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INFLUENCE OF KINEMATIC SOIL – STRUCTURE INTERACTION ON THE SEISMIC BEHAVIOUR OF REINFORCED – CONCRETE FRAME BUILDINGS

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Abstract

In earthquake-prone areas, soil–structure interaction (SSI) may play a key role in ensuring structural safety. This study investigates the effects of SSI on the seismic response of a six-storey reinforced concrete (RC) frame building, using guidelines from American codes and Eurocode 8 for soil types B and C. The analysis compares the building's behavior under various soil conditions and foundation embedment configurations. To accurately assess these effects, four models were analyzed: a fixed base model, a flexible base model, a model incorporating soil conditions beneath the foundation and on the basement walls to simulate the effects of embedment, and a model with reduced spectral acceleration due to the kinematic SSI effects. A linear-elastic analysis was conducted for all models to evaluate the structural response in terms of base shear forces, storey moments, storey displacements, and inter-storey drifts. The results show that SSI lengthens the period of the structure, which affects the values of the base shear forces. SSI generally reduces the base shear forces, but in case of very stiff structures it may increase its values. In any case, the inclusion of SSI leads to an increase in storey displacements and inter-storey drifts, particularly in models with flexible foundations and embedded basements, due to the release of rotations on the foundation level. The model with reduced spectral acceleration due to kinematic SSI effects demonstrated how the kinematic soil – structure interaction effects influence the overall seismic response of the structure. These findings highlight the importance of accounting for SSI in the structural design of buildings located in seismic regions, as neglecting these interaction can lead to an underestimation of critical design parameters such as shear forces, moments, and displacements. Incorporating SSI effects ensures more accurate seismic performance predictions and enhances the resilience of structures in earthquake-prone areas.

Keywords: soil-structure interaction, kinematic interaction, period lengthening, linear analysis, embedding

1. Introduction

With the development of earthquake engineering, the need for design of structures that can safely withstand even the strongest earthquakes by suffering damages, but avoiding complete collapse, has been increased. Each building exposed to earthquake forces responds appropriately based on its structural characteristics. Recent researches and experts in structural and geotechnical engineering [1] indicate that the response of structures to seismic events depends not only on the structural system, but also on the interaction among three interconnected systems, namely:

- Structure;
- Foundation; and,
- Surrounding soil.

This relationship is known as 'soil-structure interaction' in literature and deals with the overall response of the complex system to an earthquake [2]. In Eurocode 8 - Part 5, in Chapter 6 and Appendix D [3], essential information is provided regarding the role of the 'soil-structure interaction' phenomenon in structures. It outlines which types of structures and soils are significantly influenced by this interaction, as well as the impact it has on their inherent periods and mode shapes. However, particular attention is

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not paid to the influence of the foundation type and embedment depth of the structure. The same applies to most of the codes, as many researches [4] in this field have stated it.

Unlike Eurocode 8, American researches and pre-code guidelines delve deeper into this issue. The NIST guidelines titled 'Soil-Structure Interaction for Building Structures' [5], as well as FEMA P-2019 – 'Practical Guide for Soil-Structure Interaction' [6], provide comprehensive guidelines for incorporating soil conditions into analyses and understanding their impact on the structural response. Among other things, Eurocode 8 - Part 5 emphasizes that noticeable soil-structure interaction occurs when structures are founded in exceptionally poor soils with shear wave velocities $v_s \leq 100$ m/s. As to the American researches and regulations, the fundamental preliminary condition for assessing the magnitude of soil-structure interaction effects is expressed as:

$$\frac{h'}{v_s \cdot T} \tag{1}$$

Where, $h^{'}$ - effective height of the structure; v_s - shear wave velocity; T - natural period of oscillation.

Values greater than 0.1 [6] indicate the potential for significant influence of the soil-structure interaction on the response of a structure.

Hence, it can be concluded that the contribution of the soil-structure interaction to the structural response depends not only on the soil type, but also on the height of the structure and its natural period of vibration.

This study explores seismic structural responses of a RC frame structures set on Type B and C soils per Eurocode 8, focusing on soil-structure interaction effects. The analysis examines the influence of embedment depth and foundation type on structural behavior. Linear analysis and modal response spectrum methods were used to calculate seismic forces, assessing story displacements, inter-story drifts, moments, and shear forces. The results emphasize the importance of considering soil conditions and kinematic interactions to enhance design accuracy and prevent potential issues in structural performance.

2. Analysis methods

According to the literature [6], two fundamental methods are commonly employed for modelling the interconnection of a structure, foundation, and soil:

- the substructure approach, and
- the direct approach.

In the substructure method, the soil is represented by springs [6], with their stiffness properties calculated to simulate the behaviour of the soil under the foundation. Springs are typically placed at the foundation base (oriented normally) to prevent horizontal translation. For embedded structures, horizontal springs (oriented normally to basement walls) illustrate the horizontal translation of the foundation relative to the soil.

Conversely, the direct analysis method employs finite elements [7] to model both the structure and the soil, extending the soil medium around and beneath the structure to replicate real conditions with greater precision. While the substructure method is widely used in practice, the direct approach is reserved for critical structures like nuclear power plants and major infrastructure [8].

In this paper, two analyses were performed. A modal analysis with 12 mode shapes provided natural periods and mode shapes, followed by a linear-elastic spectral analysis to calculate seismic forces, moments, and deformations. The substructure approach was adopted to account for SSI effects.

3. Soil – Structure interaction effects

The effective ground displacement applied at the ends of the springs, which simulate soil conditions, differs from the actual displacement adjacent to the foundation. This discrepancy arises due to the

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influence of the structure and deformations occurring in the springs (representing the soil medium) [9]. As these deformations increase, a portion of the energy dissipates, which is attributed to soil-structure interaction (SSI) effects, specifically kinematic and inertial interactions.

Kinematic interaction primarily involves:

- Base slab averaging effects, and;
- Embedment effects.

Base slab averaging effects occur because of the incoherent propagation of seismic waves across the foundation's surface. Embedment effects, observed in embedded structures, reduce excitation at the foundation level due to the decreasing ground motion with depth below the surface.

Inertial interaction, on the other hand, is a dynamic interaction involving the structure, foundation, and soil. Its effects include:

- Period lengthening, caused by increased foundation flexibility;
- Foundation damping, which consists of:
    - Radial damping, from seismic wave propagation, and;
    - Soil damping, similar to viscous damping in structures [5].

SSI effects are especially significant for structures with large foundation systems, embedded structures, or those with high stiffness relative to the soil. These effects influence seismic force magnitudes and structural behavior during earthquakes.

3.1. Kinematic soil-structure interaction effects

3.1.1. Base slab averaging

Base slab averaging is the first kinematic interaction effect between the soil and the structure. This phenomenon depends exclusively on the structure and the geometry of the foundation. The reduction in spectral acceleration occurs due to the incoherence of ground motions beneath the foundation. This incoherence can result from differences in the time intervals at which seismic waves reach various points of the foundation, as well as variations in wave characteristics due to non-uniform soil conditions. As a result, one side of the structure may move in one direction while the opposite side moves in another, resisting deformation and leading to overall smaller deformations.

American guidelines provide equations to calculate the reduction coefficient for spectral acceleration under this effect. The coefficient depends on the foundation's surface area A_{base} and the average seismic wave propagation velocity v_s in the effective soil profile. The effective side length of the foundation is determined as $b_e = \sqrt{A_{base}}$ [10], with a maximum limit of 80 m [6], based on studies of real structures with effective dimensions up to 80 m.

The next step is to calculate the coefficient b_0:

$$b_0 = 0.0023\left(\frac{b_e}{T}\right) \tag{2}$$

The minimum value for T (natural period of oscilation) is prescribed to be not less than 0.2 [6].

Following b_0, the next for calculation is the coefficient B_{bsa}:

$$B_{bsa} = 1 + b_0^2 + b_0^4 + \frac{b_0^6}{2} + \frac{b_0^8}{4} + \frac{b_0^{10}}{12} \text{ for } b_0 \leq 1 \tag{3.1}$$

$$B_{bsa} = \exp\,(2 \cdot b_0^2)\left[\frac{1}{\sqrt{\pi \cdot b_0}}\left(1 - \frac{1}{16 \cdot b_0^2}\right)\right] \text{ for } \; b_0 > 1 \tag{3.2}$$

The values of the reduction coefficient for this kinematic effect of SSI are then calculated for each period value of the spectrum according to the following expression:

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$$RRS_{bsa} = 0.25 + 0.75\left\{\frac{1}{b_0^2}\left[1-\left(exp\left(-2\cdot b_0^2\right)\right)\cdot B_{bsa}\right]\right\} \quad (4)$$

The value of this coefficient is limited to 0.7 in order to ensure safety [6].

3.1.2. Embedment effects

Embedment effects reduce spectral acceleration, similar to base slab averaging. Deeper embedding results in greater reduction due to kinematic interaction, as seismic wave amplitudes decrease with foundation depth [11]. This diminishes ground motion intensity at the foundation, reducing seismic forces on the structure. The spectrum reduction coefficient is calculated using foundation depth „*e*“ and the average shear wave velocity v_s in the effective soil profile.

$$RRS_e = 0.25 + 0.75\cdot\cos\left(\frac{2\pi e}{T v_s}\right) \quad (5)$$

where,

- e is the foundation depth, and its value is limited to 6 meters. A condition is set that a minimum of 75% of the foundation structure should be at the level considered for embedding. For structures on a sloping terrain, a less shallow depth is taken as a foundation depth.

- v_s is the average effective shear wave velocity in a given soil medium, in the layers where embedding is performed, and its value should not be less than 200 m/s.

- T is the period of natural vibration of the spectrum being analyzed, and its minimum value is constrained to 0.2 s.

As for the first kinematic effect of soil – structure interaction, the value of this coefficient is also limited to 0.7 in order to ensure safety [6].

3.2. Inertial soil – structure interaction effects

3.2.1. Period lengthening

When a structure has significantly greater stiffness compared to the soil, rotations and translations of the foundation are "released," resulting in additional displacements. This process simultaneously increases the natural period of the system [12]. The increase in the natural period has a direct impact on the spectral acceleration used to calculate the design seismic force. Depending on the location of the fixed-base model's natural period within the response spectrum, incorporating soil conditions and lengthening the period can either increase or decrease the spectral acceleration [5], as illustrated in Figure 1. However, regardless of whether the spectral acceleration increases or decreases, period lengthening due to soil conditions consistently leads to higher spectral displacements.

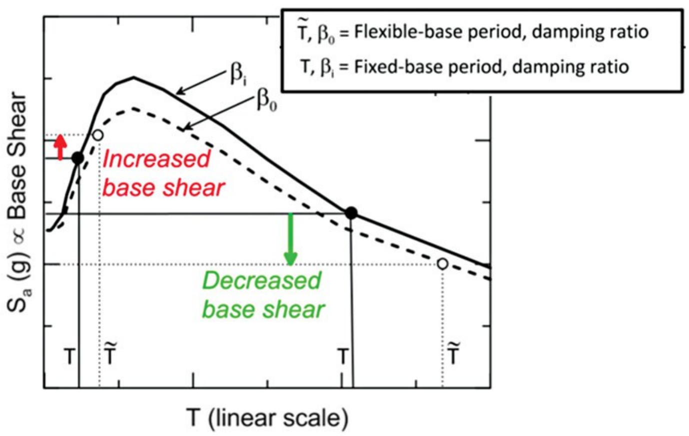

Figure 1. Example of acceleration and displacement spectra.

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4. Calculation of springs' stiffness

Vertical spring elements contribute to the vertical stiffness of the foundations, affecting the rotation of the system around its base. The rotation of the system around its base causes greater deformations when the system is subjected to horizontal (seismic) loads. There are three methods for calculating the stiffness characteristics of these spring elements [5], depending on the purpose and the type of analysis to be performed, and these are:

- Method 1 - Rigid foundation and flexible soil;
- Method 2 - Flexible foundation and nonlinear flexible soil; and,
- Method 3 – Flexible foundation and linear flexible soil.

For the purposes of this project, the stiffness characteristics of the spring elements were calculated using Method 1, and their values were then modified because, in the mathematical model, they were introduced as uniformly distributed spring elements under the entire foundation slab. Figure 2 illustrates the various methods used to calculate the stiffness characteristics of vertical spring elements.

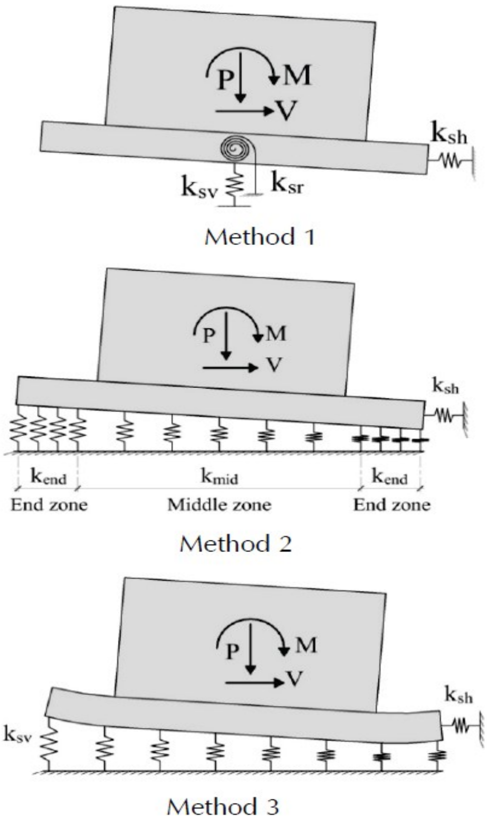

Figure 2. Three methods for foundation modeling approaches with vertical and rotational springs presented in ASCE/SEI 41 from FEMA (2018).

In ASCE/SEI 41-17 [9], equations are provided for calculating the stiffness characteristics of vertical spring elements for six degrees-of-freedom. The stiffness characteristics of the spring elements applied in the model studied in this paper were calculated according to the following expressions (Pais and Kussel, 1998) [5][13].

$$K_{z,sur} = \frac{G \cdot B}{1 - v}\left[3.1\left(\frac{L}{B}\right)^{0.75} + 1.6\right] \tag{6.1}$$

$$K_{y,sur} = \frac{G \cdot B}{2 - v}\left[6.8\left(\frac{L}{B}\right)^{0.65} + 0.8\left(\frac{L}{B}\right) + 1.6\right] \tag{6.2}$$

$$K_{x,sur} = \frac{G \cdot B}{2 - v}\left[6.8\left(\frac{L}{B}\right)^{0.65} + 2.4\right] \tag{6.3}$$

$$K_{zz,sur} = G \cdot B^3\left[4.25\left(\frac{L}{B}\right)^{2.45} + 4.06\right] \tag{6.4}$$

$$K_{xx,sur} = \frac{G \cdot B^3}{1 - v}\left[3.2\left(\frac{L}{B}\right) + 0.8\right] \tag{6.5}$$

$$K_{yy,sur} = \frac{G \cdot B^3}{1 - v}\left[3.73\left(\frac{L}{B}\right)^{2.4} + 0.27\right] \tag{6.6}$$

Where $K_{z,sur}$, $K_{y,sur}$ and $K_{x,sur}$ represent the translational stiffness of the spring elements, and $K_{zz,sur}$, $K_{yy,sur}$ and $K_{xx,sur}$ represent the rotational stiffness about the respective axes. B and L in the expressions refer to half the values of the width and length of the foundation. The same authors (Pais and Kussel, 1998) [5][13] have provided expressions for calculating correction coefficients, which serve to increase

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the stiffness of the spring elements due to the embedding of the structures [14]. They are calculated using the following expressions [5][13]:

$$ή_z = \left[1.0 + \left(0.25 + \frac{0.25}{\frac{L}{B}}\right)\left(\frac{D}{B}\right)^{0.8}\right] \quad (7.1)$$

$$ή_{yy} = \left[1.0 + \frac{D}{B} + \left(\frac{1.6}{0.35 + \frac{L}{B}^4}\right)\left(\frac{D}{B}\right)^2\right] \quad (7.4)$$

$$ή_y \approx ή_x = \left[1.0 + \left(0.33 + \frac{1.34}{1 + \frac{L}{B}}\right)\left(\frac{D}{B}\right)^{0.8}\right] \quad (7.2)$$

$$ή_{xx} = \left[1.0 + \frac{D}{B} + \left(\frac{1.6}{0.35 + \frac{L}{B}}\right)\left(\frac{D}{B}\right)^2\right] \quad (7.5)$$

$$ή_{zz} = \left[1.0 + \left(1.3 + \frac{1.32}{\frac{L}{B}}\right)\left(\frac{D}{B}\right)^{0.9}\right] \quad (7.3)$$

where $ή_z$, $ή_y$ and $ή_x$ are correction coefficients for translational stiffness calculated according to the aforementioned expressions, while $ή_{zz}$, $ή_{yy}$ and $ή_{xx}$ are correction coefficients for rotational stiffness.

5. Case study

The structure analyzed in this project, shown in Figure 3 (left), is a reinforced - concrete frame building with a basement, ground floor, and four upper floors (B+GF+4). This structural system was selected for analysis as it represents the most commonly used building type in the area of interest. The building dimensions are 27.00 m x 26.00 m at the basement and ground floor levels and 17.00 m x 16.00 m at the upper floors. Each floor has a height of 3 m, and the layout is symmetric with respect to the X and Y axes. Spans in the X direction are 5m–6m–5m–6m–5m, while in the Y direction, spans are 5m–6m–4m–6m–5m.

Columns are sized at 50 x 50 cm, except in the central part of the structure where they are 60 x 60 cm. Beams are dimensioned 35 x 50 cm, and slabs are 16 cm thick. The basement, fully embedded in the ground, includes perimeter reinforced concrete walls 20 cm thick. The foundation consists of a reinforced concrete slab 80 cm thick. Dimensions were calculated following PBAB '87 [15] and PIOVS '81 [16], which have been the primary regulations for decades. These norms were used to define the cross-sections of the structural elements, as all buildings designed in our country in the past decades adhere to these regulations. In recent years, there has been a transition towards the use of the Eurocodes. During this, parallel use of PBAB '87 and PIOVS '81 and the Eurocodes is permitted.

Linear analysis was performed using CSI ETABS 20. Seismic force calculations were based on spectral analysis in accordance with Eurocode 8 [17], employing Spectrum Type 1 for soil types B and C, with A_g=0.24g and a behaviour factor q=3.9. The chosen A_g value represents the seismic hazard of the area of interest.

For the purposes of the study, different variants (Figure 3 (right)) of the described model were considered:

- Model 1: Fixed base;
- Model 2: Foundation with vertical springs;
- Model 3: Foundation with vertical and horizontal springs; and,
- Model 4: Model 3 with a reduced spectrum accounting for kinematic interaction effects.

Further on, to each model, /B or /C label was added, referring to which soil type the model was analysed for. In this way two sub-models were generated for each model, resulting in models 1/B through 4/C.

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Model 1/B, Model 2/B, Model 3/B and Model 4/B analysed for Soil type B, and Model 1/C Model 2/C, Model 3/C and Model 4/C analysed for Soil type C.

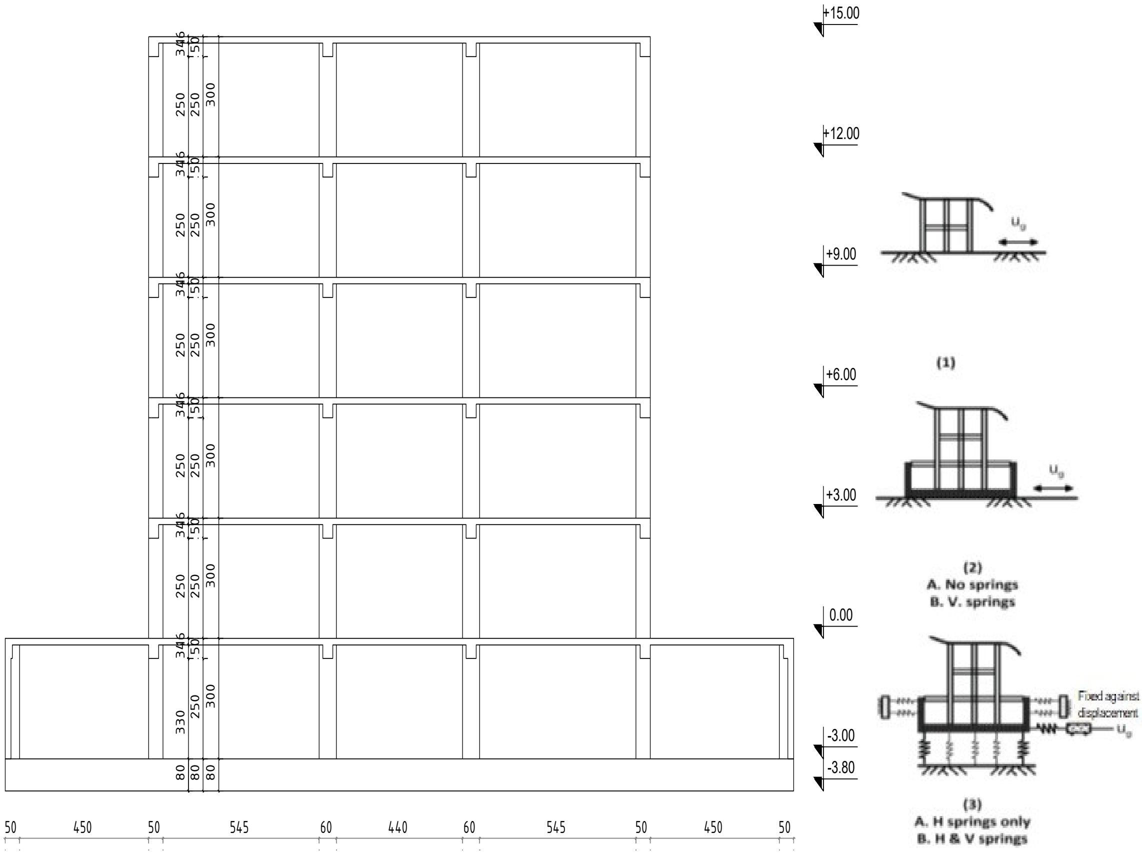

Figure 3. Elevation view of the case study structure (left) and model variants: Model 1 (1), Model 2 (2), Model 3 and Model 4 (3) (right).

6. Calculation of the springs' stiffness characteristics

According to the provided equations for calculating the stiffness characteristics of the spring elements for all three translations and rotations, as well as the equations for calculating the coefficients due to embedding of structures, calculations were performed for soil types B and C [17][18][19] according to Eurocode 8.

6.1. Soil type B

For soil type B, soil with the following characteristics was theoretically considered:

$V_s = 400\ m/s$ and $G = 70000\ kN/m^2$. The embedding depth was e=3.00m.

Based on the specified input parameters, calculation of the spring characteristics as well as the correction factor for the effects of embedment was performed. The values are presented in Table 1.

6.2.Soil type C

The same calculations were carried out for soil type C with the following characteristics:

$V_s = 250\ m/s$ and $G = 14000\ kN/m^2$. The embedding depth was e=3.00m.

Based on the specified input parameters, calculation of the spring characteristics as well as the correction factor for the effects of embedment was performed. The values are presented in Table 1.

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Table 1. Springs' stiffness and correction coefficients – Soil type B and Soil type C

Pais and Kussel (1988)	Soil type B		Soil type C	
	Spring stiffness	**Correction coefficient due to embedding**	**Spring stiffness**	**Correction coefficient due to embedding**
Degree of freedom	$\frac{kN}{m}$ / $\frac{kN/m}{rad}$		$\frac{kN}{m}$ / $\frac{kN/m}{rad}$	
Translation in z direction	6225700	1.32	1245140	1.32
Translation in y direction	5031574	1.53	1006315	1.53
Translation in x direction	5015104	1.53	1003021	1.53
Rotation around z axis	1341312106	2.64	268262421	2.64
Rotation around y axis	956491364	1.29	191298273	1.29
Rotation around x axis	905840000	1.29	181168000	1.29

7. Coefficients for spectral reduction

7.1. Base slab averaging

Using the expressions provided in 3.1.1, all the parameters necessary to determine the values of the spectrum reduction coefficient due to the first kinematic effect, base slab averaging, were calculated. The values were computed for each period (T) of the corresponding spectrum, adhering to the condition that the minimum value of the period should be taken as 0.20s. The calculated values are graphically shown in Figure 4, where it can be observed that the contribution to the spectrum reduction by the base slab averaging effect slightly occurs in structures with low periods of natural vibration. However, it should be noted that these coefficient values are related to the foundation with dimensions and geometry according to the analyzed case study.

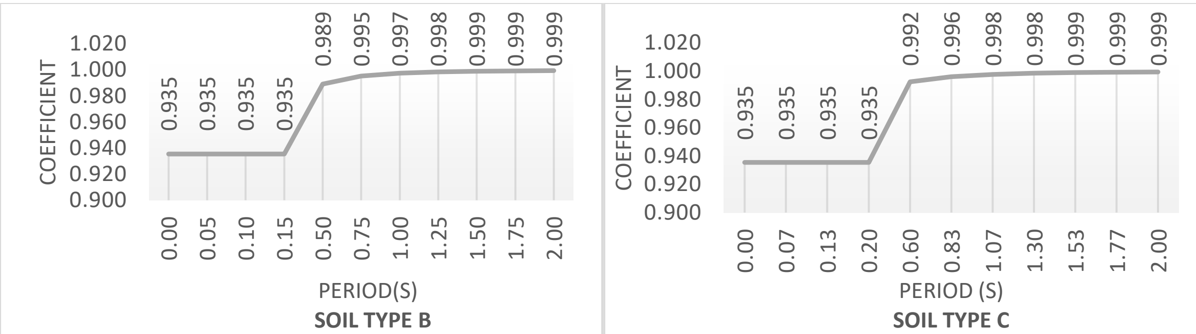

Figure 4. Spectrum reduction coefficient – Base slab averaging – Soil type B (left) and Soil type C (right)

7.2. Embedment effect

In a similar manner, based on the expressions provided in 3.1.2, calculations were performed, and the values of the coefficients for reduction of the spectral acceleration under the influence of the second kinematic effect, embedment effects, were determined.

According to the conditions of the analyzed structure, the foundation depth was established to be 3m. In accordance with this, the values of the reduction coefficient for the spectral acceleration were computed. The results for soil type B and C are graphically presented in Figure 5.

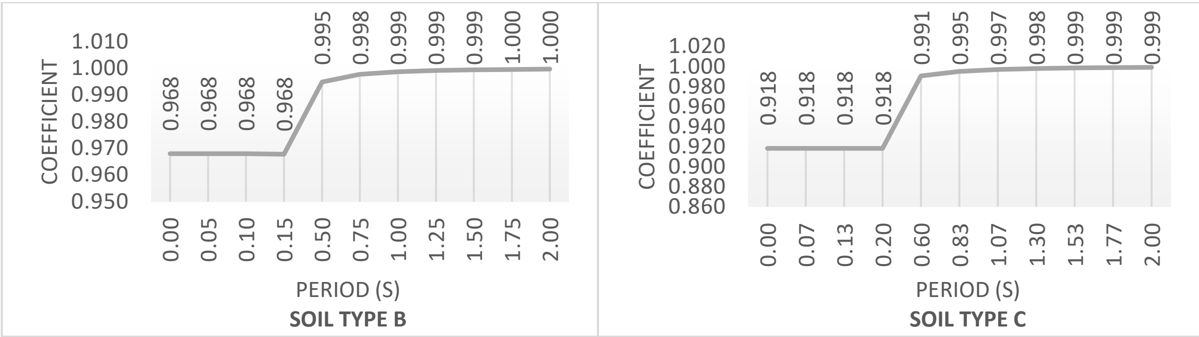

Figure 5. Spectrum reduction coefficient – Embedment effects – Soil type B (left) and Soil type C (right)

7.3.Reduced spectra

The product of the calculated values of the reduction coefficients for Spectrum Type 1, for the sorresponding soil type, from both kinematic interaction effects (RRS_{bsa} and RRS_e) and the acceleration value for the corresponding period from the design spectrum, represents a reduced value of the design spectral acceleration ($A_{g,red.}$):

$$A_{g,red.} = RRS_{bsa} \cdot RRS_e \cdot A_{g,ori.} \tag{8}$$

The values of the spectral acceleration for Spectrum Type 1, soil type B and soil type C, as well as their reduced values, are shown on a comparative graph in Figure 6.

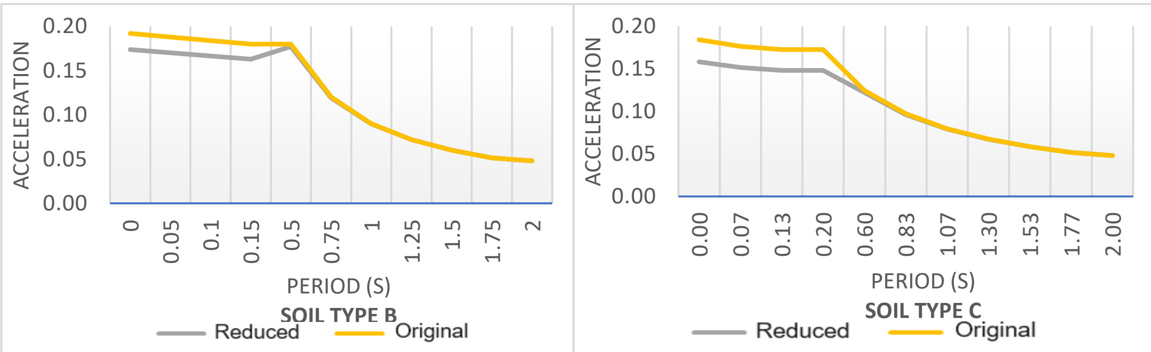

Figure 6. Original and reduced spectra – Soil type B (left) and Soil type C (right)

Hence, it can be concluded that a greater reduction in spectral acceleration is achieved for unfavorable soil conditions, as in the case of soil type C. Therefore, in the seismic analysis of the models, lower values for the seismic force were obtained for the model analyzed with springs and calculated for soil type C.

8. Linear analysis with SSI

A linear analysis of the structural model [18][19] was performed to determine static quantities (moments, forces), dynamic characteristics, seismic forces (via spectral analysis), displacements, and inter-story drifts. The analysis was conducted using ETABS for four models with soil types B and C.

Modal analysis was carried out to calculate 12 natural vibration periods and mode shapes, meeting Eurocode 8 [17] requirements (4.3.3.3.1 (2)P and (3)). Using these periods, seismic analysis was performed per Eurocode 8 [17]. Base and top displacements, as well as base moments, were then calculated.

Models with fixed bases exhibited identical dynamic characteristics, with differences arising in seismic responses due to the use of Spectrum Type 1 for soil types B (Model 1/B) and C (Model 1/C). Models

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incorporating soil conditions showed longer natural periods due to inertial interaction [18][19]. Increased flexibility led to higher deformations, proportional to period lengthening [12]. Figure 7 graphically illustrates the first-mode periods for all analyzed models.

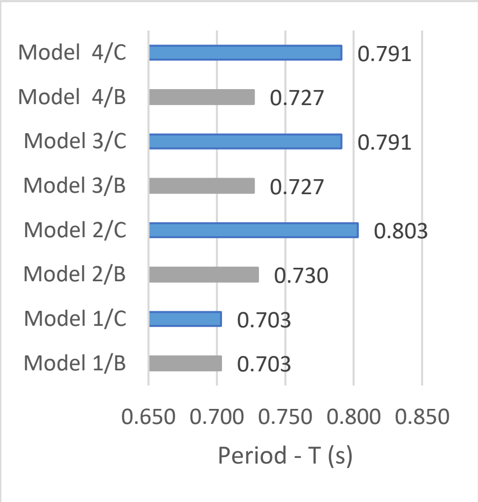

Figure 7. Natural periods of the first mode shapes

The period lengthening was more significant for the structural system on soil type C, with a 14% increase due to greater translation and rotation release. For the model on soil type B, the increase was only 4%, reflecting its stiffer foundation. Consequently, greater differences in seismic force, moments, story drifts, and inter-story drifts are obtained for models on soil type C. Linear analysis results focus on shear force, moments, story displacements, and inter-story drifts (Figures 8–11), presented in different colors for clarity. Due to the system's symmetry, results are shown only for the X direction. These results highlight the differences in the response of structural models caused by local soil conditions and the kinematic interaction effects between soil and structure [18][19].

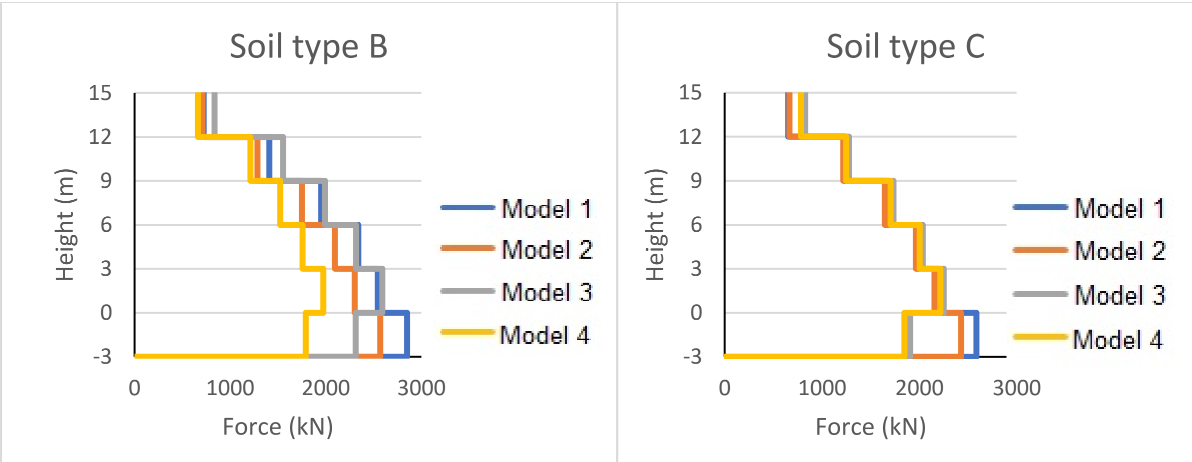

Figure 8. Story shear forces

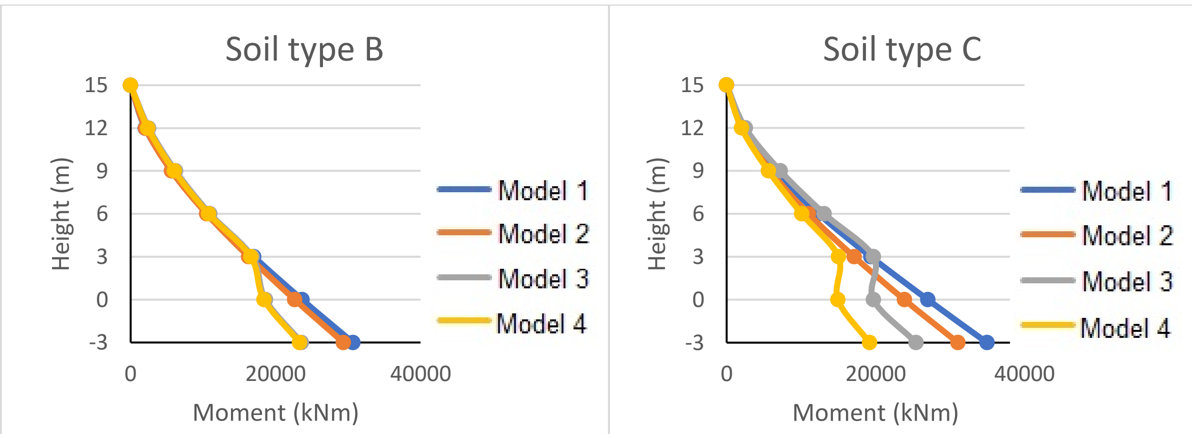

Figure 9. Story moments

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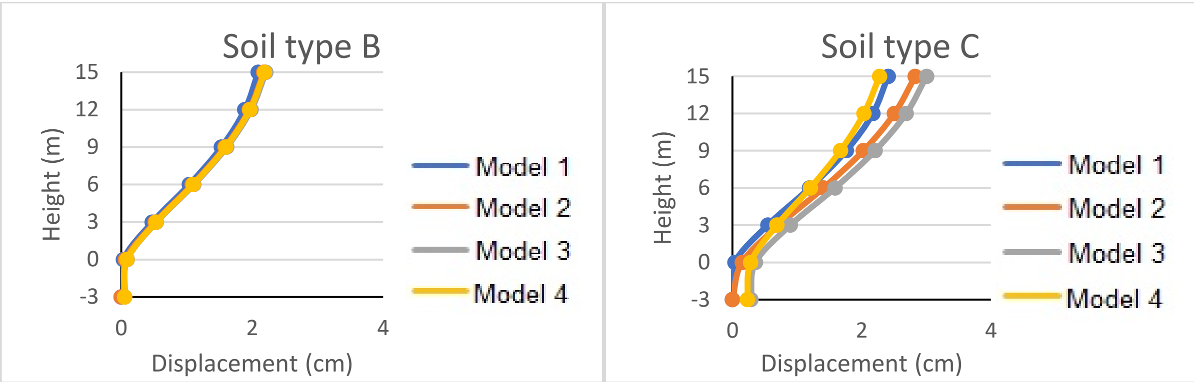

Figure 10. Story displacements

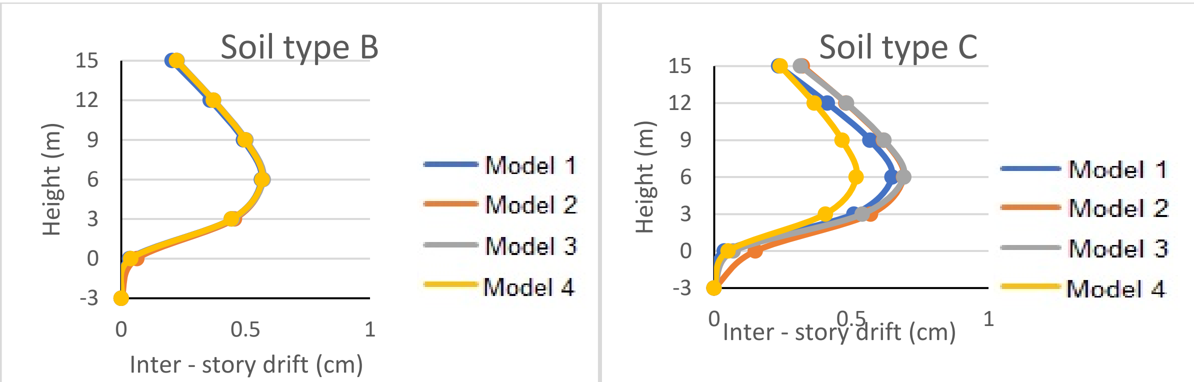

Figure 11. Inter-Story drifts

9. Conclusion

To examine the effects of soil-structure interaction (SSI) and kinematic interaction in line with American guidelines for modeling soil conditions, mathematical models of a six-story reinforced-concrete frame structure were developed. The structure was regular in plan and elevation, and modal and linear-elastic analyses were performed using ETABS. Stiffness characteristics of the springs, simulating soil conditions for soil types B and C (per Eurocode 8), were calculated based on American guidelines. From the modal, spectral and linear analysis results, the following conclusions were drawn:

- Soil conditions affect the natural vibration period, with embedment springs along basement walls slightly reducing the period compared to models with only vertical springs;
- For soil type B, the higher shear modulus (G = 70000 kN/m²) adds restraint at the embedded floor, significantly reducing seismic forces;
- For soil type C, the lower shear modulus (G = 14000 kN/m²) increases flexibility, amplifies seismic waves, and slightly increases seismic forces while reducing rotational restraint at the foundation;
- Soil type C's flexibility reduces foundation-level moments, but leaves upper-story moments largely unchanged as the moments are released on the foundation level;
- Storey displacements and drifts increase compared to fixed base models, with type B showing a 3.27% increase and type C a 21.46% increase;
- Despite spectral acceleration differences, local soil effects cause higher actual displacements than fixed base models.

This research highlights the need for a comprehensive approach to SSI and its kinematic effects during earthquakes. Structures on even favorable soils exhibit different behavior than those analyzed with fixed

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bases, underscoring the importance of including soil conditions. Unlike regulations that focus on weak soils, modeling local soil conditions is crucial for understanding changes in seismic force intensity and structural deformations. These deformations, influenced by modified seismic forces and embedment, cannot be accurately captured with fixed-base models, emphasizing the importance of incorporating soil effects for structural safety. However, this research is limited to the selected structural type, seismic hazard, and soil parameters, expressed by the shear modulus (G) and shear wave velocity (V_s). Hence, it does not provide a general consideration of soil types B and C.

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