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COMPARATIVE SEISMIC ANALYSIS OF RC BUILDINGS UNDER INFLUENCE OF SOIL-STRUCTURE INTERACTION

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UPOREDNA SEIZMIČKA ANALIZA AB ZGRADA SA UTICAJEM INTERAKCIJE TLA I OBJEKTA

ABSTRACT

In this paper the effects of soil-structure interaction (SSI) on reinforced concrete (RC) buildings are analyzed. The dynamic analysis was carried out for two buildings of different heights, founded on three different types of soils, and two different types of foundation, with and without soil interaction. Ten earthquake records, chosen for Belgrade site, were used in the response spectrum analysis. The mean spectrum at the base of the soil deposit and the mean spectra at the surface of each soil types were derived. Calculation was performed using the originally coded MATLAB program, which accounts for downward and upward wave propagation. The influence of the soil layer over the bedrock on the response of the RC buildings was calculated using the commercial software SAP2000. The conclusions were carried out according to theobtained results.

KEY WORDS

Seismic soil-structure interaction, response spectrum method, finite element method

REZIME

U ovom radu su analizirani efekti interakcije tla i konstrukcije na dinamički odgovor dve armirano-betonske zgrade različite spratnosti, koje su fundirane na tri različita tipa tla. Za dva tipa fundiranja, na temeljnoj ploči i temeljima samcima, sprovedena je dinamička analiza sa i bez uticaja tla. U metodi spektra odgovora korišćeno je deset zapisa zemljotresa izabranih za područje Beograda. Sračunat je osrednjeni spektar ubrzanja na osnovnoj steni, kao i osrednjeni spektri ubrzanja na površini terena za svaki tip tla. Proračun je sproveden primenom originalnog programa u MATLAB-u, koji uzima u obzir propagaciju talasa kroz tlo. Uticaj sloja tla iznad osnovne stene na dinamički odgovor zgrada je analiziran primenom komercijalnog programa SAP2000. Zaključci su izvedeni na osnovu dobijenih rezultata.

KLJUČNE REČI

Interakcija tla i objekta, metoda spektra odgovora, metoda konačnih elemenata

1. INTRODUCTION

Soil-structure interaction during an earthquake could considerably affect dynamic response of a structure. It could happen due to the kinematic interaction between soil and foundation and due to the fact that the presence of soil deposit over bedrock could considerable modify the input ground motion.

The 1985 Mexico City and many recent earthquakes demonstrated that the rock motions could be amplified at the base of a structure by over a factor of five. Therefore, estimation of the possible earthquake motion as well as determination of realistic site-dependent free field surface motion at the base of a structure is one of the most important steps in the earthquake resistant design of any structure [10]. In practice, in dynamic analysis, it is assumed that input motion at the foundation level of the structure is equal to the free field ground motion [10]. This assumption is correct only for structures founded on bedrock [5].

Having all above mentioned in mind, the dynamic analyses of two buildings with different number of stories were performed with and without soil interactions in order to maintain the influence of the local site properties on the earthquake ground motions, as well as on the dynamic response of the structure. For SSI three different types of soil, specific for the location of Belgrade, were taken into account. They correspond to the soils of types A, B and C according to EC8-1. Ten accelerograms, chosen according to the seismogenetic features of the Belgrade site, were used to obtain the mean spectrum at the ground level, which corresponds to the soil of type A. Then, the effect of the soil deposit was taken into account to calculate the mean spectrum at the base of the soil deposit, as well as the mean spectra at the surface of soil types B and C. The derived spectra were used in SAP2000 for the response spectrum analysis of fixed base structures and structures with soil.

Also, two types of foundation were taken into account in SSI analysis: foundation plate and single foundations. The outputs obtained from each model were used to compare the ratio of shear forces and story deflections, between the structures with soil and fixed-base structures. Also, the influence of soil layer on acceleration spectra and dynamic response of buildings were analyzed comparing the response of fixed base structures due to the appropriate original ground spectra.

2. DYNAMIC MODEL

In this research, structural models that represent the conventional type of buildings have been chosen. Two frame structures, with the height of 5 and 10 stories, were analyzed. The characteristic of their structural elements are presented in Table 1.

Table 1: Frames characteristics
Tabela 1: Karakteristike ramova

Number of stories	Number of bays	Story height (m)	Bay width (m)	Columns h/b (cm)	Beams h/b (cm)	Plates H (cm)	Foundation		Additional mass per story (t)
							Plate	Single	
5 10	3x6	3	4	50/50	40/30	12	D_p=30 cm grid 120x30 cm	2x2 m	160

Table 2: Earthquake ground motions used in analyses
Tabela 2: Zapisi zemljotresa korišćeni u analizi

No.	Earthquake	Year	Station	Magnitude
1	San Fernando	1971	Lake Hughes 4	6.61
2	El Centro	1979	Cerro Prieto	6.53
3	Chalfont Valley	1986	Lake Crowley – Shehor Res.	5.77
4	Superstition Hills	1987	Wildlife Liquef. Array	6.22
5	Landers	1992	Duarte – Mel Canyon Rd.	7.28
6	Northridge	1994	Antelope Buttes	6.69
7	Kobe	1995	Kakogawa	6.90
8	Kocaeli	1999	Arcelik	7.51
9	Duzce	1999	Mudurnu	7.14
10	Hector Mine	1999	Heart Bar State Park	7.13

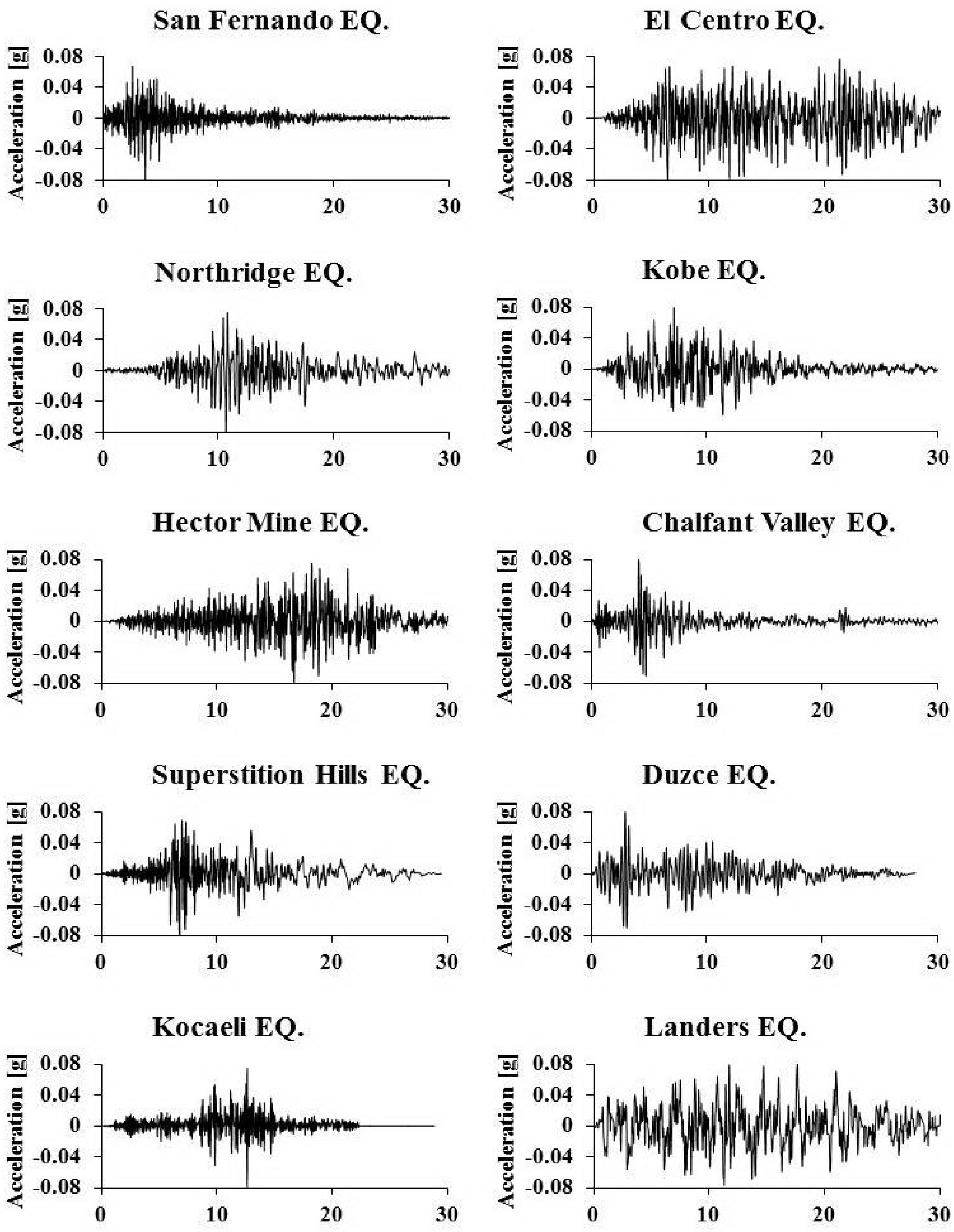

Figure 1. Chosen accelerograms
Slika 1. Akcelerogrami izabranih zemljotresa

Three types of soil, which represent types A, B and C according to the classification of EC8-1, were considered in this research. The characteristics of the soil were obtained from the report of Geophysical Institute [2] and are given in Table 3.

Table 3: Geotechnical characteristics of the soils
Tabela 3: Geotehničke karakteristike tla

No.	Soil type	Soil	$v_{s,30}$ [m/s]	γ [kN/m^3]	ξ [%]	E [MPa]	G_o [MPa]	υ [-]
1	Bedrock at the ground level	A	> 800					
2	Alluvial gravel	B	450	20.0	1	1010	405	0.25
3	Marl clay	C	325	20.0	1	550	210	0.30

The soils of type B and C were treated as viscoelastic. The reduction of shear modulus G_o and augmentation of damping coefficient due to the increase of shear deformations in the equivalent linear analysis were taken according to the Refs. [7] and [9].

3. DYNAMIC ANALYSIS

The dynamic response of the buildings was carried out using response spectrum method in two different ways: (a) fixed-base structures on rigid ground (Fig 2.a) and (b) structures with constant layer of subsoil, 54 m deep (Fig 2.b). Only earthquakes in X-direction were considered in this dynamic analysis.

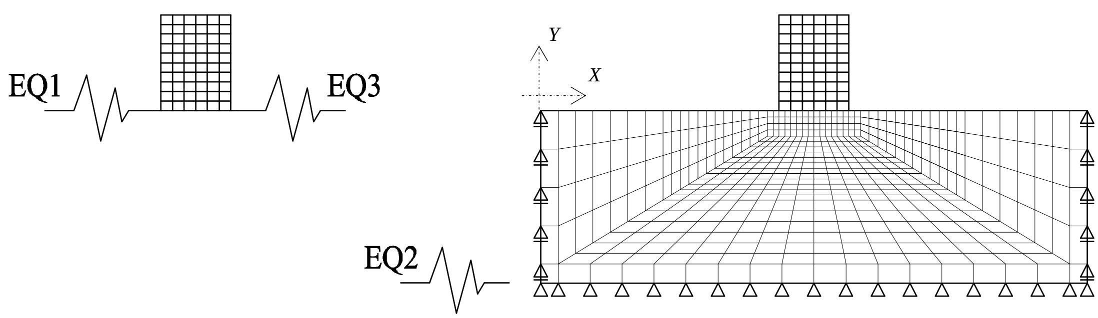

Figure 2. a) Fixed-base model b) Structure with soil
Slika 2. a) Kruto uklješteni model b) Konstrukcija sa tlom

Direct method of dynamic soil-structure analysis is usually applied in SSI analysis. In this research the response spectrum method was used in order to check its capabilities for adequate simulation of such problems. Besides that, the response spectrum method has been applied in order to reduce computational effort, since time-history analysis could be time consuming, especially if increased number of earthquake records is taken into account. The number of modes used for analyses was chosen with respect to the recommendations given in EC8-1. Columns and beams of the structures were modeled using 3D beam elements, while the plates were modeled as rigid in their plane. The soil was modeled using solid finite elements, as shown in Fig. 2b. The primary boundaries were applied in the soil at the sufficient distance from the structure: 82 m in the horizontal and 54 m in the vertical direction. Response spectrum method was applied to massless foundation model and model with foundation mass, in order to check the influence of the soil mass on the global structural response. Due to moderate earthquake peak accelerations, equal damping ratios in the structure and in the soil of 5% were assumed. The earthquake spectra of accelerograms and their mean value used in the fixed-base structure analysis (EQ1) are presented in Fig. 3a.

The earthquake motion at the base of the soil deposit was calculated using the downward shear wave propagation through 54 m thick layer type of ground A ($v_{s,30}$ = 800 m/s, γ=22 kN/m^3 and ξ = 1.0%).

The bedrock characteristics are: $v_{s,30}$ = 1600 m/s, γ=27 kN/m^3, ξ = 0.2%. The response spectra at the bedrock is presented together with their mean value (EQ2) in Fig. 3b.

After that, the upward wave propagation through the soil deposit of type B and C was carried out to obtain the free-field surface displacements (EQ3B and EQ3C). For this purpose a one dimensional pure shear model in the frequency domain was used [7]. The eventual nonlinear behavior was modeled applying equivalent linear analysis. For that purpose the computer program was developed in MATLAB [3-4]. In Fig. 4 the mean-value spectra at the ground for soil types B and C are presented in comparison with EC8-1 spectra and spectra on the bedrock (EQ2).

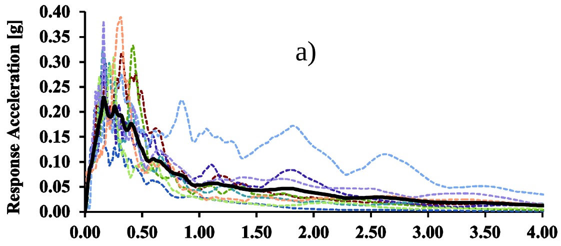

Figure 3. Response spectra and their mean values (a) EQ1- at the ground A and (b) EQ2 at the bedrock
Slika 3. Spektri odgovora i njihove srednje vrednosti (a) EQ1-na površini tla tipa A i (b) EQ2-na osnovnoj steni

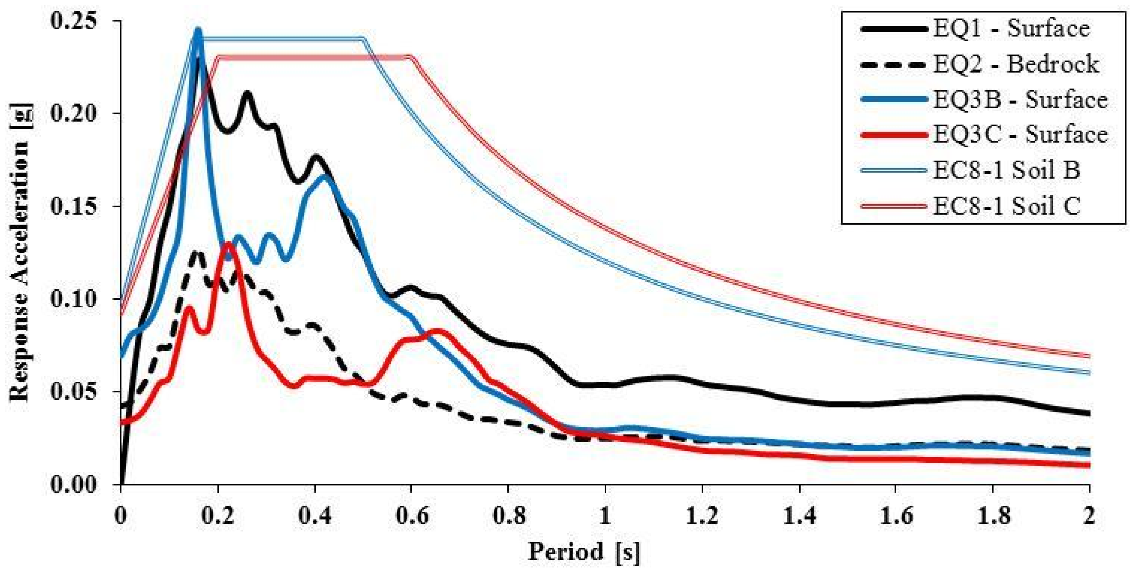

Figure 4. Mean values of the response spectra for EQ1, EQ2, EQ3B and EQ3C
Slika 4. Srednja vrednost spektara odgovora za EQ1, EQ2, EQ3B and EQ3C

The response spectrum analysis of two buildings was carried out for fixed-base structures using ground spectra for each type of soil (EQ1, EQ3B and EQ3C).

In the case of soil-structure interaction earthquake spectra EQ2 was applied to each soil-structure model at the base. Two models of soil were considered: with and without mass. All buildings were analyzed in two different ways: (a) as founded on the plate and (b) as founded on the system of single column foundations.

4. RESULTS AND DISCUSSIONS

In order to check the influence of incorporation of soil in finite element model some numerical examples were considered. Since the mean spectra were used in the analyses, the results obtained for each model were treated as average results. The ratio of story deflection and story shear were calculated for models with soil (EQ3B and EQ3C) and fixed base models (EQ2). EQ3B and EQ3C refer to the soils of type B and C, respectively. Story shear represents the shear force at the level of each story of the building, while story deflections are the horizontal displacements at each level of the building, in X-direction.

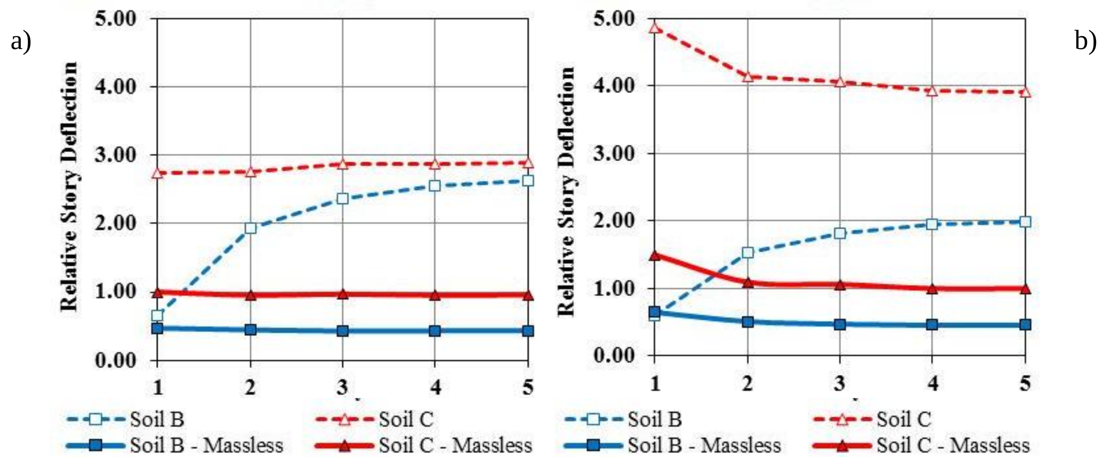

Figure 5. Relative story deflection for 5 stories building: a) plate foundations and b) single foundations
Slika 5. Relativno pomeranje sprata za zgradu sa 5 spratova fundiranoj na a) temeljnoj ploči i b) temeljima samcima

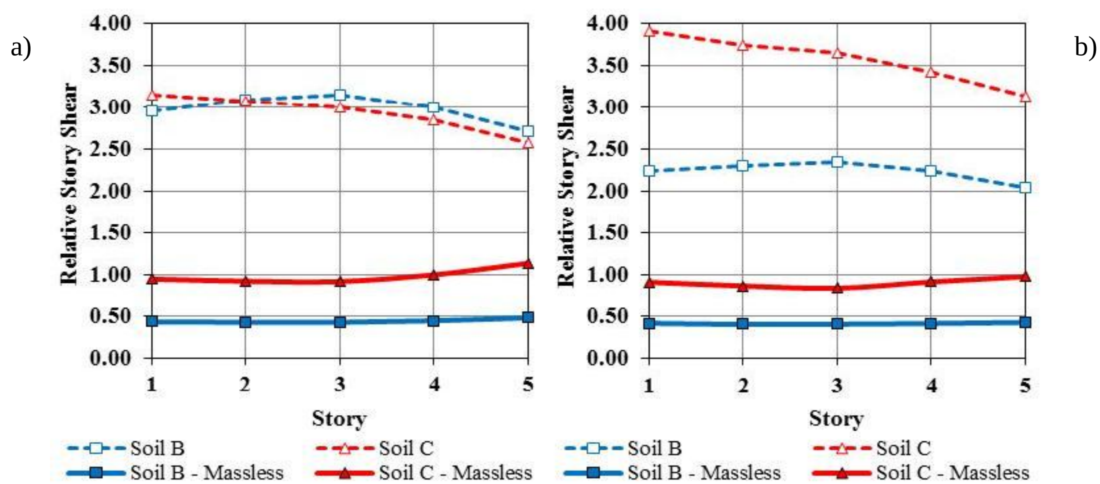

Figure 6. Relative story shear for 5stories building: a) plate foundations and b) single foundations
Slika 6. Relativna sila smicanja sprata za zgradu sa 5 spratova fundiranoj na a) temeljnoj ploči i b) temeljima samcima

Figs. 5-6 show that relative story deflections and story shears of model with soil mass included (EQ2) are amplified three to five times in comparison with the fixed base models (EQ3B and EQ3C). That is due to the fact that the soil mass induced additional inertia forces. Since these inertia forces should not be taken into account, only the results of the massless models will be discussed in the following part.

For five-story building, the relative story displacements of the model with soil type C and the fixed base case (Fig. 5) are around 1. In the case of soil type B the relative story displacements are around 0.5 for each level of the building for both types of foundations. In the case of separate foundations the relative displacements are slightly higher, especially in the lower part of the building. The differences in the amplification of displacements and shear forces between these two building-soil models are the result of the different dynamic behavior of the soils exposed to the presented earthquake records. If we examine the ground spectra for these two soils (EQ3B and EQ3C) and primary ones (EQ1) shown in Fig. 4, it is obvious that severe differences are present in the ground accelerations obtained for the fundamental period of 5-story buildings T_5~0.53s.

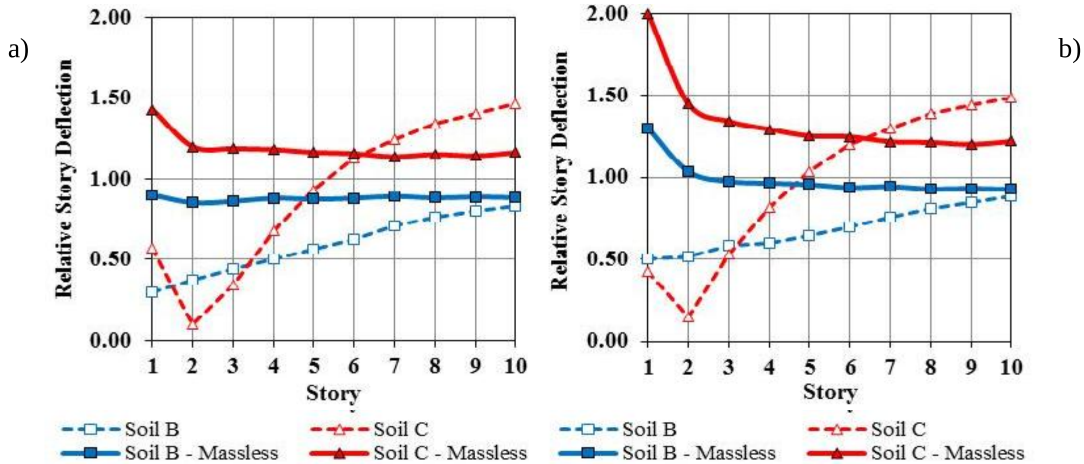

Figure 7. Relative story deflection for 10 stories building: a) plate foundations and b) single foundations
Slika 7. Relativno pomeranje sprata za zgradu sa10 spratova fundiranoj na
a) temeljnoj ploči i b) temeljima samcima

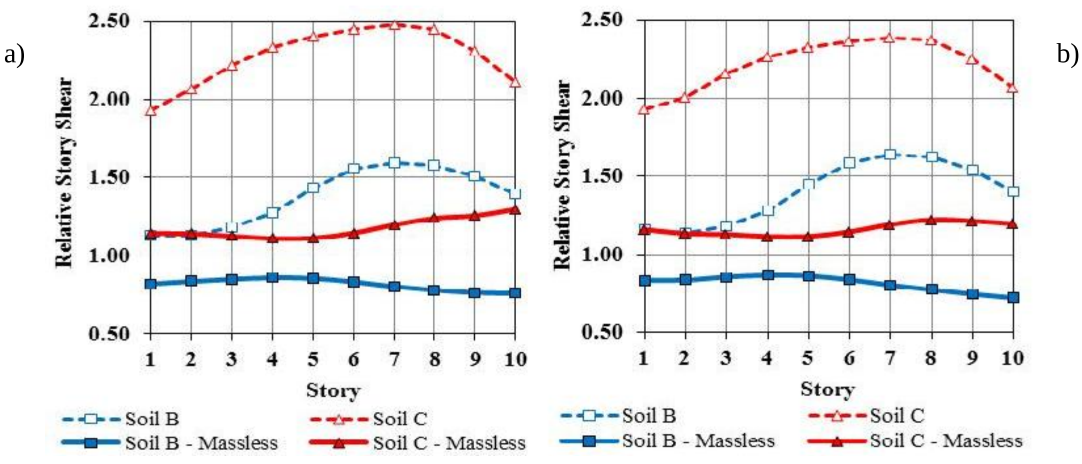

Figure 8. Relative story shear for 10 stories building: a) plate foundations and b) single foundations
Slika 8. Relativna sila smicanja sprata za zgradu sa 10 spratova fundiranoj na a) temeljnoj ploči i b) temeljima samcima

For ten-story building the massless foundation model gave more realistic results then the model with the soil mass. Relative story displacements of structures modeled with a flexible base with soil type B and C are presented in Fig. 7. Model with soil type C gave relative story displacements which are higher than 1 due to the effect of SSI. Influence of SSI is opposite in the case of soil type B, since the relative displacement is less than 1 at each level of the building. In the case of separate foundations relative displacements are generally higher than relative displacements of building with foundation plate, especially in the lower part of building.

Similar conclusions can be carried out for relative story shear, presented in Fig 8. Again, higher shear forces were obtained for structure modeled with soil type C (EQ3C) than in the case with the fixed base (EQ2). Relative story shears are between 1.15 and 1.35. For model with soil type B relative story shears are between 0.5 and 0.75. Also, the ratios of story shear are almost independent of the foundation type, Fig. 8.

a) b)

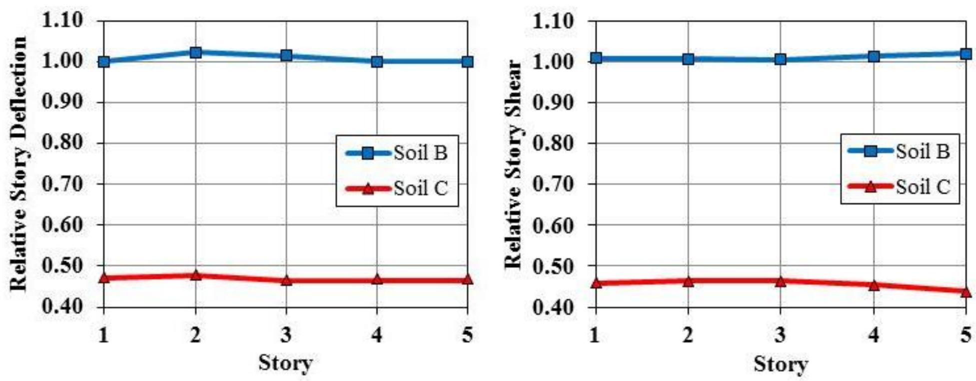

Figure 9. Relative story deflection (a) and shear (b) for 5-story building, fixed base
Slika 9. Relativna spratna pomeranja i smicanja sprata za zgradu sa 5 spratova, kruto uklješten model

a) b)

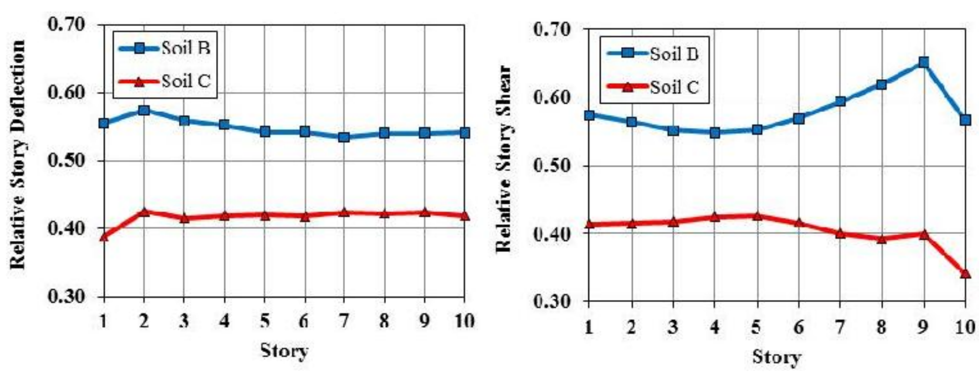

Figure 10. Relative story deflection (a) and shear (b) for 10- story building, fixed base
Slika 10. Relativna spratna pomeranja i smicanja sprata za zgradu sa 10 spratova, kruto uklješten model

In order to check the validity of the fixed base model (EQ3) and the error that is made using the original response spectrum at the ground level (EQ1), the results of the response spectrum analysis obtained using the response spectra EQ3B and EQ3C were compared with the results obtained using the original response spectrum EQ1. Relative deflection and story shear are presented for five-story and ten-story buildings in Figs. 9 and 10, respectively.

For five-story building the relative story deflections (Fig. 9) are around 1.0 for all stories in the case of soil type B. In the case of soil type C, the relative story deflections are less than 0.5 for all stories. The same results are obtained for the relative story shears. It means that application of original mean spectrum (EQ1) gives almost the same results as the mean spectrum obtained for soil type B (EQ3B), but quite conservative ones in the case of soil type C.

For ten-story building relative story deflections and shears for both types of soil are less than 1.0 for all stories. It means that original response spectrum (EQ1) gives conservative values of story deflections and shears, which is on the safe side in engineering sense. Again, this behavior is provoked by the differences in amplitudes of the response spectra EQ1 and EQ3 (Fig. 4), in the area of fundamental frequencies of building relevant for the spectrum response analysis. Obviously, for the application of response spectrum method in SSI analysis, it is of the great importance to understand the fundamental dynamic properties of the building and the soil which is analyzed.

5. CONCLUSIONS

The effects of soil-structure interaction in the analysis of RC buildings were analyzed. The response spectrum method with commercial software SAP2000 was conducted. Two reinforced concrete buildings with regular basis and different heights, founded on three different types of soils, with two different types of foundation were analyzed. The recommendations of Seismological Institute of Serbia were accounted while selecting the appropriate accelerograms for Belgrade site. The results of the model with soil were compared with the results obtained using the fixed base model, which is traditionally used in dynamic analysis of RC buildings because of its simplicity.

The numerical analysis presented in this paper confirmed the influence of SSI on the dynamic response of RC buildings. It is shown that amplification of motion from bedrock to the ground can be very high after the upward wave propagation through some types of soil. This phenomenon, which is usually neglected by some authors, is illustrated in two numerical examples. On the other hand, the negative influence of soil mass incorporated in numerical model is confirmed.

It is shown that fixed base model can be either the conservative or no conservative if the original record of ground accelerations is used in the response spectrum method. This highly depends on type of the soil deposit under the structure. It is also shown that the choice of the fundament type doesn't influence the overall dynamic properties of the soil-structure model severely, for the buildings with regular basis.

The next step in this research is to investigate the limits of response spectrum method in SSI analysis, and to investigate the influence of higher mode shapes on the overall response of SSI model. Due to that, the direct step-by-step time history integration will be applied in the analysis of the characteristic building models, using different earthquake records.

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