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# Evaluating the Influence of Soil-Structure Interaction on Seismic Response of Commercial Structures in Ecuador

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***Abstract***

Ecuador is a country with a high seismic threat due to its location within the Pacific Ring of Fire and the presence of soft soils in certain areas. Generally, an infinitely rigid base is assumed in structural modelling, however this consideration does not always provide reliable results even though many guidelines recommend the assessment of soil-structure interaction (SSI) in the design process. Therefore, this research work aims to recognize the influence of SSI on the seismic response of structures through a parametric study in the design process using the NIST methodology. For the commercial building in consideration, this study showed a general increment in design parameters as soil quality dwindled and seismic hazard worsened. The results provide an opportunity to optimize the design and enhance the safety of the structure.

***Keywords:*** Soil-structure interaction, impedance functions, structural response, structural flexibility

## 1 Introduction

The rapid development of populations has generated the need to increasingly build taller and more complex buildings. In this context, civil engineers are confronted with diverse challenges, such as designing and assemble on unstable soils, the interaction between adjacent structures, the influence of the foundation type on the superstructure, high seismic risk, among others.

The Ecuadorian territory is characterized by being exposed to a high risk of large magnitude seismic events due to its location in the subduction zone of the Nazca and South American plates [1]. Therefore, comprehending the actual structural behavior of buildings becomes a focal point of study with great interest in this region. Research conducted on the dynamic behavior of structures has demonstrated that results can vary considerably when implementing a SSI analysis instead of assuming rigid supports [2]-[3]-[4]. One of the main reasons for this difference lies in the fact that the energy of the structure when located on a flexible medium, tends to dissipate due to the hysteric action of the respective medium [5].

SSI analyses allow us to understand the dynamic behavior and phenomena related to wave propagation in coupled soil-structure systems [6]. Indeed, the structural behavior of a building is influenced by the interaction between the surface of the substructure and the soil [7].

The interaction between the soil and the foundation can be described through three categories [8]. The first one considers the movement experienced by a layer of soil over a rocky stratum, where the soil layer exhibits a different displacement compared to the rock. This phenomenon is known as soil motion amplification and is present even when there is no additional load, such as a building's load. The second one analyses the embedding of the foundation in the soil, considering it as a rigid base. In this case, horizontal displacement generates inertial loads on the structure that depend on its height. As a result, the movement of the soil-structure system is affected by the reflection of waves in the foundation, which is known as the wave dispersion effect. Finally, the third category refers to the inertial loads that generate overturning moments and shear forces acting at the base of the structure, leading to soil displacement. This phenomenon causes an amplification in the foundation movement and becomes evident in very heavy structures, making it necessary to conduct a SSI analysis regardless of the soil type. A real SSI analysis is primarily affected by the inertial and kinematic components. The inertial component induces elongations in the structure's periods and modifications in damping. This behavior is represented in the equations provided by NIST [9]. The second component describes the deviation of the initial motion of the foundation.

Several investigations, including the contributions of Wolf[5]-[8]-[10]-[11] have attempted to describe SSI. However, there is still a lack of consensus among researchers in determining the effects of seismic response on structures. For this reason, this type of analysis has not been incorporated into certain regulations, despite the significant need to include it in structural designs [12].

This research is based on the manuals "Soil-Structure Interaction for Building Structures" and "Practical Guide to Soil-Structure Interaction" proposed by the NIST [9] and FEMA [13]. These manuals provide clear methodologies for SSI analysis, considering various types and geometries of foundations, as well as the geotechnical characteristics of the study site. Therefore, the objective of this study is to identify the dynamic behavior of a typical commercial building in Ecuador, considering different types of foundations and soils, to assess the influence of SSI analysis on seismic response.

## 2 Methodology

### 2.1 Structural model

For this study, a 6-story commercial building is considered, with concrete of compressive strength equal to 28 MPa and reinforced with A615 steel. The height of each floor is 3 meters, resulting in a total building height of 18 meters. The structural layout in plan view is shown in Figure 1. The building's structure consists of moment-resisting special frames with perimeter columns measuring 0.70x0.70 meters and interior columns measuring 0.65x0.65 meters, for the first 3 floors. In the last 3 levels, the columns dimensions are 0.65x0.65 meters and 0.60x0.60 meters, respectively. A ribbed slab with a thickness of 0.20 meters was used in one direction, considering an imposed dead load (Dt) of 5.62 kN/m$^2$, which includes the weight of walls, installations, and finishes. Additionally, a live load (Lo) of 2.4 kN/m$^2$ was considered, extracted from Table 4.3-1 of the ASCE 7-22 [14].

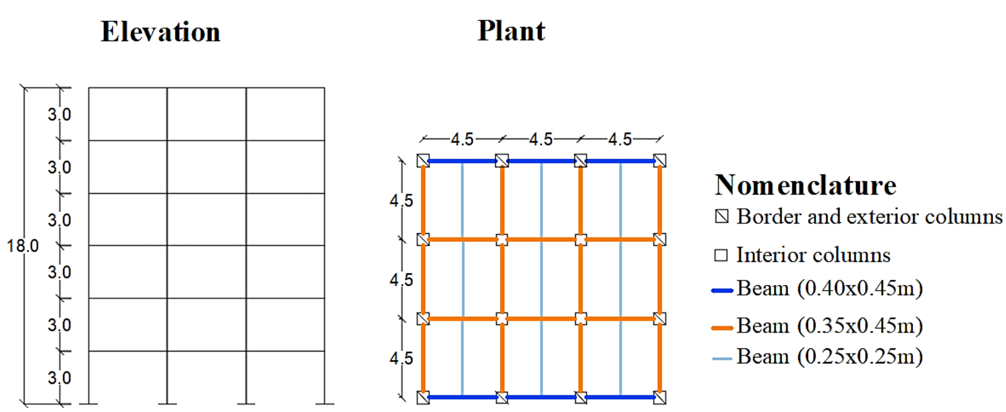


Fig. 1: Elevation and plant configuration of building type.

For the parametric study, 27 cases were established. The initial 9 cases correspond to fixed based models, first varying the zone factors for Ecuador (Z) of 0.15, 0.40, and 0.50, in other words, the Peak Ground Factor (PGA). Subsequently, the soil type varied between C, D and E. The following cases involve SSI and alter the parameters likewise; however, even-numbered cases relate to deep foundations, while odd-numbered ones concern shallow foundations.

To model the dynamic effect of seismic activity on the structure, the design response spectrum established by NEC SE-DS (National Earthquake Code - Spectral Elastic Design Response) [15] is utilized in each study zone, accounting for zone-specific accelerations, soil type, and the structural importance factor. Nine acceleration spectra were then derived following the NEC SE-DS procedure, employing an importance factor (I) of 1 and a seismic resistance reduction factor (R) of 6. For instance, Figure 2 shows the inelastic spectra applied in case 6, these are used to represent the ground motion characteristics in the seismic analysis of the building.

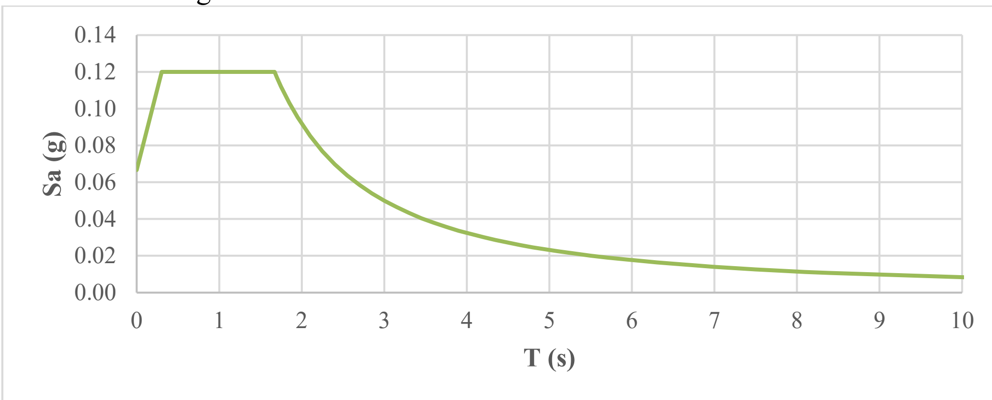


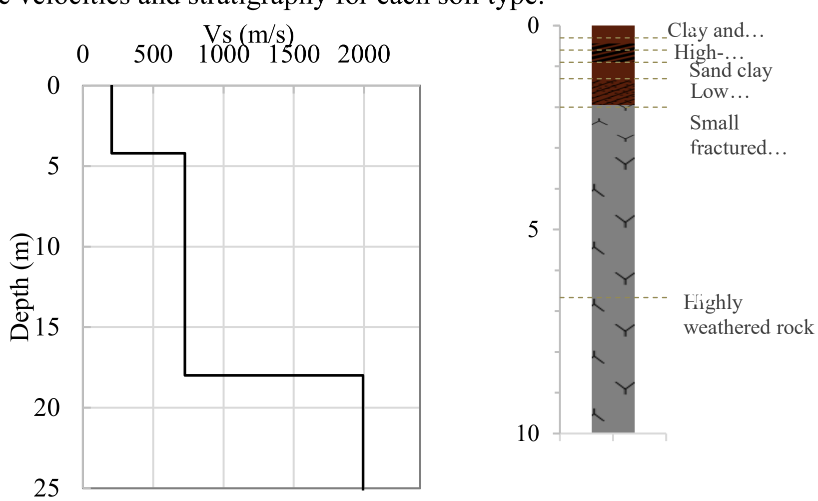

Figure 2: Response spectrum for case study number 6.

For the design of both the shallow and deep foundations, the most critical case was selected, which corresponds to a soil type E and zone factor 0.4. The soil characteristics will be described in Section 2.2, considering the loads from the superstructure and the properties of the underlying stratum. For the shallow foundation, a continuous footing was established in one direction, measuring 1.9 meters in width, and having a thickness of 0.35 meters. Additionally, a foundation beam measuring 0.50x0.90 meters was placed at a depth of 1.20 meters. Regarding the deep foundation, square piles with dimensions of 0.50 meters were chosen at a depth of 40 meters.

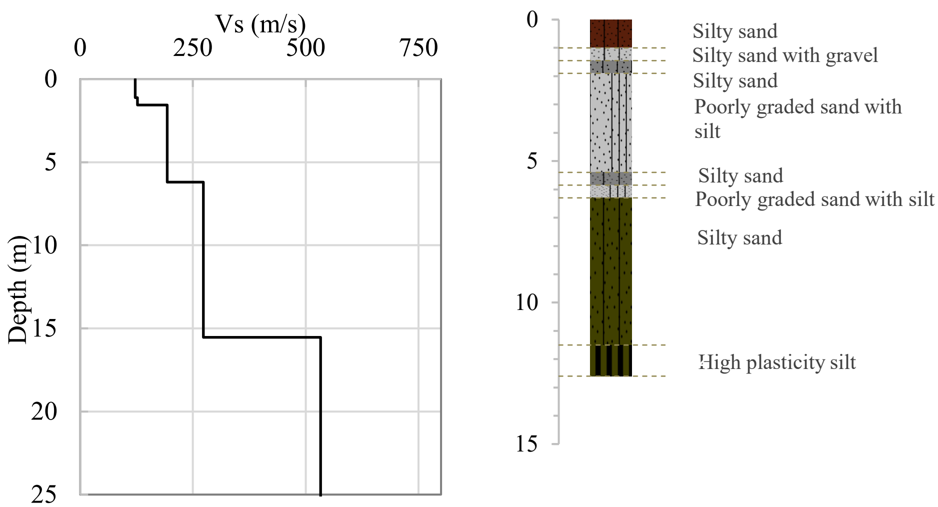
## 2.2 Soil characteristics

To establish the characteristics of soil types C, D, and E, geotechnical studies provided by the consulting company Geoestudios S.A from previous projects carried out in the city of Guayaquil were used.

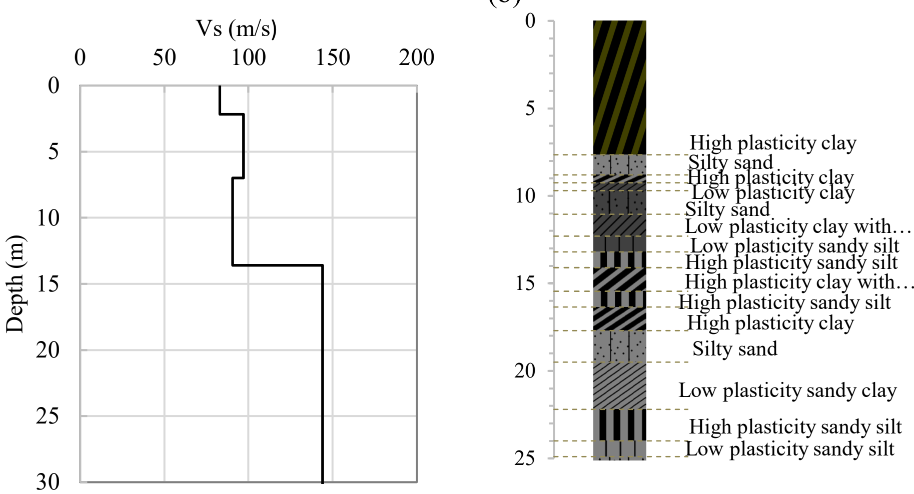
The tests conducted aimed to determine the shear wave velocities of the soils. For soil type C, the shear wave test at an average depth of 30 meters with a shear wave velocity of 660 m/s was chosen due to its higher accuracy in describing the soil type. For soil type D, a shear wave velocity of 305.59 m/s was established, while for type E, it was 113 m/s. Fig. 3 illustrates the wave velocities and stratigraphy for each soil type.




(a)




(b)




(c)

Fig. 3: Ground wave velocity and stratigraphy: (a) Soil type C, (b) type D, (c) type E

The Poisson's ratio was determined based on the soil stratum classification underlying each foundation type. For soil type C, the stratigraphy reveals clayey soils with 39% of sand in the first 3 meters, followed by a layer of clayey sand, and finally, a highly weathered rock. Consequently, the Poisson's ratios are 0.40 for the first stratum, where the shallow foundation is placed, and 0.32 for the deep foundation.

Soil type D is predominantly sandy with a Poisson's ratio ($\upsilon$) of 0.30. On the other hand, soil type E consists of clayey soils, where the first stratum at a depth of 9.70 meters has a Poisson's ratio ($\upsilon$) of 0.40, and sandy soils at greater depths with a Poisson's ratio ($\upsilon$) of 0.30. These values were chosen considering the ASCE 7-16[14] and ASCE 41-17 [16].

## 2.3 SSI numerical simulation

To represent the behavior of the system using a SSI analysis, springs are incorporated at the base of the structure modeled in a finite element method software, placed at degrees of freedom where the soil contributes flexibility depending on the type of foundation (shallow or deep). These springs are calculated using impedance functions, which describe the stiffness and damping characteristics, considering the interaction between the soil and the type of foundation. These impedance functions are essential in capturing the dynamic response of the structure-soil system and enabling a more accurate representation of the real-world behavior. This study analyzes the SSI in the linear range; therefore, according to ASCE 7-16, kinematic effects should not be considered.

### 2.3.1 Shallow foundation

Equation (1) describes the function for calculating the stiffness of springs in shallow foundations.

$$k_j = K_j * \alpha_j * \eta_j \quad (1)$$

Where, $\eta_j$ correspond to the embedment modifier, $K_j$ represents the static stiffness of shallow foundations in the j-th mode. For this purpose, Pais and Kausel [17] establish impedance functions that obtain the translational and rotational stiffness as a function of the shear modulus, G, mean width, B, Poisson's ratio, $v$,, and mean length, L, of the foundation

Finally, $\alpha_j$ corresponds to dynamic stiffness modification factors that depend on $\alpha_0$ , as described in Equation 2.

$$a_0 = \frac{2\pi B}{\tilde{T} v_s} \quad (2)$$

$\tilde{T}$, corresponds to the fundamental period of the flexible base model, and $v_s$ represents the average effective shear wave velocity. It is important to mention that it should be corrected considering that these measurements are generally taken away from the foundation's embedment depth. As a result, the shear modulus varies with the depth of the soil, and the addition of an additional weight (building) complicates the selection of the appropriate wave velocity. The correction process is described in section 2.2.2, and the equations to obtain $K_j, \eta_{j,} \alpha_j$ can be found in Table 2-2a, 2-2b, and 2-2c of the NIST 2012 report [9].

### 2.3.2 Deep foundation

For vertical deep foundations of a single pile, the calculation of the spring stiffness factor $k^p$ is shown in Equations 3 and 4, obtained from [9].

$$k_j^p = K_j^p * \alpha_j^p \quad (3)$$

$$K^p = \chi_j * E_s * d \quad (4)$$

$K_j^p$ corresponds to the static stiffness in the j-th mode of vibration, which depends on $\chi_j$, a dimensionless constant that is a function of the dimensionless modulus of subgrade reaction $\delta_j$, Young's moduli of the soil $E_s$, the material of the pile $E_p$ and the weight factors $w_{pj,} w_{sj}, w_{bj}$ . $d$, represents the diameter of the pile. Equation 5 shows how to obtain $E_s$.

$$E_s = 2 * (1 + v) * G \quad (5)$$

The Young's modulus of the soil is related to the Poisson's ratio $v$, and the shear modulus $G$, which is determined by the active length of the pile.

The $\alpha_j^p$, similarly to shallow foundations, it corresponds to dynamic modification factors. In this case, $a_0$ obtained from [18] is shown in Equation 6.

$$a_0^p = \frac{2\pi d}{\tilde{T} v_s} \quad (6)$$

The equations for calculating $\chi_j$, and its factors considering the translational case in the x-axis and z-axis, and $\alpha_j^p$ are shown in Table 2-4a and 2-4b [9].

# 3 Results

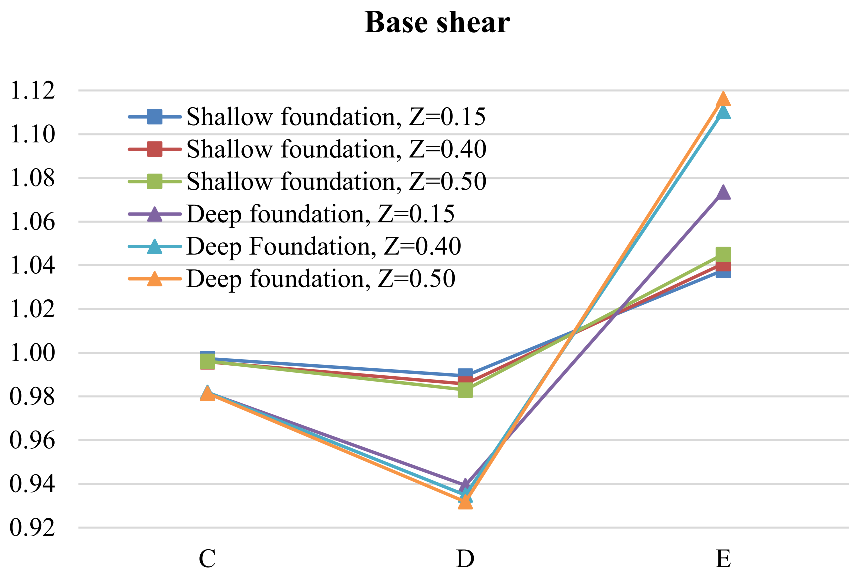



Fig. 4: Base shear and moments ratios of the SSI model to the fixed model

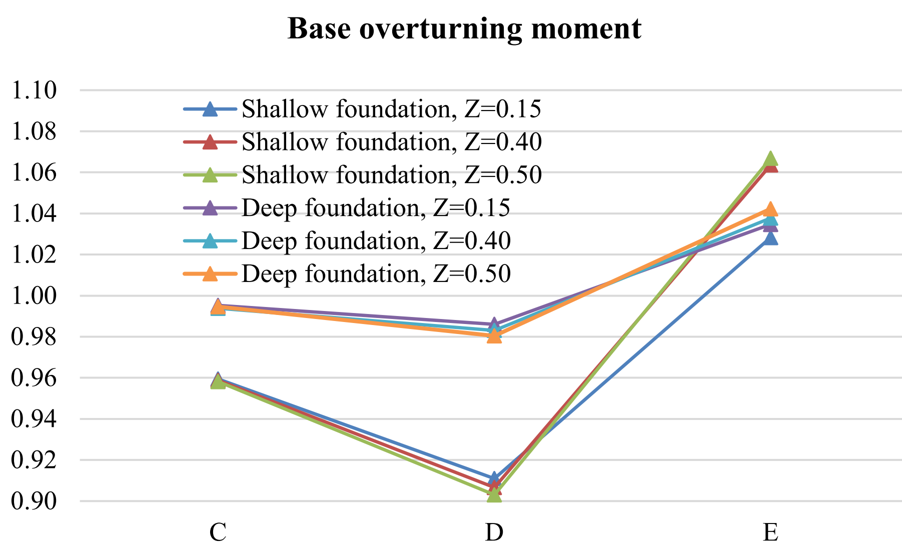
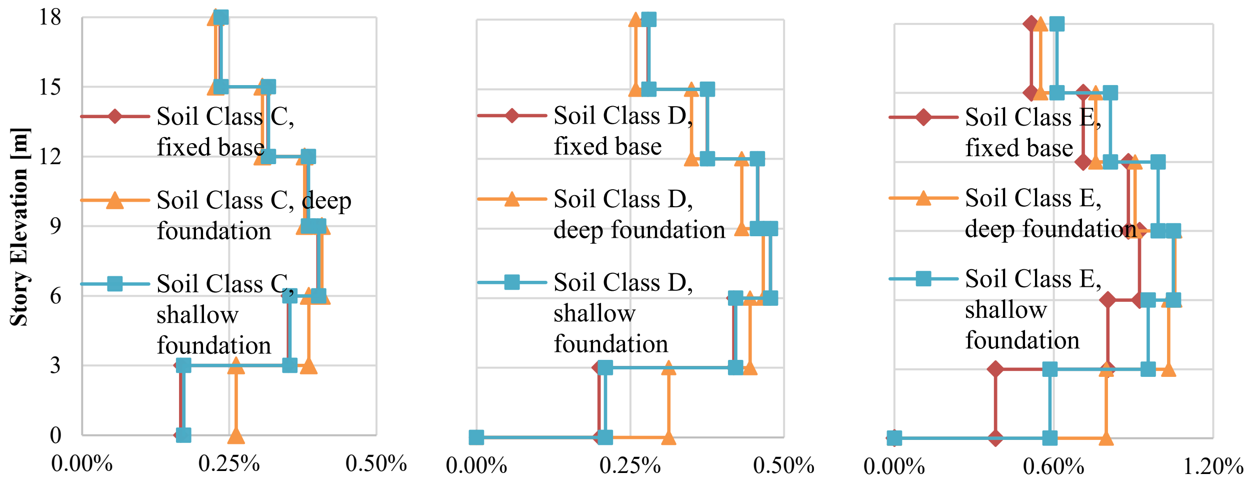
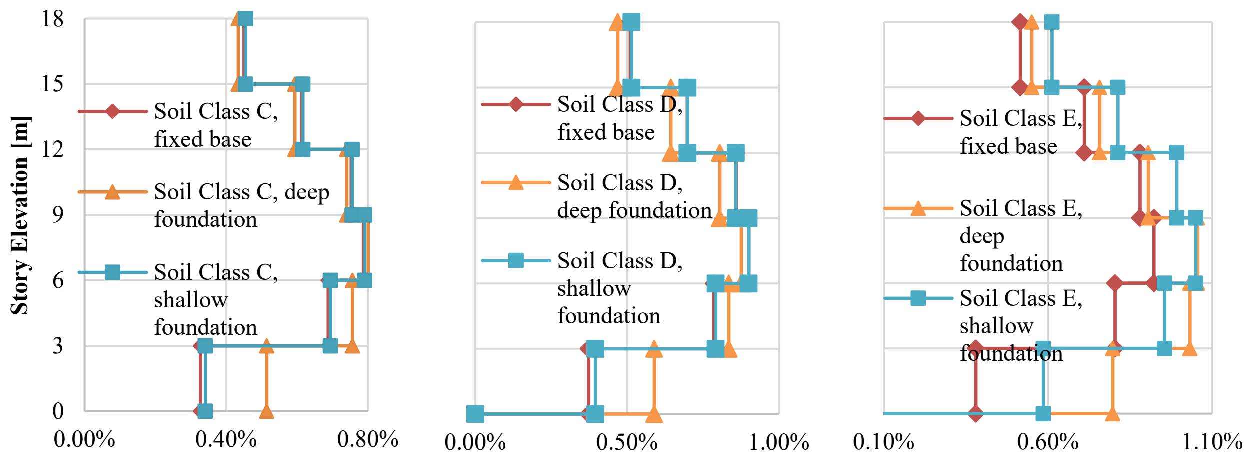


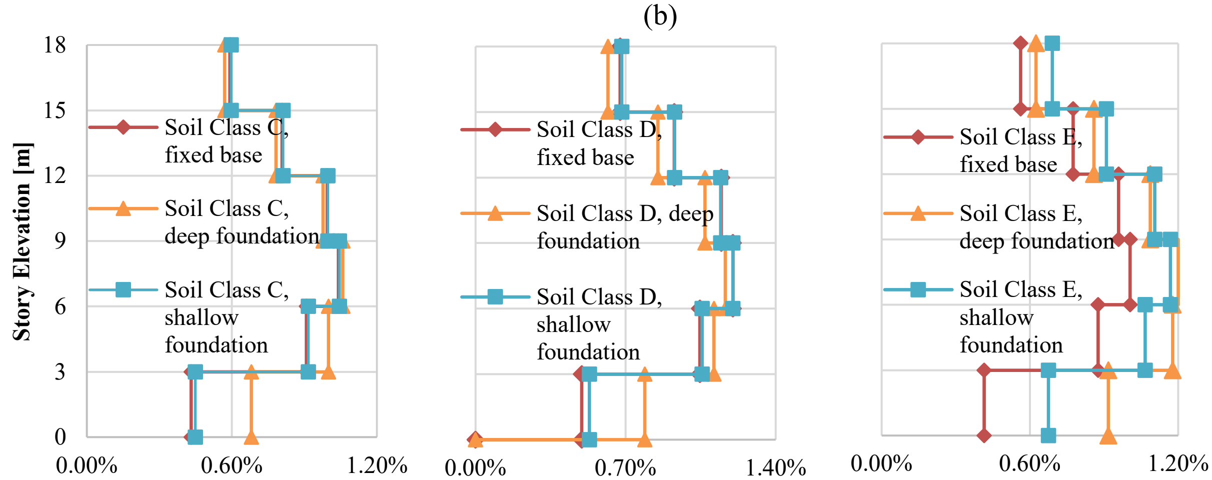

Fig. 5: Base shear and moments ratios of the SSI model to the fixed model




(a)




(b)




(c)

Fig. 6: Story drifts according to seismic zone: (a) Z=0.15, (b) Z=0.40, (c) Z=0.50 in rows and soil types C, D, E in columns

Figures 4 and 5 compare the base shear and moments using different types of soils and seismic zones. The ratios are defined as $r = \frac{Force\ in\ fixed\ base}{Force\ in\ flexible\ base}$, where values of $r > 1$; signify that the forces obtained through SSI analysis were greater than those from models with fixed bases.

According to the obtained results, for both shallow and deep foundations, fixed-base models provide a good approximation for soils of type C and D in any seismic zone. However, when analyzing a building on type E soil, the resulting forces at the base can increase by up to 12% when conducting an SSI analysis.

Figure 6 shows the story drift for each type of soil, foundation (fixed or elastic base), and seismic zone. In no case does the floor drift exceed the recommended 2% limit stipulated by the Seismic Hazard Regulations outlined in NEC (NEC-SE-DS) for reinforced concrete constructions. In all scenarios, the shallow foundation yields slightly higher drifts than the models with deep foundations or fixed bases. However, this variation is very small for soils of type C and D in all seismic zones.

In type E soils, a more significant increase in inter-story drift is observed between the models with fixed and elastic bases. For the case of shallow foundation with Z=0.50, the drift increases up to 0.26%, while for deep foundation, there is an increment of 0.5%.

# 4 Conclusions

A parametric study of 27 models was conducted to evaluate the structural behavior of a commercial building, considering SSI analysis in three types of soils, with three different seismic zones, and two types of foundations in Ecuador. The main objective was to compare these models with parallel ones that assume an infinitely rigid support at the base. The study aimed to understand how the different soil types, seismic zones, and foundation types influence the structural response of the building and to assess the importance of considering SSI effects in the seismic analysis of the structure.

In the most critical case (type E soil, Z=0.50), the drifts assuming SSI increased by 0.26%, and the shear force increased by 4% for the shallow foundation. This is because the SSI model considers the overturning effects generated by the seismic force throughout the entire structural system (substructure and superstructure).

Deep foundations showed a behavior close to fixed-base models, with only a 0.5% increase in drifts and 12% in shear forces. However, the SSI analysis remains more conservative and allows for representing the building's behavior, considering the stratigraphic diversity of the soil and how it influences the type of deep foundation. In this case, a single pile per column was analyzed, but future works could compare it with pile groups to gain further insights into the behavior of the structure.

For structural design, determining the performance characteristics is of utmost importance. Based on the results of this study, implementing an SSI analysis is crucial for the design of tall buildings founded on weak soils, as assuming a fixed-base model results in lower inter-story drifts and shear forces than actual values.

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