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INTEGRATING SOIL-STRUCTURE INTERACTION ALONG BASEMENT WALLS IN STRUCTURAL ANALYSIS PROGRAMS

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ABSTRACT

Recent field and laboratory studies have shown that the effect of Soil-Structure Interaction (SSI) can be not conservative to a structure if not considered. In evaluating the SSI effect along basement walls on the seismic response of moment-resisting frame buildings with multiple basements, a parametric study is performed on multiple story buildings resting on flexible grounds. The number of basements is varied and UBC suggested site conditions are considered. Comparing results obtained by Plaxis that considers SSI along basement walls and Robot that consider it only at foundation level (by mean of springs), one can observe that SSI along basement walls greatly affects the seismic performance of buildings subjected to ground movements. Results obtained from Plaxis and integrated into the Robot model by means of springs along basement walls with specific extracted stiffness values proved the accuracy of the method. These stiffness values are calculated using force-displacement relationships, and charts that relate stiffness to depth of basements are generated.

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INTRODUCTION

The assumption of fixing the building at the base used in structural analysis programs, neglects the flexibility of the soil under foundation and around basements. Even though this assumption is a common practice, it has been proved that SSI could clearly affect the seismic response of the building. Khalil et al. explained that the flexibility of the soil induce an increase in the period of the structure (Khalil et al., 2006). Most building codes treat low and medium rise regular buildings with multi-level underground stories with the same recommendations used for buildings with surface foundations. The U.S. seismic regulations (FEMA 450, 2003) suggest a simplified procedure to take into account the effect of SSI. These procedures that are based on traditional expressions of SSI, assumes that the ground has a linear-elastic behavior. Other, the seismic code ATC-3-06 offers a simple formula for estimating the fundamental period and damping coefficient of a structure.

According to PS92, when buildings have underground stories, the code demands the use of a part of the underground height depending on the type of the foundation soil (Règles, 1995). As far as Eurocode 8 is concerned, considering the effect of soil-structure interaction is beneficial for most conventional building structures since it reduces the bending moments and shear forces in various elements of the superstructure (Eurocode, 1998). In brief, the current state-of-practice for seismic design of buildings with multiple underground stories involves approximate approaches that primarily differ according to the designer's judgment and experience. This is a consequence of lack of relevant recommendations in building codes. However, it is important to incorporate the underground stories, basement walls, foundation soil and side soil explicitly in the mathematical model of the structure to be able to assess the actual effect of the seismic load on the building. Foundation engineers generally use Geotechnical programs such as Plaxis (Plaxis, Version 8) that take into consideration SSI, while structural engineers use programs such as Robot, (Autodesk, 2013) that do not involve SSI along basement walls in the dynamic analysis of structures. The objectives of this work is to evaluate the effects of SSI along basement walls on the seismic behavior of structures by comparing the two

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programs and to find a procedure to integrate these effects obtained from Plaxis into structure analysis programs, such as Robot. This study will be limited to the effect of soil-structure interaction on the top displacement of the building and its fundamental frequency, noting that the soil-structure interaction is not limited to variations in the fundamental period of the structure, but has also lots of different effects.

Description of the building models

The parametric study involves the investigation of seismic behavior of buildings with 5, 10, 15 and 20 stories with 3, 5 and 7 basements. The models adopted herein are reinforced concrete moment resisting frames of 5m spans. Each story height is 3m, the thickness of the floor was taken equal to 0.25m according to the rules of the ACI 318M-08 (American, 2008). The slabs were considered rigidly connected to the columns and the buildings were assumed to rest on a mat type foundation. The gravity loads assigned to the buildings were the dead loads consisting of the own weight of structural components, in addition to the load due to non-structural elements and the live load. These loads are presented in the Table 1.

Table 1. Gravity loads acting on the buildings

Unit weight of the concrete	25 KN/m ³
Nonstructural components	5 KN/m ²
Live load	2.5 KN/m ³

The concrete used for structural elements has a compressive strength $f_c = 25$ MPa, an elastic modulus $E = 32000$ MPa, a shear modulus $G = 13300$ MPa and a Poisson's ratio equal to 0.2. The buildings site has a 35-m-thick deposit of homogeneous soil underlain by the bedrock.

Table 2. Soil properties

	γ_{unsat} [kN/m ³]	γ_{sat} [kN/m ³]	E [kN/m ²]	ν (nu)	C [kN/m ²]	ϕ [°]	ψ [°]	V_s (m/s)
SC	18	20	7.64 e+05	0.3	1	33	7	400
SD	18	19	2.057e+05	0.3	1e-3	30	20	200
SE	16	18	4.224e+04	0.3	2	24	0	100

Table 3. Parametric study

Nb. Of Floors	20	15	10	5
Nb. Of Basements	3	5	7	
Soil Type	SC	SD	SE	

Table 4. Rigidities of columns and basement walls for various stories considered.

	5 Stories	10 Stories	15 Stories	20 Stories
Normal Rigidity [kN/ml]	8.000 e +06	8.000 e +06	9.600 ^E +06	1.120 ^E +07
Flexural Rigidity [kN.m ³ /ml]	4.167 e+04	4.167 e+04	7.200 ^E +04	1.143 ^E +05

The information of this layer are used to calculate the foundation's properties and the static pressure on basement walls according to ACI 318M-08. No groundwater is considered; also the deformation modulus E and the shear modulus G of the soil are the dynamic modulus used for small deformation (FASCICULE, 2012; Bourgeois, 1997).

Three soil types considered for the parametric study similar to those presented in UBC97 (Uniform Building Code, 1997):

- Soil Class C, corresponding to a very dense soil to soft rock,

- Soil Class D, corresponding to a stiff soil profile,
- Soil Class E, corresponding to a soft soil profile.

Preliminary analysis of the buildings

The five, ten, fifteen and twenty story buildings were modeled using the structural analysis program ROBOT assuming fixed base condition. In order to simplify the comparison between models, column sections were not changed since the objective of this study is the seismic behavior of the building rather than its seismic design. Seismic loads are calculated using the code UBC97 (Uniform Building Code, 1997). On the other hand, the superstructure is considered to remain in the elastic range during the seismic excitation (Khouri, 2009; Khouri, 2011). The basement walls must resist the lateral earth pressure, the bending moment and shear. Table 4 provides the stiffness of columns and basement walls obtained.

Buildings considered in this study involve different vertical loads on foundations in addition to several types of soils; this wide range of variable parameters results in different thicknesses for the mat foundation. In order to reduce the complications of the comparison process between various models, the same raft thickness was used for all buildings with the same soil class type. Consequently, the bearing capacity safety factor is higher for buildings with 5 floors and decreases by increasing the number of floors. For soil class C, a raft of 1.5m was used; also for soil class D, a raft of 1.5m was used, however the study was carried out only for 5, 10 and 15 floors and not for 20 floors; this is because the bearing capacity of the soil cannot support the loads of the 20 floors. On the other hand, the raft thickness used for soil class E was 2m and buildings with 5 and 10 floors were only considered for this type of soil.

Table 5. Ultimate bearing capacity for the soil types and basements considered

Ca [kg/cm ²]	3 basements	5 basements	7 basements
Soil SC	4.8	5.8	6.9
Soil SD	2.8	3.7	4.8
Soil SE	1.9	2.6	3.6

Even though the bearing capacity is important in the analysis of any structure, the effect of varying it was not significant for our study because we are mostly involved with the basement

walls subjected to lateral loads. Table 5 shows the ultimate bearing capacity of each soil type for each excavation depth.

PLAXIS modeling

Literature has shown that PLAXIS software has proven its efficiency in many engineering cases for modeling SSI. Many articles address how Plaxis can efficiently be applied as a tool in seismic SSI problems (Besseling and Lengkeek, 2012). The Plaxis bulletin in many issues contains descriptions of practical projects in which Plaxis has been used for modeling SSI (Plaxis Bulletin, 2006). Plaxis performs analysis in plane strain and allows introducing the whole soil-structure system; this system is subjected to seismic excitation at the impermeable bedrock level. The linear elastic elements in PLAXIS, are represented by their normal inertia EA and bending inertia EI as “plate” elements. The load includes self-weight, superimposed dead load plus 25% of the live load, and physical damping in the building and the ground is simulated by Rayleigh formula. In addition, Mohr-Coulomb was used to model the soil and the presence of groundwater is neglected.

The seismic loading was applied as a time history corresponding to a maximum seismic acceleration of 0.2g. This time history was obtained from recordings on a bedrock site made in Turkey and presented in Figure 1. The vertical limits are taken far from the building and considered as absorbent boundaries; they absorb the seismic waves and prevent their reflections in the ground, see Figure 2. The seismic excitation time was taken to be 10s for all models, and the time-displacement at the top of the building and the fundamental period obtained from PLAXIS are to be compared to the Robot Model.

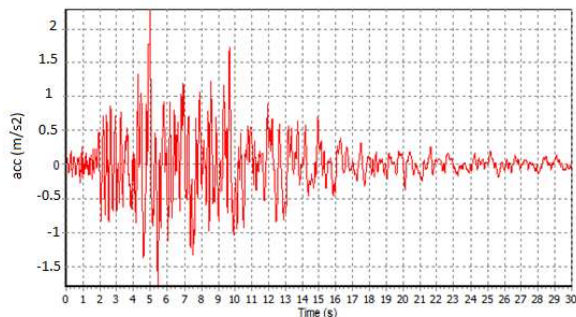


Figure 1. Time history used with maximum acceleration of 0.2g

ROBOT modeling

ROBOT was used to model the structure that was assumed to be supported on elastic springs to consider flexible foundations as shown in Figure 3; K_h is the horizontal stiffness and K_v is the vertical stiffness.

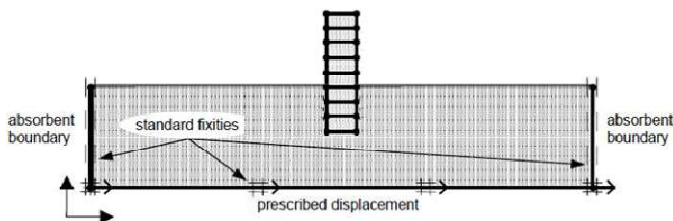


Figure 2. Boundary conditions for the basic model in Plaxis (5 floors, 3 basements)

The difference between Robot Model and Plaxis Model will only be the SSI along basement walls. The stiffness coefficients of the springs are determined from the expressions of Newmark and Resenblueth for rectangular foundations (Newmark, 1971).

$$K_h = 2(1+\nu).G.\beta_x\sqrt{B.L}$$

$$K_v = \frac{G}{1-\nu} \beta_v\sqrt{B.L}$$

With:

- L/B = 1 and ($\beta_x=1, \beta_v = 2.16$),
- L/B = 2 and ($\beta_x=0.94, \beta_v = 2.2$),
- L/B = 4 and ($\beta_x=1, \beta_v = 2.4$),

Where L and B are the length and width of the foundation, taken in this case equal to 1 considering the rigidities per square meter of the floor. Table 6 gives the values of the spring stiffness for both directions depending on the shear wave velocities associated with the three types of soils studied. The seismic loading at the base of the building will be the amplified accelerogram obtained from a site response analysis carried out within PLAXIS at the foundation level. The time-displacement curve at the top of the building will be compared to that obtained from PLAXIS in addition to the natural frequency. Consequently, the influence of the SSI along basement walls will be the difference between the two models.

Table 6. Properties of each soil type

Soil type	SC	SD	SE
Shear wave velocity Vs [m/s]	400	200	100
Density ρ [kN/m ³]	18	18	16
Poisson's ratio ν	0.3	0.4	0.3
K_h [T/m]	76440	20572	4246
K_v [T/m]	90720	26450	5039

RESULTS AND DISCUSSION

Numerical simulations using Plaxis and Robot were made by varying the parameters of the structure and the soil (see section 2). For each combination of parameters, time-displacement curve at the top of the building was obtained; this allowed exposing the influence of SSI along basement walls on the behavior of the structure.

Case Study

For a soil type SC, twenty stories with 7 basements, the two time-displacement curves obtained from both model (Plaxis and Robot) are presented in Figure 4. Note that the periods of the 2 curves are approximately the same, but the displacement at the top of the building is a little bit larger in Plaxis than in Robot. This shows that not considering SSI along basement walls in Robot can be harmful to the building as it increases the displacement at the top of the building without changes in the fundamental frequency. On average, the ratio of frequency variation between the two models is $F_{plaxis}/F_{robot} = 1.09$, while the ratio of the maximum displacement variation is $\Delta_{plaxis}/\Delta_{robot} = 0.5$.

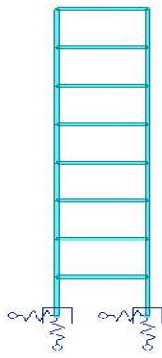


Figure 3. Robot model for 5 floors, 3 basements

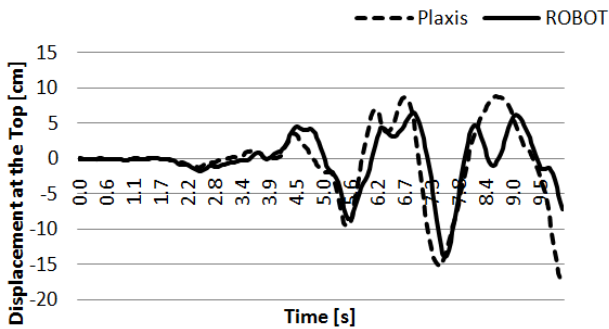


Figure 4. Time-displacement curves. (SC - 20 Stories - 7 basements)

The same curves were generated for each case study, and the ratio of the frequencies from Plaxis over that obtained from robot are presented in the chart of Figure 5. Similarly, the ratio of the displacements at the top of the building determined by Plaxis over that by Robot are presented in the chart of Figure 6.

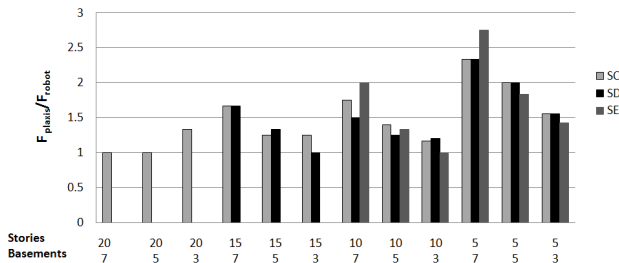


Figure 5. Chart for the frequency ratio for all soil types

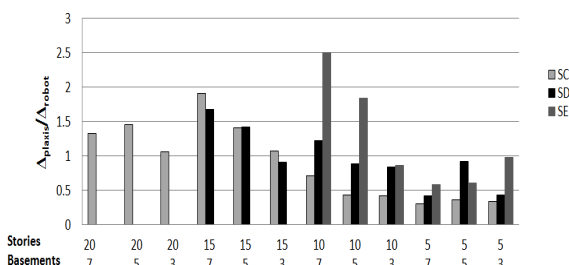


Figure 6. Chart for the displacement ratio for all soil types

Influence of SSI

To evaluate the influence of SSI along basement walls on the behavior of the structure, one needs to compare its influence

on the natural frequency of the building with its influence on the displacement at the top. The relationship between frequency and displacement ratios can be summarized as follows:

- If SSI causes an increase in frequency ratio ($F_{plaxis}/F_{robot} > 1$) with an increase in displacement ratio ($\Delta_{plaxis}/\Delta_{robot} > 1$), it would be the worstcase where the SSI is harmful to the building if not considered in the model.
- If SSI causes ($F_{plaxis}/F_{robot} > 1$) with ($\Delta_{plaxis}/\Delta_{robot} < 1$), this means that the behavior of the structure has been modified, and the structure tends to behave as a rigid structure which absorbs greater forces as it moves less.
- If SSI causes ($F_{plaxis}/F_{robot} < 1$) with ($\Delta_{plaxis}/\Delta_{robot} > 1$), the SSI can be beneficial and the structure tends to behave as a flexible structure which receives less forces but the top displacement should be checked to remain within code limits.
- Finally, if SSI causes ($F_{plaxis}/F_{robot} < 1$) with ($\Delta_{plaxis}/\Delta_{robot} < 1$), then SSI tends to be beneficial since it reduces the bending moments and shear forces in the superstructure thereby reducing the displacement of the building.

In the charts of Figures 5 and 6, it can be noticed that the cases where the SSI leads to ($F_{plaxis}/F_{robot} > 1$ with ($\Delta_{plaxis}/\Delta_{robot} > 1$)) are for buildings with high number of floors and basements and for soil type SE. For soil type SC and high number of floors, SSI has a slight influence. It is because of the ratio between the height of the superstructure divided the height of the basement is reduced which produce less lateral effects of the soil in this configuration. The same can be observed for SD soil type. In addition, from the charts, it can be observed that by decreasing the number of basements, the influence of SSI decreases for all soil types and for a small number of floors the structure is relatively rigid as it receives more forces and moves less. Consequently, it is important to incorporate the basement walls and side soil explicitly in the mathematical model of the structure in order to be able to assess the seismic effect on the underground part of the building and hence determine the actual forces acting on various structure elements. The question that arises at this stage is how to incorporate SSI into the Robot model. Following is the modeling method of the SSI by side springs with charts to calculate the lateral stiffness K of these springs. Structural engineers and designers can use these charts for proper modeling and evaluation of structures.

Method for modeling the SSI effects by lateral elastic springs

The preceding observations clearly show that the SSI along basement walls affect the behavior of the structure, and can sometimes be harmful if not considered especially for soft grounds. The question that arises is how we can integrate this effect into any structural analysis programs. Using lateral springs along the basement walls to model the soil behavior, the soil exerts compression on these walls but no tension; therefore, these springs must have zero stiffness in tension. Consequently, the springs are placed on one side of the building as in Figure 7. In this way, when the springs are compressed, they represent the resistance of the soil on one side of the building and when the springs are stretched, they represent the compression of the soil on the other side.

Including these springs in the Robot structural model incorporates the soil effect on the basement walls obtained by the Plaxis model.

Stiffness Calculations

Using Plaxis model for the building with 20 floors and 7 basements for a soil type SC, the shear curve on the walls of the 7 basements are obtained as shown in Figure 8.

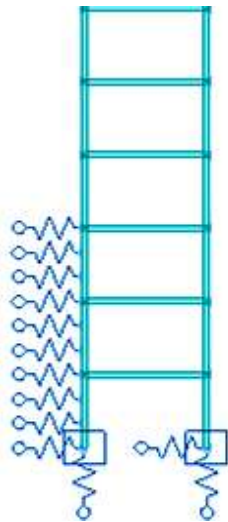


Figure 7. Modeling the SSI by lateral springs

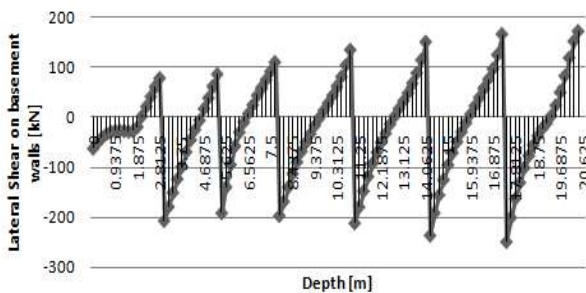


Figure 8. Shear along basement walls obtained from Plaxis for 20 floors, 7 basements and soil SC

The derivative of each derivable part of the curve gives the load on the basement walls; this is dynamic earth pressure on the wall. The derivative is done by increments, according to the following formula: $f' = \frac{\Delta V}{\Delta z}$, where ΔV is the difference in shear values between two consecutive points, and $\Delta z =$ difference in depth between two consecutive points. The reactions of the slabs on the walls are calculated from the difference in shear force at each slab. These results can be compared to the static earth pressure ($P = \rho \cdot g \cdot h \cdot K_0$) and are presented in Figure 9. Results show that the additional dynamic earth pressure is maximum at the surface of the ground and decreases until it becomes zero at foundations as expected. This clearly explains the graph obtained. The total earth pressure is greater than the static earth pressure at the surface of the ground and increases with depth, approaching the static earth pressure. Considering slab reactions as forces on the soil from PLAXIS, the equivalent soil stiffness is deduced according to $F=K.U$, where K is the stiffness of the side springs. For the case under consideration which is (20 stories, 7 basements, SoilSc), rigidities obtained are shown in Figure 10.

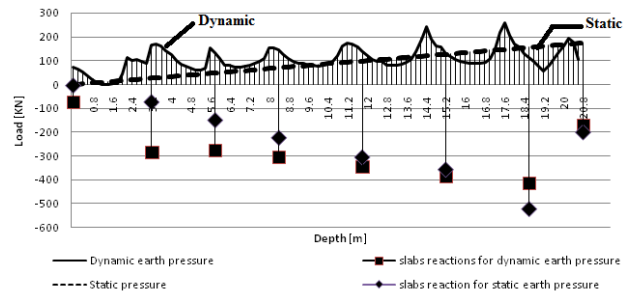


Figure 9: Static and Dynamic Earth pressure on basement walls for (20 floors, 7 basements, Soil SC)

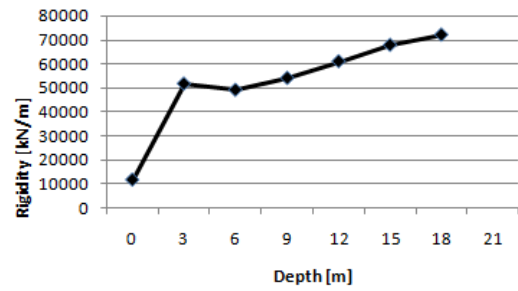


Figure 10. Rigidity of the side springs for 20 Stories, 7 basements, and soil SC

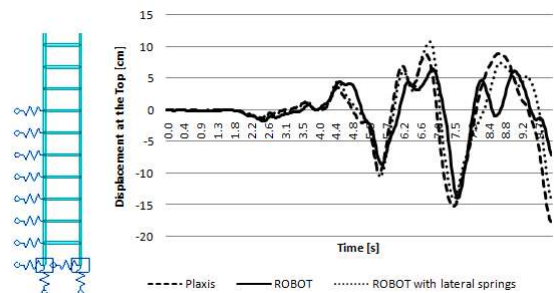


Figure 11. Comparison of the top displacements obtained by Plaxis, Robot and Robot with Lateral Springs for 20 stories, 7 basements and soil SC

Introducing the above rigidities into Robot mode land comparing in Figure 11, the displacement curves obtained at the top of the structure for Plaxis, Robot and Robot with lateral springs, it is clearly seen that the behavior of the structure (i.e. Robot model with side springs) converged to the results obtained by Plaxis. Also, Figure 12 shows the same graphs done for the case of 10 stories, 7 basements and soil SC. The same calculations were conducted for all models and parametric variations. Rigidities obtained are presented in Tables 7,8 and 9:

Rigidity graphs

From the stiffness results, an average equivalent rigidity was calculated for each soil type and number of basements. The values are shown in the graphs of Figures 13,14 and 15. Each point of these charts is the average rigidity of several models of computation from Tables 7, 8 and 9. Note that for 7 basements results are clear and consistent, since the soil-structure influence becomes more determined.

Table7. Equivalent stiffness for soil type SC [T / ml]

STORIES	SOIL TYPE SC											
	5			10			15			20		
	BAS.	3	5	7	3	5	7	3	5	7	3	5
K1	2000	1400	9950	1200	2000	1500	1850	900	780	900	600	1150
K2	2450	1570	19440	3970	2300	2085	7035	2800	1200	5100	3000	5200
K3	2265	1490	17260	3650	2100	2300	7420	2900	1600	5200	2800	4900
K4		1650	17877		2250	2700		2880	2000		2850	5400
K5		1765	18440		2380	3200		2920	2300		2950	6100
K6			18570			3760			2700			6770
K7			16970			4100			2950			7200

Table8. Equivalent stiffness for soil type SD [T/ml]

STORIES	SOIL TYPE SD											
	5			10			15			20		
	BAS.	3	5	7	3	5	7	3	5	7	3	5
K1	46888	3977	37227	7423	120	2650	800	1000	3100	-	-	-
K2	22873	26487	51750	45500	412	33220	4965	3300	27000	-	-	-
K3	20768	18848	50140	30360	370	33158	4038	3600	28850	-	-	-
K4		27492	60000		530	39879		4400	36000	-	-	-
K5		19818	69823		545	48320		5200	47380	-	-	-
K6			79750			57900			64240	-	-	-
K7			105570			78200			112450	-	-	-

Table 9. Equivalent stiffness for soil type SE [T/ml]

STORIES	SOIL TYPE SE											
	5			10			15			20		
	BAS.	3	5	7	3	5	7	3	5	7	3	5
K1	490	700	700	100	665	90	-	-	-	-	-	-
K2	347	720	305	270	500	320	-	-	-	-	-	-
K3	445	500	455	450	520	490	-	-	-	-	-	-
K4		440	568.4		625	530	-	-	-	-	-	-
K5		532	760		725	625	-	-	-	-	-	-
K6			1003			742	-	-	-	-	-	-
K7			1284			865	-	-	-	-	-	-

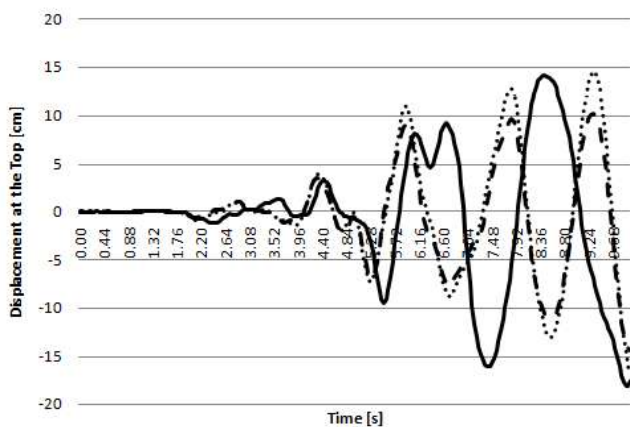


Figure 12. Comparison of the top displacements obtained by Plaxis, Robot and Robot with lateral springs for 10 stories, 7 basements and soil SC

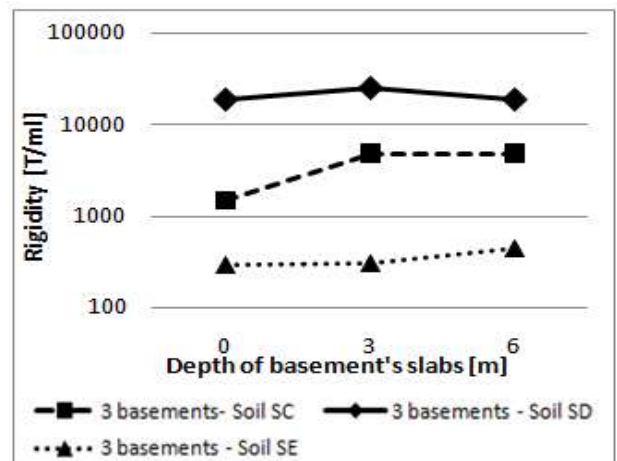


Figure 14. Side Springs Rigidities for 3 basements

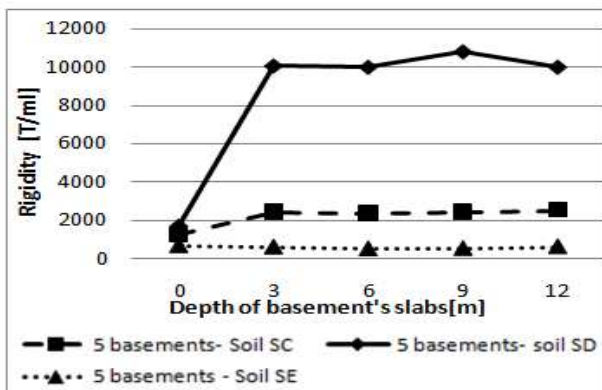


Figure 15. Side Springs Rigidities for 5 basements

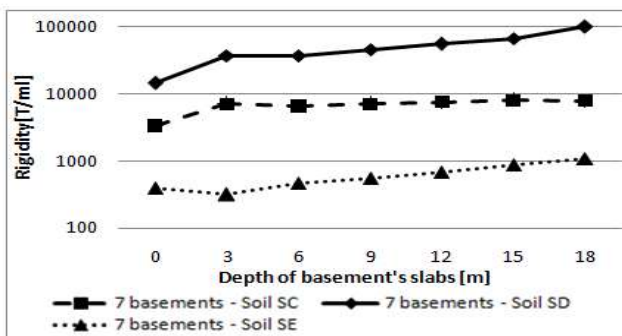


Figure 16. Side Springs Rigidities for 7 basements

Conclusions

In this study, the impact of the soil-structure interaction along basement walls on the dynamic behavior of the structure was investigated. The seismic behavior of buildings with multiple stories and underground stories examined and three soil types considered for the parametric study similar to those presented in UBC97. The work steps that were done can be presented as follows:

- A model was generated by Robot taking into consideration that the foundation was sitting on flexible soil.
- A model was generated by Plaxis to evaluate the SSI; the model was in Plane strain for the soil section and 2-D for the structure.
- Comparison was made between the two models Robot and Plaxis for the top displacement and the natural frequencies of the structures. Results showed that not including the effect of the basement walls surrounding soil can generate a large error in the analysis.
- Values for the equivalent stiffness K were determined from Plaxis using the force-displacement relationships and integrated into Robot to incorporate the effect of the soil surrounding the basement walls of the structure.
- The results of the SSI modified Robot model that incorporates the basement walls surrounding soil proved to be very close to the results obtained by Plaxis when compared for the top displacement and the natural frequency.
- After having a match between the results of the two model (Robot vs. Plaxis), a parametric study was performed to

determine the values of K and graphs were generated as a function of the basement depths.

- These K graphs allow structural analysts to use in their programs (any structural analysis program) to incorporate the SSI generated by the basement surrounding soils.

The findings can be summarized as follows:

- Results indicate that SSI can considerably affect the seismic response of buildings.
- It was found that the SSI effect was most critical for buildings with high number of floors and basements surrounded by soil type SE. For soils SD and SC, the SSI can change the behavior of the structure and the load path in structural elements especially for low and medium rise buildings.
- Making use of these stiffness values can make the structural analysis more accurate and close to the actual behavior of structures.
- This method allows the evaluation of the dynamic behavior of the structure, but gives no results regarding the behavior of the basement walls.
- More research need to be done to validate this work with 3D studies in order to obtain a complete modeling method that can be recommended and used not only in various structural analysis programs but also in different seismic codes.

Finally, this paper presents an analysis technique that allows the proper evaluation of structures with multiple basements situated in seismic zones. Analysis and designers that use structural analysis programs such as Robot can utilize the outcome of this work to incorporate the SSI into their designs.

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