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24-26. SEPTEMBAR

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Mira Petronijević[1], *Dragan Kovačević, Miroslav Marjanović, Marko Radišić, Miloš Marjanović*

UTICAJ INTERAKCIJE TLA I OBJEKTA NA SEIZMIČKI ODGOVOR ARMIRANO-BETONSKIH ZGRADA

Rezime:

U ovom radu su analizirani efekti uticaja tla na dinamički odgovor armirano-betonskih zgrada različite spratnosti. Analizirana su dva 3D modela armirano-betonskih zgrada visine 5 i 10 spratova, fundiranih na temeljnoj ploči, odnosno temeljima samcima za dva različita tipa tla, meko i kruto. Primenjena su dva tipa dinamičke analize: direktna dinamička analiza i metoda spektra odgovora. Dobijeni rezultati su upoređeni. Korišćeno je deset zapisa zemljotresa izabranih za područje Beograda. Propagacija talasa kroz tlo uzeta je u obzir primenom originalnog programa napisanog u MATLAB-u. Na osnovu dobijenih rezultata izvedeni su odgovarajući zaključci.

Ključne reči: *seizmička interakcija tla i objekta, metoda spektra odgovora, direktna dinamička analiza, metod konačnih elemenata*

INFLUENCE OF SOIL-STRUCTURE INTERACTION ON THE SEISMIC RESPONSE OF RC BUILDINGS

Summary:

In this paper the effects of the soil-structure interaction (SSI) on dynamic response of reinforced-concrete (RC) buildings of different heights are analyzed. Two 3D numerical models of 5 and 10-storey reinforced-concrete buildings founded on two different foundation types: plate and single foundations, lying on two types of soils: soft and stiff ones, are considered. Two types of the dynamic analysis are carried out: time history analysis and response spectrum method. The obtained results are compared. Ten earthquake records chosen for Belgrade site are used. The wave propagation in the soil is taken into account using the originally coded MATLAB program. The appropriate conclusions are derived according to the obtained results.

Key words: *seismic soil-structure interaction, response spectrum method, time history analysis, finite element method*

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1 INTRODUCTION

Interaction between the soil and the foundation (known as the soil-structure interaction - SSI) during an earthquake could considerably affect the dynamic response of a structure. The presence of soil deposit over the bedrock could considerably modify the seismic ground motion. The bedrock motions could be amplified at the foundation level by over a factor of five, which can lead to the collapse of the structure. Therefore, the estimation of the possible earthquake motion as well as the determination of the 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 [1]. In engineering practice it is usually assumed that input motion at the foundation level of the structure is equal to the free field ground motion. This assumption is correct only for structures founded on the bedrock [2].

The purpose of this paper is to highlight the importance of SSI in seismic design of typical reinforced-concrete buildings and to check the applicability of the time history analysis and the response spectrum method in SSI analysis. Numerical finite element models of two buildings with different number of stories, with and without the influence of SSI, are used. Three different types of soil (A, B and C according to EC8-1 [3]) specific for the location of Belgrade are taken into account.

According to the seismogenetic features of the Belgrade site, ten accelerograms are chosen for the family of time history analyses conducted in this research. These accelerograms are used also to obtain the mean spectrum at the foundation level. Then, the influence of the soil deposit is taken into account to calculate the modified input accelerograms and the mean spectrum at the base of the soil deposit (bedrock level). Finally, the input accelerograms and the mean spectra at the surface of the soil types B and C are calculated using the originally coded MATLAB program [4]. The obtained accelerograms/spectra are used in SAP2000 [5] for the time history analysis as well as for the response spectrum analysis of fixed base structures and the structures founded on the soil. Two types of foundation are considered in the numerical analysis: plate foundation and single foundations.

The obtained results are used to compare the ratio of shear forces, story deflections (in both analyses) and inter-story drifts (only in the time history analysis) between the structures with soil and fixed-base structures. Finally, the responses of the fixed base structures under the modified accelerograms/spectra are compared with the responses obtained using the appropriate original accelerograms/spectra, and the conclusions are derived.

2 NUMERICAL MODEL

In this research two frame structures with the height of 5 and 10 stories are analyzed. The floors are divided with RC beams into 3x6 bays (bay width = 4m). Story height is 3 m. The characteristic of the structural elements of the buildings are presented in Table 1. The chosen accelerograms are given in Table 2.

Table 1: Characteristics of the structural elements

Columns h/b [cm]	Beams h/b [cm]	Plates H [cm]	Foundation plate [cm]	Single foundations [m]	Additional mass per story [t]
50/50	40/30	12	D_p = 30 Grid 120x30	2x2 m	160

Table 2: Earthquake ground motions used in the analyses

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

The characteristics of the soil are obtained from the report of Geophysical Institute [6] and are given in Table 3. The soils of type B and C are treated as viscoelastic. The reduction of the shear modulus G_0 and augmentation of damping coefficients due to the increase of shear deformations in the equivalent linear analysis are taken according to the Refs. [7] and [8]. The dynamic analysis of the buildings is carried out using two different numerical models: **(a)** fixed-base structures on the rigid ground (Figure 1a) and **(b)** structures with the constant (54 m deep) layer of subsoil (Figure 1b).

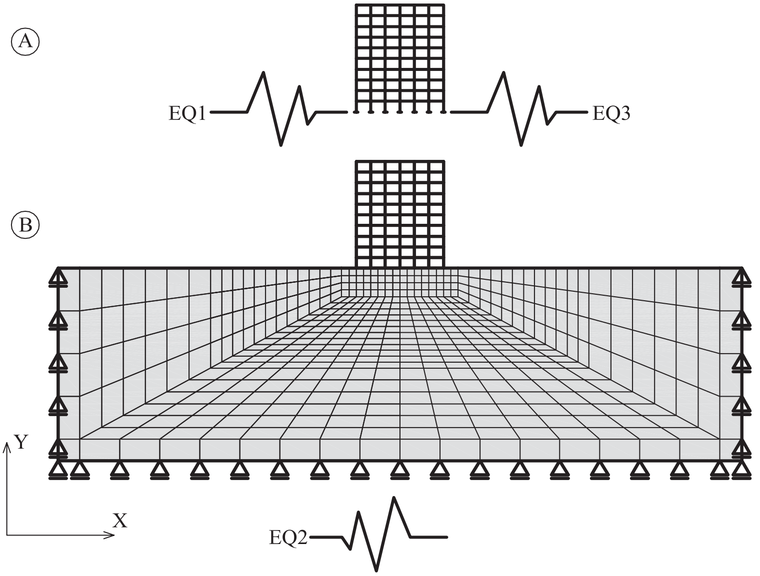

Figure 1 – Fixed-base model (A) and model of the structure with soil (B)

Columns and beams are modeled using the 3D beam elements, while the floors are modeled as rigid diaphragms. The soil is modeled using the solid finite elements (Figure 1b). The primary boundaries are applied in the soil at the sufficient distance from the structure: 82 m in the horizontal and 54 m in the vertical direction.

Table 3: Geotechnical characteristics of the soils

No.	Soil type	Soil	$v_{s,30}$	γ	ξ	E	G_o	υ
			[m/s]	[kN/m^3]	[%]	[MPa]	[MPa]	[-]
1	Bedrock, 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

3 DYNAMIC ANALYSIS

In the dynamic analysis, only the earthquakes in X-direction are considered. Starting from the accelerograms chosen for the Belgrade site, which are supposed to be recorded on the top of the soil deposit of type A – **EQ1** (Figure 1a), the earthquake motions at the base of the soil deposit (**EQ2** in Figure 1b) are calculated using the downward shear wave propagation through the 54 m thick layer of the soil of type 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} and ξ = 0.2%. Thereafter, the upward wave propagation through the soil deposit of types B and C is carried out to obtain the free-field surface displacements (**EQ3B** and **EQ3C**, respectively – see Figure 1a). One dimensional pure shear model in the frequency domain is used [7]. The eventual nonlinear behavior was modeled applying the equivalent linear analysis. For that purpose the computer program is coded in MATLAB [4, 9].

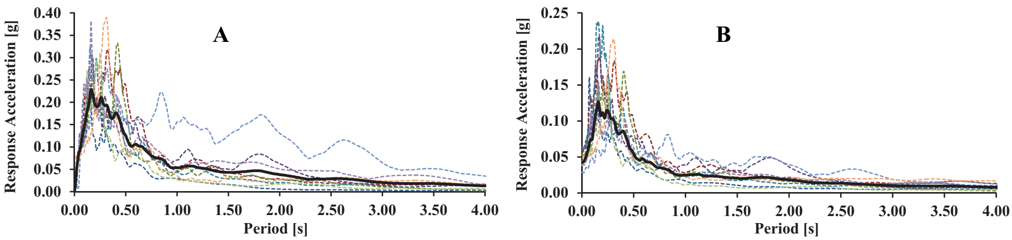

Figure 2 - Response spectra for the chosen accelerograms and their mean values at the top of the soil deposit of type A – EQ1 (A) and at the bedrock - EQ2 (B)

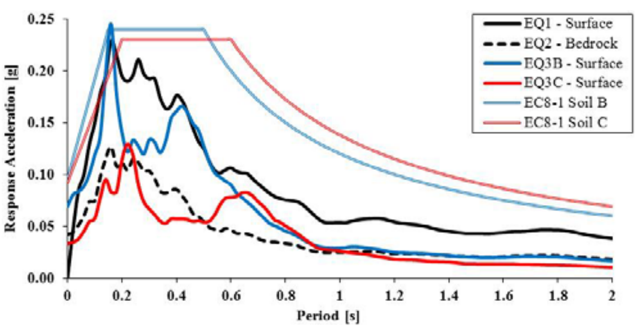

Figure 3 - Mean values of the response spectra for EQ1, EQ2, EQ3B and EQ3C in comparison with the characteristic EC8-1 spectra

The earthquake spectra obtained from the chosen accelerograms and their mean value used in the fixed-base structure analysis (**EQ1**) is presented in Figure 2A, while the response spectra at the bedrock is presented together with their mean values (**EQ2**) in Figure 2B. Figure 3 illustrates the mean-value spectra at the foundation level for soil types B and C, in comparison with the mean spectra on the bedrock (**EQ2**) and the characteristic EC8-1 spectra. The amplitudes of the response spectra are reduced due to downward propagation, and than amplified due to upward propagation through deposit of soil type B or C.

First, the response spectrum and time history analysis of two buildings are carried out for the fixed-base structures. The appropriate mean spectra and ten different accelerograms for each type of soil (**EQ1**, **EQ3B** and **EQ3C**) are used. Then, the mean spectra and ten different accelerograms obtained at the bedrock level (**EQ2**) are applied to the soil-structure model in order to check the influence of the soil deposit on the global structural response. In their previous analyses [10], authors have shown that the model with soil mass has the negative influence on the dynamic response, by adding the spurious inertial forces to the system, so the massless soil is taken into account. Equal damping ratios of 5%, in the structure and in the soil, are assumed. All buildings are analyzed in two different ways: founded on the plate and founded on the system of single foundations under the columns. The number of modes used for analyses is selected according to the recommendations given in EC8-1.

4 RESULTS AND DISCUSSION

In order to check the influence of the soil on dynamic response of typical RC buildings the finite element models of 5 and 10-story buildings with and without SSI are considered using commercial software SAP2000. The numerical analysis is carried out using response spectrum method and time-history analysis. The obtained results are given in this section.

In the response spectrum method, the appropriate mean spectra are used, so the results (story displacements or shear forces) obtained for the each model are treated as average results. Story shear represents the shear force at the level of each story of the building; story deflections are the horizontal displacements at each level of the building in X-direction, while the inter-story drift represents the relative horizontal displacements of the adjacent floors. It is well-known that the response spectrum method is unable to give the information about the exact time point in which the story deflections and shear forces reached the maximum values of interest. Because of that, the calculation of the maximum inter-story drift is performed only in the time history analysis. This quantity is very important because it is one of the main indicators of the damage that could be expected in the buildings during the earthquakes. This is especially important when the tall buildings are analyzed.

In the time history analysis, independent calculations are performed for each earthquake record, and the obtained results are averaged. The ratio of story deflection, story shear and inter-story drift are calculated for models with soil (**EQ3B** and **EQ3C**) and fixed base models (**EQ2**).

In Figure 4 relative story displacements and relative story shear for structure founded on the soil type B and C, obtained using time history analysis and response spectrum method, are presented. The relative story displacements and shears are calculated in respect to the story displacements and shears obtained for the fixed base models. For the 10-story building, relative story displacements strongly depend on the soil type. For the soil type B, these values are close to 1.00, while for the soil type C they are around 1.20. Values are slightly higher in the case of single foundations in respect to the case with foundation plate, especially at the lower part of the building. Also, higher relative values are obtained using the response spectrum analysis. The differences in relative displacements for two types of the soil used in the models are the result of the different dynamic behavior of the soils exposed to the presented earthquake records. The similar conclusions can be carried out for the relative story shear. Again, higher shear forces are obtained for the structure modeled with the soil type C (**EQ3C**) than in the case with the fixed base (**EQ2**). Relative story shears are between 1.15 and 1.35. For the model with the 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. Higher relative values are obtained using the response spectrum analysis.

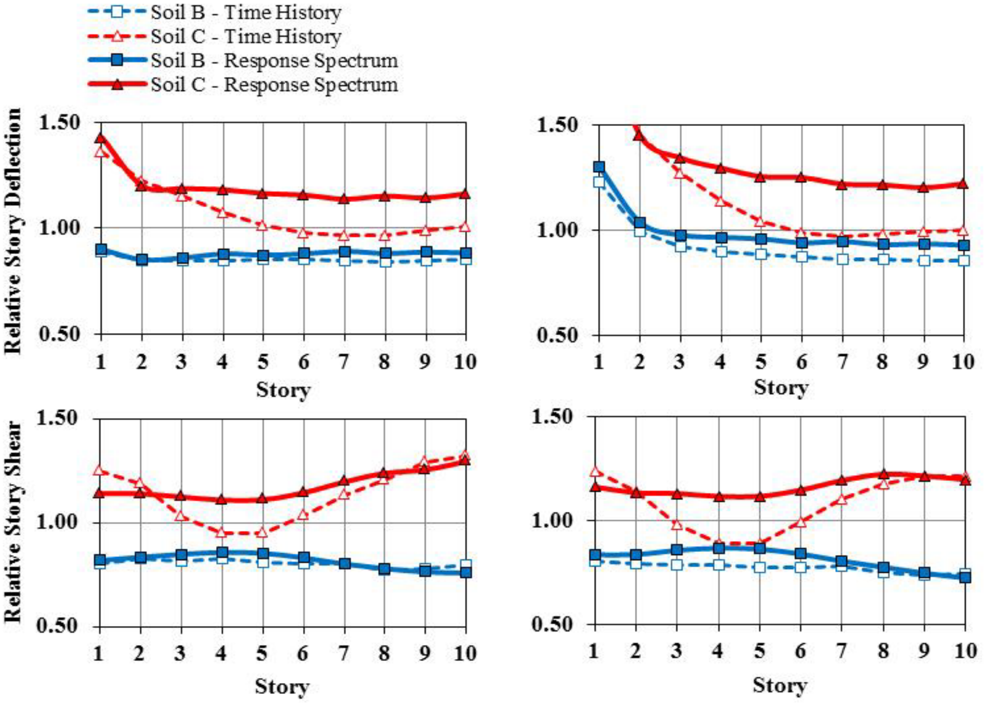

Figure 4 - Relative story deflection and story shear for 10-stories building founded on the plate foundations (left) and single foundations (right)

Figure 5 presented relative story displacements and shears for the 5-story building. Relative story displacements of the model with the soil type B are around 0.50. These values are slightly higher in the case of single foundations, especially at the lower stories of the building. For the soil type C, these relative ratios are close to 1 for the plate foundations, while for the single foundations these values increase in the lower part of the building. The type of the analysis does not influence the results for the soil type C. Very similar trend is obtained for the relative story shear values.

Figure 6 illustrates the relative inter-story drift. For the soil type B, the values are around 0.80, while they are slightly higher for the soil type C. It is shown that the values are not influenced severely by the foundation type, except in the level of the first story. If single foundations are used, the relative inter-story drifts at the level of the first story are higher. This confirms that for the typical reinforced-concrete buildings foundation on plate is beneficial since it could reduce the damage that might occur during the earthquake ground motion. Generally, the very same trend is obtained for the 5-stories building. In this case the values of the inter-story drift are expectedly lower in comparison with the 10-stories building.

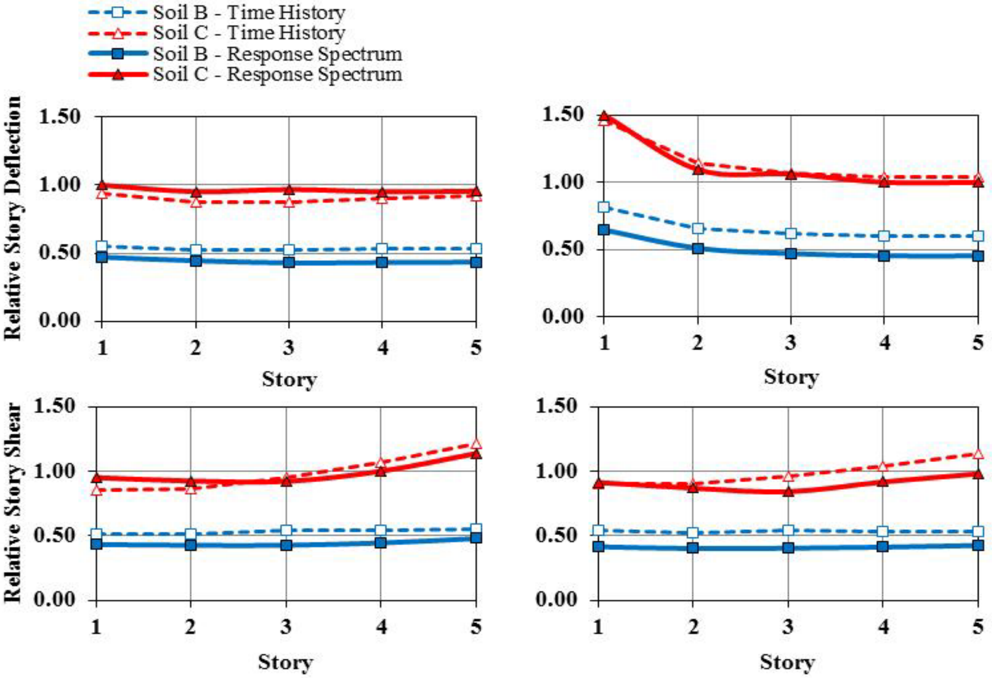

Figure 5 - Relative story deflection and story shear for 5-stories building founded on the plate foundations (left) and single foundations (right)

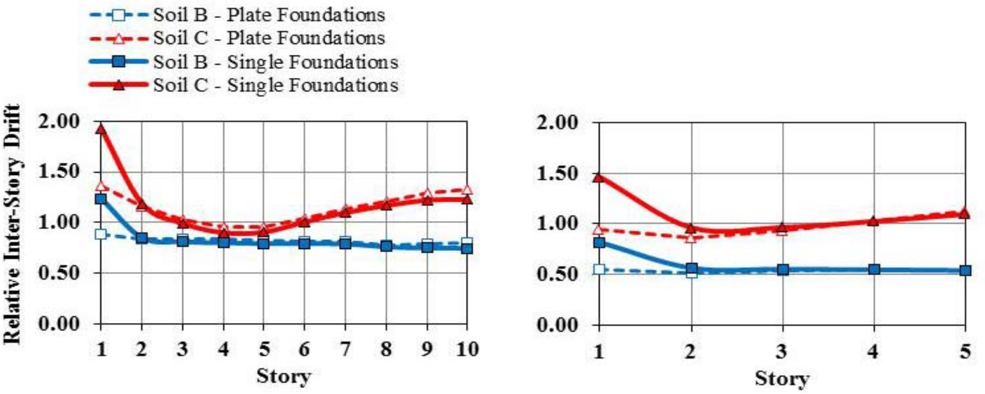

Figure 6 - Relative inter-story drifts for 10- and 5-stories building founded on the plate foundations (left) and single foundations (right)

In order to check the validity of the fixed base model (**EQ3**) and the error that is usually made in engineering practice using the original data obtained at the ground level (**EQ1**), the results of the analyses obtained using the accelerograms and the response spectra for **EQ3B** and **EQ3C** are compared with the results obtained using the original earthquake records **EQ1**. Relative story deflections and relative story shear are presented in Figures 7-8, for 10-stories and 5-stories buildings, respectively.

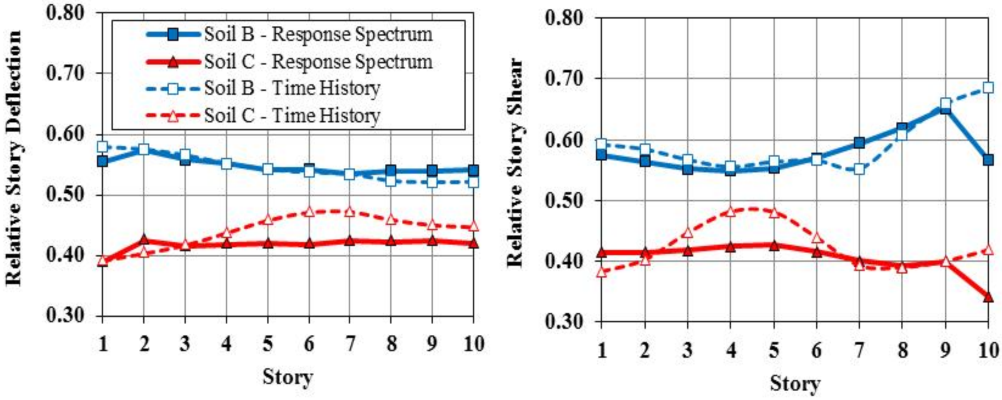

Figure 7 - Relative story deflection and story shear for 10-stories building obtained for EQ3B and EQ3C in comparison with the results obtained for EQ1

For 10-stories building the relative story deflections and relative story shears for both types of soil are less than 1.0. It means that the original response spectrum (**EQ1**) gives conservative values of the story deflections and shears, which is on the safe side in the engineering sense. Again, this behavior is provoked by the differences in the accelerograms and the amplitudes of the response spectra **EQ1** and **EQ3,** given in Figure 3, in the zone of fundamental frequencies of observed buildings. The type of analysis does not influence the results severely, but it is more pronounced for the soil type C.

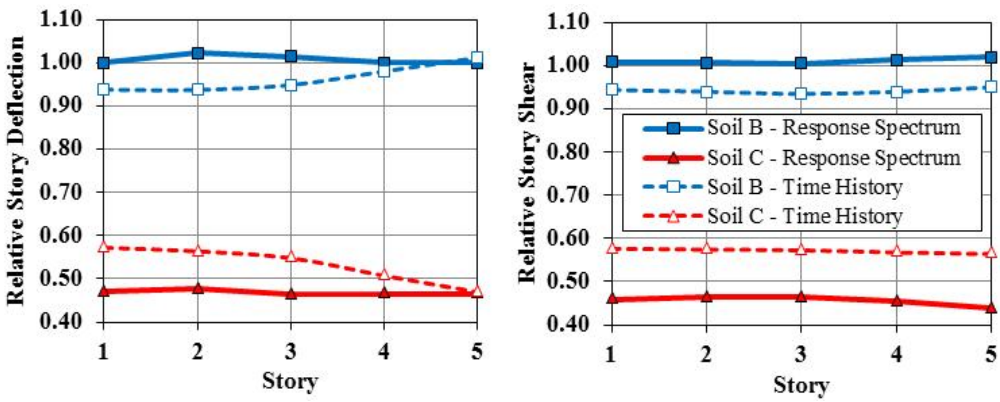

Figure 8 - Relative story deflection and story shear for 5-stories building obtained for EQ3B and EQ3C in comparison with the results obtained for EQ1

For 5-stories building the relative story deflections are presented in Figure 8. These values are around 1.0 for all stories in the case of the soil type B. For the soil type C, the relative story deflections are between 0.5-0.6. The same results are obtained for the relative story shears. It means that application of the original earthquake data (**EQ1**) gives almost the same results as the results where the earthquake data for the soil type B (**EQ3B**) are used, but quite conservative ones in comparison with the results where the earthquake data for the soil type C (**EQ3C**) are used. The influence of the analysis type is slight, as it is illustrated in Figure 8.

The conducted numerical analysis have clearly shown that neglection of the soil-structure-interaction during the seismic design could considerably affect the results of the calculation. The influence of the earthquake on the structure could be underpredicted, detrimental or beneficial, wich depends on type of soil and frequency of the structure.

5 CONCLUSIONS

The effects of soil-structure interaction on the dynamic response of reinforced-concrete buildings are analyzed in this paper. Two methods are applied: time history analysis and the response spectrum method. The analyses are conducted using the commercial software SAP2000. Two reinforced concrete buildings with regular basis and different heights, founded on two different types of soils according to EC8-1, with two different types of foundations were analyzed. The recommendations of Seismological Institute of Serbia were accounted while selecting the appropriate accelerograms for Belgrade site. For both methods, the relative ratio of the results from the model with the soil in comparison with the results obtained using the traditional fixed base model is shown. The soil mass is neglected in the calculation. The both analyses presented in this paper confirmed the influence of SSI on the dynamic response of RC buildings (which is usually neglected in the engineering practice).

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 dynamic analysis. This highly depends on type of the soil deposit under the structure and fundamental frequency of 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. Generally, higher values for displacements are obtained in the response spectrum method, which confirmed that this method is conservative in comparison with the time history analysis. The difference in the results is highly influenced by the soil type. The differences are lower in the case of the soil of better quality. The advantage of the response spectrum method with respect to the time history analysis is simpler and faster calculation, but the disadvantage is the lack of the information regarding the time point where the displacements or forces reach the maximum value. All these confirmed that the SSI should not be excluded during the seismic design, especially in the case of high buildings and soft soils, because of its influence on the structural response.

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LITERATURE

[1] Tabatabaiefar HR, Massumi A: A simplified method to determine seismic responses of reinforced concrete moment resisting building frames under influence of soil–structure interaction. Soil Dynamics and Earthquake Engineering 2010; 30:1259–67.

[2] Petronijević M, Rašeta A: Analiza seizmičke interakcije konstrukcije zgrada i tla. Savremeno graditeljstvo - Naučno-stručni časopis za graditeljstvo Republike Srpske 2010; 2(4):40-9

[3] EC8-1: Design of structures for earthquake resistance. Part 1: General rules, seismic actions and rules for buildings. European Standard EN 1998-2004.

[4] Marjanović M: Proračun pomeranja podloge usled zemljotresa primenom transfer funkcija. Seminarski rad, Građevinski fakultet, Univerzitet u Beogradu, 2013.

[5] SAP2000 - Analysis Reference Manual. Computers and Structures Inc, Berkeley, 2002.

[6] Inženjerskogeološka dokumentacija u zoni trase lakog metroa – Knjiga 1 – Osnovna dokumentacija, Geoinstitut, Beograd, 2006.

[7] Seed HB, Wong RT, Idriss IM, Tokimatsu K: Moduli and damping factors for dynamic analyses of cohesionless soils. Journal of Geotechnical Engineering 1986; 112 (11):1016-32.

[8] Sun JI, Golesorkhi R, Seed HB: Dynamic moduli and damping ratios for cohesive soils. Report No. EERC-88/15, Earthquake Engineering Research Center, University of California, Berkeley, 1988.

[9] Matlab - The Language of Technical Computing. MathWorks Inc, 2011.

[10] Petronijević M, Marjanović M, Radišić M, Marjanović M, Nefovska Danilović M: Comparative seismic analysis of RC buildings under influence of soil-structure interaction. Proceedings of the 4th International Conference Earthquake Engineering and Engineering Seismology. Borsko jezero, Serbia, 343-352.