The effect of soil structure interaction on structural seismic demand: Neglected or considered?

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ABSTRACT

Construction industry has advanced significantly in terms of size and type in recent years in Albania. However, the design is generally based on a fixed based structural model, and the dynamic soil-structure interaction is often neglected even for soft soils. Investigating the seismic demand including soil-structure interaction (SSI) effects is a relatively difficult task due to the complexity of the coupled dynamic problem: uncertainty of the soil and structure parameters and the inherent randomness of the earthquake ground motion.

The main objective of this paper is to focus on the SSI effects on the seismic demand. This goal is accomplished through studying an eight storey building frame in conjunction with two different soil deposits: stiff soil with shear wave velocity approximately 600 m/s; and soft soil with shear wave velocity less than 180m/s. The frame is modelled and analyzed under two different boundary conditions: Fixed-based assuming the foundation is completely rigid; and considering the soil-structure interaction, modelling the soil-structure system as a mass with springs at the base.

A response spectrum analysis is performed and the results of the structural models are compared in terms of natural period, vibration shape modes, structural displacement, inter-story drift and internal forces and moments.

INTRODUCTION

With expansion of technology and urbanization, Albanian construction industry is growing on its size and type. Widespread and extensive projects are being designed, some of which should be implemented under adverse geotechnical conditions. Recently, dynamic problems have been in focus, especially the seismic response of an engineering structure. When analyzing the seismic response of structures it is common to assume the base of the structure to be fixed, which is a big assumption since in most situations the foundation soil is flexible.

It is obvious that the seismic response of an engineering structure is influenced by the medium on which it is founded. The structure responds to the dynamics of the soil, while the soil also responds to the dynamics of the structure (H. R. Tabatabaiefar, 2011). So, the response of the structure is governed by the interplay between the soil characteristics, the structure, and the input motion. The process, in which the response of the soil influences the motion of the structure and vice versa, is referred to as *Soil-Structure Interaction (SSI).* These coupled systems are relatively complex due to the uncertainty in soil and structural parameters and inherent randomness of the input ground motion.

Since 1990s, great effort has been made worldwide for substituting the classical methods of design by the new approaches considering the concept of soil- structure interaction. First efforts belong to Jennings and Bielak (Jennings and Bielak, 1973); Veletsos (Veletsos and Meek, 1974); Veletsos (Veletsos and Nair, 1975); Gazetas (Gazetas and Mylonakis, 1998); Wolf (Wolf and Deeks, 2004); Galal (Galal and Naimi, 2008) studying the behaviour of structures subjected to earthquake under the influence of soil-structure interaction. They also recognized that SSI consideration can either increase or decrease the seismic demand of the structures depending on the parameters of the system and the characteristics of the input motion (M. Moghaddasi, 2010). The effects of SSI and its complicated process of analysis are ignored in most building codes requirements with exception of part five of Eurocode 8. Unfortunately, Albanian's codes KTP-N.2-89 does not offer specifications on this regard.
According to the available literature, generally when the shear wave velocity of the supporting soil is less than 600 m/s, the effects of soil-structure interaction on the seismic response of structural systems are significant (H. R. Tabatabaiefar, 2011). The controversy regarding the role of SSI on the seismic demand of structures raises the important question of whether SSI is beneficial or detrimental (Mylonakis and Gazetas, 2000), and, further, should it be considered in every day design procedures or not?
Thus, for ordinary building structures, the necessity of a better insight into the effects of soil-structure interaction problems has been recognised. To accomplish the above aim the following objectives were identified:
Comparing the results of a building frame modelled and analyzed under two different boundary conditions and in conjunction with two different soil deposits, in terms of:

(i) natural period
(ii) vibration shape modes
(iii) structural displacement
(iv) inter-story drift
(v) Internal forces and moments.

STRUCTURAL AND GEOTECHNICAL CHARACTERISTICS OF THE MODELS

In this study, a common structural model, consisting of an 8 storey building frame, representing the conventional types of buildings in a relatively high risk earthquake prone zone (I=8 ball), is selected in conjunction with two soil types with the shear wave velocity approximately 600m/s and less than 180m/s, representing classes B and D respectively, according to Eurocode.

Number of Storey	**Storey Height (m)**	**Bay Width (m)**	**Total Height (m)**
8	3	4	24

Table 1: Characteristics of the studied concrete frame

Structural sections are designed according to KTP-N.2-89. The frame is modelled under two different boundary conditions: Fixed-based assuming the foundation is completely rigid; and considering the soil-structure interaction, modelling the soil-structure system as a mass with springs at the base. In the following table are given characteristics of the modeled foundations. The characteristics of the earthquake ground motions are tabulated in Table 4.

	Soil Type	Pad Footing Dimensions
Fixed Base	Stiff Soil	2.5x2.8
		2.5x3.5
	Soft Soil	2.5x3.5
		3.5x3.8

Table 2: Foundations dimensions

	Stiff Soil	**First Pad Foot (Spring Characteristics)**	**Second Pad Foot (Spring Characteristics)**
Flexible Base		G=476554.53 (kN/m2)	G=476554,53 (kN/m2)
		49 m	Rtr=1.76 m
		Rrot=1.55 m	Rrot=1.88 m
		Kxx=8115042,9 KN/m	Kxx=9585553.9 KN/m
		Kyy=1670744,1 KN/m	Kyy=1973496 KN/m
		Kφφ=6997110,6 KN/m	Kφφ=12078120.1 KN/m
	Soft Soil	**First Pad Foot (Spring Characteristics)**	**Second Pad Foot (Spring Characteristics)**
		G=17329.25(kN/m2)	G=17329.25(kN/m2)
		Rtr=1.66 m	Rtr=2.05 m
		Rrot=1.83 m	Rrot=2.12 m
		Kxx=328760.7 KN/m	Kxx=405998.4 KN/m
		Kyy=67685.8 KN/m	Kyy=83587.9 KN/m
		Kφφ=405083.9 KN/m	Kφφ=329795.16 KN/m

Table 3: Springs characteristics (Calculated based on G. Menditto, "Esercitazioni di Tecnica delle costruzioni", 1983)

Soil Category	S	TB (sec)	TC (sec)	TD (sec)
B	1.35	0.05	0.25	1.2
D	1.8	0.1	0.3	1.2

Table 4: Characteristics of the earthquake ground motion

The characteristics of the utilized soils are summarized in the table below (Table 5)

Soil Category	γ_0	γ	w	w_s	w_p	E	Φ^0	c	k	$v_s(m/s)$
B	*26.9*	18.7	25.48	37	25.3	$1.31*10^4$	22	23	$1.5*10^{-6}$	600
D	*26*	17	14	50	40	$6.9*10^4$	26	0	10*-3	180

Table 5: Characteristics of the soils

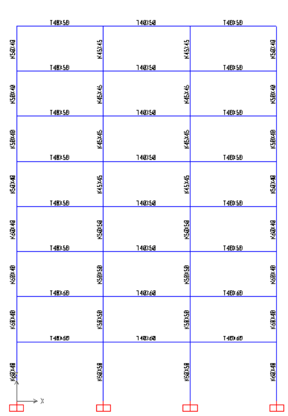


Fig.1: Model with fixed base

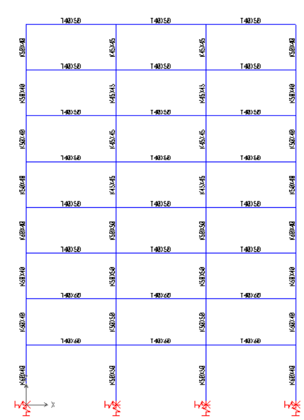


Fig.2: Model with flexible base

RESULTS AND DISCUSSIONS

Maximum values for four parameters of structural demand were examined: (i) vibration shape modes and natural mode period, (ii) system inter-story drift, (iii) structural displacement, (iv) internal forces and moments. Structural total displacement includes structural distortion, structural lateral displacement due to rocking of the foundation and horizontal displacement of the foundation (M. Moghaddasi, 2011), while inter-story drift are defined as the difference of inter-storey drift value. Large drift values can cause second-order P-Δ effects.

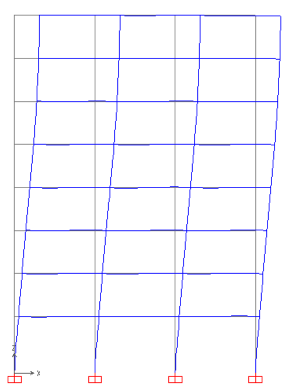
Results for the first type of soil- Hard soil with Vs=600m/s

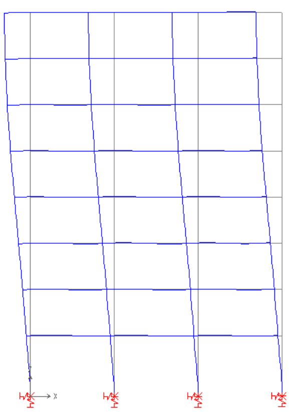
To simplify the presentation of the results, the maximum values for SSI systems were presented compared to the fixed based system results.

Fig.3: Model with fixed base *Model with flexible base*

First Mode

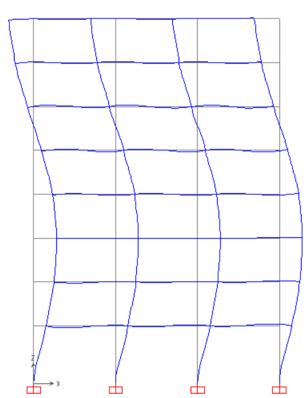
T1=0.76120 T1=0.76710

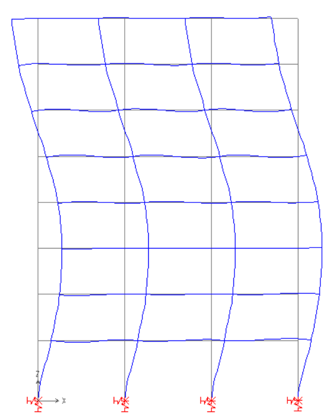




Second Mode

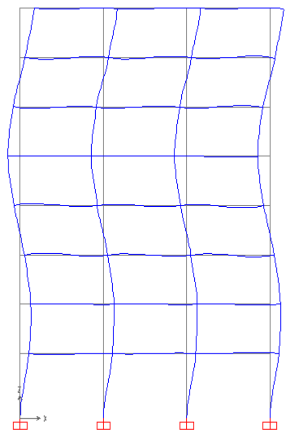
T1=0.26386 T1=0.26445



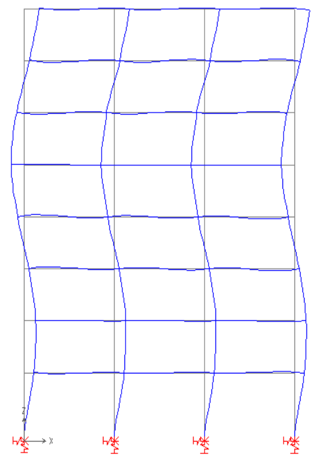


Third Mode

T1=0.15127

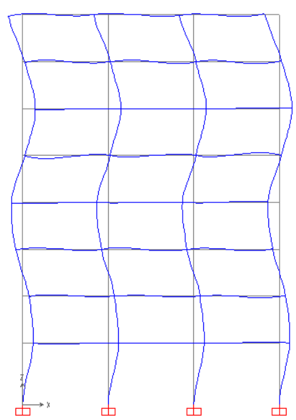


T1=0.15149

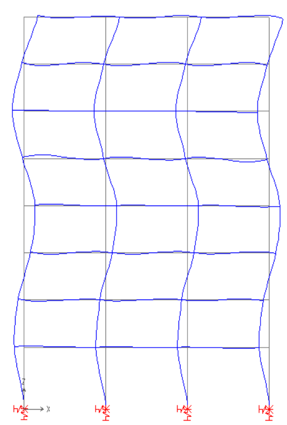


Forth Mode

$T_3 = 0.06819$



$T_3 = 0.06836$



Related to the first four modes, it is clearly that periods of two structures are almost the same and also the mode shapes. We can see that in this case the soil structural interaction effect is inconsiderable. It is obvious that this result is expected because the soil has a large velocity V_S = 600 m/s, which means that we have to do with hard soil or bedrock. As a confirmation to this result are the data of total displacement, inter-story drift and internal forces and moments displayed in the tables below.

		1	2	3	4	5	6	7	8	9
Fixed Base	Displacement	0	0.0103	0.0193	0.0293	0.04	0.0503	0.0574	0.0637	0.0674
	Inter-story Drifts	0	0.0103	0.0114	0.0098	0.0093	0.0083	0.0071	0.0063	0.0037
Flexible Base	Displacement	0	0.0106	0.0221	0.0319	0.0413	0.0497	0.057	0.0644	0.0679
	Inter-story Drifts	0	0.0106	0.0115	0.0098	0.0094	0.0084	0.0072	0.0065	0.0045

Table 6: Displacement and Inter-story drift values

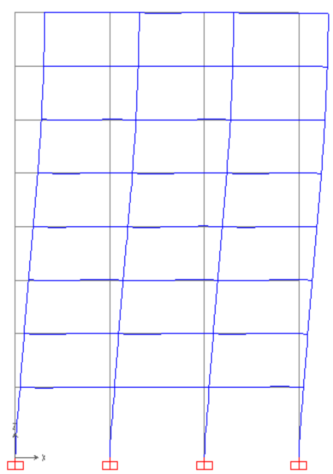
Results for the second type of soil- Soft soil with Vs=180m/s

In order to see more clearly the effects of soil structural interaction, a real soil (softer one) is considered, by decreasing the soil velocity, and the same model was analysed as a mass with springs at the base. The results are analogously presented and compared to the fixed based system

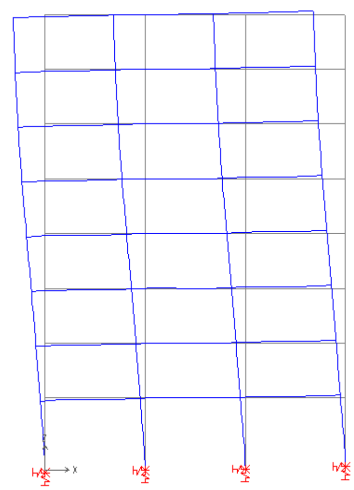
Fig.4: Model with fixed base *Model with flexible base*

First Mode

T1=0.76120

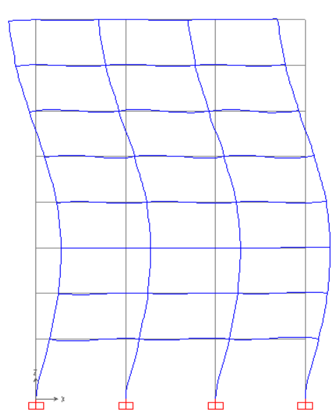


T1=0.92124

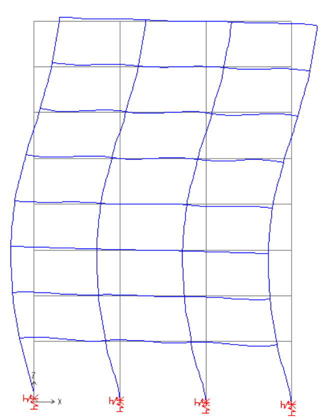


Second Mode

T1=0.26386

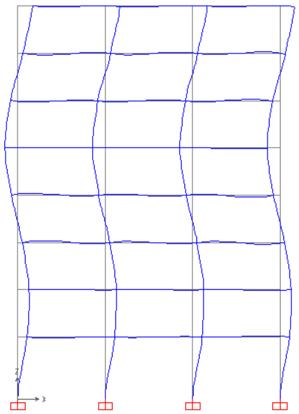


T1=0.27513

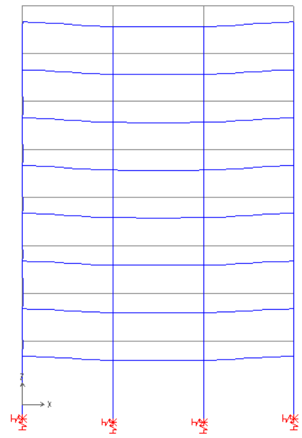


Third Mode

T1=0.15127

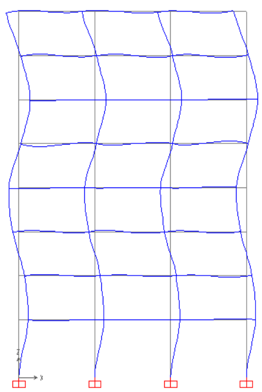


T1=0.19522

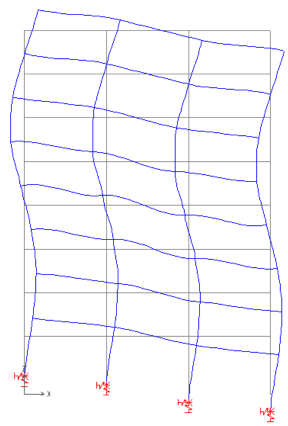


Forth Mode

T1=0.10160



T1=0.16064



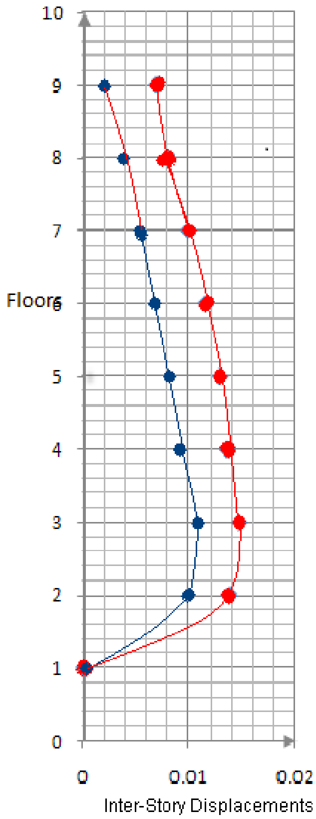
In this case it is clearly that differences are considerable. First mode is more than 20% greater when we are taking into consideration soil effect. In the second, third and fourth mode the differences in period are not so much but the form of the mode shape is very different especially the third mode.

Also, the results of the total displacement, inter-story drift and internal forces and moments displayed in the tables below.

		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Fixed Base	Displacement	0	0.0103	0.0193	0.0293	0.04	0.0503	0.0574	0.0637	0.0674
	Inter-story Drifts	0	0.0103	0.0114	0.0098	0.0093	0.0083	0.0071	0.0063	0.0037
Flexible Base	Displacement	0	0.0138	0.0285	0.0421	0.0550	0.0665	0.0764	0.0844	0.0913
	Inter-story Drifts	0	0.0138	0.0147	0.0136	0.0129	0.0115	0.0099	0.0080	0.0069

Table 7: Displacement and Inter-story drift values

In Fig.5 there is a graphical representation of the system inter-story drifts which shows the considerable differences wile considering soil structure interaction.



	Total Displacement
Fixed Base Model	*0.0674*
Flexible Base Model	*0.0913*

Table 8: Total Displacement Values

Fig.5: Graphical representation of the Inter-story drifts comparing two systems

The internal forces are tabulated below for three characteristics level of the column related to first three floors:

(i) Bottom
(ii) Middle Length
(iii) Top of the column

Table 9: Internal forces

Element		1			2			3		
Relative Height		0	2.1	4.2	0	1.6	3.2	0	1.6	3.2
Fixed Base Model	Moment	-96.28	29.8	84.7	-99.94	-7.6	98.07	-63.27	8.01	47.6
	Axial Force	-1323.3	-1310.8	-1298.6	-1147.8	-1138.8	-1129	-2273.6	-2260.8	-2247.9
	Shear Force	-43.05	-43.05	-43.05	-61.7	-61.7	-61.7	-26.4	-26.4	-26.4
Flexible Base Model	Moment	-87.9	39.27	114.61	-154.26	-10.86	146.73	-72.4	18.55	75.22
	Axial Force	-1480	-1467.6	-1455.3	-1278	-1268.5	-1259.5	-2108.7	-2095.8	-2083
	Shear Force	-48.53	-48.53	-48.53	-93.79	-93.79	-93.79	-35.16	-35.16	-35.16

According to the results of the numerical investigation conducted in this study for the 8 storey reinforced concrete building frame, resting on soil classes B and D, it is observed that internal base moments of the structure modelled with soil as flexible-base are less than the fixed base model. This is due to shifting from the ideal fixed base to the real flexible base of the structure. In addition, by decreasing the shear wave velocity of the subsoil, we may notice a redistribution of internal moments throughout the column length, resulting in increasing values in the upper quotes of the column. It is also observed that a redistribution of the shear and axial forces has occurred. In these conditions, finally, we may say that in soft soil effect of soil structural interaction is visible and certainly must be take into consideration.

CONCLUSION

When analyzing the seismic response of structures it is common in practice to assume the base of the structure to be fixed, which is a realistic assumption only when the structure is founded on solid rock or when the relative stiffness of the foundation soil compared to the superstructure is high. In all other cases, (real situations) compliance of the soil may induce different effects on the response of the structure

Comparing the natural periods and shape modes, inter-storey drifts, and total displacement of fixed-base and flexible-base models resting on soil of class B (Fig. 3), it is observed that the values do not differ much for both structural models. As a result, the performance level of the model resting on stiff soils remains in life safe level even if the SSI is neglected.

The results are more adverse for the models on softer soils (Vs=180m/s), as the performance level of the structures substantially increase (Fig. 4). The inter-storey drifts may exceed the lateral drift criterion. Such a significance change in the mode shapes, inter-storey drifts, total displacement and other performance parameters' level of the model resting on soft soils, can be a safety threatening. This threaten may become more hazardous for tall structures such as towers or chimneys, with massive foundations such as bridge piers, etc., and for structures where P-Δ effects play a significant role.

Thus, as a conclusion, a design procedure including the SSI is needed in order to guarantee the structural safety of the design especially for construction projects on soft soils.

REFERENCES

[1] Jennings, P. C., and Bielak, J. (1973). "Dynamics of building-soil interaction". *Bulletin of the Seismological Society of America*, 63(1), 9-48

[2] Veletsos, A. S., and Meek, J. W. (1974). "Dynamic behavior of building-foundation systems." *Earthquake Engineering and Structural Dynamics*, 3(2), 121-138.

[3] Veletsos, A. S., and Nair, V. D. (1975). "Seismic interaction of structures on hysteretic foundations." *Journal of Structural Engineering*, 101(1), 109-129

[4] Mylonakis, G., and Gazetas, G. (2000). "Seismic soil-structure interaction: Beneficial or detrimental?" *Journal of Earthquake Engineering*, 4(3), 277-301.

[5] Gazetas, G. and Mylonakis, G. (1998). Seismic Soil-Structure Interaction: New Evidence and Emerging Issues, *Proceedings of the Specialty Conference on Geotechnical Earthquake Engineering and Soil Dynamics III*, Eds. Dakoulas, P., Yegian, M. and Holtz, R.D. ASCE Geotechnical Special Publication No.75, Vol. 1, pp 1119-1174.

[6] Galal, K., and Naimi, M. (2008). "Effect of soil conditions on the response of reinforced concrete tall structures to near-fault earthquakes." *The Structural Design of Tall and Special Buildings*, 17(3), 541-562.

[7] Tabatabaiefar, H.R., Massumi, A. (2010). 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,* 30(11), 1259-1267, Elsevier Ltd., (**ISI**)..

[8] Wolf, J. P. and Deeks, A. J.(2004). Foundation vibration analysis: a strength-of-materials approach. Elsevier, New York

[9] Eurocode 8: Design of structures for earthquake resistance, Part 5: Foundations, retaining structures and geotechnical aspects, (2002), Draft no.6

[10] Albanian seismic design code KTP-N.2-89, (1989).

[11] Moghaddasi, M., Cubrinovski, M., Pampanin, S., Carr, A. (1989). “Soil-Foundation-Structure Interaction Effects on Nonlinear Seismic Demand of Structures”, *Proceedings of the* NZSEE Conference

[12] Menditto, G.,(1983).“Esercitazioni di Tecnica delle costruzioni", Liguori.