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Kinematic SSI effects on seismic performance of RC structures

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Professional paper

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In seismic regions, understanding soil–structure interaction (SSI) is crucial. This study examines the SSI effects on a six-storey RC-frame building using American guidelines for soil types B and C as per Eurocode 8. Structural responses of a constant structural system under various soil types and embedment conditions are compared, revealing significant influences on seismic behaviour. The study employs linear-elastic analysis to demonstrate that local soil and embedment conditions decrease base shear forces but increase total horizontal displacements and inter-storey drifts. This study highlights the importance of considering local soil conditions and embedment configurations to ensure structural resilience in earthquake-prone areas.

Key words:

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

Stručni rad

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Učinci kinematičke interakcije između tla i konstrukcije na seizmičko ponašanje armiranobetonskih konstrukcija

Interakcija između tla i konstrukcije može biti od osobite važnosti u seizmički aktivnim područjima. U ovom radu, uz pomoć američkih normi, analizirana je interakcija šesterokatne armiranobetonske okvirne konstrukcije i tla tipa B i C prema Eurokodu 8. Usporedbom odgovora na seizmičku pobudu te konstrukcije, temeljene na različitim tipovima tla i s različitim konfiguracijama ukopavanja, prikazuje se utjecaj interakcije tla i konstrukcije. Iz rezultata dobivenih linearno elastičnom analizom može se uočiti da uključivanje lokalnih uvjeta tla i ukopavanja temelja, doprinosi smanjenju seizmičkih sila, ali istodobno povećava ukupne horizontalne i međukatne pomake. Ovaj rad naglašava potrebu za uključivanjem lokalnih uvjeta tla i ukopavanja temelja u analizu kako bi se osigurala sigurnost i izbjegle nepredviđene deformacije tijekom seizmičkih djelovanja.

Ključne riječi:

interakcija tlo-konstrukcija, kinematička interakcija, produženje perioda, linearna analiza, ukopavanje

1. Introduction

With the development of earthquake engineering, the design of structures that can safely withstand even the strongest earthquakes with damage while avoiding complete collapse is increasingly needed. Each building exposed to earthquake forces responded appropriately based on its structural characteristics. Recent research and experts in structural and geotechnical engineering [1, 2] indicate that the response of structures during seismic events depends not only on the structural system, but also on the interaction among the three interconnected systems: structure, foundation and surrounding soil.

In the literature, this relationship is known as 'soil–structure interaction' (SSI) and deals with the overall response of a complex system during an earthquake [3-6]. In Eurocode 8 - Part 5, in Chapter 6 and Appendix D [7], essential information is provided regarding the role of the SSI phenomenon on structures. It outlines the types of structures and soils that are significantly influenced by this interaction as well as its impact on the inherent periods and mode shapes of the structures. However, particular attention has not been dedicated to the influence of the foundation type and depth of the embedment of the structure. The same applies to most codes, as stated by many studies [8-11] in this field.

Unlike Eurocode 8, American research and pre-code guidelines delve deeper into this issue. The NIST guidelines titled 'Soil–Structure Interaction for Building Structures' [12], as well as FEMA P-2019 – 'Practical Guide for Soil–Structure Interaction' [13], provide comprehensive guidelines for incorporating soil conditions into analyses and understanding their impact on the structural response. Among other things, Eurocode 8 - Part 5 emphasises that noticeable SSI occurs when structures are founded on exceptionally poor soils with shear wave velocities $v_s \leq 100$ m/s. According to American research and regulations, a fundamental preliminary condition for assessing the magnitude of the SSI is expressed as

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

where is:
h' - the effective height of the structure
v_s - the shear-wave velocity
T - the natural period of oscillation.

Values greater than 0.1 [13] indicate the potential for significant influences of SSIs on the response of the structure.

From this, it can be concluded that the contribution of the SSI 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.

Given the in-depth exploration of this issue in American codes and guidelines, quantitative recommendations were applied to model and analyse a structural model placed on Type B and Type C soils according to Eurocode 8 for the purposes of this project. This was performed to understand the impact of soil conditions on the structural response and to emphasise the necessity of incorporating these considerations into design practices. The goal is to comprehensively and realistically analyse structural systems and avoid potential undesired consequences if not considered. Special attention is given to the effects of the kinematic interactions between the soil and structure, aiming to understand the influence of the structure's embedment and foundation type on the structural response. Although SSI can influence structures found on superior load-bearing soils (Soil Type A), it falls outside the scope of this research because Soil Type A anticipated to offer nearly complete stiffness of the foundation. As a result, no release of translation or rotation of the foundation is expected, leading to minimal observable changes in the seismic force magnitudes and bending moments caused by these forces compared with a fixed-base model.

This paper presents a comprehensive analysis of the structural response to seismic forces under different soil conditions and embedding configurations while the structural system remains constant. Linear analysis techniques were employed to assess the behaviour of the structures. The seismic forces were calculated using modal response spectrum analysis techniques in accordance with Eurocode 8 standards. The structural response was interpreted by examining storey displacements, inter-storey drifts, storey moments, and storey shear forces induced by seismic loading. The effects of varying soil conditions and embedding configurations on the structural response are thoroughly investigated and discussed.

2. Methods for modeling soil-structure interaction

According to the literature [13, 14], when modelling the interconnection of the structure, foundation, and soil, two fundamental methods can be employed: the sub-structure and direct approaches.

In the substructure method, the soil is represented using springs [13, 15], and their stiffness characteristics are defined through calculations to simulate the presence and behaviour of the soil on (in) where the structure is founded. Depending on the degree to which the soil conditions need to be incorporated, these springs can only be placed at the base of the foundation (oriented normally), preventing horizontal translation of the foundation. In the case of embedded structures, horizontal springs (oriented normally to the basement walls) were used to illustrate the possibility of horizontal translation of the foundation relative to the surrounding soil.

By contrast, the direct analysis method is based on modelling using finite elements [16, 17] for both the structure and half-space. The soil modelling was extended sufficiently under and around the structure to simulate real conditions with greater precision. The dimensions of the soil medium to be modelled were chosen based on the size of the structure, ensuring that the negative effects of the boundary conditions [20] on the analysis were avoided. In both methods, a seismic force is applied at the end of the soil medium (springs) through which seismic waves travel and excite the structure. During this process, the structure, along with its weight and characteristics, influences the behaviour of the soil.

In practice, the substructure method is more commonly applied, whereas the direct analysis method is reserved for larger structures of vital importance [18, 19], such as nuclear power plants and major infrastructure projects (bridges, tunnels)."

In this study, two analyses were performed. Modal analysis with 12 mode shapes was performed to obtain the natural periods and mode shapes of the structure. Subsequently, a linear-elastic analysis was conducted to determine the seismic forces acting on the structure. This analysis provides the forces, moments, and deformations experienced by structural elements because of calculated seismic forces. The substructure approach was employed to capture SSI effects.

3. Soil-structure interaction effects

The effective ground displacement applied at the ends of the springs, which simulated the soil conditions, differed from the actual displacement immediately next to the foundation. This is because of the influence of the structure and the deformations that occur in the springs (soil medium) [21]. A portion of the energy dissipated as the deformation in the soil increased. This is a consequence of the effects of SSI, namely, the effects of kinematic and inertial interactions. The primary effects of the kinematic interactions consist of base slab averaging and embedment effects.

Base–slab averaging effects occur because of the incoherent propagation of seismic waves across the foundation surface. Embedment effects reduce excitation at the foundation level because of decreased ground motion with an increase in depth below the ground surface for embedded structures.

In addition to kinematic interactions, which represent the link between the excitation and structure, inertial interactions also exist. The inertial interaction is a dynamic interaction between the structure, foundations, and soil medium. The effects of inertial interaction include period lengthening and foundation damping. Foundation damping encompasses radial damping and soil damping.

The period lengthening occurs due to the increased flexibility of the foundation and the 'release' of the structure from the fixed base condition. Radial damping is the damping in a soil-structure system created by the propagation of seismic waves outside the foundations, which occurs because of the dynamic movement of the foundation structure relative to the soil. Soil damping is material damping and is similar to viscous damping in structures that arises from linear and nonlinear deformations in the soil [12]. As previously mentioned, in certain situations, SSIs can have a significant impact and make a substantial difference in the behaviour of structures during an earthquake, as well as in the design magnitudes of seismic forces. These effects [22] are of significant importance in structures with foundation systems covering large areas, embedded structures, and structures with a high ratio of their own stiffness to the soil stiffness on which they are founded. The first two cases are the effects of the kinematic interaction, whereas the latter is the effect of the inertial interaction between the soil and structure.

3.1. Kinematic soil–structure interaction effects

3.1.1. Base slab averaging

Base slab averaging is the first effect of the kinematic interaction between the soil and the structure. This effect depends solely on the structure and geometry of the foundation. A reduction in the spectral acceleration occurs because of incoherence in the ground motions beneath the foundation. This can be caused by differences in the time intervals at which waves reach different points on the foundation structure, as well as their characteristics, owing to possible variations in soil conditions beneath various parts of the structure. Consequently, one side of the structure may move in one direction, whereas the other side may move in the opposite direction, resulting in resistance to deformations and smaller overall deformations.

According to American guidelines and recommendations, equations have been adopted to calculate the reduction coefficient of the spectrum under the influence of this phenomenon. For the calculation, only the surface area of the foundation structure A_{base} and the average propagation velocity of the seismic waves in the effective soil profile v_s were considered.

The starting point for calculating this coefficient was to determine the effective size of the foundation side [23], given by $b_e = \sqrt{A_{base}}$. The maximum value was limited to 80 m [13, 24] because the research conducted to derive these values was based on real structures, with the maximum effective dimensions of the foundation being 80 m. Next step is to calculate the coefficient b_0, according to Eq. (2):

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

The minimum value of T (the natural period of oscillation) was prescribed to not be less than 0.2 [13]. After determining b_0, the coefficient B_{bsa} was calculated as follows.

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

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

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

$$RRS_{bsa} = 0{,}25 + 0{,}75\left\{\frac{1}{b_0^2}\left[1-\left(exp\left(-2\cdot b_0^2\right)\right)\cdot B_{bsa}\right]\right\} \quad (4)$$

The value of this coefficient was limited to 0.7 to ensure safety [13].

3.1.2. Embedment effects

Similar to the base slab averaging effects, the embedment effects also influence the reduction in the spectral acceleration. In principle, the deeper the embedding, the greater the reduction in spectral acceleration [25]. This is also a result of the effect of the kinematic interaction between the soil and structure, and stems from the fact that seismic wave amplitudes decrease with an increase in foundation depth. This effect diminishes the intensity of the ground motion at the foundation level, resulting in a reduction in the seismic force that excites the structure. To calculate the spectrum reduction coefficient, the foundation depth "*e*" and the average shear wave velocity in the effective soil profile v_s were required.

$$RRS_e = 0{,}25 + 0{,}75\cdot\cos\left(\frac{2\pi e}{Tv_s}\right) \quad (5)$$

where is:
- *e* - the foundation depth, which is limited to 6 m. A condition is set that a minimum of 75 % of the foundation structure should be at the level considered for embedding. For structures on sloping terrain, a shallower foundation depth was considered.
- v_s - the average effective shear wave velocity in a given soil medium in the layers where the embedding was performed, and its value should not be less than 200 m/s.
- *T* - the period of the natural vibration of the spectrum being analysed, and its minimum value is constrained to 0.2 s.

As it was for the first kinematic effect of soil–structure interaction, the value of this coefficient is also limited to 0.7 to ensure safety [13].

3.2. Inertial soil–structure interaction effects

3.2.1. Period lengthening

In cases where the structure has significantly greater stiffness compared to the soil, rotations and translations of the foundation structure are released, leading to additional displacements of the structure, simultaneously increasing the system's natural period [26, 27]. This increase in the natural period directly affects the value of the spectral acceleration used to calculate the design seismic force. Depending on the part of the spectrum, the period of the mathematical model analysed on a fixed base is located, and increasing the period of natural vibrations of the model by incorporating the soil conditions can either increase or decrease the value of the spectral acceleration [12], as shown in Figure 1.

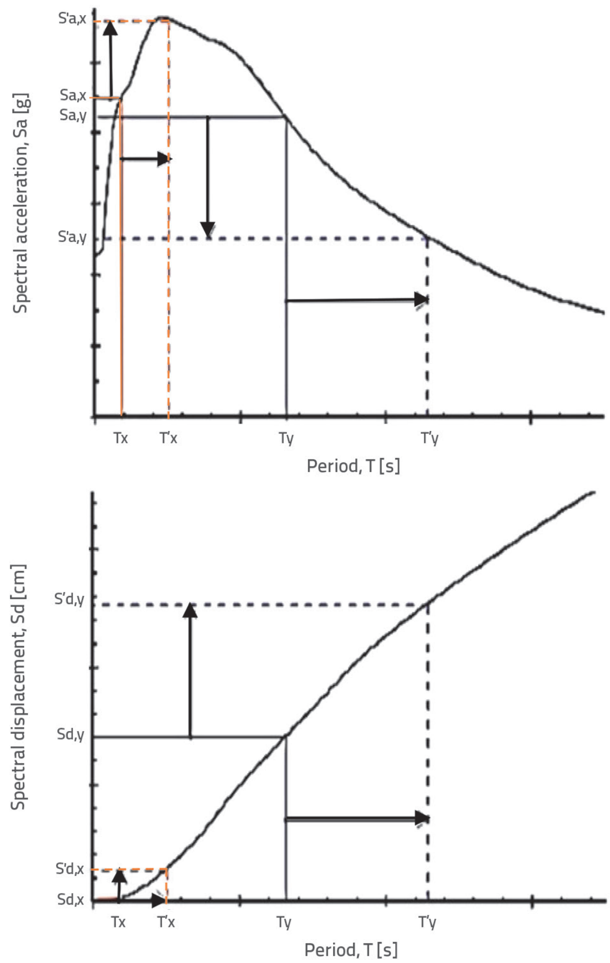

Figure 1. Example acceleration and displacement spectra

For rigid structures with low natural period values, incorporating local soil conditions usually increases the value of the spectral acceleration. In contrast, structures whose period is after the maximum values for spectral acceleration, including local soil conditions and increasing the natural period of vibrations, contribute to a reduction in acceleration values. Regardless of whether the spectral acceleration increases or decreases, the lengthening of the natural period owing to the implementation of local soil conditions always results in an increase in spectral displacements.

4. Calculation of springs stiffness

The vertical spring elements contribute to the vertical stiffness of the foundation and affect the rotation of the system around its base. The rotation of the system around its base causes greater deformation when the system is subjected to horizontal (seismic) loads. There are three methods for calculating the stiffness characteristics of spring elements [12], depending on the purpose and type of analysis to be performed.

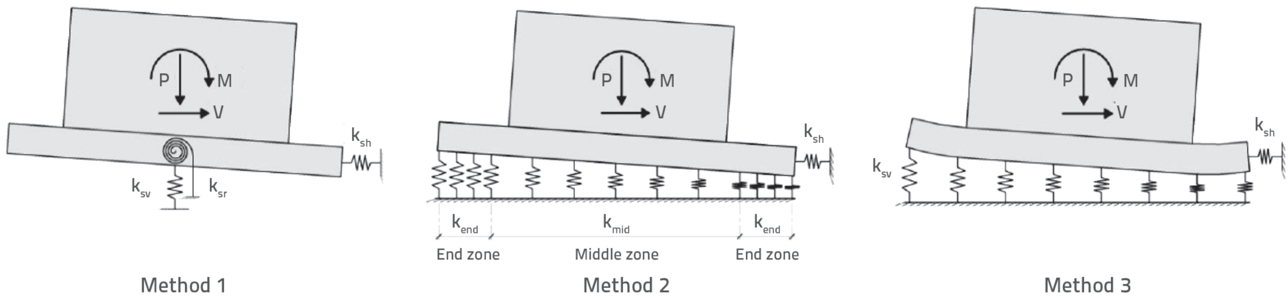

Figure 2. Three methods for foundation modelling approaches with vertical and rotational springs presented in ASCE/SEI 41 from FEMA (2018)

- Method 1: Rigid foundation and flexible soil.
- Method 2: Flexible foundation and nonlinear flexible soil.
- 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.
In ASCE/SEI 41-17 [15], equations are provided to calculate the stiffness characteristics of the 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 [12, 28]:

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

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

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

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

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

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

Where $K_{z,sur}$, $K_{y,sur}$ and $K_{x,sur}$ represent the translational stiffness of the spring elements, and $K_{zz,sur}$, $K^{y}_{y,sur}$ and $K_{x,xsu}$ represent the rotational stiffness about the respective axes. B and L refer to half width and length of the foundation, respectively. The same authors (Pais and Kussel, 1998) [12, 27, 28 provided expressions for calculating correction coefficients that served to increase the stiffness of the spring elements owing to the embedding of the structures[29, 30]. These values were calculated using the following expressions [12, 28]:

$$\acute{\eta}_z = \left[1.0 + \left(0.25 + \frac{0.25}{\frac{L}{B}}\right)\left(\frac{D}{B}\right)^{0.8}\right] \tag{7.1}$$

$$\acute{\eta}_y \approx \acute{\eta}_x = \left[1.0 + \left(0.33 + \frac{1.34}{1+\frac{L}{B}}\right)\left(\frac{D}{B}\right)^{0.8}\right] \tag{7.2}$$

$$\acute{\eta}_{zz} = \left[1.0 + \left(1.3 + \frac{1.32}{\frac{L}{B}}\right)\left(\frac{D}{B}\right)^{0.9}\right] \tag{7.3}$$

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

$$\acute{\eta}_{xx} = \left[1.0 + \frac{D}{B} + \left(\frac{1.6}{0.35 + \frac{L}{B}}\right)\left(\frac{D}{B}\right)^{2}\right] \tag{7.5}$$

Where $\acute{\eta}_z$, $\acute{\eta}_y$ and $\acute{\eta}_x$ are correction coefficients for translational stiffness calculated according to the aforementioned expressions, while $\acute{\eta}_{zz}$, $\acute{\eta}_{yy}$ and $\acute{\eta}_{xx}$ are correction coefficients for rotational stiffness.

5. Case study

The structure analysed in this project, as shown in Figure 3, is a reinforced concrete frame structure [31] with a basement, ground floor, and four upper floors (B+GF+4). This structural system was chosen because it is representative and the most commonly used in the area of interest. The dimensions at the basement and ground floor levels are 27.00 x 26.00 m, while at the upper floors, these are 17.00 x 16.00 m. The floor height at all the levels was 3 m. The structure in the plan is symmetrical with respect to the X- and Y-axes. The spans were 5–6–5–6–5 m in the X direction and 5–6–4–6–5 m in the Y direction. All the columns had dimensions of 50/50 cm, except for the columns in the central part of the structure, which had dimensions of

60/60 cm. All beams had dimensions of 35/50 cm. The slabs had a thickness of 16 cm.

The basement of the structure was entirely embedded in the ground, and around its perimeter, basement-reinforced concrete walls with a thickness of 20 cm were installed along the full height. The foundation was an reinforced concrete foundation slab with a thickness of 80 cm. The dimensions of the structural elements were calculated based on PBAB '87 [32] and PIOVS '81 [33]. These norms were employed to define the cross-sections of the structural elements, as all buildings designed in the past decades in our country adhere to these regulations. In recent years, there has been a transition towards the use of Eurocodes. This transition is progressing slowly, and the parallel use of PBAB '87 and PIOVS '81 and Eurocodes is currently permitted.

Linear analysis of the model was performed using CSI ETABS 20 [34]. The calculation of the seismic force was conducted through spectral analysis according to Eurocode 8 [32], employing Spectrum Type 1 for soil types B and C, with A_g = 0.24g, and a behaviour factor q = 3.9, calculated based on the structural characteristics of the building. Spectrum type 1 was employed with respect to Section 3.2.2.2 (2)P from Eurocode 8. Accordingly, if the earthquakes that contribute most to the seismic hazard defined for the site for the purpose of probabilistic hazard assessment have a surface-wave magnitude Ms greater than 5.5, spectrum type 1 should be adopted. The value of A_g = 0.24g, was chosen as the value which was most abundant in the area of interest. In this study, various variants (Figure 4) of the described model were considered.

- Model 1: Fixed base model.
- Model 2: Foundation supported on vertical spring elements.
- Model 3: Foundation with both vertical and horizontal spring elements on the basement walls.
- Model 4: Similar to Model 3, but with the seismic forces calculated using the design spectrum adjusted for kinematic interaction effects.

Furthermore, for each model, the/B or /C label was added, which refers to the soil type for which the model was analysed. Thus, the following models were generated:

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

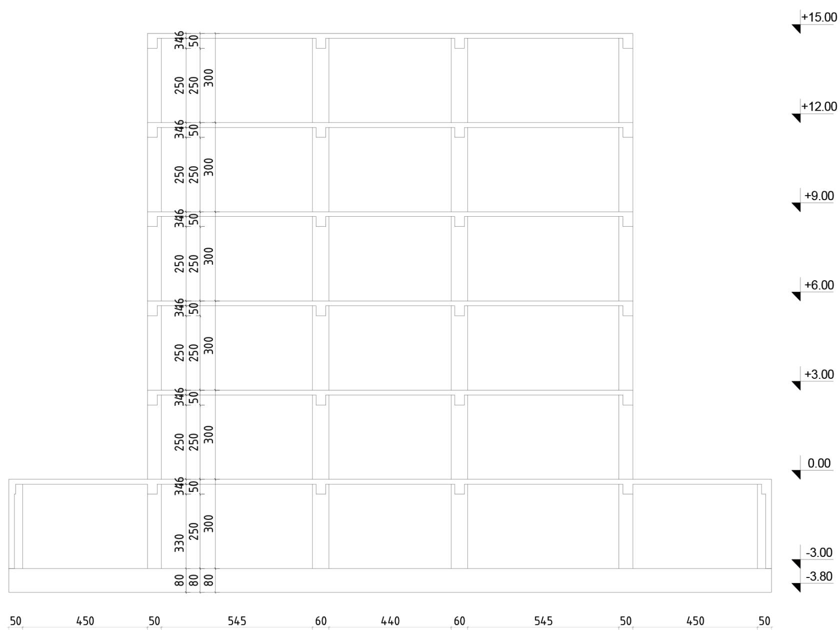

Figure 3. Elevation view of the case study structure

6. Calculation of the springs' stiffness characteristics

According to the equations provided for calculating the stiffness characteristics of spring elements for all three translations and rotations, as well as the equations for calculating the coefficients due to the embedding of objects, calculations were performed for soil types B and C [35, 36] as per Eurocode 8. Although significant SSI effects can occur with soil type D, this soil type was not analysed in this study because it is not present in the area of interest and therefore falls outside the scope of this analysis. The values for *Vs* and *G*, as the main parameters in the

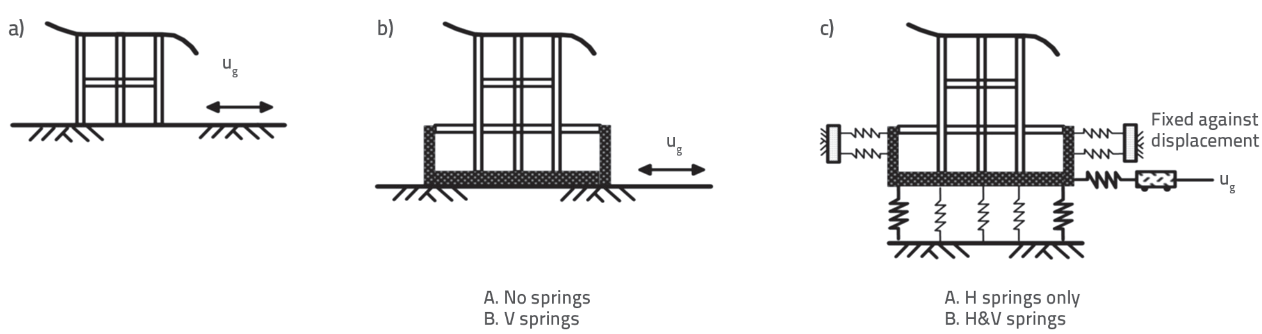

Figure 4. Model variants: a) Model 1; b) Model 2; c) Model 3 and Model 4

calculations for both soil types B and C, were hypothetically chosen to represent how different soil parameters influence the SSI. An embedding depth of 3 m was chosen because it aligns with the typical depth at which buildings are mostly embedded in the area of interest.

6.1. Soil type B

For soil type B, theoretically, soil with the following characteristics is considered: v_s = 400 m/s and G = 70000 kN/m^2. The embedding depth is e = 3.00 m.
Based on the specified input parameters, the calculation of the spring characteristics was performed, as well as the correction factor for the effects of embedment. These values are listed in Table 1.

6.2. Soil type C

Same calculations were conducted for soil type C with the following characteristics considered: v_s = 250 m/s and G = 14000 kN/m^2. The embedding depth is e = 3.00 m.
Based on the specified input parameters, the calculation of the spring characteristics was performed, as well as the correction factor for the effects of embedment. These values are listed in Table 2.

Table 1. Spring's stiffness and correction coefficients–Soil type B

Pais & Kussel (1988) [28] / Degree of freedom	Spring stiffness [kN/m] / [(kN/m)/rad]	Correction coefficient due to embedding
Translation in z direction	6225700	1.32
Translation in y direction	5031574	1.53
Translation in x direction	5015104	1.53
Rotation around z axis	1341312106	2.64
Rotation around y axis	956491364	1.29
Rotation around x axis	905840000	1.29

Table 2. Spring's stiffness and correction coefficients–Soil type C

Pais & Kussel (1988) [28] / Degree of freedom	Spring stiffness [kN/m] / [(kN/m)/rad]	Correction coefficient due to embedding
Translation in z direction	1245140	1.32
Translation in y direction	1006315	1.53
Translation in x direction	1003021	1.53
Rotation around z axis	268262421	2.64
Rotation around y axis	191298273	1.29
Rotation around x axis	181168000	1.29

7. Coefficients for spectral reduction

7.1. Base slab averaging

7.1.1. Soil type B

Using the expressions provided in Section 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 spectrum, adhering to the condition that the minimum value of the period was taken to be 0.20s. The calculated values are graphically represented in Figure 5, which shows that the contribution to the spectrum reduction by the base-slab averaging effect is slight for structures with low periods of natural vibrations. However, these coefficient values relate to the foundation structure with dimensions and geometry according to the analysed case study.

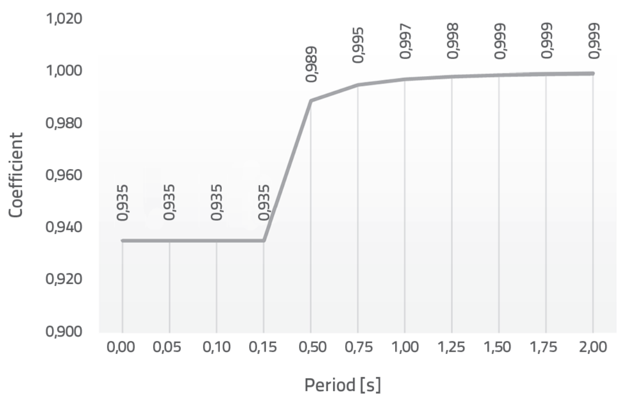

Figure 5. Spectrum reduction coefficient–Base slab averaging–Soil type B

7.1.2. Soil type C

The same calculations were performed for foundations with identical dimensions but based on soil type C. This implies that the reduction coefficients were applied to Spectrum Type 1 for soil type C according to Eurocode 8. Consequently, different values for the period *T* of the spectrum emerge from this analysis. The values obtained are presented graphically in Fig. 6.

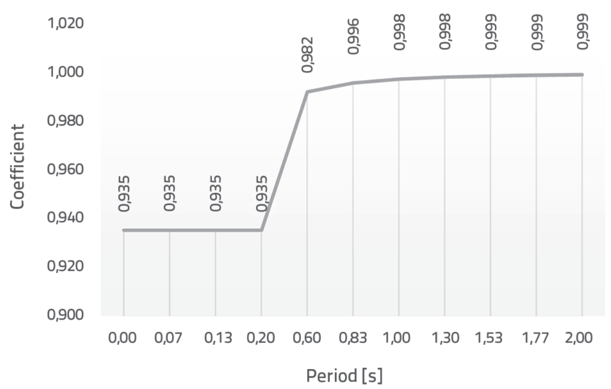

Figure 6. Spectrum reduction coefficient–Base slab averaging–Soil type C

7.2. Embedment effect

7.2.1. Soil type B

Similarly, based on the expressions provided in Section 3.1.2, calculations were performed, and the values of the coefficients for the reduction of spectral acceleration under the influence of the second kinematic effect, the embedment effect, were determined. According to the conditions of the analysed structure, the foundation depth has been established to be 3m. Accordingly, the values of the reduction coefficient for the spectral acceleration were computed, and the results for soil type B are graphically presented in Figure 7.

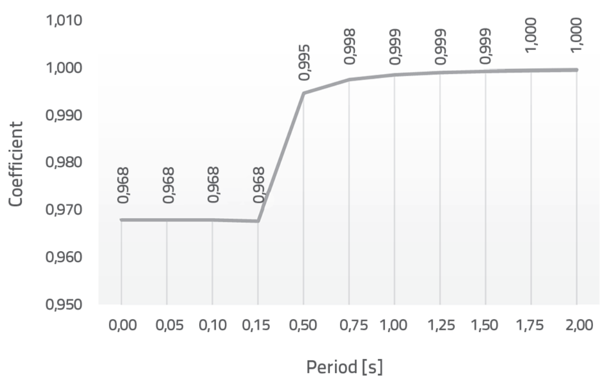

Figure 7. Spectrum reduction coefficient–Embedment effects–Soil type B

7.2.2. Soil type C

The calculations for the reduction coefficient of the spectral acceleration values were conducted in the same manner for soil types C and B. The obtained values are presented in Figure 8.

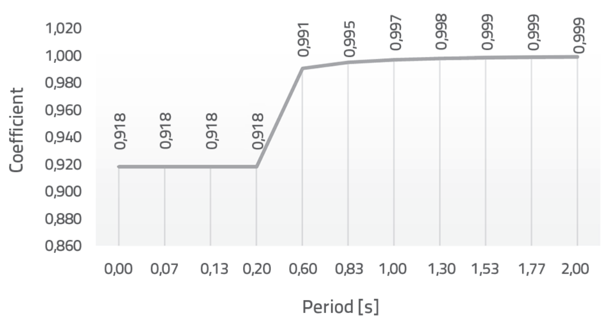

Figure 8. Spectrum reduction coefficient–Embedment effects–Soil type C

7.3 Reduced spectra

The product of the calculated values of the reduction coefficients for Spectrum Type 1 for Soil Type B from both the kinematic interaction effects (and) and the value of acceleration for the corresponding period from the design spectrum represents the reduced value of the design spectral acceleration ($A_{g,red}$):

$$A_{g,red} = RRS_{bsa} \cdot RRS_{e} \cdot A_{g,ori} \quad (8)$$

The values of the spectral acceleration for Spectrum Type 1 and soil type B, as well as their reduced values, are shown in the comparative graph in Figure 9.

From the comparative display of the spectral values shown in Figure 10, the differences in the spectral acceleration values for Spectrum Type 1 for soil type B can be observed. The reduced spectral values, resulting from the effects of kinematic interaction between soil and structure, have an impact on objects whose fundamental periods of natural vibrations range from 0.20s to 0.50s. For objects with larger fundamental periods of natural vibrations, the effects of kinematic interaction would not contribute significantly to the additional reduction of seismic force.

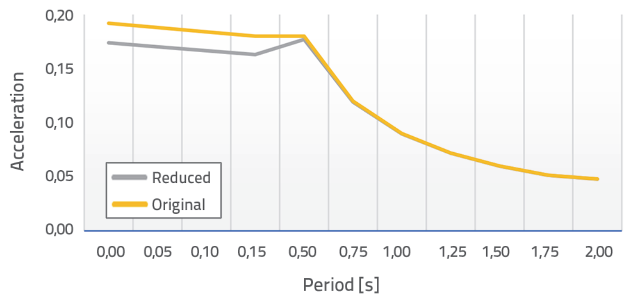

Figure 9. Original and reduced spectra–Soil type B

Similarly, by multiplying the respective reduction coefficients from the kinematic effects for soil type C with the spectral acceleration from Spectrum Type 1 for soil type C, the reduced values for the spectral acceleration were obtained.

From this, it can be concluded that a greater reduction in spectral acceleration is achieved for unfavourable soil conditions, as in the case of soil type C. Therefore, in the seismic analysis of the models, smaller values for seismic force will be obtained for the model analysed with springs calculated for soil type C. This is because the seismic force is calculated by applying spectral analysis, where the seismic weight of the object is multiplied by the spectral acceleration for each of the calculated periods of natural vibrations.

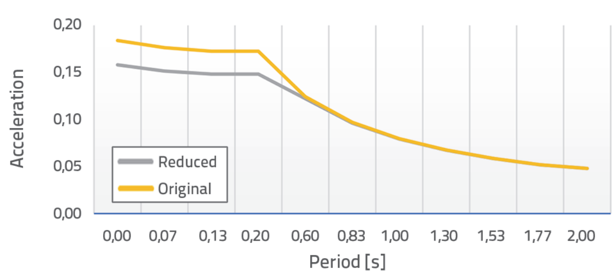

Figure 10. Original and reduced spectra–Soil type C

8. Linear analyses with SSI

On the defined structural model [36], a linear analysis was conducted to obtain basic static quantities (moments and forces), dynamic characteristics, horizontal seismic force (obtained through spectral analysis), as well as moments, minimum and maximum storey displacements and inter-storey drifts under the influence of the calculated seismic force [37-39].

Linear analysis was performed using ETABS software for four separate models with soil types B and C.

Modal analysis was conducted for each model to obtain 12 natural periods of vibration and mode shapes. Twelve natural periods were chosen for the analysis to satisfy the requirements stated in 4.3.3.3.1 (2)P and 4.3.3.3.1 (3) in Eurocode 8 [35]. Thus, the responses of all modes of vibration that contribute significantly to the global response should be considered. This requirement can be satisfied if either the sum of the effective modal masses for the modes considered amounts to at least 90 % of the total mass of the structure, or all modes with effective modal masses greater than 5 % of the total mass are considered. By incorporating 12 mode shapes into the analysis, effective modal masses of 93.56 % in the X direction and 95.67 % in the Y direction of the total mass of the structure were achieved.

Using the calculated natural periods, seismic analysis of the mathematical models was performed according to Eurocode 8 [35], with the seismic force obtained for each model separately. The displacements at the base and top of the structures and the moments at the base were then calculated.

Figure 11 illustrates the type 1 elastic response spectra for the response of the structures according to Eurocode 8, depending on the type of soil in which they are situated.

The models analysed with a fixed base, without considering the SSI, exhibited identical dynamic characteristics. The only anticipated difference in these models is expected to be observed in the seismic response because spectral analysis was conducted with Spectrum Type 1 for soil type B for Model 1/B and Spectrum Type 1 for soil type C for Model 1/C. Differences in the natural vibration periods in models with incorporated soil conditions result from the effects of inertial interactions between the soil and structure [40]. Because of the release of translations and rotations, structures become more flexible, and their natural vibration periods become longer [26, 27].

According to the positions of the fundamental periods in the presented spectra, for all models, an increase in the natural vibration period was expected to lead to a reduction in the seismic force (Figure 11). The green line in Figure 11 corresponds to the spectral acceleration at period of 0.7*s*, for soil type B, while the red line is associated with the spectral acceleration at period of 0.7*s*, for soil type C. However, this is accompanied by an increase in deformations due to greater flexibility, and the tendency for deformations to increase proportionally with the increase of the period.

For a better visual representation, the results of this effect for the period of the first mode for each of the analysed models are graphically displayed in Figure 12.

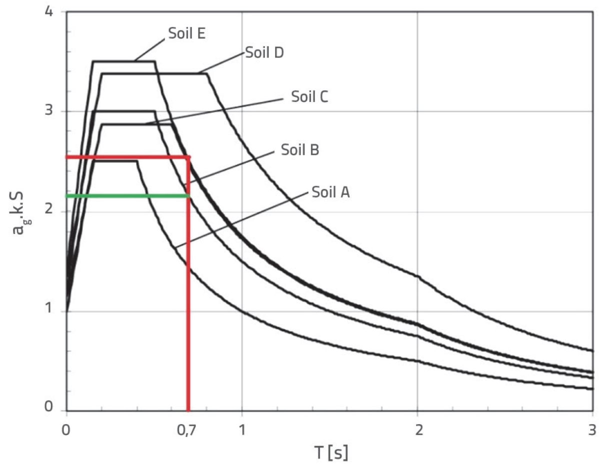

Figure 11. Elastic spectra–Eurocode 8

The differences in the lengthening of the period were significant for the structural system located on soil type C, amounting to 14 %, owing to the greater release of translations and rotations. For the structural model situated on soil type B, owing to its characteristics resembling a stiffer foundation, the increase in the period was 4 %. Consequently, the differences in seismic force values, moments, storey drifts, and inter-storey drifts are expected to be greater for the models analysed for soil type C. Below are the results obtained through the linear analysis of the structural models, focusing on the values of the horizontal force, moments, storey displacements, and inter-storey drifts (Figure 13–16). The values are represented using different colours for better visualisation.

Because of the symmetry of the structural system, the results are presented only in the X-direction. From these results, one can observe the degree of difference in the response of individual structural models, the result of incorporating local soil conditions, and the effects of kinematic interactions between the soil and structure [36].

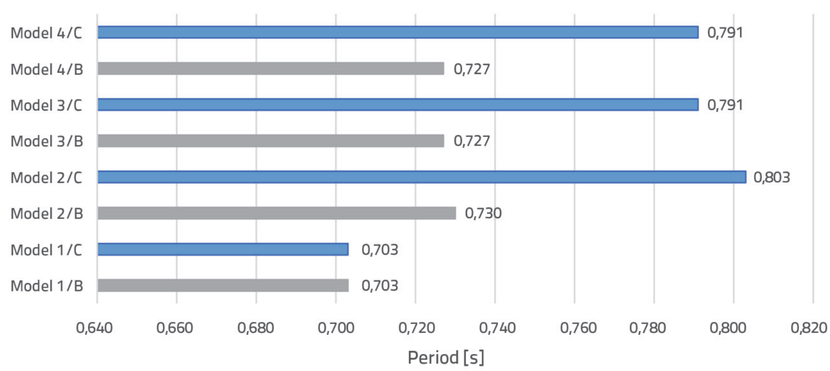

Figure 12. Natural periods of the first mode shapes

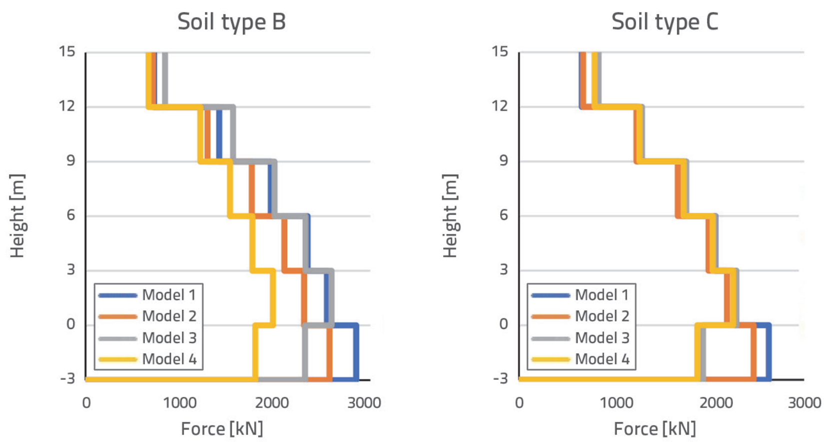

Figure 13. Story shear forces

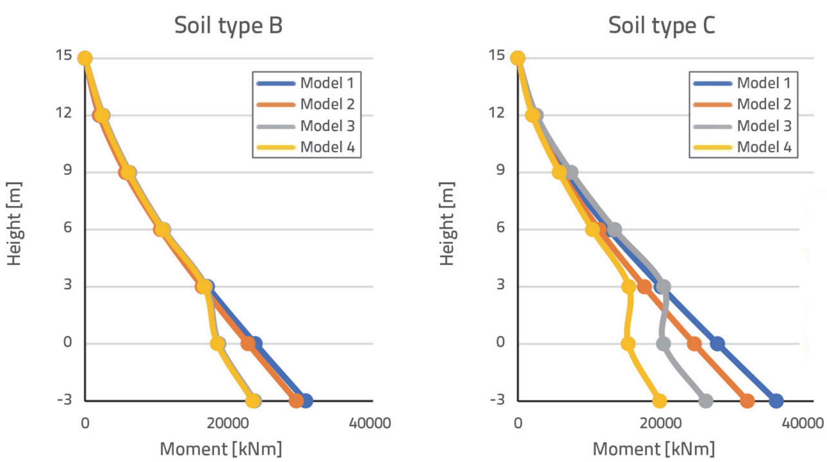

Figure 14. Story moments

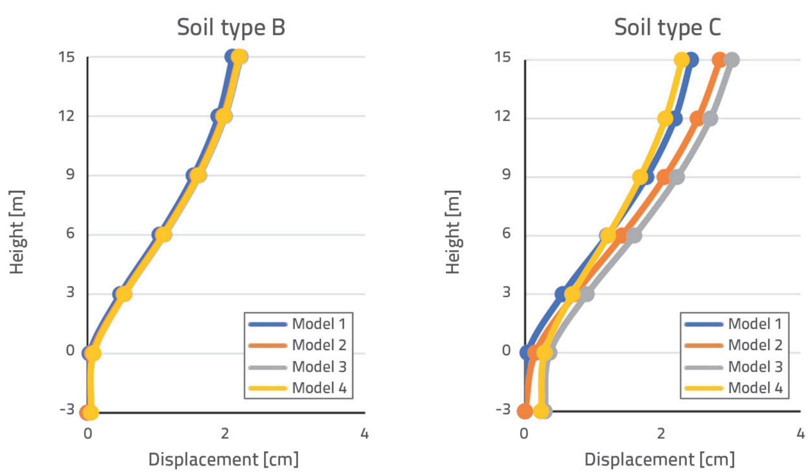

Figure 15. Story displacements

9. Conclusion

To determine the influence of SSI, as well as the effects of kinematic interaction between the soil and structures, mathematical models of a reinforced-concrete frame structure were created in accordance with American regulations and guidelines for modelling soil conditions. The reinforced-concrete frame structure studied in this project consists of six stories and is regular in terms of plan and elevation. Modal and linear elastic analyses were conducted on the mathematical model using ETABS computer software. First, in accordance with the American guidelines, the stiffness characteristics of springs simulating the soil conditions of soil types B and C, as per Eurocode 8, were calculated. From the linear analysis of the models, for which a spectral analysis was performed to calculate the seismic forces, the following conclusions were drawn:

- The inclusion of the soil conditions affected the length of the natural vibration period for all models. In the case of embedding, the springs along the surface of the basement walls slightly decreased the period compared to the models analysed with only vertical springs.
- The inclusion of local soil conditions for soil type B introduces additional restraint to the structure at the embedded floor height because of the more favourable soil characteristics, resulting in a drastic reduction in the seismic force. The more favourable soil conditions in soil type B are reflected by the higher value of *G* taken in the calculations, which is a critical parameter for calculating spring stiffness. Specifically, *G* was assigned a value of 70000 kN/m^2 for soil type B and 14000 kN/m^2 for soil type C.
- The inclusion of soil conditions for soil type C on the basement walls did not significantly reduce the seismic force, as was the case when only vertical springs were applied to the foundation slab. This is because soil type C has greater flexibility and deformability regarding the value of the shear modulus *G*, compared to soil type B, meaning that it cannot effectively prevent translation

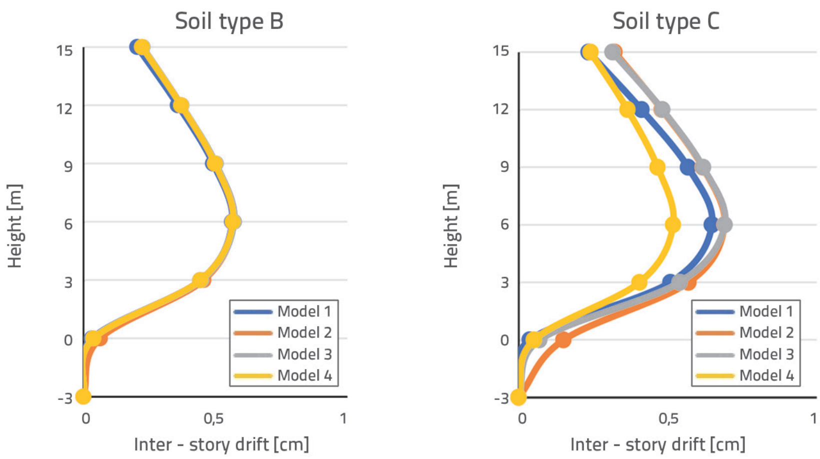

Figure 16. Inter-storey drifts

and rotation at the embedded floor and simultaneously amplify seismic waves, which slightly increases the seismic force.

- The higher flexibility and deformability of Soil Type C primarily facilitated the rotational release at the foundation level, resulting in notably reduced moment values. However, the moments on the upper stories remained relatively unchanged, as modifications were confined to the foundation level through the incorporation of local soil conditions and the embedding configuration.
- The inclusion of soil conditions affected the values of storey displacements and inter-storey drifts of the structures compared to the same structures analysed on a fixed base, especially for soil type C. The maximum displacement for the model analysed for soil type B was 3.27 % greater than that for a fixed base model; for the model analysed for soil type C, the same value was greater by 21.46 %, even though a lower value for the seismic force was considered.
- Although the spectral acceleration values differ for soil types B and C and are considered in seismic calculations and the calculation of displacements, simulating local soil conditions reveals higher actual displacement values relative to the structure analysed on a fixed base.

From the overall research and analyses conducted for the purposes of this work, it can be concluded that a more serious and comprehensive approach to SSI is necessary, along with the effects of kinematic interactions between the soil and structures. This conclusion is based on the observation that structures exhibit different responses and behaviours during earthquakes, even when founded on favourable soils, compared to their response when analysed as fixed at their base. Therefore, the inclusion of soil conditions in the analysis of structures is necessary primarily because of the presence of kinematic interaction effects. This is distinct from nearly all regulations that consider the modelling of local soil conditions only in the presence of weak-bearing soils. Modelling and incorporating local soil conditions are essential not only to account for changes in seismic force intensity, but also to consider the overall deformations that the structure undergoes under the influence of this modified seismic force. Such deformations would not be adequately captured if the structure were analysed with a fixed base. This emphasises the need for modelling and considering local soil conditions to ensure safety, not only in terms of changes in seismic force intensity, but also especially in terms of the total deformations experienced by the structure under the influence of the modified seismic force and embedding configuration.

However, this research was limited to the selected structural type, seismic hazard, and soil parameters expressed by the shear modulus (*G*) and shear wave velocity (*Vs*). Hence, it does not provide a general consideration of soil types B and C. Further research should consider different structural systems with plan and elevation irregularities. In addition, performing non-linear analysis is of crucial importance in assessing the performance and capacity of buildings under varying soil types and embedding configurations.

REFERENCES

[1] Kraus, I., Džakić, D., Papić, J., Cerovečki, A.: Influence of foundation contact pressure on response spectrum-based design, GRAĐEVINAR, 72 (2020) 1, pp. 11-20, https://doi.org/10.14256/JCE.2365.2018

[2] Bačić, M., Ivšić, T., Kovačević, M.S.: Geotechnics as an unavoidable segment of earthquake engineering, GRAĐEVINAR, 72 (2020) 10, pp. 923-936, https://doi.org/10.14256/JCE.2968.2020

[3] Borghei, A., Ghayoomi, M.: The role of kinematic interaction on measured seismic response of soil-foundation-structure systems, Soil Dynamics and Earthquake Engineering, 125 (2019) 105674.

[4] Lulayehu Tadesse, Z., Krishna Padavala, H., Koteswara Rao P.V.: Effect of subterranean levels on the foundation input motions for dynamic response analysis of building structure, Asian Journal of Civil Engineering, 24 (2022), pp. 793-808.

[51] Zogh, P., Motamed, R., Ryan, K.: Empirical evaluation of kinematic soil-structure interaction effects in structures with large footprints and embedment depths, Soil Dynamics and Earthquake Engineering, 149 (2021), p. 106893.

[6] Abdulaziz, M., Hamood, M., Fattah, M.: A review study on seismic behavior of individual and adjacent structures considering the soil – Structure interaction, Structures, 52 (2023), pp. 348-369.

[7] European Committee for Standardization: Eurocode 8: Design of structures for earthquake resistance - Part 5: Foundations, retaining structures and geotechnical aspects, CEN, Brussels, 2004.

[8] Bararnia, M., Hassani, N., Ganjavi, B., Amiri, G.: Estimation of inelastic displacement ratios for soil-structure systems with embedded foundation considering kinematic and inertial interaction effects, Engineering Structures, 159 (2018), pp. 252-264.

[9] Asadi-Ghoozhdi, H., Attarnejad, R.: A Winkler-based model for inelastic response of soil–structure systems with embedded foundation considering kinematic and inertial interaction effects, Structures, 28 (2020), pp. 589-603.

[10] Vishwajit, A.: Soil-structure Interaction: A State-of-the-Art Review, Structures, 16 (2018), pp. 317-326.

[11] Mekkiab, M., Elachachia, S.M., Breyssea, D., Nedjarb, D., Zoutat, M.: Soil-structure interaction effects on RC structures within a performance-based earthquake engineering framework, European Journal of Environmental and Civil Engineering, 18 (2014) 8, pp. 945-962.

[12] NEHRP Consultants Joint Venture: Soil-Structure Interaction for Building Structures, First edition, U.S. Department of Commerce - National Institute of Standards and Technology, Gaithersburg, MD, 2012.

[13] Applied technology council: A Practical Guide to Soil-Structure Interaction, First edition, Federal Emergency Management Agency (FEMA), Washington, DC, 2020.

[14] Dhehbiya, G., Salah, K.: Effects and dynamic behaviour of soil - framed structure interaction, GRAĐEVINAR, 74 (2022) 1, pp. 9-20, https://doi.org/10.14256/JCE.2301.2017

[15] Sanghai, S.S., Pawade, P.Y.: Effectiveness of friction dampers on seismic response of structure considering soil-structure interaction, GRAĐEVINAR, 72 (2020) 1, pp. 33-44, https://doi.org/10.14256/JCE.1982.2017

[16] Edip, K., Garevski, M., Sheshov, V., Bojadjieva, J.: Boundary effects in simulation of soil-structure interaction problems, Soil Mechanics and Foundation Engineering, 54 (2017) 4, pp. 239-243

[17] Sheshov, V., Talaganov, K.: Relevant Aspects of Applying Soil Improvement Method for Liquefaction Mitigation – Case Study, Fourth International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, Rolla (MO), 2001.

[18] Sheshov, V.: Lecture Notes: Dynamic Soil structure Interaction, Institute of earthquake engineering and engineering seismology, Skopje, 2010.

[19] Lou, M., Wang, H., Chen, X., Zhai, Y.: Structure–soil–structure interaction: Literature review, Soil Dynamics and Earthquake Engineering, 31 (2011) 12, pp. 1724-1731.

[20] Petrov, N.: Experimental and numerical methods in earthquake geotechnical engineering, Seminar work, Institute of Earthquake Engineering and Engineering Seismology, Skopje, 2024.

[21] ASCE/SEI 41-17: Seismic Evaluation and Retrofit of Existing Buildings, Second edition, American Society of Civil Engineers, Reston, Virginia, 2017.

[22] Oliver, S., Hare, J., Harwood, N.: Soil Structure Interaction Starts With Engineers, Same Risks – New Realities – New Zealand Society for Earthquake Engineering, Wellington, 2013.

[23] ASCE/SEI 7-16: Minimum Design Loads and Associated Criteria for Buildings and Other Structures, American Society of Civil Engineers, Reston, Virginia, 2017.

[24] Seunghyun, K., Jonathan, S.: Kinematic soil-structure interaction from strong motion recordings, Journal of Geotechnical and Geoenvironmental Engineering, 129 (2003) 4, pp. 323-335.

[25] Thusoo, S., Modi, K., Kumar, A., Kumar, R.: Dynamic Soil Structure Interaction in Buildings, International Journal of Civil and Environmental Engineering, 10 (2016) 5, pp. 617-622.

[26] Khalil, L., Sadek, M., Shahrour, I.: Influence of the soil–structure interaction on the fundamental period of buildings, Earthquake Engineering Structural Dynamics, 36 (2007) 15, pp. 2445–2453.

[27] Mercado, J., Arboleda-Monsalve, L., Mackie, K.: IFCEE: International Foundations Congress & Equipment Expo. (Chapter) Study of Period Lengthening Effects in Soil–Structure Interaction Systems, Dallas, 2021.

[28] Pais, A.: Kausel, E.: Approximate formulas for dynamic stiffnesses of rigid foundations. Soil Dynamics and Earthquake Engineering, 7 (1988) 4, pp. 213–227.

[29] Brandis, A., Kraus, I., Petrovčič, S.: Simplified Numerical Analysis of Soil–Structure Systems Subjected to Monotonically Increasing Lateral Load, Applied Sciences, 11 (2021) 9, https://doi.org/10.3390/app11094219

[30] Brandis, A., Kraus, I., Petrovčič, S.: Nonlinear Static Seismic Analysis and Its Application to Shallow Founded Buildings with Soil-Structure Interaction, Buildings, 12 (2022) 11, https://doi.org/10.3390/buildings12112014

[31] Apostolska, R., Necevska-Cvetanovska, G., Bojadjiev, J., Bojadjieva, J.: Seismic performance of RC high-rise buildings-a case study of 44 storey structure in Skopje (Macedonia), Technical Gazette, 23 (2016) 4, pp.1177-1183

[32] Sojuzen zavod za standardizacija: Pravilnik za tehnicki normative za beton I armiran beton, Sluzben list na SFRJ, 11 (1987), pp.309-352.

[33] Sojuzen zavod za standardizacija: Pravilnik za tehnicki normative za izgradba na objekti na visokogradba vo seizmicki podracja, Sluzben list na SFRJ, 31 (1981), pp. 844-854.

[34] Computers and Structures, Inc.: ETABS 20.0, Version 20.0. Walnut Creek, CA.

[35] IEEE Style: European Committee for Standardization: Eurocode 8: Design of structures for earthquake resistance - Part 1: General rules, seismic actions and rules for buildings, CEN, Brussels, 2004.

[36] Petrov, N.: Kinematic Soil – Structure interaction effects on seismic performance of RC frames, Institute of Earthquake Engineering and Engineering Seismology, Skopje, 2023.

[37] Kostikj, I.: Nonlinear static analysis of RC building with incorporation of local soil conditions according to EC8, Institute of Earthquake Engineering and Engineering Seismology, Skopje, 2020.

[38] IZIIS: IZIIS – In-Situ Geo –Laboratorija, Izvestaj 2021-62, Institute of Earthquake Engineering and Engineering Seismology, Skopje, 2021.

[39] Kausel, E., Whitman, R., Morray, J., Elsabee, F.: The spring method for embedded foundations, Nuclear Engineering and Design, 48 (1978) 1-2, pp. 377-392.

[40] Zanwar, K., Hosur, V.: Study on Soil Structure Interaction, International Journal for Scientific Research & Development, 4 (2016) 5, pp. 1645-1649.