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SINARG 2023

PROCEEDINGS

VOLUME 2

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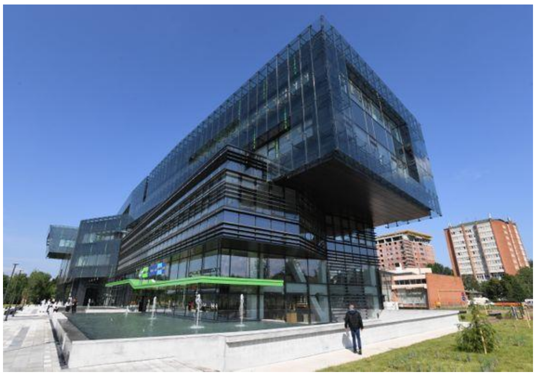

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ANALYSIS OF THE INTERACTION BETWEEN THE FOUNDATION SLAB AND THE SOIL IN A MULTI-STOREY REINFORCED CONCRETE BUILDING

Marijana Janićijević[1], Stefan Mihajlović[2]

Abstract

Analysis of the interaction between the foundation soil and the structure is a very important aspect of aseismic design. During the action of an earthquake, seismic waves deform the underlying soil, transferring stresses to the structure. Soil-structure interaction is a concept that refers to the building structure, the foundation structure, and the geological environment in which the foundation structure is located. Understanding the interaction process can, in some cases, reduce the intensity of the forces acting on the structure, mostly by damping and extending the period of vibration of the structure.

This paper presents an analysis of the interaction between the foundation slab and the soil using a model of a reinforced concrete building with Bsmt+GF+4 floors. The construction of the building is skeletal - it consists of reinforced concrete frames with a distance of 5 m in two orthogonal directions. The reinforced concrete elements have the same cross-section on all floors. The soil under the foundation slab is modeled as a half-space, which implies representing the soil volumetrically, using volumetric finite elements with appropriate properties. In this type of modeling, the soil is described by two parameters: the type of soil is determined by the deformation modulus and Poisson's ratio. The analysis shows the dependence of the static influences on the thickness of the foundation slab and the size of the finite elements for three different values of the soil deformation modulus. The software package TOWER 8 was used for modeling, design and calculation of the effect of all structural reinforced concrete elements, applying the European standards - Eurocodes.

Key words: *soil structure interaction, seismic action, static influences, soil parameters*

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1. INTRODUCTION

The interaction between the foundation slab and the underlying soil is a critical aspect of civil engineering [1]. The actual behavior of the structure under seismic action requires modeling of the interaction between the structure and the underlying soil (SSI -soil structure interaction), which introduces the flexibility of the foundation structure and soil into the analysis. The effects on the structure during earthquake action depend on the interaction of three interrelated systems: the structure itself, the foundation structure, and the geologic subsoil on which the foundation structure is located [2]. This means that the behavior of the foundation soil affects the construction and vice versa. Therefore, it is important to combine knowledge of geophysics, civil engineering, and geotechnical engineering to make the analysis of the interaction as high quality as possible [1]. When seismic waves propagate through the soil without foreign bodies, the soil behaves in a certain way, but when a foreign body (foundation structure) with a certain stiffness is found in that soil, the soil changes its behavior depending on the properties of the structure (Figure 1).

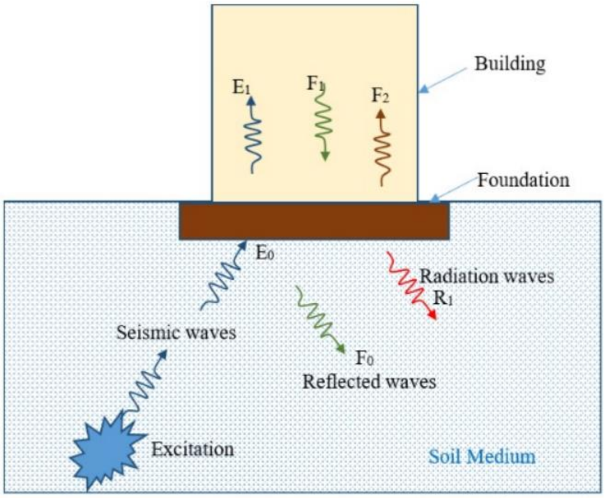

Figure 1. Soil structure interaction effect and wawe propagation [3]

The interaction between the structure, the foundation, and the underlying soil can have significant effects on the behavior of each of these elements, as well as on the general behavior of the entire system. For example, the relative stiffness of the structure, its subgrade, and the underlying soil will affect stresses and displacements, both in the structure and in the underlying soil [4].

Two basic factors that characterize the mutual influence of the building and the ground under the structure are deformations of the soil from loads that are transferred from the structure to the ground through the foundation and the ability of the structure to follow the soil deformations. With the use of various types of soil for supporting the foundation, the need to include the effects resulting from soil deformation in the calculation of the construction of the building is becoming more and more frequent. The magnitude of such influences in the structure depends on the stiffness of the structure. As a consequence of soil deformation under the building, subsidence, horizontal movement, and rotation of the foundation of the building occur. For absolutely rigid structures, the amount of rotation is very important, both for the foundation and for the object as a whole. In the case of absolutely flexible structures, the average amount of settlement is important in order to evaluate the changes that may occur during the exploitation of the structure. When calculating structures of finite stiffness, soil deformations should also be taken into account. In this calculation, the structure should be considered together with the soil, taking into account the mutual influence of the structure and the soil, which represents a very complex problem. It should be emphasized that there are methods that allow the calculation to include the mutual influences of the structure and the soil. Therefore, deformations of the soil under the foundation under the influence of external loads are particularly significant for the evaluation of the behavior of the structure during exploitation. Its safety and exploitability depend on the amount of deformation of the soil under the foundation of the structure [5]. Computational models for the calculation of the complete soil-structure interaction in different cases and combinations of loads that occur during construction and during the use of the structure are very complex, extensive, and demanding task that is rarely fully implemented in practice. Simplifications of calculation models and calculations are very common in order to make the problem simpler and practically predictable [6].

It has been proven that SSI can affect aspects related to the seismic performance of a building such as energy dissipation, strength, and ductility. In some cases, the capacity of the structure can be overestimated if the SSI analysis is omitted, resulting in unreliable results [7].

2. METHODOLOGY

Solutions to problems between deformable bodies have a very wide application in many engineering disciplines, but they can only be obtained by applying very complex numerical methods. The simplest solutions describe the combination of linearly elastic and ideally rigid bodies, and for such problems, the solution can be obtained in an analytical form. However, in the case of practical problems that are usually quite complex, even when the simplest linear elastic model is used, the solution to the problem can be obtained by approximate, that is numerical methods. In order to obtain realistic results of construction calculations, it is necessary, among other things, to solve the interaction of the object with the foundation and the soil during all phases of the construction of the object. Given that the mechanical properties of the soil are very complex, the solution to the problem of the interaction of the foundation soil with the structural elements requires certain simplifications, which approximate the real state with a computational model. Without such simplifications, the problem would be insoluble. The level of simplification must be such that it excludes features that do not affect or very little the final result while retaining the essential mechanical characteristics of the structure and soil. More complex material models, if properly applied, give more realistic results on the basis of which it is possible to design and build more rationally. However, their application is not always necessary or justified [8]. When creating a model for static stress, the soil is an infinite space with an unbounded domain. Therefore, for such an analysis, a fictitious boundary is taken that is far enough from the structure that the stress effect stops at that boundary [9].

There are two methods to deal with the interaction between the foundation soil and the structure, direct and indirect. A direct method is an approach in which the entire structure is analyzed as a whole using computer software, while the indirect method first analyzes the inertial and kinematic interactions separately, after which these interactions are added together to obtain the overall analysis. The direct method uses the finite element method, it is more complex than the indirect method, but also more precise. In this construction method, the foundation and soil are modeled together in one step [1].

The finite element method is a numerical method for solving complex engineering problems. Unlike other numerical methods that are based on the mathematical discretization of the equations of boundary problems, the finite element method is based on the physical discretization of the considered area. Instead of elements of differentially small dimensions, the basis for the analysis is a part of the area of finite dimensions - the finite element. Therefore, the basic equations used to formulate the problem are simple algebraic. This means that the considered area, as a continuum with an infinite number of degrees of freedom, is replaced by a model of interconnected finite elements with a finite number of degrees of freedom. The basic task is to choose a model that will best approximate the boundary value problem. The accuracy of the calculation is defined by the quality of the selected mesh and the type of finite elements. The most commonly used finite elements in the analysis are 2D and 3D finite elements. Modeling the object using these elements, then defining the limitations and loads, as well as all the necessary mechanical properties of the material from which they are made, and finally solving the problem with numerical methods, leads to the desired results [10].

This paper presents an analysis of the interaction between the foundation slab and the soil using a model of a reinforced concrete building with Basement+GF+4 floors. The construction of the building is skeletal - it consists of reinforced concrete frames with a distance of 5 m in two orthogonal directions. The reinforced concrete elements have the same cross-section on all floors.

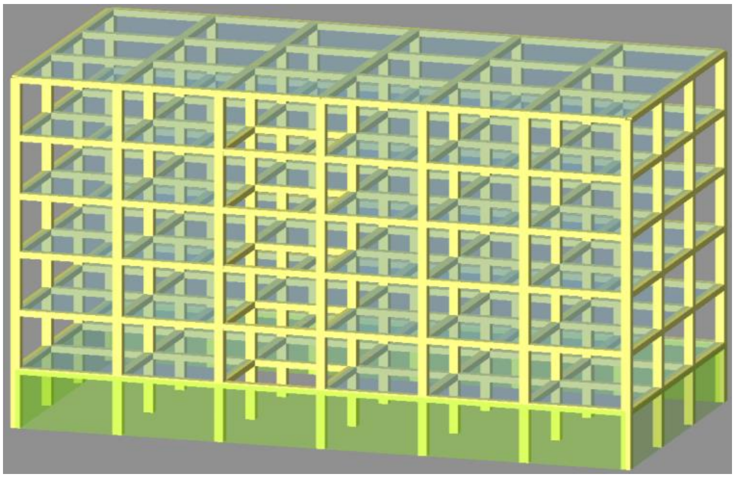

Figure 2. Model off the structure

The soil under the foundation slab is modeled as a half-space. This type of modeling involves representing the soil volumetrically, that is, using volumetric finite elements of appropriate characteristics. For the described object, for the sake of simplifying the calculation, a semi-space with a depth of 10 m was adopted, with dimensions 5 m wider on each side compared to the dimensions of the object, although the modeling of the ground as a semi-space theoretically means that the semi-space is unlimited except on the upper side, where it is limited by the surface soil. With this type of modeling, the soil is described with two parameters: the type of soil is determined by the deformation modulus and Poisson's ratio. For the specific case, the soil whose Poisson's ratio is equal to 0.20 was adopted. The volumetric weight of the soil is adopted equal to 20 kN/m^3. The mesh of the finite elements of the subject-object is shown in Figure 3. The soil deformation modulus is variable for different cases of the soil model. The analysis shows the dependence of static influences on the thickness of the foundation slab and the size of the finite elements for different values of the soil deformation modulus. The following parameters were varied: the soil deformation modulus (10 MPa, 20 MPa, and 40 MPa), the thickness of the foundation slab (0.40 m, 0.50 m, and 0.70 m), and the size of the finite element (1.25 m, 1.5 m and 2 m).

The software package TOWER 8 was used for modeling, design, dimensioning of the structural elements and calculation of the effect of all structural reinforced concrete elements, applying the European standards - Eurocodes.

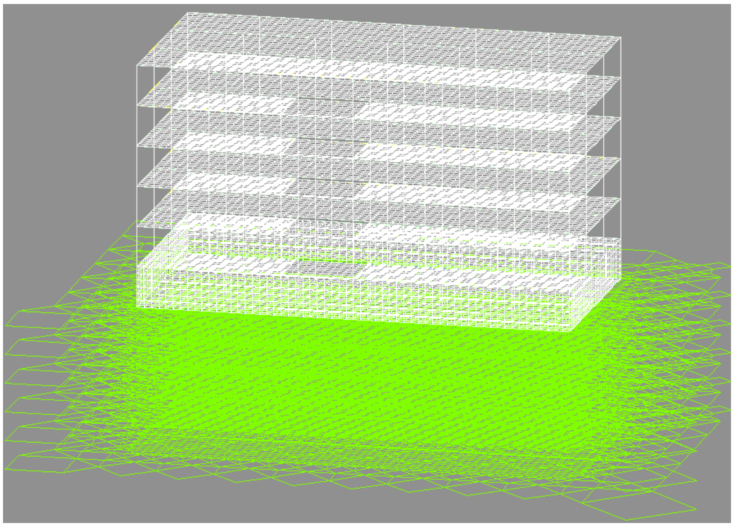

Figure 3. Finite elements mesh

During the analysis, the effects of seismic action and gravity (constant and variable) load were considered. Seismic impacts were determined by multimodal analysis with a design spectrum for the horizontal direction. EN 1998-1 prescribes the elastic response spectrum for horizontal seismic action with the following parameters: type 1 elastic response spectrum, soil category C (S=1.15, T_b=0.2 s, T_c=0.6 s, and T_d=2 s), maximum ground acceleration a_g=0.2g, correlation factor due to damping η=1 and building significance factor γ=1). For the analyzed construction, a high ductility class DCH was adopted, for which a total behavior factor of q=5.85 was determined.

For the dimensioning of the supporting elements, concrete C30/37 and reinforcements B500B were used. The columns are reinforced with 8Ø32 and are weighted with stirrups Ø8/7,5 cm on the length of the critical area and on the rest of the length Ø8/15 cm. The beams in the supporting zones are reinforced in the upper zone with 5Ø20 and in the lower zone with 3Ø20, and in the field in the lower zone with 3Ø20 and in the upper zone with 2Ø20. Stirrups are placed at a distance of 10 cm. The foundation slab is modeled as unreinforced.

3. RESULTS

As reference parameters for the analysis, the following were derived from all the influences that occur in the structure: bending moments in the foundation slab (Mx and My), stresses occurring in the foundation soil under the foundation slab (σ), and soil settlement under the foundation (s). Below, the results are presented graphically, and the exact values on the diagrams are tabulated.

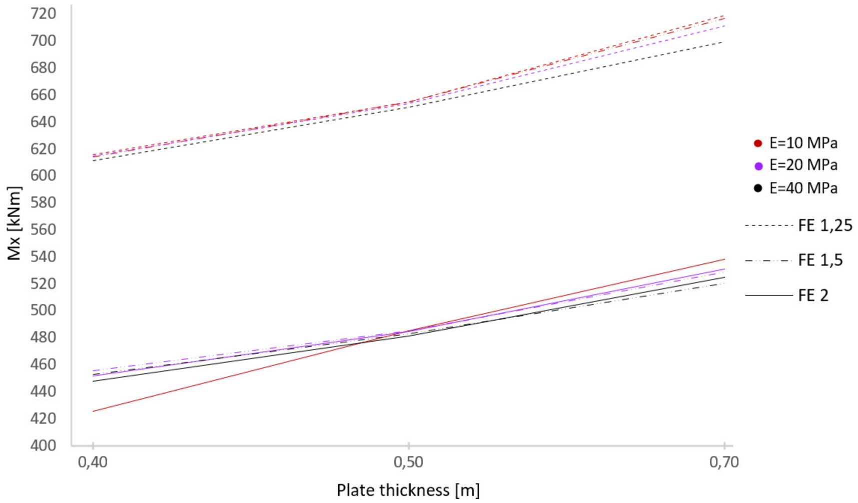

Figure 4. Bending moments Mx in the base plate

Table 1. Values of bending moments Mx in the base plate [kNm]

	E=10 [MPa]			*E=20 [MPa]*			*E=40 [MPa]*		
	plate thickness [m]			*plate thickness [m]*			*plate thickness [m]*		
FE [m]	*0,40*	*0,50*	*0,70*	*0,40*	*0,50*	*0,70*	*0,40*	*0,50*	*0,70*
1,25	*615,9*	*655,2*	*719,3*	*615,1*	*654,3*	*711,5*	*611,9*	*651,2*	*700,0*
1,5	*614,5*	*655,0*	*717,9*	*455,8*	*485,7*	*529,0*	*453,4*	*483,3*	*520,7*
2	*425,5*	*485,7*	*538,3*	*451,8*	*484,7*	*531,5*	*448,2*	*481,8*	*525,3*

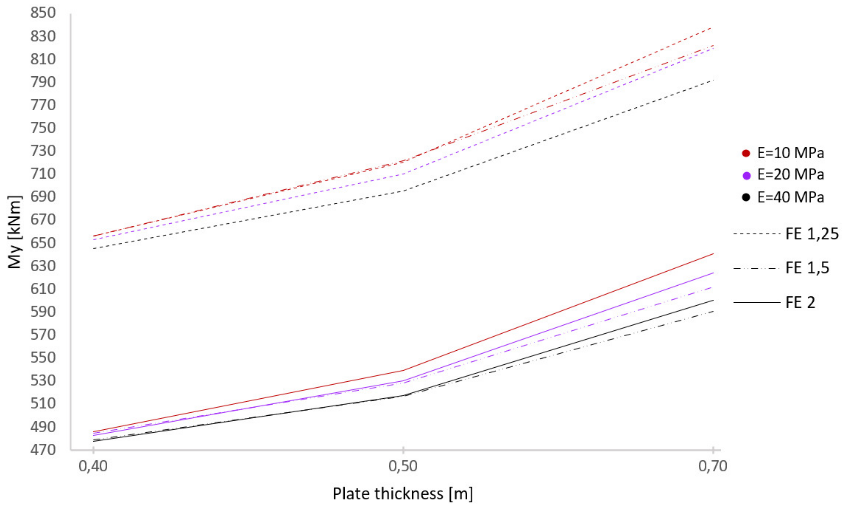

Figure 5. Bending moments My in the base plate

Table 2. Values of bending moments My in the base plate [kNm]

	E=10 [MPa]			E=20 [MPa]			E=40 [MPa]		
	plate thickness [m]			plate thickness [m]			plate thickness [m]		
FE [m]	0,40	0,50	0,70	0,40	0,50	0,70	0,40	0,50	0,70
1,25	656,7	720,5	838,4	653,1	710,6	819,7	645,6	695,9	792,4
1,5	656,4	721,8	822,6	484,6	528,3	611,9	487,8	517,1	590,8
2	486,2	539,4	641,2	482,9	530,6	624,6	478,5	517,8	600,3

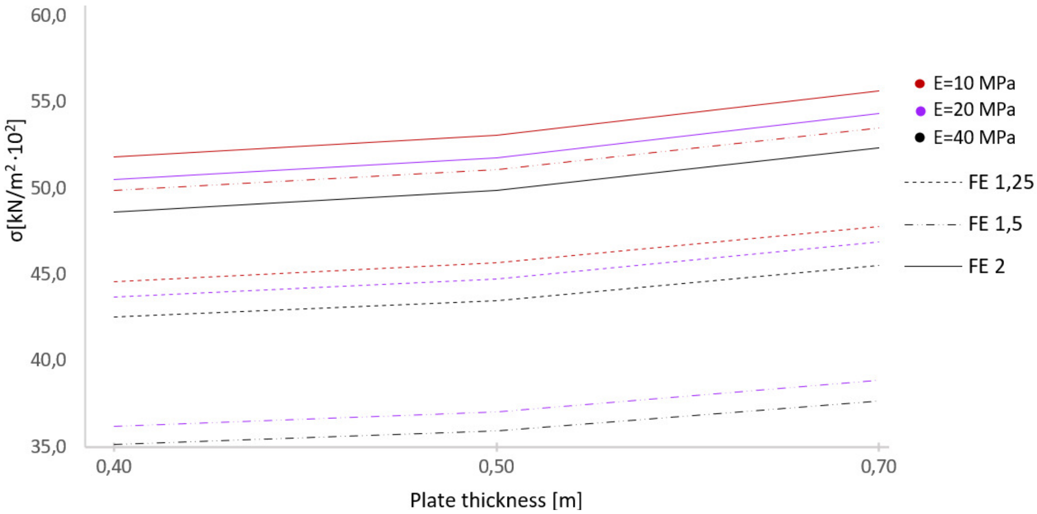

Figure 6. Stress in the underlying soil

Table 3. Values of stress in the underlying soil [kN/m²·10²]

	E=10 [MPa]			E=20 [MPa]			E=40 [MPa]		
	plate thickness [m]			plate thickness [m]			plate thickness [m]		
FE [m]	0,40	0,50	0,70	0,40	0,50	0,70	0,40	0,50	0,70
1,25	44,63	45,69	47,82	43,74	44,78	46,93	42,58	43,50	45,56
1,5	49,90	51,10	53,54	36,20	37,07	38,87	35,18	35,95	37,67
2	51,84	53,12	55,65	50,51	51,78	54,36	48,74	49,88	52,37

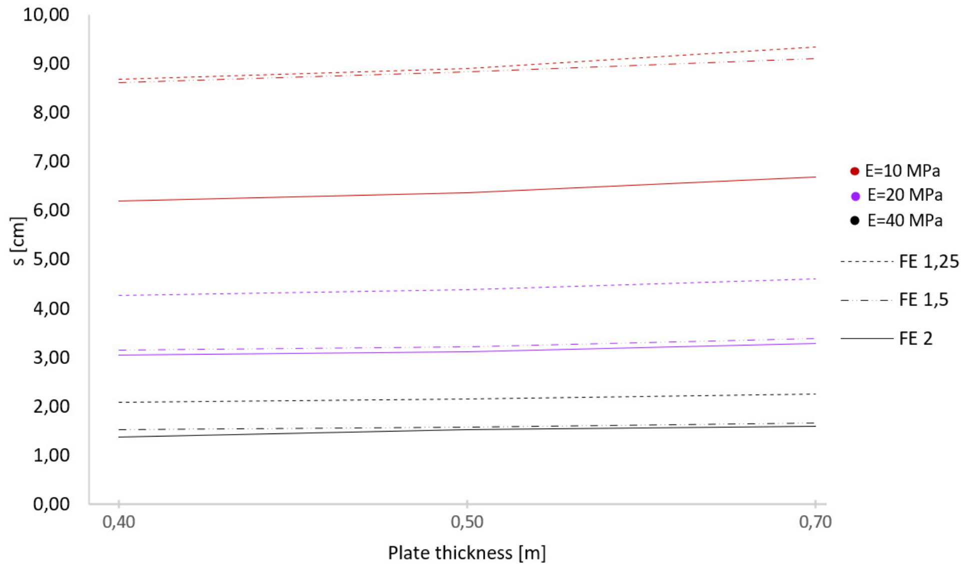

Figure 7. Ground settlement

Table 4. Values of ground settlement [cm]

	E=10 [MPa]			E=20 [MPa]			E=40 [MPa]		
	plate thickness [m]			plate thickness [m]			plate thickness [m]		
FE [m]	0,40	0,50	0,70	0,40	0,50	0,70	0,40	0,50	0,70
1,25	8,72	8,93	9,31	4,32	4,46	4,64	2,11	2,24	2,31
1,5	8,61	8,80	9,13	3,11	3,23	3,47	1,57	1,68	1,77
2	6,24	6,96	6,79	3,05	3,16	3,35	1,42	1,52	1,63

4. DISCUSSION

By comparing the influence in the construction for different values of the soil deformation modulus E, shown in the diagrams in Chapter 3, the following can be concluded:

- Bending moments are proportionally smaller with increasing values of soil deformation modulus.
- If the dependence of the observed static influences on the thickness of the base plate is observed, the bending moments increase proportionally with the increase in the thickness of the base plate.
- From the aspect of analyzing the influence of the size of the finite elements, with which the soil is modeled, on the static effects, it can be noted that the size of the finite elements of 1.25 m and 1.5 m for the soil deformation module E=10 MPa give approximate values of the bending moments, and for the size of finite elements of 2 m and soil deformation modulus E=10 MPa, moment values are significantly lower. For the soil model with a mesh of finite elements of size 1.5 m and 2 m, for soil deformation modulus E=20 MPa and E=40 MPa, the bending moments

are approximately the same, while with finite elements of size 1.25 m, they are significantly higher.

- Observing the stresses in the foundation soil, it can be seen that the stresses in the soil increase with the increase in the thickness of the foundation slab and the size of the finite elements used to model the soil. With the increase of the deformation modulus of the soil, the stresses in the soil decrease.
- When it comes to soil settlements under the foundation, with the increase in the size of the finite element, the settlements decrease. The settlement curves on the presented diagrams for finite element sizes of 1.25 m and 1.5 m show that, for the soil deformation modulus of 10 MPa, the settlement values are approximately the same. For E=20 MPa and E=40 MPa and sizes of finite elements 1.5 m and 2 m, the settlement values are approximate.
- Settlements, when the soil is modeled with a soil deformation modulus of 10 MPa and finite elements of size 2 m, are significantly smaller than in the model where finite elements are of size 1.25 m and 1.5 m, while for E=20 MPa and E=40 MPa and mesh with the size of the finite elements of 1.25 m, the settlements are much larger compared to the model where the finite elements are 1.5 m and 2 m.
- With an increase in soil deformation modulus, settlements decrease proportionally.

5. CONCLUSION

The interaction of the foundation soil and the structure has a very important role in aseismic engineering. Globally, the objective strength of an earthquake is not important, but the consequences it leaves on objects are important. Given that the time of earthquake formation cannot be predicted, the only thing we can do is to mitigate the consequences of an earthquake by proper aseismic construction, and knowing the interaction of the underlying soil and the structure is one of the ways to mitigate the consequences [1].

Earthquake waves travel towards the surface of the ground for several tens of kilometers, which is impossible to model in calculations, but the depth of the ground is taken, which will include the effects of the earthquake and be comparable to the geometry of the structure. The interaction between the structure and the foundation soil is a combined system model that can physically and mathematically describe changes in the stiffness or flexibility of the foundation soil. Conventional theories talk about how the interaction effect is positive or beneficial to the structural response, while some analyses recommend ignoring the interaction terms, which can lead to poor structural design. It is true that interaction effects are insignificant in certain situations. but there are facilities and local soil conditions that do not allow calculations. Therefore, only a detailed knowledge of the interaction of the foundation soil and the structure is a guarantee of a successful and safe calculation [1].

If the time required for the calculation is excluded, it is recommended to model the construction with as many finite elements as possible, in which case the calculation is on the side of safety. Since rationality is one of the most important factors during the design phase, it is possible to use finite elements of larger dimensions, where the rational explanation for this procedure would be the use of safety coefficients and the adoption of a slightly larger amount of reinforcement in the cross-section than the required amount in the dimensioning process. If the building is built on soil with given characteristics (Poisson's ratio is 0.20, bulk soil weight is 20 kN/m^3, soil deformation modulus is 10 MPa), the proposal is to use a mesh of finite elements with the same size of 1.25 m, at in such a case, the influences in the construction are the greatest and therefore the designer is on the side of safety. The disadvantage of this model is that it is computationally the longest, due to the time required for the software to calculate all the necessary elements. Although it is computationally simpler, it is not recommended to model the soil with the size of finite elements of 2 m, due to the appearance of significantly smaller influences in the construction. If an object is designed on soil with a deformation modulus of 20 MPa or 40 MPa, it is recommended to model the soil with finite elements of size 1.25 m. In contrast to what was said previously (when E=10 MPa), here the sizes of finite elements of 1.5 m and 2 m give approximately the same values of the observed impacts, which are significantly smaller than the soil model with the size of finite elements of 1.25 m.

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