Soil-Structure Interaction in RC Frame Buildings from Strong-Motion Recordings

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ABSTRACT: In this study, Soil-structure interaction (SSI) of Reinforced Concrete (RC) buildings which are instrumented by building monitoring systems is detected and identified. SSI can have a major influence on the seismic response of buildings constructed on soft soils. The dominant frequency recorded for a building subjected to SSI is always smaller than the dominant frequencies of the fixed-based building, and of the foundation when no building is present. The identification of SSI refers to extracting natural frequencies of the fixed-based building and the foundation from recordings of the foundation and upper stories. This interaction can be identified easily from the dynamic characteristics of the structure obtained by using seismic vibration records on the structures and if in addition to the records from the building, there are also free-field surface records available from nearby locations that are not influenced by building's vibrations. Two examples are studied according to the mentioned method by using their recorded responses during the two strongest earthquakes nearby Antakya since 2006.

Key Words: *Soil-structure interaction, Building monitoring, RC framed buildings, Earthquake*

Betonarme Çerçeveli Yapıların Zemin-Yapı Etkileşimlerinin Kuvvetli Yer Hareketi Kayıtları Kullanılarak Belirlenmesi

ÖZET: Bu çalışmada, bina izleme sistemleri ile donatılmış olan betonarme çerçeveli yapıların zemin-yapı etkileşiminin belirlenmesi gerçekleştirilmiştir. Yumuşak zemin üzerine inşa edilen binaların sismik titreşimlere karşı tepkilerinde zemin-yapı etkileşimi çok etkili bir durumdur. Zemin-yapı etkileşimi olabilecek bir binanın kaydedilen hakim frekansı, zemine ankastre olarak oturmuş bir binaya göre daha küçüktür. Zemin-yapı etkileşimi, ankastre olarak zemine oturmuş bina ve zeminin doğal titreşim periyotlarından, binanın temel seviyesinden ve üst katlarındaki kayıtlardan elde edilmiş titreşim periyotlarının çıkarılmasını ifade etmektedir. Bina üzerinde elde edilmiş sismik titreşim kayıtlarından ve bu bina üzerindeki kayıtlara ek olarak, binanın titreşiminden etkilenmeyen ve bina yakınında bulunan serbest alan kayıtları kullanılarak bu etkileşim kolaylıkla bulunabilir. Değinilen metot kullanılarak iki örnek binada, 2006 yılından bu yana kadar kaydedilmiş en şiddetli iki deprem kayıtları kullanılarak zemin-yapı etkileşimi çalışılmıştır.

Anahtar Kelimeler: *Zemin-yapı etkileşimi, Bina izleme, Betonarme çerçeveli binalar, Deprem*

1. INRODUCTION

Soil-structure interaction can significantly alter the characteristics of recorded vibrations in buildings. If it is not taken in to account during the analysis, SSI can cause erroneous interpretation of recordings of such buildings. Except flexible buildings located on very stiff soil or rock, SSI is always present to some degree. It is generally assumed, when SSI is small, that the recorded motions at foundation level are not influenced by the motions of upper stories. Therefore, the building can be assumed to be fixed-based and the foundation level recordings can be taken as the base excitation. When SSI is significant, this assumption is not valid because of the feedback from the building to the foundation and the surrounding soil medium. This feedback makes the building a closed-loop dynamic system, where the input (i.e., the foundation motion) and the output (i.e., the motion of the superstructure) are coupled. The identification of SSI is relatively easy if, in addition to the records from the building, there are also free-field surface or down hole records available from nearby locations that are not influenced by the building's vibrations. If there are no free-field records, also this interaction can be identified theoretically by the finite-element (FE) models of the buildings with soil springs or transmitting boundary conditions, and then determine the characteristics of the springs or the transmitting boundaries by trial and error until the recorded super-structure motions are matched.

SSI problems are considered as systems with infinite or semi-infinite extension. Modeling of the building with FE methods require a large-scale mesh to represent the surrounding soil medium (near-field), which is bounded by the far-field that is represented by artificial boundaries. In numerical modeling of wave propagation problems, artificial boundaries introduce spurious reflections, which contaminate the solution. Lysmer and Kuhlemeyer [1], and White et al. [2] developed special boundary conditions called non-reflecting viscous boundary conditions that absorb the wave energy. However, the use of the Boundary Element Method (BEM) is more effective than the non-reflecting viscous boundary conditions [3]. The scaled boundary-finite element method (SBFEM) is an alternative and effective method for modeling systems with finite and infinite

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*Correspondence Author: Genes, M.C., mcgenes@mku.edu.tr extension having non-homogeneous and incompressible material properties.

The SBFEM is applied to SSI problems both in time and frequency domains by Wolf and Song [4], and Genes and Kocak [5]. These approaches, however, does not lead a unique solution, since a large number of soil and structural system combinations and variation of parameters can match the recorded motions. Also, these approaches require a great effort to model and analyze the structure and the surrounding soil. There are several studies on direct identification of SSI from recorded motions and the most notable being by Luco et al.[6], and Şafak [7]. Luco et al. [6] used an eccentric mass vibration generator at the roof level of a building, and recorded the response at four locations for a range of frequencies of the excitation. Using the experimentally obtained frequency responses, they isolated the effects of SSI on the structure. Şafak [7] used acceleration records at the 30th floor and foundation level of Pacific Park Plaza in North-South and East-West directions during Loma Prieta Earthquake to identify the SSI.

The present paper investigates the identifiability of SSI from earthquake recordings. The records have been obtained from two buildings instrumented with accelerometers in Antakya, Turkey. The building monitoring systems are composed of three accelerometers in the buildings (two at the traverse corners and one at the basement) and one accelerometer at the free-field around 20-25 m far away from the buildings. Because of available earthquake records from the 4 sensors of the building monitoring system, the identification of SSI is fairly straightforward. The free-field recording is considered as the input, and foundation and upper story recordings as the output to identify the SSI system as a whole using open-loop identification techniques.

2. MATERIAL and METHOD

2.1. Detection of SSI

Since SSI alters the frequency characteristics of the recorded vibrations, it is important to determine, before to analyses of the records, if the building is subjected to SSI. Generally, the vibration of the building is recorded at the foundation level, top story, and several intermediate stories. If there is no SSI, the building can be identified by considering the recordings at the foundation level as the input, and the recordings at the upper stories as the output. Since there is no coupling between the input and the output, such systems are termed open-loop systems. A building with no SSI represents a causal system. When the building subjected to SSI, the motions of the upper stories influence the motion of the foundation. Since the input and the output of the system are coupled, such systems are termed closed-loop systems. A building with SSI represents a noncausal system and it can be shown from impulse response function. Impulse response function can be calculated by taking the foundation acceleration as the input, and the top story accelerations as the output, and using the method given in Ljung [8]. A more straightforward approach to calculate the impulse response function is to find the transfer functions by taking the ratio of the Fourier transforms, and then to take the inverse Fourier transforms of the transfer function. However, this method does not give a correct and stable impulse response because of the noise in the records. The method suggested by Ljung [8] is more robust and mathematically more accurate for noisy signals.

2.2. Identification of SSI

The identification of SSI means that, extracting dynamic characteristics of the fixed-base building, and the foundation from the recordings of the foundation and the upper stories. If there are recordings from a nearby free-field station, (whose vibration is not influenced by the vibration of the building), the identification of SSI is straightforward. We take the free-field recordings as the input, and the foundation and upper story recordings as the output, and identify the SSI system as whole using open-loop identification techniques. Generally, in most cases, we don't have such free-field records. But in this study, because of the existence of free-field records, both an open-loop and closed-loop systems are.

3. RESULTS and DISCUSSIONS

In this section, two examples are studied for the detection and identification of SSI by using the methods mentioned briefly earlier. The first example is a six-story hospital building (Figure 2a) and the second one is a four-story school building (Figure 2b) instrumented within a joint project called SERAMAR. The both examples will use the recorded responses at the dates 9th October 2006 and 17th June 2009.

3.1. Building I: Antakya Hospital

The first example is a 6-story, rectangular-shaped reinforced concrete building, used as a Hospital located in North of the Antakya city center. A general view of the building is given in Figure 2a. The properties of the soil where the building rested is a kind of stiff silty clay. But we have not a detailed soil profile obtained by borehole soil tests from the foundation of the building. Because of the size and stiff shear walls and massy mat foundation of the building, and also the surrounding soil conditions the response of the building likely to be influenced by the SSI effect during a strong earthquake excitation. From several records were recorded during the three years time period, two of acceleration responses of the buildings are used during this study.

The recorded earthquake responses from the instruments located at the top (sixth story), foundation and free-field of the building are presented in Figures 3

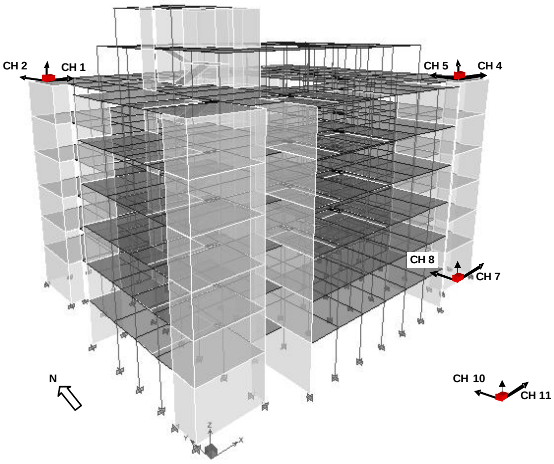


Figure 1. Model of Antakya Hospital and accelerometers location in the building.

and 4. As figures 3 and 4 show, the dominant motion of the building is in E-W direction during the both earthquakes. The spectral ratio of the accelerations (top floor/foundation), along with the scaled Fourier Amplitude Spectra (FAS) of the top floor and foundation displacements are given in Figures 5 and 6 for E-W and N-S directions for the earthquake recorded in Oct. 09, 2006 and in Jun. 17, 2009, respectively. The reason for plotting the FAS of displacements rather than of accelerations is that the displacement FAS provide much better visualization of frequency modes in this building. Figure 5 shows Fourier Amplitude Spectra of displacements, and spectral ratio of accelerations of the 6th floor and foundation of the Antakya Hospital during the earthquake in Oct. 09, 2006. In this Figure, the ratio for the N-S direction has a peak at 3.37 Hz, which is a peak at 3.37 Hz, and which is again larger than the dominant frequency 2.97 Hz of the 6th floor response. These frequency shifts are evidence of the SSI in both directions. Although the frequency shift (0.28 Hz) in N-S direction is smaller than the frequency shift (0.40 Hz) in E-W direction, it is much bigger than the frequency resolution (0.006 Hz) of the spectra. We therefore conclude for the both N-S and E-W directions that the dominant frequency of the building for the fixed-base case is 3.37 Hz, and with the SSI it reduces to 3.09 Hz in N-S and 2.97 Hz in E-W direction. The similar characteristics of the Antakya Hospital can be identified from Figure 6, for the earthquake records obtained in June 17, 2009. In this Figure, the ratio for the N-S direction has a peak at 3.31 Hz, which is larger than the dominant frequency, 2.44 Hz, of the 6th floor response.

Also, the ratio for the E-W direction has a peak at 2.83 Hz, and which is again larger than the dominant frequency 2.54 Hz of the 6th floor response. Since the difference between the frequencies, the SSI has to be taken in to account during the analyzing of the Antakya Hospital building. The summary of the frequencies are listed in Table 1.

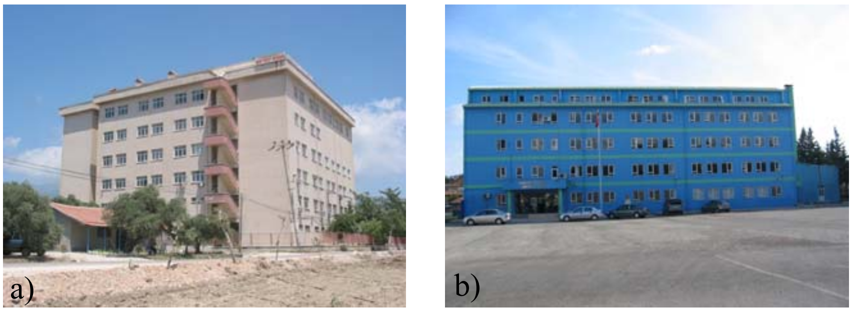

a)
b)

Figure 2. Instrumented buildings (a) The Antakya hospital, (b) The Huseyin Ozbuğday high school

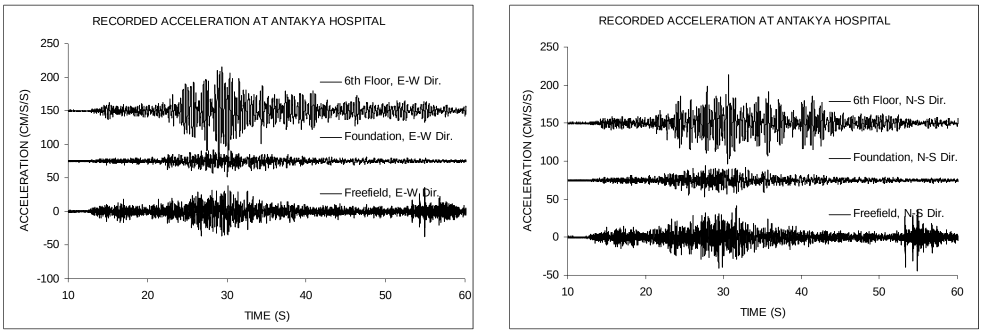


Figure 3. Recorded 6th floor, foundation and freefield accelerations at the Antakya Hospital in E-W and N-S directions during the earthquake in Oct. 09, 2006.

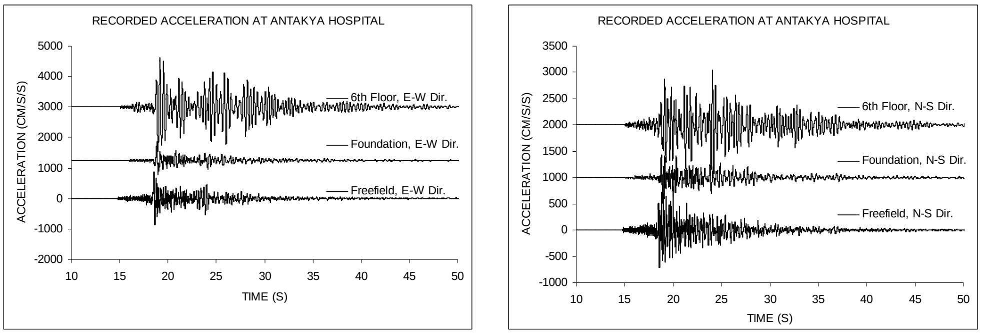


Figure 4. Recorded 6th floor, foundation and freefield accelerations at the Antakya Hospital in E-W and N-S directions during the earthquake in Jun. 17, 2009.

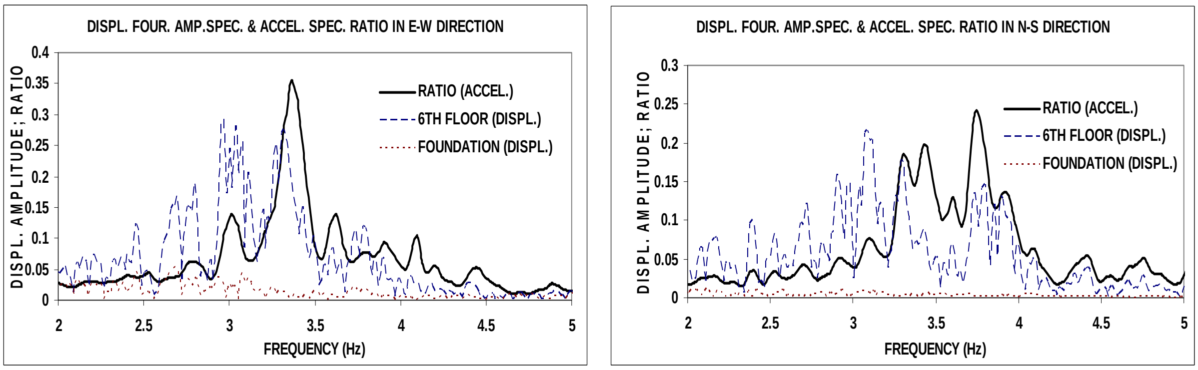
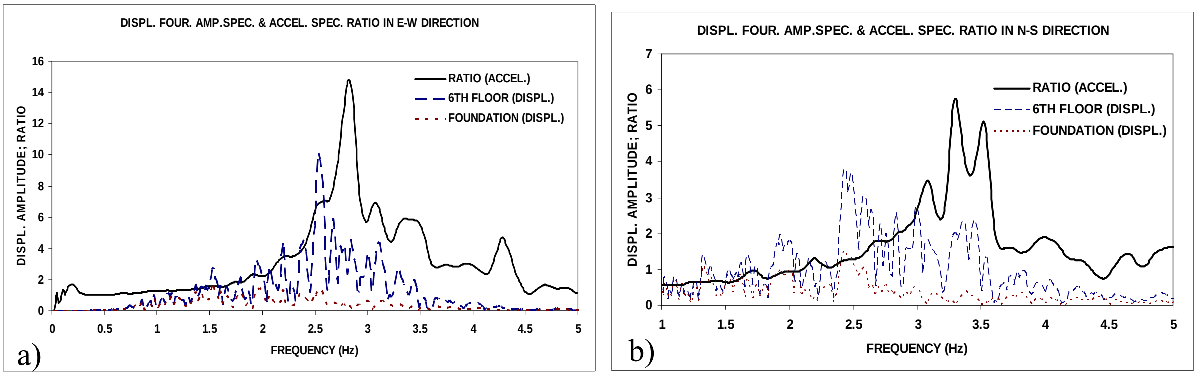


Figure 5. Fourier Amplitude Spectra of displacements, and Spectral Ratio of accelerations of 6th floor and foundation of the Antakya Hospital during the earthquake in Oct. 09, 2006.

Table 1. Dominant natural frequencies of the Antakya Hospital by considering the SSI

Event	Direction	Max. Acc. At Freefield (mg)	Frquencies (Hz)			Natural Freq. of Build. (Hz)	SSI
			Spectral Ratio of Acc.	FAS of Disp.	Difference (%)		
9th Oct. 2006	N-S	4.44	3.37	3.09	0.28 (8%)	3.09	**Yes**
	E-W	3.97	3.37	2.97	0.40 (13%)	2.97	**Yes**
17th Jun. 2009	N-S	85.8	3.31	2.44	0.87 (25%)	2.44	**Yes**
	E-W	88.5	2.83	2.54	0.29 (11%)	2.54	**Yes**



a) b)

Figure 6. Fourier Amplitude Spectra of displacements, and spectral Ratio of accelerations of 6th floor and foundation of the Antakya Hospital during the earthquake in Jun. 17, 2009.

As it can be seen from Table 1 that, the dominant natural frequency of the building has considerably difference in E-W direction during two earthquakes. And also, the difference between the frequency of the foundation and the building is much more high during the last earthquake than the earlier one. The reason of this difference could be result of the magnitude of the earthquakes. When the magnitude of the earthquake increasing, the SSI effect is increasing and the natural frequency of the building is degreasing.

3.2. Building II: Huseyin Ozbuğday High School

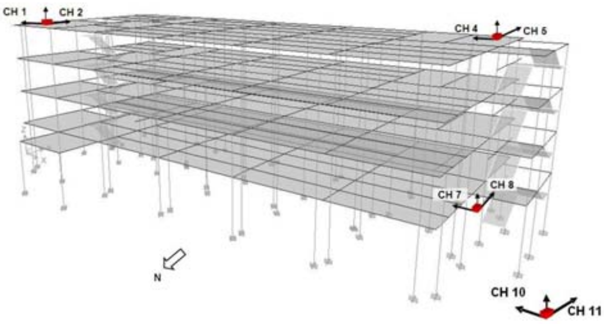


Figure 7. Model of Hüseyin Özbuğday High School and accelerometers location in the building.

The second example is a 4-story, rectangular-shaped reinforced concrete building, used as a High School located in North of the Antakya city center. A general view of the building is given in Figure 2b. The model and the location of the instruments are shown in Figure 7. The properties of the soil where the building rested is a kind of granular soil. Because of the size and stiff shear walls and massy mat foundation of the building, and also the surrounding soil conditions the response of the building likely to be influenced by the SSI effect during a strong earthquake excitation. From several records were recorded during the three years time period, two of acceleration responses of the buildings are used during this study.

The recorded earthquake responses from the instruments located at the top (fourth story), foundation and free-field of the building are presented in Figures 8 and 9. As figures 8 and 9 show, the dominant motion of the building is in E-W direction during the both earthquakes. The spectral ratio of the accelerations (top floor/foundation), along with the scaled Fourier Amplitude Spectra (FAS) of the top floor and foundation accelerations are given in Figure 10 for E-W and N-S directions. The reason for plotting the FAS of accelerations rather than of displacements is that the acceleration FAS provide much better visualization of frequency modes in this building. The ratio for the N-S direction has a peak at 3.44 Hz, which is larger than the dominant frequency, 3.12 Hz of the 4th floor response. Also, the ratio for the E-W direction has a peak at 3.47 Hz, and which is slightly larger than the dominant frequency 3.34 Hz of the 4th floor response. These frequency shifts are resulting from the SSI in both directions. Although the frequency shift (0.13 Hz) in E-W direction is smaller than the frequency shift (0.32 Hz) in N-S direction, it is much bigger than the frequency resolution (0.006 Hz) of the spectra. We therefore conclude for the both N-S and E-W directions that the dominant frequency of the building for the fixed-base case is 3.4 Hz, and with the SSI it reduces to 3.12 Hz in N-S and 3.34 Hz in E-W direction. The similar characteristics of the Huseyin Ozbuğday High School can be identified from Figure 11, for the earthquake records obtained in June 17, 2009. In this figure, the ratio for the N-S direction has a peak at 6.1 Hz, which is almost equal to than the dominant frequency, 6.1 Hz, of the 4th floor response.

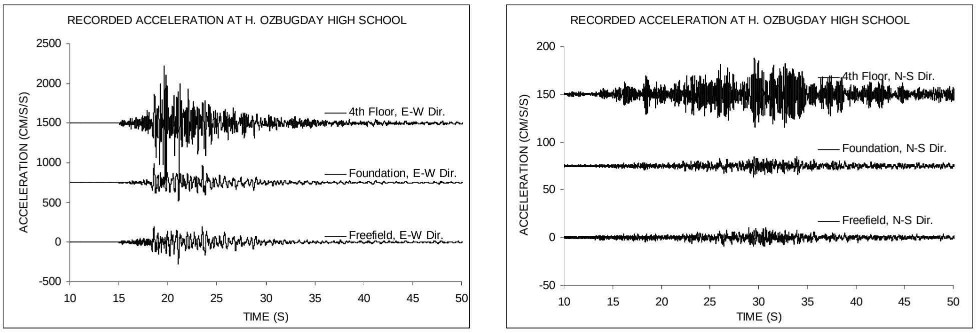


Figure 8. Recorded 4th floor, foundation and freefield accelerations at the H. Ozbugday High School in E-W and N-S directions during the earthquake in Now. 09, 2006.

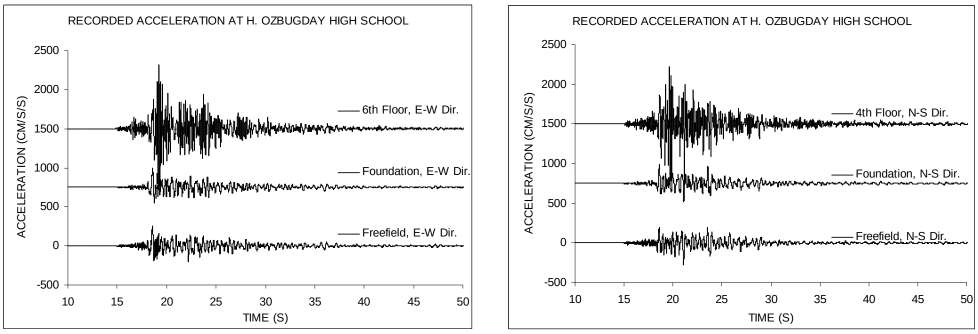


Figure 9. Recorded 4th floor, foundation and freefield accelerations at the H. Ozbugday High School in E-W and N-S directions during the earthquake in June 17, 2009.

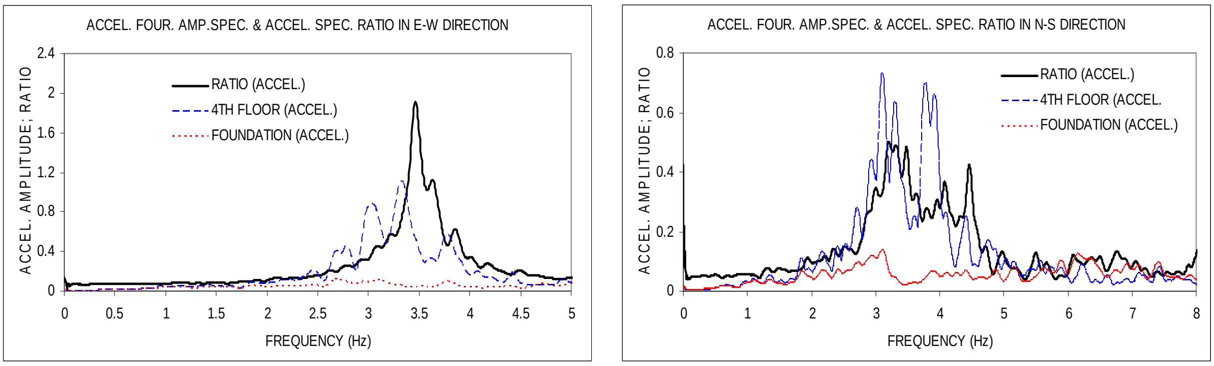


Figure 10. Fourier Amplitude Spectra of accelerations, and Spectral Ratio of accelerations of 4th floor and foundation of the Huseyin Ozbugday High School during the earthquake in Oct. 09, 2006.

Table 2. Dominant natural frequencies of the Huseyin Ozbugday High School by considering the SSI

Event	Direction	Max. Acc. At Freefield (mg)	Frequencies (Hz)			Natural Freq. of Build. (Hz)	SSI
			Spectral Ratio of Acc.	FAS of Acc.	Difference (%)		
9th Oct. 2006	N-S	1.11	3.44	3.12	0.32 (10%)	3.12	Yes
	E-W	1.18	3.47	3.34	0.13 (2%)	3.34	No
17th Jun. 2009	N-S	27.3	6.10	6.10	0.00	6.10	No
	E-W	25.4	6.20	5.64	0.56 (11%)	5.64	Yes

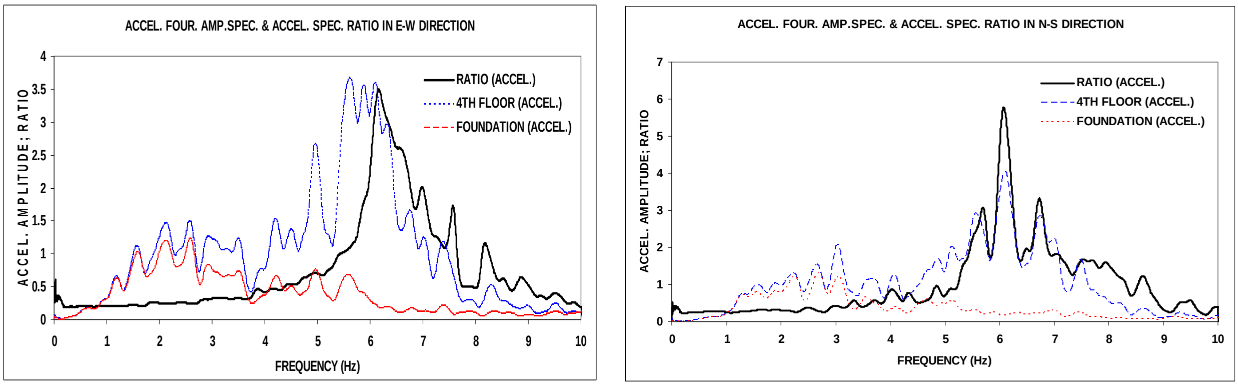


Figure 11. Fourier Amplitude Spectra of accelerations, and Spectral Ratio of accelerations of 4th floor and foundation of the Huseyin Ozbugday High School during the earthquake in June 17, 2009.

4. CONCLUSION

Two RC framed buildings are investigated to identify the SSI by using strong motion data. For each building two earthquake records are used and the results are compared with each other. For the first building (Antakya Hospital) the SSI is identifed during the both earthquakes, and in both directions. For the second building (H. Ozbugday High School) also SSI is identified during the both earthquakes, dominantly in E-W direction.The effects of Soil-Structure Interaction may considerably vary, and therefore the dynamic characteristics of the buildings are not always the same for all recordings. This SSI effect can be generalized for the RC framed building stock by considering (a) the soil conditions of Antakya city at each region (this can be identified by soil tests and noise measurments), (b) the size of the buildings (width, length and hight), (c) the magnitude of the earthquake could be recorded in Antakya.

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