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ORIGINAL PAPER

Assessment of soil-structure resonance in southern Riyadh City, Saudi Arabia

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Abstract Because of the site response effects can increase earthquakes damage, the assessment of soil–structure interaction is an important parameter to reduce seismic risk at a specified location. Southern Riyadh residential area is one of the densely populated districts of Riyadh city, so protection of these structures with human who lives in these buildings is of utmost importance. This is achieved through assessment of soil-structure resonance in this area. Microtremor measurements have been conducted at ten free-field sites and inside four buildings. The horizontal-to-vertical spectral ratio (HVSR) technique has been applied in order to assess the fundamental frequencies of the sediments, beside the longitudinal and transverse fundamental frequencies of each building based on the amplitude spectra and the floor spectral ratio (FSR) methods. In case of the building frequency is close to a nearby free-field fundamental frequency, a potential soil-structure resonance is present. The results clarified that the surveyed buildings have low danger level of soil-structure resonance.

Keywords Microtremors · Soil-structure resonance · Risk mitigation · Riyadh

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Introduction

Southern Riyadh residential zone represents an urban extension of the city, which has become densely populated (Fig. 1). In addition, this zone includes one of the major industrial cities in Riyadh and cement plant, which represents a source to generate ground vibrations in the nearby area. The majority of the existing buildings in the area is of two- or three-story building, and few buildings are of four-story building including the ground floor. The low-rise buildings characterized by relatively high values of fundamental frequencies which can coincide with the frequency range of relatively thin sedimentary cover.

The horizontal-to-vertical spectral ratio (HVSR) technique (Nakamura et al. 2000) is being used on a worldwide scale to estimate the fundamental frequency and the corresponding amplification factor of soil deposits due to its simplicity and low cost (Ohmachi et al. 1991; Lermo et al. 1992; Field and Jacob 1993, 1995; Bard 1998). HVSR exhibits a clear peak at the fundamental frequency of the sediments, in case of high impedance contrast between the sediments and underlying bedrock. Some criticism has been oriented to HVSR method (Mucciarelli and Gallipoli 2001) while some standards have been provided later through SESAME-project (2004) recommendations.

Recently, the applications of microtremor measurements have been extended to identify the fundamental frequencies of buildings (Gosar 2010), their vulnerability and soil-structure resonance (Nakamura et al. 2000; Mucciarelli et al. 2004; Gosar 2007; Gosar et al. 2010; Herak et al. 2009). The theory and interpretation of ambient vibration measurements inside the buildings are described (Gallipoli et al. 2004; Parolai et al. 2005 and Gallipoli et al. 2010). Accordingly, soil-structure resonance, which can increase the potential of damage, should be considered in any seismic risk assessment (Mucciarelli et al. 2001; Mucciarelli and Gallipoli 2007; Boutin and Hans

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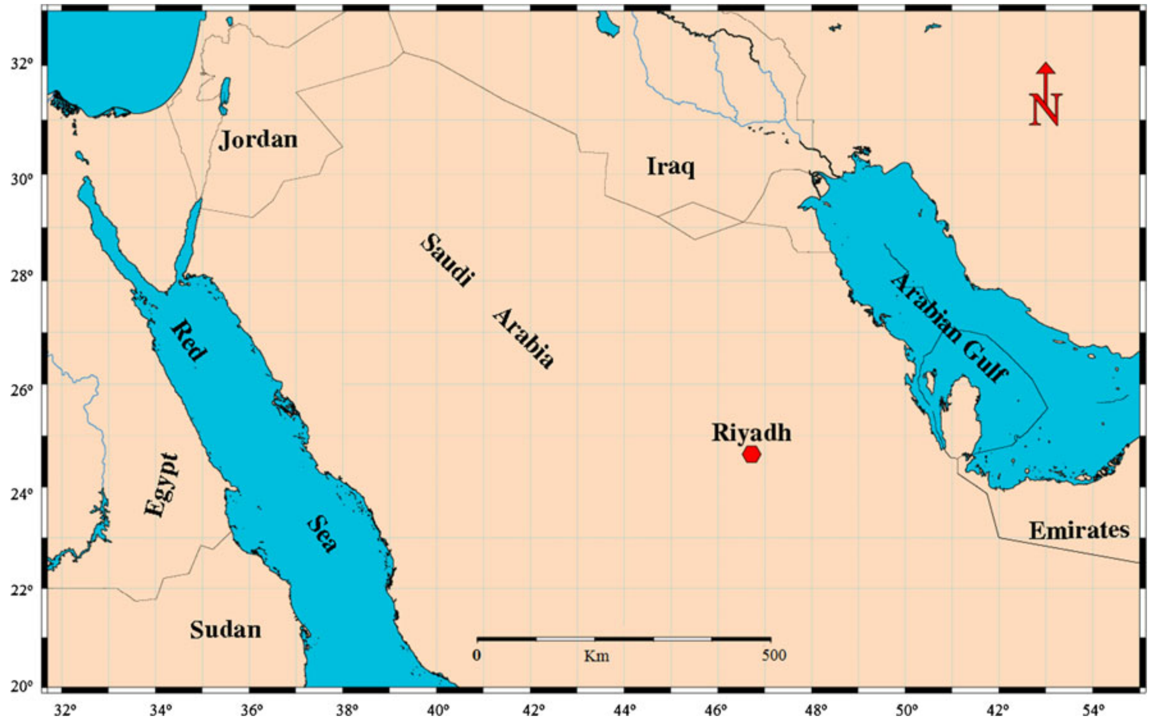

Fig. 1 Location map of Riyadh City

2008; Gosar 2012). Fundamental frequencies of longitudinal north–south (N–S) and transverse east–west (E–W) components can be identified from the amplitude spectra and the spectral ratio between upper floor and the basement for both directions (Gosar et al. 2010 and Herak et al. 2009). Furthermore, the danger potential of soil-structure resonance has been assessed by comparing frequencies of the sediments with those of the buildings (Gosar 2007). Usually N–S fundamental frequency is higher than the E–W (Gosar 2007). When this is not the case, the mass center may be distinct from the geometrical center or heterogeneities in construction may exist.

Geologic setting

According to Vaslet et al. (1991), the study area is underlain by sedimentary rocks of the western edge of the Arabian shelf basin, unconformably covered by Quaternary eolian, alluvium, and gravel deposits (Fig. 2). These deposits crop out in a gently dipping homocline and have been assigned to Mesozoic age as follows: (1) *The Arab Formation* (Steinek et al. 1958) with 127.5 m thick of limestone, clay intercalations, and anhydrite from shallow-water marine. This formation is subdivided into four members arranged from Arab-D at the bottom to Arab-A at the top. (2) *The Sulaiy formation* (Kjs) is composed of limestone (Powers et al. 1966) with a total thickness of about 115 m.

Microtremor measurements

Free-field measurements

Microtremor measurements have been conducted at ten sites using two digital seismographs (*Taurus model*, *Nanometrics Corp.*) equipped by triaxial velocity seismometers (Trillium Compact), GPS receiver, and flash memory card. The complete system was installed in a common case to avoid electronic and mechanical noise, which can be introduced by wiring between equipment parts. Good ground coupling on soft soil was achieved. Four of measuring sites have been acquired near buildings but far enough to avoid its influence (Fig. 3). These sites have been selected carefully to avoid noise from buildings, traffic, and the cultural activities because the noise, in some cases, can severely affect the reliability of HVSR analysis (SESAME-project 2004; Ali et al. 2010).

The data have been recorded continuously for 1 h at each site and then, processed using GEOPSY software to calculate the HVSR at each site through processing sequence; recorded time series were checked to identify the erroneous measurements and stronger transient noise; each record was then split into 30 s-long windows tapered with 5 % cosine function; fast Fourier transform (FFT) was calculated for each window in each component. The Fourier spectra were smoothed using Konno and Ohmachi (1998) algorithm with 40 smoothing constant based on the color-coded chart of HVSR functions for minimum ten windows. According to SESAME-project

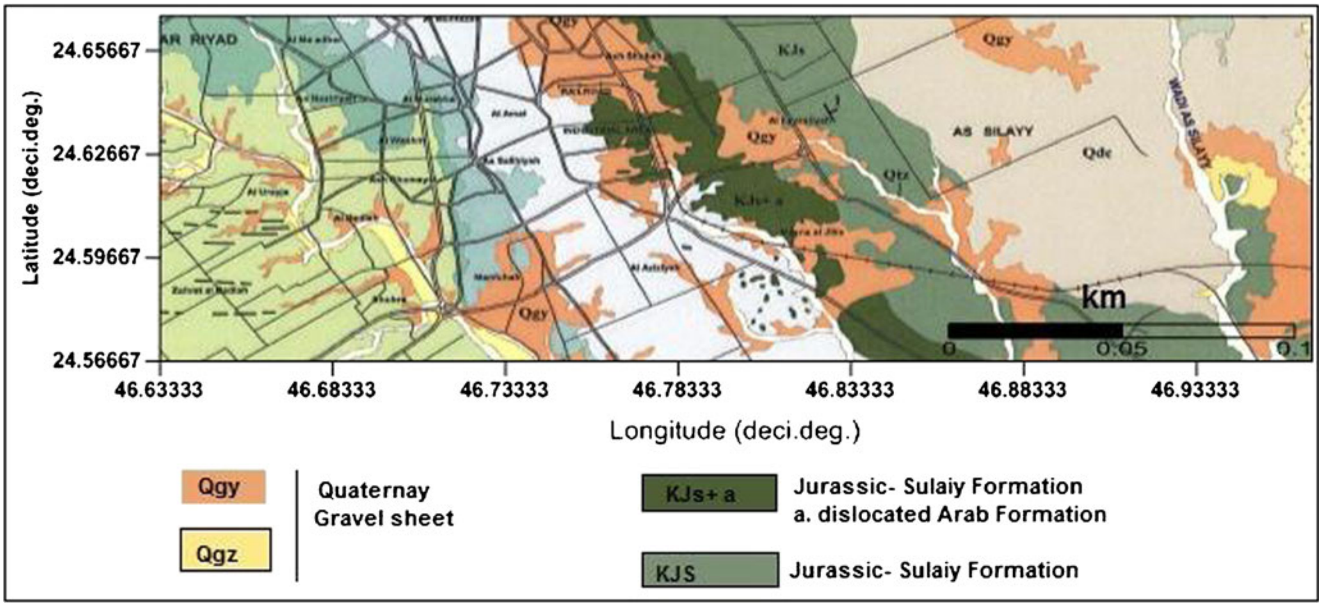

Fig. 2 Geological setting for the study area

(2004), several criteria have been applied to identify the clear peak through the HVSR analyses of free-field measurements. Three criteria have been selected depending on the relation between the peak frequencies to the window length, the number significant cycles, and the standard deviation of the peak amplitude; two criteria depend on the relation with the peak amplitude to the HVSR curve level, standard deviations of the peaks frequencies, and its corresponding amplitude. Results of HVSR are presented in Fig. 4.

According to SESAME-project (2004), peaks of industrial origin exhibit narrow peaks and/or troughs and characterized by the following: (1) They can be seen up to distances of several kilometers from their source. (2) Fourier spectra should exhibit sharp narrow peaks at the same frequency on

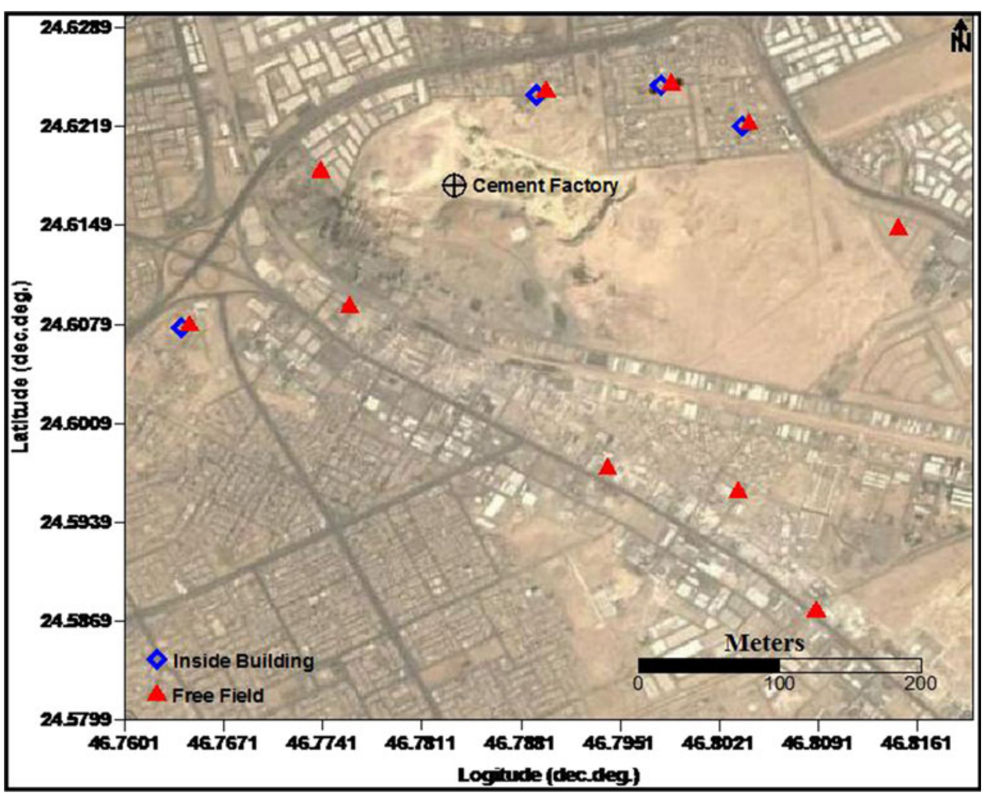

Fig. 3 Location of microtremor measurements

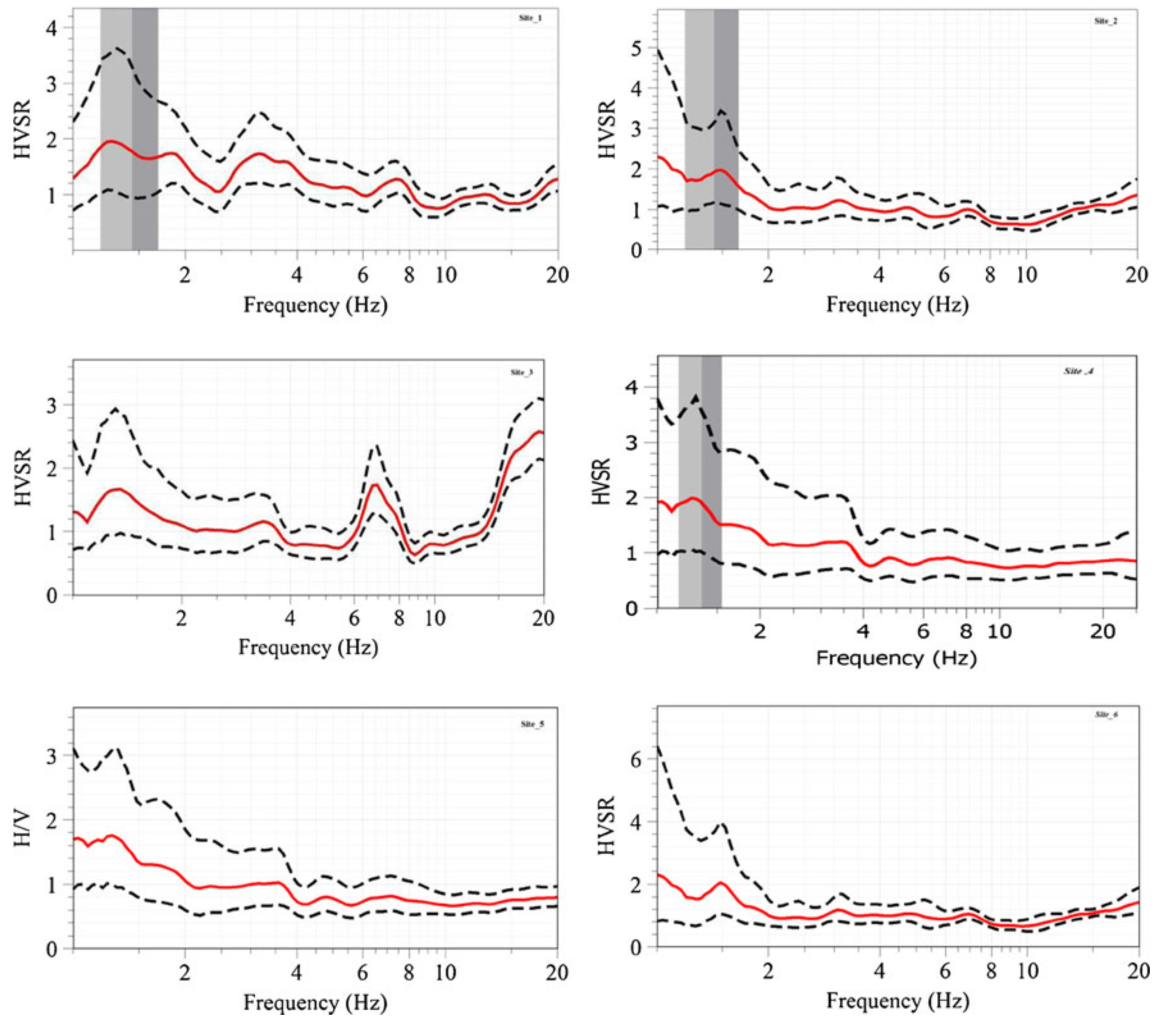

Fig. 4 HVSR of free-field microtremor measurements

the three components. (3) H/V peak should become sharper and sharper. (4) If other measurements have been performed in the same area, determine whether a peak exists at the same frequencies with comparable sharpness. (5) If the corresponding damping (*z*) of the impulse response around the frequency of interest is very low (below 1 %), an anthropic origin may be assumed almost certainly, and the identified frequency should be completely discarded because it has no link with the subsurface structure (Dunand et al. 2002). Accordingly, the free-field measurements have been checked to define the origin of peaks of either natural and/or industrial origin. Figure 5 illustrates the industrial origin of f_0=6.77 and 17.87 Hz at site_3 compared with the natural peak at 1.33 Hz.

Free-field measurements have been tested to fulfill the recommended SESAME-project criteria for reliable HVSR curves. In general, the identified f_0 ranges from 1.27 to 1.4 Hz in the study area. Four of measuring sites present clear f_0 peaks except two sites; site_5 illustrates small peak that most probably due to the local underground structure does not exhibit sharp impedance contrast; site_1 exhibits several peaks which may be due to the presence of an underground slopping interface between softer and harder layers.

Inside building measurements

The buildings in the area of study are mainly masonry with reinforced concrete floors. These buildings are residential houses and consist of two and three stories with few buildings of four stories (including basement floor). Four buildings have been selected, in this study to conduct the inside building measurements on the basement and the upper floors of each building using the same instruments of free-field measurements. The two horizontal components of the instrument were oriented as one in the N–S direction and the second in the E–W direction of the building. Shorter spikes were mounted at the bottom of the seismograph to achieve the precise leveling. The seismograph was installed as close as possible to the mass center of the building and close to the wall. The recording length was 40 min, although frequencies below 1 Hz were not of interest (SESAME-project 2004). The recording length on

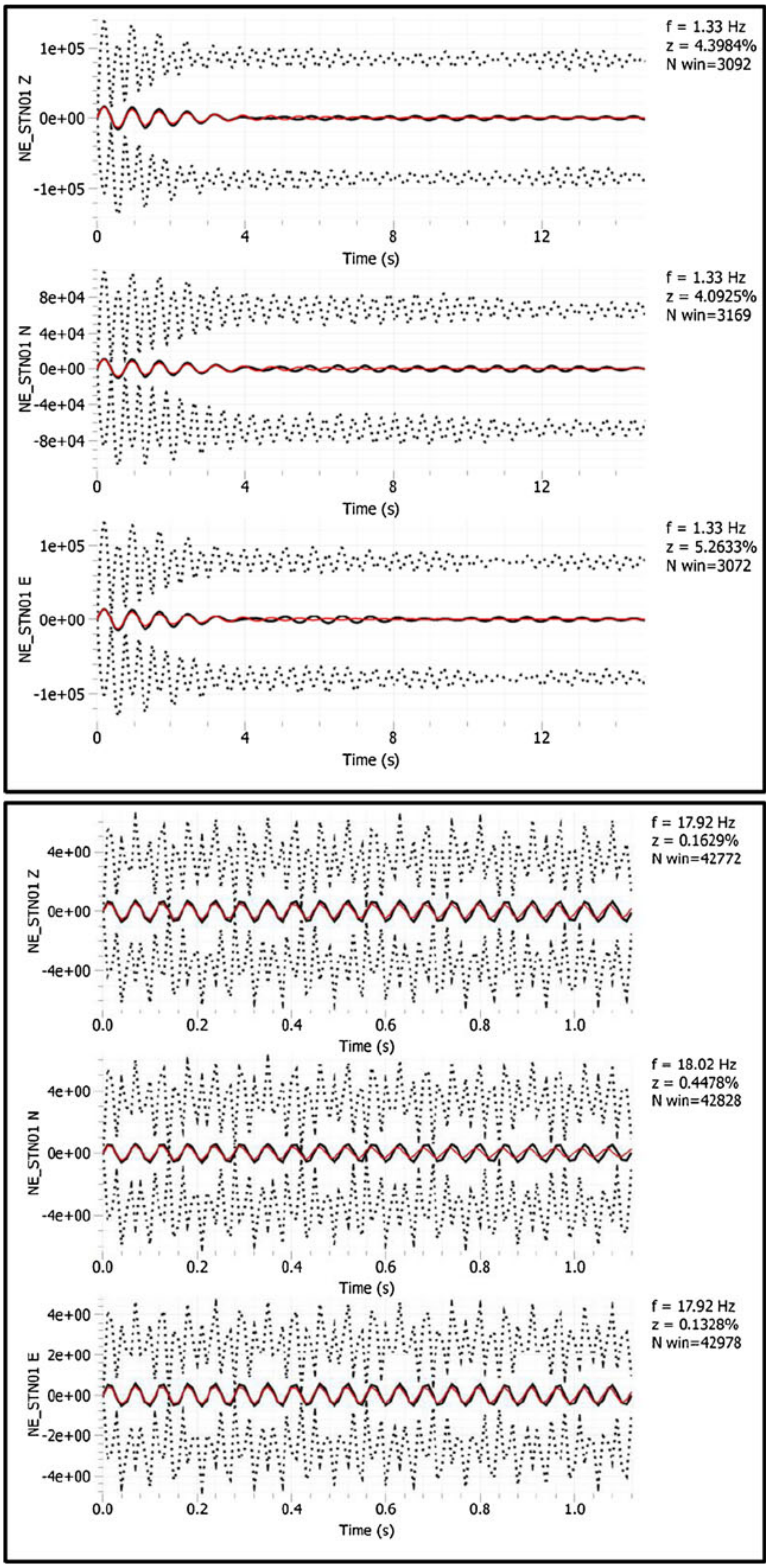

Fig. 5 f_0 of natural (*top*), industrial (*bottom*), and origin using damping test

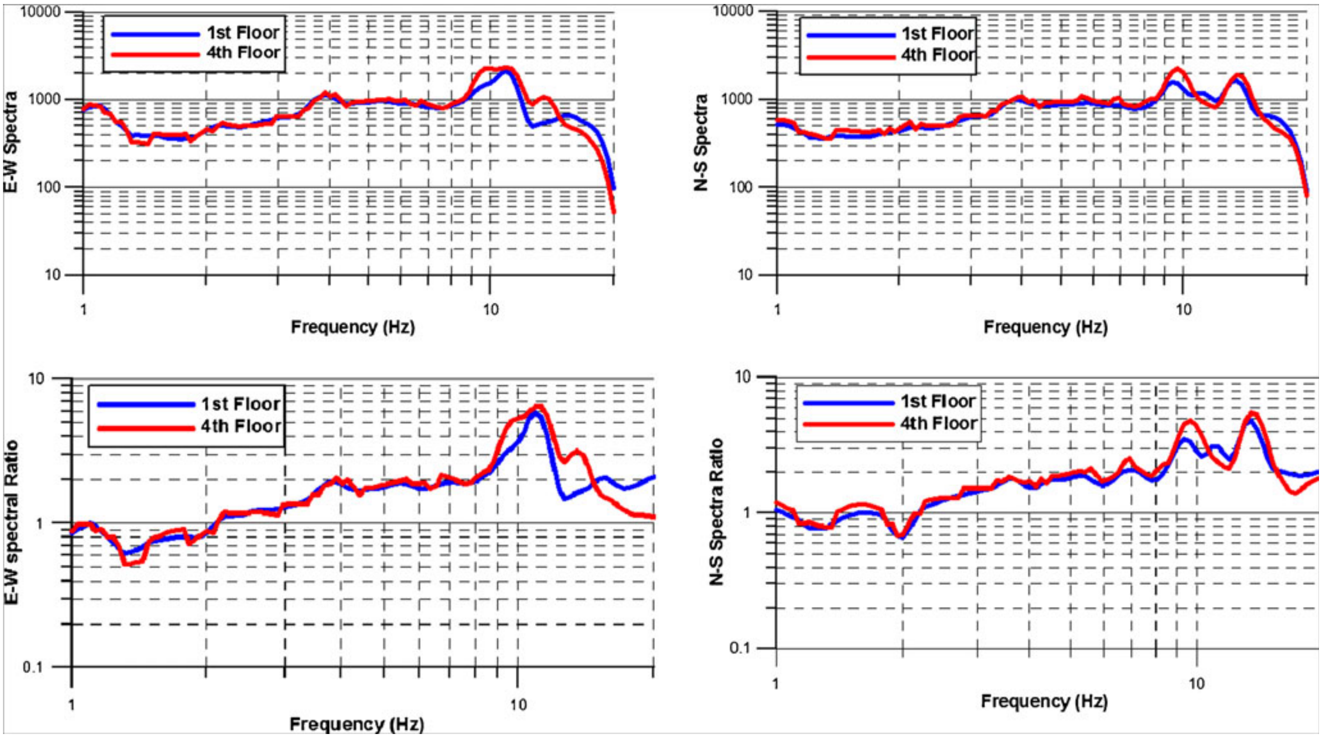

Fig. 6 Spectral amplitude and spectral ratio for E–W and N–S inside building 1

the basement floor was continued more than 1 h because there are two instruments which have been installed synchronously for 40 min; one outside the building (free-field) while the second on the basement floor of the building. Later, the free-field seismograph has been removed to the upper floor of the building and installed for 40 min again.

Although HVSR presents reasonable frequencies inside the buildings in most cases, Gosar (2007) proposed Floor Spectral

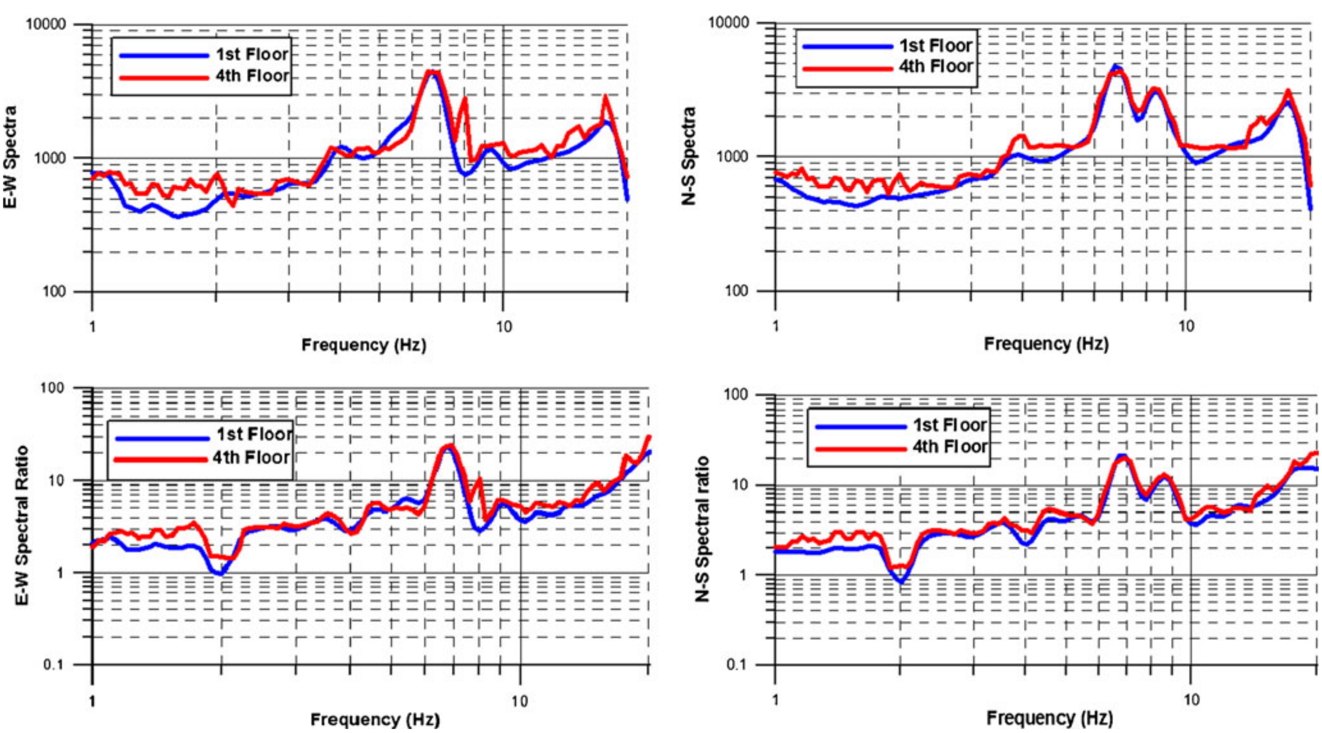

Fig. 7 Spectral amplitude and spectral ratio for E–W and N–S inside building 2

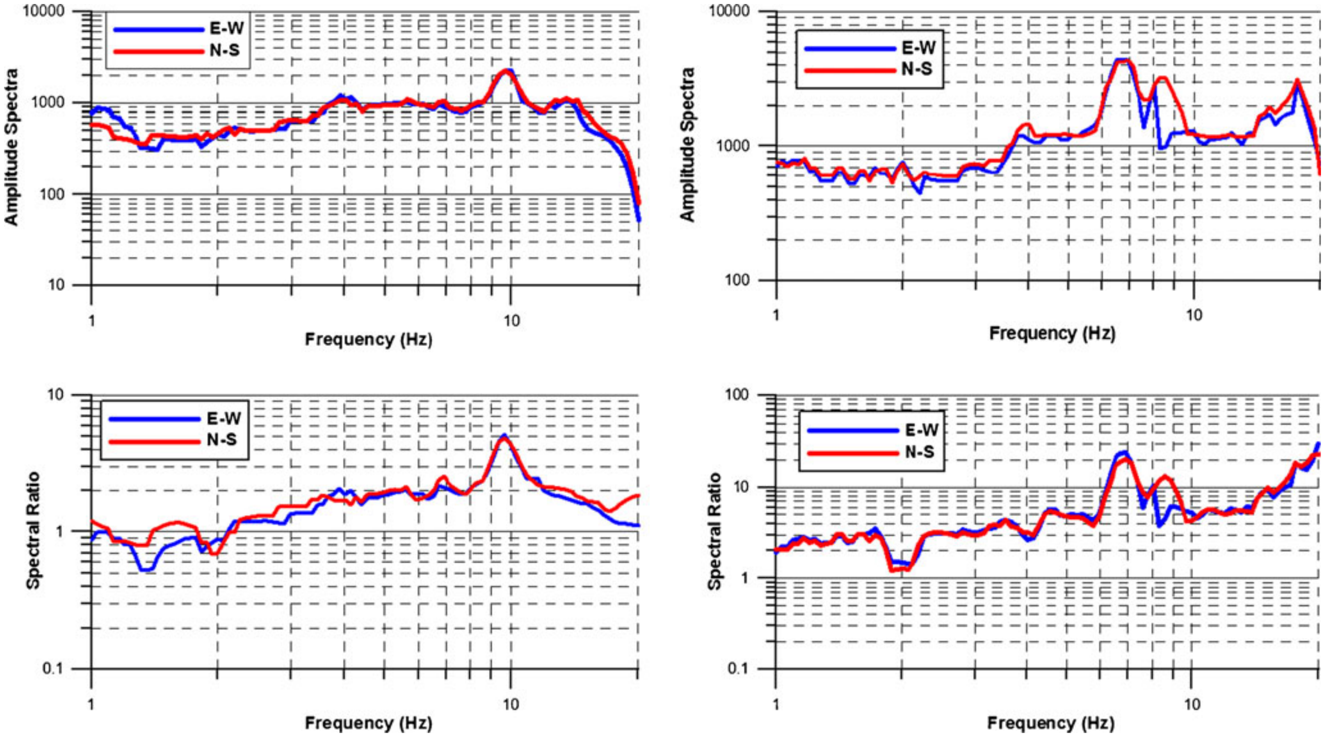

Fig. 8 Building no. 1 where the danger level of soil-structure resonance is low. *Top*: fourth floor of the building—spectral method. *Center*: fourth floor of the building—standard spectral ratio. *Bottom*: free-field HVSR

Ratio (FSR) technique for identifying the frequency of the building. In this study, the inside building measurements have been processed using amplitude spectra (E–W and N–S) of ambient noise inside the buildings and spectral ratio between the highest and basement floors for the horizontal components (Herak et al. 2009). In the spectral analyses, each record was split into 10 s-long non-overlapping windows for which amplitude spectra were computed using a cosine tapper with 5 % cosine function. An FFT was calculated for each window in each component. The Fourier spectra were smoothed using Konno and Ohmachi (SESAME-project 2004) with 40 smoothing constant. The average amplitude spectra for each component were computed from selected windows. Then, to derive the natural frequencies of the building using FSR

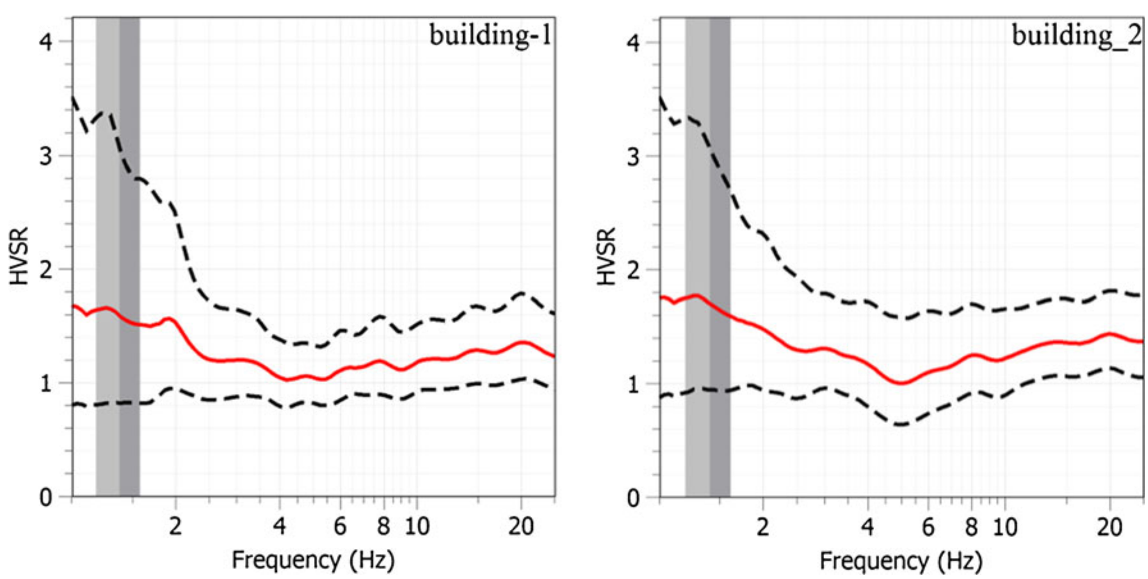

Fig. 9 Building no. 2 presents low level of soil-structure resonance. *Top*: fifth floor of the building—spectral method. *Center*: fifth floor of the building—standard spectral ratio. *Bottom*: free-field HVSR

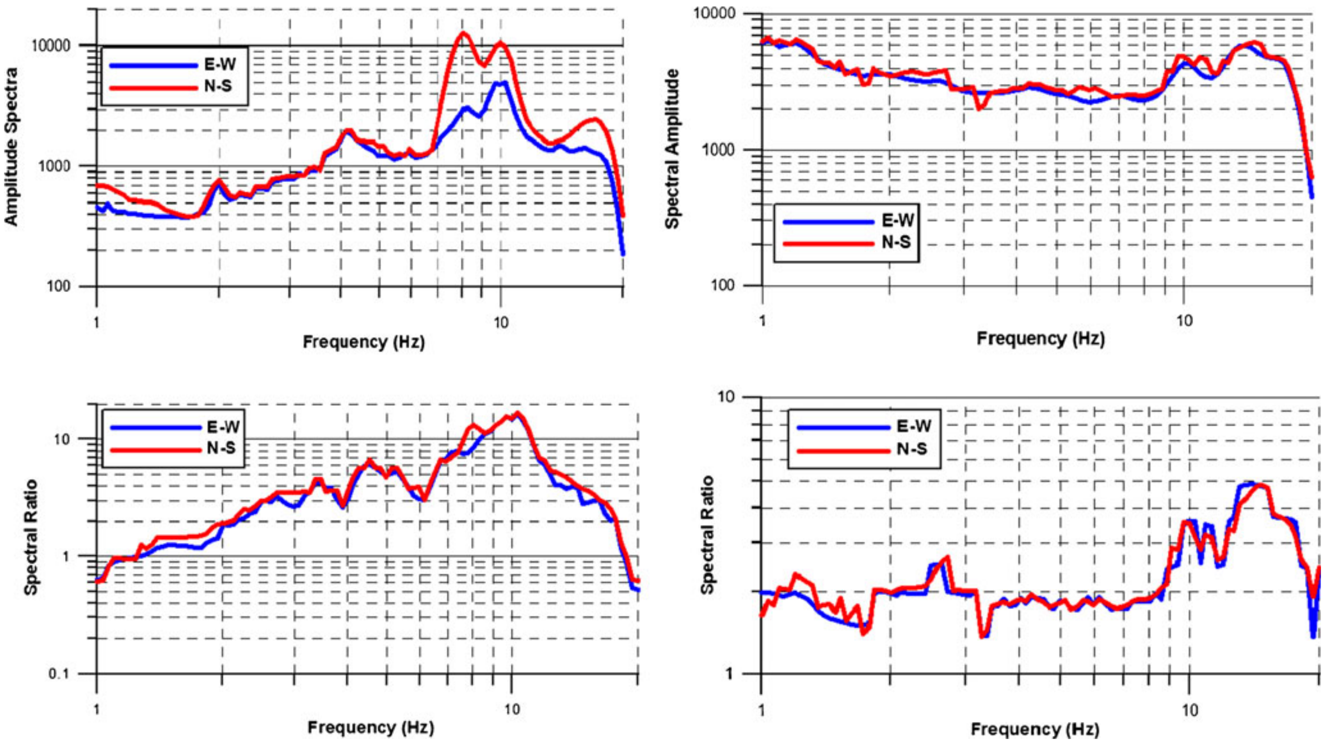

Fig. 10 Building no. 3 presents low level of soil-structure resonance. *Top*: fifth floor of the building—spectral method of each horizontal component. *Center*: fifth floor of the building—standard spectral ratio (building/free-field) of vibration of each horizontal component. *Bottom*: free-field HVSR

method can occurred as the spectral analysis to the upper floor and free-field measurement. Furthermore, divided between upper floor and free-field measurement are occur. Figure 6 presents the amplitude spectra and FSR methods from N–S and E–W vibrations on the basement and fourth floor of building 1.

According to Fig. 6, the frequency of the building derived from FSR method is 9.45 Hz for basement and 9.64 Hz for the fourth floor of E–W component. The spectral method shows the frequency of the building is 9.5 Hz for basement floor and 9.74 Hz for the fourth floor. Whereas N–S component shows that the amplitude spectra

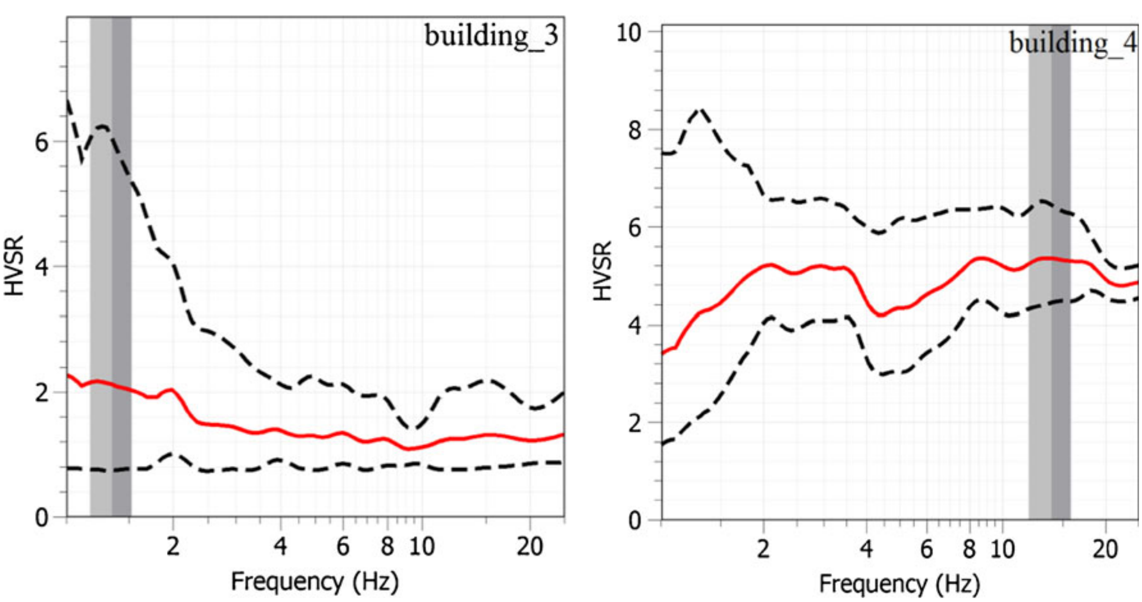

Fig. 11 Building no. 4 presents low level of soil-structure resonance. *Top*: fourth floor of the building—spectral method of each horizontal component. *Center*: fourth floor of the building—standard spectral ratio (building/free-field) of vibration of each horizontal component. *Bottom*: free-field HVSR

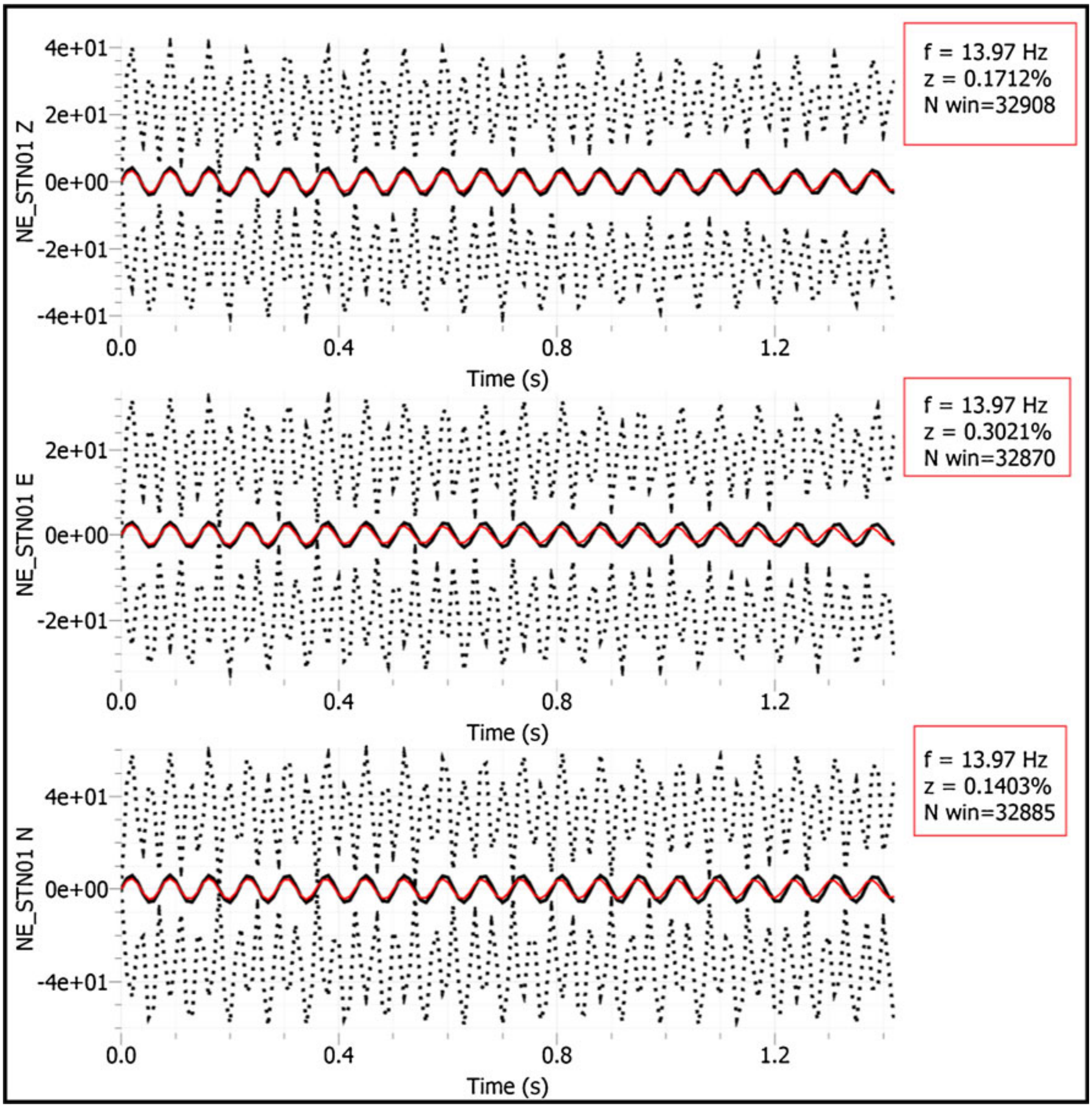

Fig. 12 Industrial origin for f_0 peak at 13.97 Hz free-field near building no. 4

method has a clear peak at a frequency of 6.74 Hz for the basement and the fourth floors. This value has been confirmed in the FSR method where a clear peak at a frequency of 6.74 Hz. The frequency difference between both horizontal directions is usually small which indicates the symmetrical shape of building no. 1.

Figure 7 indicates that the frequency for E–W component of building no. 2 that has been derived from FSR method is 6.74 Hz for the basement and the fifth floors. The spectral method shows that the frequency of the building is 6.67 Hz for the basement and the fifth floors. Whereas N–S component shows that the amplitude spectra method has a clear peak at a frequency of 6.81 Hz for the basement and the fifth floors. This value has been confirmed in the FSR method where a clear peak at frequency of 6.81 Hz. The frequency difference between both horizontal directions is usually small which indicates the symmetrical shape of building no.2.

Table 1 Results of microtremor measurements for the surveyed buildings

Building no.	f_0 using spectra method		f_0 using FSR method		f_0 Free-field	Level of danger
	E–W	N–S	E–W	N–S		
1	9.74	9.74	9.64	9.64	1.33	Low
2	6.74	6.74	6.81	6.81	1.4	Low
3	10.28	8.08	10.3	10.3	1.34	Low
4	13.78	14.65	13.93	14.73	2.08	Low

FSR Floor Spectral Ratio, *E–W* east–west, *N–S* north–south

Soil-structure resonance

The longitudinal and transverse frequencies of the peaks have been identified for all measurements. The amplitude spectra of horizontal components and standard spectral ratio (building spectral divided by free-field spectral) as proposed by Gosar (2007) have been applied in this study. The soil-structure resonance has been identified through comparison between the frequencies of sediments and inside buildings. Danger levels of soil-structure resonance have been estimated by selecting the building frequency peak that is closer to the free-field frequency peak and then computing the ratio between them. Gosar (2010) stated that, if the difference is within ±15 %, the danger of soil-structure resonance is high, if it is within 15–25 %, it is medium, and if it is higher than ±25 %, then it is low. Figure 8 clarified a clear peak at a frequency of 1.33 Hz with an amplitude of 1.6 which has been identified from free-field measurement near building no.1. Whereas the inside building measurements show clear peak at 9.74 Hz in E–W component using spectral method and at 9.64 Hz using FSR method; while N–S component presents 9.74 Hz for amplitude spectra and 9.64 Hz for FSR methods. This building is of three-story masonry house with low danger level soil-structure resonance because of the difference with the free-field is higher than 25 %. It is characterized by almost identical frequency values of 9.74 Hz for E–W and N–S components, which reflects symmetrical shape.

Building no. 2 (Fig. 9) presents clear peak at a frequency of 1.4 Hz with an amplitude of 1.7 in free-field measurement. The inside building measurements clarify a clear peak at 6.74 Hz for E–W and N–S components by using spectral method and at 6.81 Hz for E–W and N–S components using FSR method This building is of four-story masonry house with low danger level soil-structure resonance because of the difference with the free-field measurement is higher than 25 %. It is characterized by almost identical frequency values of 6.74 Hz for E–W and N–S components, which reflects symmetrical shape. Building no. 3 (Fig. 10) presents a peak at a frequency of 1.34 Hz with an amplitude of about 2.12 in the free-field measurement. The inside building measurements illustrate a clear peak at 10.27 Hz for E–W component using spectral method and at 10.3 Hz using FSR method. The N–S component exhibits a clear peak at 8.08 Hz using spectral method and at 10.3 Hz using FSR method. This building is of four-story masonry house with low danger level soil-structure resonance because of the difference with the free-field measurement is higher than 25 %.

Building no.4 (Fig. 11) shows two peaks at frequency 2.08 and 13.97 Hz with amplitudes of about 5.25 and 5.4, respectively in the free-field measurement. The origin of f_{0o}=13.97 is industrial and thus should not be considered in the interpretation (Fig. 12). Then the value of f_0=2.08 is the fundamental frequency at this site. The inside building measurements reveal a clear peak at 13.78 Hz for E–W and at 14.65 Hz for N–S components using spectral method while FSR method shows clear peak at 13.93 Hz for E–W and at 14.73 Hz for N–S component. This building is of four-story masonry house with low danger level of soil-structure resonance because the difference with the free-field measurement is higher than 25 %.

Results of microtremor measurements are presented in Table 1, together with the free-field frequency and level of soil-structure resonance. The frequency difference between both horizontal directions is usually small, because most buildings have a rather symmetrical shape.

Conclusions

Microtremor measurements have been carried out at ten free-field sites. Furthermore these measurements are conducted inside four buildings in the southern suburb of Riyadh city. These measurements have been processed according to SESAME-project recommendations. The results of free-field measurements illustrated that the fundamental frequency, f_0, ranges from 1.27 to 1.4 Hz. These values indicate the presence of thick bedrock overlying by thin soft sediments. This is confirmed by the small amplitudes of the measured data. On the other hand, the fundamental frequency of the surveyed buildings ranges from 6.74 to 14.65 Hz for E–W and N–S components using spectral amplitude method. Whereas the FSR method illustrated that f_0 ranges from 6.81 to 14.73 Hz for E–W and N–S components. Accordingly and based on the results of the free-field and inside building measurements, it is cleared that the difference in f_0 between both results is higher than 25 % which indicates the low danger level of soil-structure resonance for the surveyed buildings. Depending on the abovementioned discussion, conducting of inside buildings microtremor measurements together with the free-field at the residential area for assessing the danger level of soil-structure resonance is highly recommended.

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