT AND DISCUSSION

The research findings are presented progressively, beginning with the evaluation of structural dynamic characteristics and followed by the structural response under seismic loading. One of the most critical dynamic parameters in structural analysis is the fundamental natural period, which reflects the vibration characteristics of a building as governed by its mass and stiffness distribution.

When soil–structure interaction (SSI) is incorporated into the analytical model, modifications in structural stiffness occur, leading to changes in dynamic properties. Several studies have reported that the inclusion of SSI generally increases the fundamental natural period of structures [12]. In particular, previous research indicates that the period may increase by approximately 12.2% when SSI effects are considered [13]. This increase in period directly influences the seismic demand obtained from the response spectrum and subsequently affects base shear and displacement responses. This SSI analysis will result in a more accurate design by determining the appropriate seismic load based on the structural conditions. However, if it is ignored, the structure will be treated as resting on rigid (fixed) supports, even if the foundation used is different. The design cannot account for different types of foundations. This analysis can lead to inaccurate estimates of the internal forces acting on the structure. In some cases, such calculations may not provide sufficient safety.

### 4.1 Structure Period

This study evaluates the influence of soil–structure interaction (SSI) by comparing the fundamental period of structural models with different numbers of stories. The objective is to examine the extent of period elongation induced by SSI. Modal analysis was performed to determine the fundamental natural period of each structural configuration. The calculated period values for both fixed-base and SSI models are presented in Table 3.

Table 3. Structural period and frequency

| Structural model | Period | Freq. | Ratio of freq. |
|---|---|---|---|
| 5-story fixed base | 0.984 | 1.016 | 1.233 |
| 5-story with SSI | 1.213 | 0.824 | |
| 10-story fixed base | 2.347 | 0.426 | 1.164 |
| 10-story with SSI | 2.989 | 0.366 | |

As presented in Table 3, the frequency ratio reflects the relative stiffness of the structural system. The inclusion of soil–structure interaction (SSI) reduces overall system stiffness due to the flexibility of the soil and foundation, thereby elongating the structural period. Structures modeled with SSI, therefore, exhibit a greater tendency toward deformation. The interaction between the soil and foundation, including shear, rotational, and bending deformations, further contributes to the increase in the fundamental period [14,15].

A comparative evaluation of the 5-story and 10-story models indicates that the 10-story structure experiences a more pronounced period elongation. This behavior is attributed to its greater height and inherently more flexible structural system. Under identical soil and foundation stiffness conditions, the influence of SSI on dynamic characteristics becomes more significant as the structural height increases.

### 4.2 Base Shear

The elongation of the structural period due to soil–structure interaction (SSI) reduces the corresponding spectral acceleration, thereby decreasing the seismic forces acting on the structure. Previous studies have similarly reported that SSI generally reduces peak floor accelerations throughout the structural height [16]. Under seismic excitation, inertial forces develop from the interaction between structural mass and ground acceleration, producing horizontal shear forces that accumulate at the base, commonly referred to as base shear. When SSI is incorporated into the analytical model, the flexibility of the soil–foundation system decreases the overall structural stiffness and modifies the dynamic response, resulting in lower base shear values compared to the fixed-base condition[17].

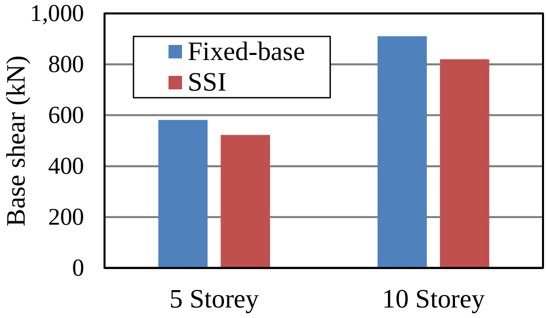


Fig. 4 Base shear

As shown in Fig. 4, incorporating SSI reduces the seismic base shear in both structural models. The reduction is approximately 10% for the 5-story and 9% for the 10-story. This reduction is attributed to the elongation of the fundamental period, which shifts the structural response beyond the constant-acceleration plateau of the response spectrum. For structures with periods near 1.0 seconds, this shift leads to a noticeable decrease in spectral acceleration and, consequently, a lower base shear demand [18].

The consideration of SSI also influences the distribution of shear forces along the height of the structure. Figs. 5 and 6 present the variation of story shear in the 5-story and 10-story models, respectively. The redistribution is non-uniform: lower stories generally experience more pronounced reductions in shear demand, while upper stories show minor changes or slight increases. Such variations may alter internal force demands and, in some cases, shift the location of peak shear. Therefore, accurate SSI modeling is essential to ensure reliable estimation of seismic forces, particularly for structures with irregular mass or stiffness distributions.

These results suggest that future investigations may incorporate probabilistic approaches to account for the spatial variability of soil properties and their potential influence on SSI behavior.

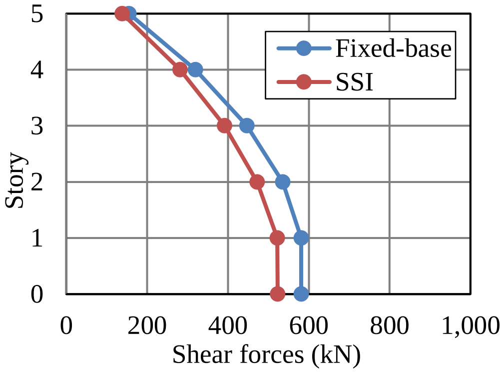


Fig. 5 Shear force of a 5-story

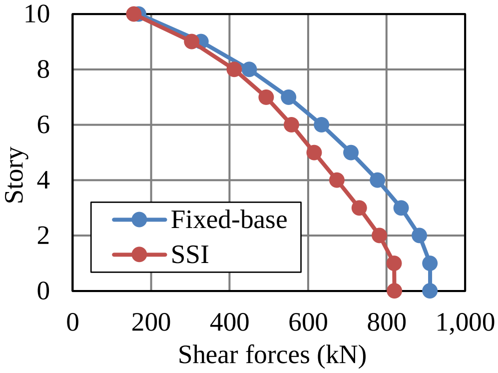


Fig. 6 Shear force of a 10-story

### 4.3 Displacement

The effect of SSI on the 10-story structure is much greater than that of the 5-story structure. The base shear decrease in the 10-story structure affects the shear force distribution, with the most significant decrease occurring at the first story. As the building height increases, the seismic shear force decreases proportionally.

Although SSI structures receive smaller earthquake forces, they experience larger displacements than fixed-base structures [19]. The displacement comparison is shown in Figs. 7 and 8. It can be seen in both figures that at the bottom (story-0), there is a shift at the base, indicating that the SSI model no longer assumes a fixed support condition.

This shift at the base confirms that the foundation no longer behaves as a rigid support, allowing relative movement between the structure and the ground. As a result, the deformation profile along the height becomes more gradual, reflecting the added flexibility from the soil.

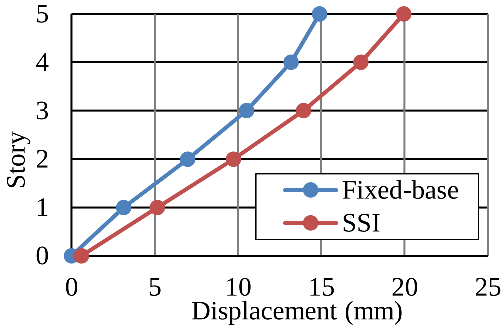


Fig. 7 Displacement of a 5-story

The displacement of the 5-story structure increases by approximately 40% due to SSI effects. The increase in displacement due to soil–structure interaction occurs as a result of changes in the response of the structure to the forces it receives from the ground.

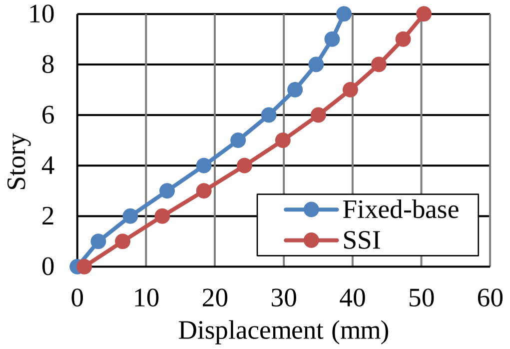


Fig. 8 Displacement of a 10-story

When there is interaction between the structure and the ground, the support considered initially rigid becomes more flexible. This additional flexibility causes an increase in deformation in the structural elements, which is especially noticeable on the ground floor, and the support becomes more susceptible to changes in stiffness. The flexibility of the foundation that supports the structure plays an essential role in increasing the deformation of the structure [20].

The 10-story structure experienced an increase in displacement due to the influence of SSI by 26%. This value exceeds the increase observed in the 5-story structure. The increase in displacement due to SSI in the 10-story structure is greater than that in the 5-story structure because taller structures tend to have longer periods, allowing for greater deformation. Although the stiffness of the foundation is the same, the height of the structure increases the difference in displacement due to the distribution of earthquake shear forces on each floor.

### 4.4 Drift

In addition to increasing displacement, SSI can increase the story drift value through its impact on the dynamic behavior of the structure. When there is interaction between the structure and the ground, there is a redistribution of forces in the structure. One of the effects is the increase in lateral deformation and story drift of the building due to SSI [21, 22].

The behavior of this structure shows that the change in stiffness at the restraint, which is the modeling of the SSI, allows the structure to be more exposed to lateral displacement, thus increasing the story drift of the building. As seen in Fig. 9, the drift ratio increases when modeling SSI. The magnitude of the increase varies for each floor.

As well as for the 10-story structure in Fig. 10. An increase in the drift ratio also occurs when modeling the structure with SSI. The average increase for all floors is about 32% in the 5-story structure, while in the 10-story structure, it is 38%. This increase in the 10-story structure is greater than that in the 5-story structure. This occurs because the 10-story structure has lower stiffness than the 5-story structure, and the additional flexibility introduced by SSI further amplifies the drift response.

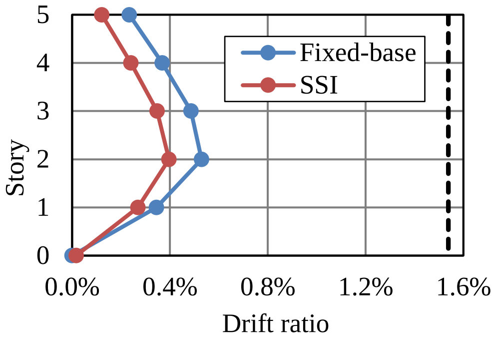


Fig. 9 Story drift of a 5-story

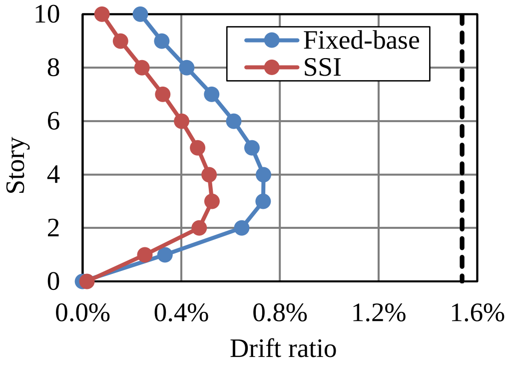
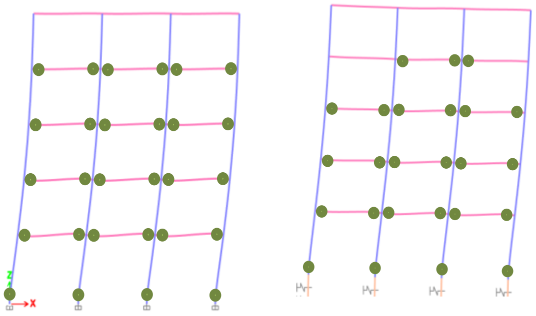


Fig. 10 Story drift of a 10-story

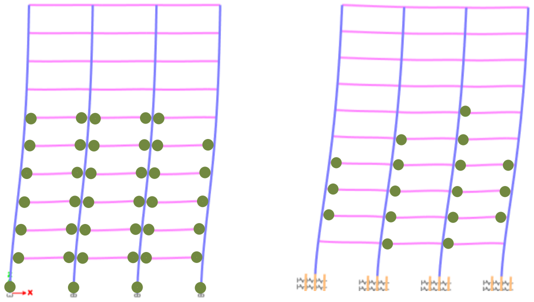
### 4.5 Performance Structure

Pushover analysis is performed on all structural models until the structure yields. The yielding is characterized by the appearance of plastic hinges in several structural components, as shown in Fig. 11. An ideal collapse mechanism occurs when plastic hinges form at the ends of all beams and at the bottom end of the column bases. The plastic hinges that occurred in this study are considered the ideal collapse mechanism, and there is no soft story mechanism.

The lower number of plastic hinges occurs (Fig. 11) because less seismic load is transferred to the upper structure than if fixed supports were assumed. From a structural resilience perspective, this condition is highly advantageous as it maintains structural integrity and residual stiffness following an earthquake. Structures with fewer plastic hinges are also less likely to experience global collapse mechanisms and tend to exhibit smaller residual drifts.



(a) 5-story with fixed-base (b) 5-story with SSI



(c) 10-story with fixed-base (d) 10-story with SSI

Fig. 11 Plastic hinge mechanism

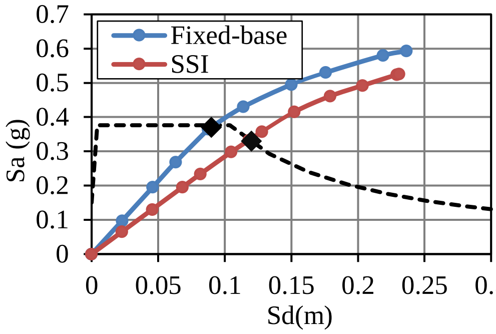


Fig. 12 Pushover curve of a 5-story

A comparison of the capacity curve resulting from the pushover analysis can be seen in Figs. 12 and 13. The intersection point of the capacity curve and the response spectrum curve represents the performance point of the structure. Figs. 12 and 13 show that the point of intersection is located after the yield point is reached, which is represented by the curve that is no longer linear.

A higher performance index indicates better structural performance. Table 4 shows that the structure with SSI has a greater performance index than the fixed base structure, both at 5 stories and at 10 stories. This confirms that SSI contributes positively to structural performance. Therefore, incorporating SSI into seismic design may lead to more efficient and resilient structural systems.

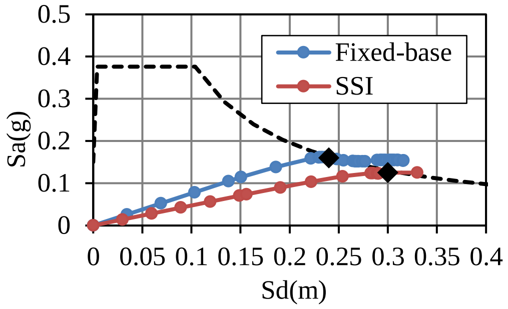


Fig. 13 Pushover curve of a 10-story

Table 4. Performance index

| Indicator | 5-story fixed-base | 5-story SSI | 10-story fixed-base | 10-story SSI |
|---|---|---|---|---|
| Sa (g) | 0.37 | 0.33 | 0.16 | 0.14 |
| Sd (m) | 0.09 | 0.12 | 0.22 | 0.27 |
| Base shear (kN) | 5075 | 4547.3 | 7102.9 | 6217 |
| Displ. (m) | 0.12 | 0.16 | 0.29 | 0.34 |
| Index Performance | 0.033 | 0.039 | 0.035 | 0.037 |

## 5. CONCLUSION

This study investigates the influence of SSI on 5-story and 10-story buildings, comparing mid- and high-rise buildings with significant differences in structural periods, reinforced concrete moment-resisting frame structures using response spectrum and nonlinear pushover analyses.

The results indicate that SSI significantly influences the dynamic behavior and seismic response of the analyzed structures. The fundamental natural period of the 10-story structure is longer than that of the 5-story structure, resulting in a smaller seismic base shear coefficient for the taller structure. The frequency ratio, which represents the stiffness ratio between fixed-base and SSI models, confirms that mid-rise structures are particularly sensitive to SSI effects due to the reduction in restraint stiffness caused by soil flexibility.

The inclusion of SSI leads to a reduction in seismic base shear for both structural configurations, with reductions of approximately 10% for the 5-story structure and 9% for the 10-story structure. However, despite experiencing lower seismic forces, structures modeled with SSI exhibit larger displacements compared to fixed-base models. The decrease in restraint stiffness results in displacement increases of approximately 40% for the 5-story structure and 26% for the 10-story structure.

Nonlinear analysis further reveals that SSI reduces the number of plastic hinges formed within the structure compared to the fixed-base condition. Consequently, the structural performance index indicates that structures incorporating SSI achieve a better overall performance level under seismic loading. SSI should be included when drift governs. Fixed-base models may be unconservative for serviceability.

Further research could be expanded to account for nonlinear soil behavior and ground motion variability in order to further refine SSI-based performance assessments.

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