DERIVATION OF SEDIMENTS ISO-FREQUENCY MAP FOR THE LITIJA BASIN (CENTRAL SLOVENIA) BY MICROTREMOR ANALYSIS AND IMPLICATIONS FOR SOIL-STRUCTURE RESONANCE

Andrej GOSAR

University of Ljubljana, Faculty of Natural Sciences and Engineering and Environment Agency of Slovenia, Seismology and geology office, Dunajska 47, 1000 Ljubljana, Slovenia
**Corresponding author's e-mail* andrej.gosar@gov.si

(*Received* January 2012*, accepted* April 2012)

ABSTRACT
The town of Litija was hit by four damaging earthquakes in the last 120 years which reached a maximum intensity of VII-VIII MSK. The town is located in a shallow sedimentary basin filled with relatively soft Quaternary sediments in which seismic site amplification is expected. On the other hand no borehole or geophysical data are available to support quantitative assessment of site effects. As a contribution to the first seismic microzonation of the area, we performed a free-field study based on the microtremor HVSR method in order to assess the resonance frequency of the sediments. In general clear spectral peaks were obtained for 57 measuring points which show distribution of frequencies in a broad range between 4.4 and 22.7 Hz. The iso-frequency map was prepared by using natural neighbour interpolation algorithm. For soil-structure resonance assessment we considered large building stock from different Slovenian towns, because the building typology is similar in wider area. Low-rise masonry family houses with two or three floors prevail. By microtremor measurements inside 45 such buildings their fundamental longitudinal and transverse frequencies were determined and statistically analysed in a complementary study. To assess the possible occurrence of soil-structure resonance in general, the average fundamental frequency +/– one standard deviation interval is obtained for these two building heights, which gives the range 5.6–11.1 Hz. The free-field microtremor data shows that this frequency range occupies 37% of the urban area in the Litija basin. This study has shown that soil-structure resonance issue for low-rise buildings is frequently overlooked, but should be considered seriously in shallow sedimentary basins, characterized by relatively high free-field frequencies, because many towns are located in such geological environment. Second application of the derived iso-frequency map is to support soil classification, because recent investigations have shown that fundamental frequency of sediments can be used together with the average shear velocity in the upper 30 m to improve classifications according to different seismic codes.

KEYWORDS: microtremors, ambient vibrations, Horizontal-to-Vertical Spectral Ratio method, seismic site effects, soil-structure resonance

INTRODUCTION

The town of Litija was hit in the last 120 years by four damaging earthquakes which reached intensities from VI to VII-VIII MSK. Also the historic seismicity contributes to relatively high seismic hazard in this area; the design ground acceleration for a rock site is 0.2 g for 475-year return period. Litija is situated in a shallow sedimentary basin formed at the location of a pronounced Sava river bend (Fig. 1). The basin is filled with relatively soft Quaternary sediments composed of gravel, sand and clay, which overlay Palaeozoic and Triassic bedrock. This indicates that site effects can enhance the seismic ground motion in case of an earthquake. Nevertheless, no microzonation study was performed so far in the area.

As a contribution to the first seismic microzonation, we decided to perform a study based on the microtremor Horizontal-to-Vertical Spectral Ratio (HVSR) method. This study was motivated by the two facts. The first is that no direct information from drilling or geophysical investigations is available on the thickness and physical properties of Quaternary sediments to support quantitative assessment of site effects by seismic modelling. Recent investigations have shown that the main resonance frequency of sediments (f_0) can be used together with the average shear velocity in the upper 30 m ($Vs_{,30}$), to improve classifications of sediments according to different seismic codes (e.g. Luzi et al., 2011). The second reason is related to the height of the buildings which prevail in the area. Large majority of buildings in Litija have two or three floors, including the ground floor. For low-rise buildings relatively high fundamental frequencies are characteristic which can coincide with the frequency range of relatively thin sedimentary cover. Soil-structure resonance, which can enhance the damage, should be therefore considered in any seismic risk assessment (Gosar, 2012).

The aim of this study was to derive the sediments iso-frequency map for the urban part of the Litija basin and to compare the results with the building resonance frequencies. A detailed free-field microtremor survey was performed to accomplish the first task, which is the focus of this paper. For soil-structure resonance assessment we decided to consider larger building stock from different Slovenian towns in which microtremor measurements were conducted recently to derive the range of fundamental frequencies for comparison, because the building typology is similar in wider area. Determination of masonry building fundamental frequencies in five Slovenian towns, including Litija, by microtremor excitation and implication for seismic risk assessment is the focus of a complementary paper (Gosar, 2012).

SEISMOLOGICAL CHARACTERISTICS

The town of Litija is located 25 km east of Ljubljana (the capital of Slovenia) in the Sava valley, in the area characterized by relatively high seismicity, although earthquakes are limited to moderate magnitudes. In the last century, the most damaging was the Litija earthquake in May 1963, which had a Ml=4.7 and VII MSK maximum intensity. It was followed by a Ml=4.2 aftershock in November 1963, which had VI MSK maximum intensity. Litija was significantly damaged also by the great Ljubljana earthquake, which occurred in April 1895 and had a magnitude of 6.1. In Litija the intensity of this event was VII-VIII MSK. Another damaging earthquake with Ml=4.4 and VI-VII MSK intensity occurred in May 1939. In the last decades the Litija region is characterized by increased seismicity (Fig. 1), but earthquakes are limited to small magnitudes and do not result in damage to buildings. Most of the epicentres are located to the W and SW of the town at the distance of 2-4 km (Prosen et al., 2001; Čarman et al., 2009). Relocation of hypocenters by using double-difference hypocenter determination has shown that they are aligned along almost vertical region extending about 6 km in NW-SE direction at the depths between 6 and 13 km. Fault plane solutions for two stronger events also indicate almost vertical fault of Dinaric (NW-SE) direction and a right-lateral strike-slip mechanism with a small reverse component (Čarman et al., 2009).

According to the seismic hazard map of Slovenia for a 475 –year return period (Lapajne et al., 2001), a relatively high seismic hazard is characteristic of the area, with a design ground acceleration value of 0.2 g for a rock site. The town of Litija has around 9,000 inhabitants; in addition there are several important industrial and transport facilities in the area, which should be considered in a seismic risk assessment.

METHODOLOGY

The microtremor method has been widely used for microzonation and site effect studies in the last decade. Reviews on the method can be found in Bard (1999). However, the theoretical basis of the Horizontal-to-Vertical Spectral Ratio (HVSR) method of free-field microtremor measurements is still debated, and different explanations on the content of body and surface waves in microtremors have been considered. More widely accepted is the "surface waves" explanation (Bard, 1999; Bonnefoy-Claudet et al., 2006), by which HVSR is related to the ellipticity of Rayleigh waves, which is frequency dependent. HVSR therefore exhibits a sharp peak at the fundamental frequency of the sediments, when there is a high impedance contrast between the sediments and underlying bedrock. Criticism of the HVSR method was often related to the fact that there is no common practice for data acquisition and processing (Mucciarelli and Gallipoli, 2001) but some standards have been provided later (SESAME, 2004). Today it is widely accepted that the frequency of the HVSR peak reflects the main resonance frequency of the sediments. The main advantages of the HVSR method are a straightforward estimate of the resonance frequency of sediments without knowing the geological and shear waves velocity structure of the underground, and simple, low-cost measurements. This frequency can be used directly to assess the danger of soil-structure resonance or independently, because there is a trend to consider also the resonance frequency or period of sedimentary cover in different soil classifications for seismic microzonation (e.g. Pitilakis, 2004; Luzi et al., 2011).

The use of microtremors was later extended to the study of dynamic parameters of buildings, for instance for identification of their fundamental frequencies and of the possible danger of soil-structure resonance (Mucciarelli et al., 2001; Gallipoli et al., 2004; Mucciarelli and Gallipoli, 2007; Boutin and Hans, 2008). The theory and interpretation of ambient vibration measurements inside buildings are not so structured and straightforward as they are for the free-field case. However, some useful advice and instructions for measurements in buildings and their interpretation are described in e.g. Gallipoli et al. (2004), Parolai et al. (2005) or Gallipoli et al. (2010). In general it is possible to obtain at least the fundamental frequencies in two horizontal orthogonal directions (longitudinal and transverse).

MICROTREMOR MEASUREMENTS

Microtremor measurements were performed in approximately 1.5 km^2 large area which extends across the whole urban area of Litija, situated on the both sides of the Sava river (Fig. 2). Altogether 66 free-field measurements were conducted with the spacing of 100-250 m between measuring points. The locations were carefully selected to avoid as much as possible the influence of buildings, industrial facilities, trees, underground structures and traffic. However, in the built urban environment this was not

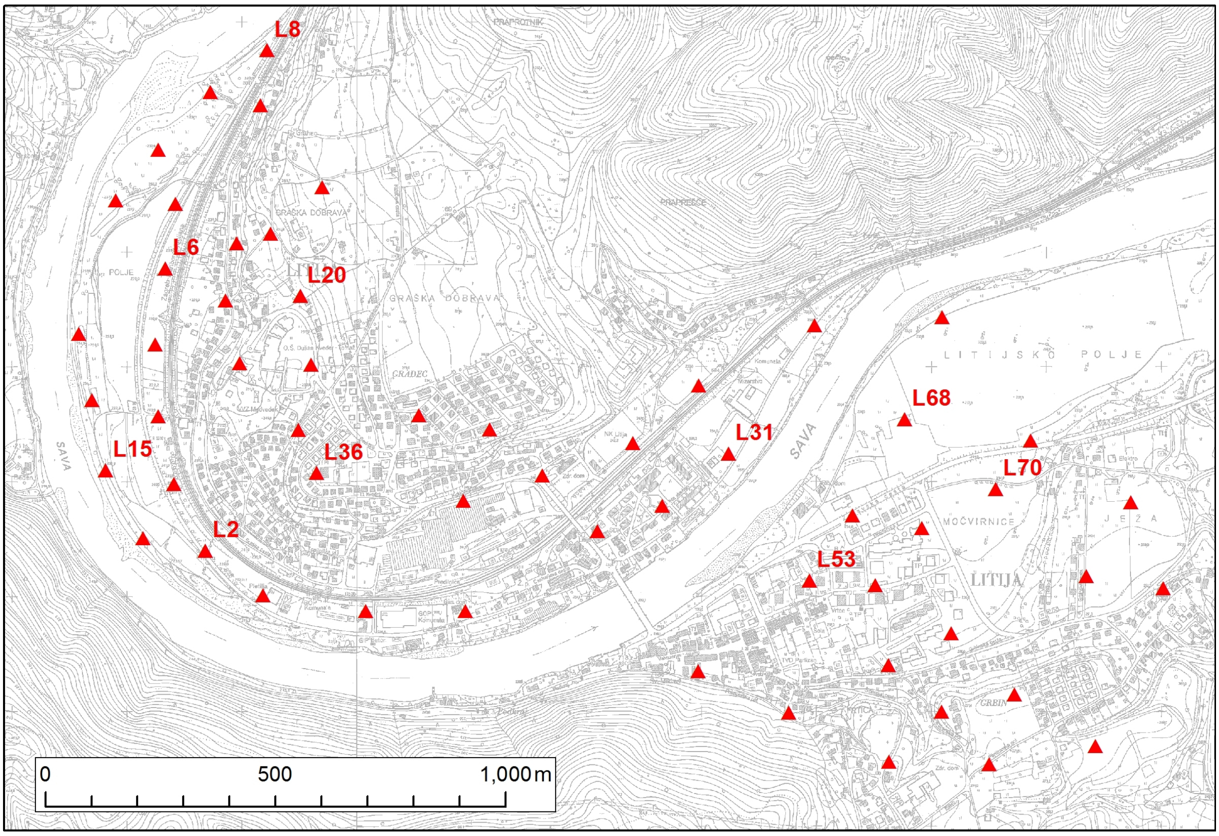

Fig. 2 Position map of microtremor free-field measurements (red triangles) in the Litija basin. Labels indicate examples of HVSR analyses shown in Figure 5.

always possible, therefore the grid of measuring points is quite irregular. Especially in the old town centre the free-field space between houses is very limited, whereas most of industrial facilities have a restricted access to their premises.

Measurements were performed by two Tromino seismographs (Micromed, 2005) composed of three orthogonal electrodynamic velocity sensors, a GPS receiver, digitizer and recording unit with a flash memory card. All parts are integrated 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 obtained by using long spikes mounted at the base of the seismograph. The sampling frequency was 128 Hz and the recording length at each point 20 minutes. The experimental conditions of microtremor measurements (e. g. Chatelain et al., 2008) were mainly favourable. The main difficulties arose from the low-frequency or monochromatic traffic and industrial noise.

The HVSR analysis was performed in the following way. Recorded time series were visually inspected to identify possible erroneous measurements and stronger transient noise. Each record was then split into 30 s long non-overlapping windows, for which amplitude spectra in the range 0.1–64 Hz were computed using a triangular window with 5 % smoothing and corrected for sensor transfer function. The HVSR was computed as the geometric average of both horizontal component spectra divided by the vertical spectrum for each window. Amplitude spectral curves (Fig. 3a) shows a clear difference between both horizontal and the vertical component in a narrow frequency range. This difference results in a sharp peak on the HVSR curve (Fig. 3b). From the colour-coded plot of HVSR functions for all windows, the windows including strong transient low-frequency noise were identified in order to be excluded from further computation (Fig. 4). After removal of noisy parts of the record the signal to noise ratio has improved, narrowing the 95 % confidence interval, especially in the low-frequency part of the spectral ratio (Fig. 4d). Finally, the average HVSR function of all windows with the corresponding 95 % confidence interval was computed (Fig. 3b). In addition, a directional HVSR analysis was performed in 10° angular steps to identify possible directions of noise sources, but no preferential directions were established.

The HVSR analyses of free-field measurements showed that most of them (Fig. 5) fulfil the criteria for reliable measurements and a clear peak (SESAME, 2004). Three of these criteria for a reliable HVSR curve are based on the relation of the peak frequency to the window length, the number of significant cycles

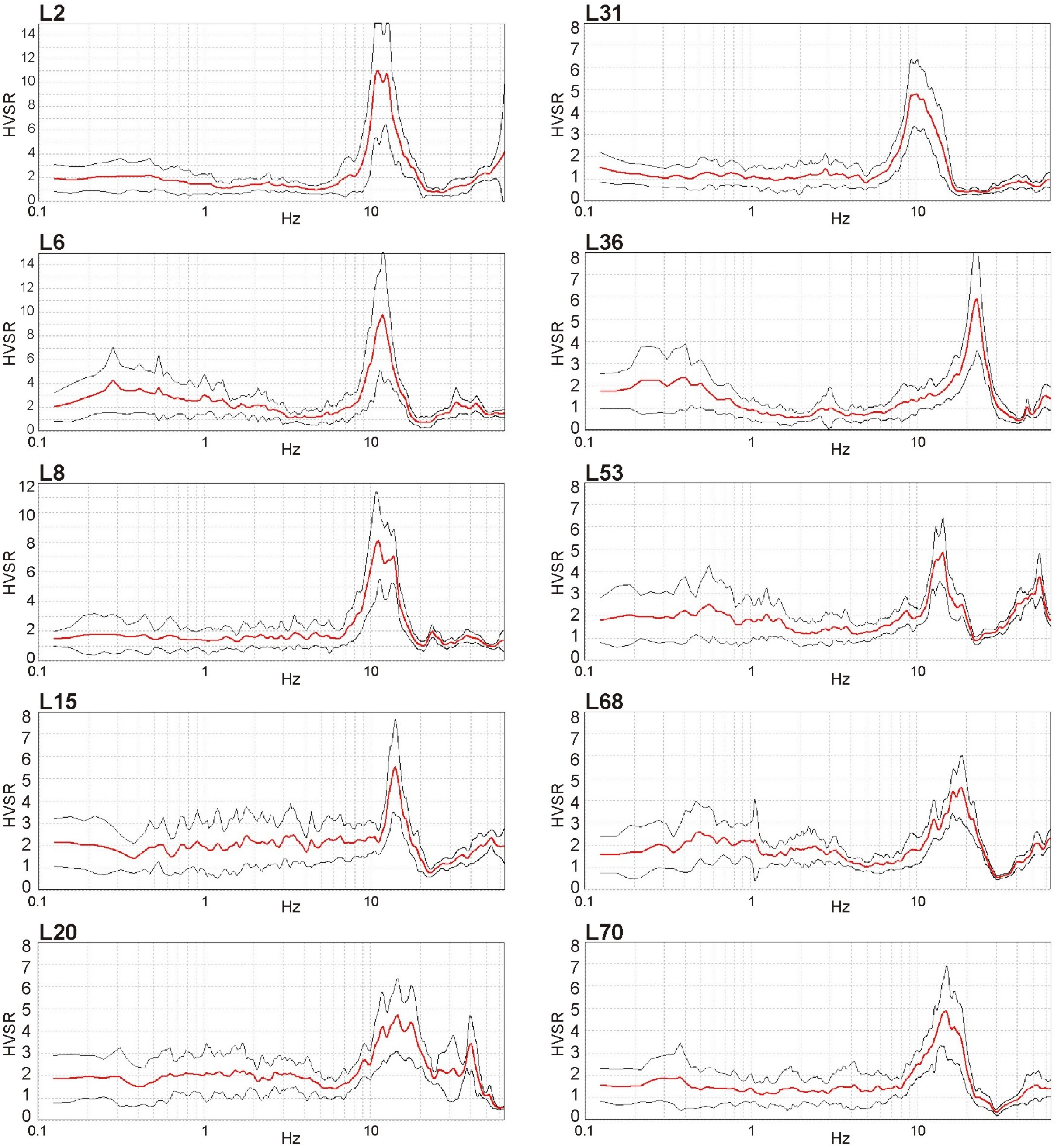

Fig. 5 Some examples of microtremor measurements (HVSR). Locations of measurements are shown in Figure 2. Thin lines represent the 95% confidence interval.

and the standard deviation of the peak amplitude. The next six criteria for a clear peak are based on the relation of the peak amplitude to the level of the HVSR curve elsewhere, and standard deviations of the peak frequency and of its amplitude (the amplitude should decrease rapidly on each side). If all three criteria for a reliable curve and at least five criteria for a clear peak are fulfilled, the frequency of the peak is considered to be the fundamental frequency of sediments down to the first strong impedance contrast. The main reasons for the failure of the above criteria are: a) high level of low-frequency noise during whole 20 minutes of recording, b) two or more peaks in a spectrum, or c) too small amplitude of the peak or a flat spectral ratio. In cases in which the small amplitude of the HVSR peak caused failure to the criteria for a clear peak, we compared the results with adjacent measurements. If the frequencies of questionable peaks were comparable with the frequencies obtained at adjacent points, we kept them in the database. At the end, for 57 measuring point out of 66 it was possible to reliably define the peak frequency. Distribution of established frequencies is shown in Figure 6. Most of the values (45) fall in the

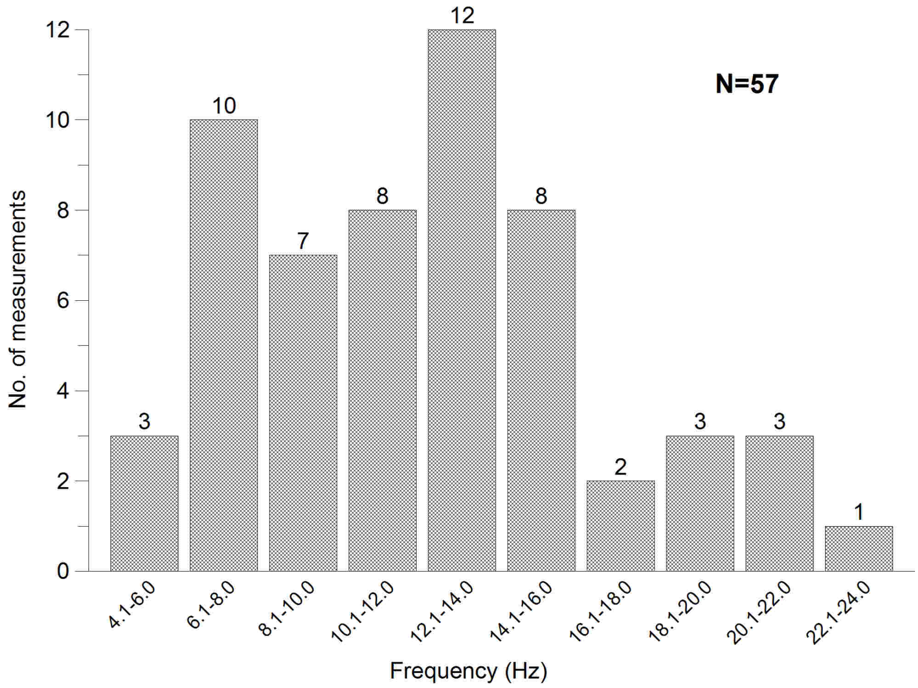

Fig. 6 Distribution of sediments main frequency derived from microtremor HVSR measurements for all measurements.

frequency range 6.1-16.0 Hz. Higher frequencies are rare and presumably do not reflect the total thickness of Quaternary sediments, but are related to the presence of a secondary impedance contrast within them.

Several examples of the HVSR graphs are shown in Figure 5; locations of these measurements are shown in Figure 2. In general, clear peaks were obtained showing the broad range of fundamental frequencies between 4.4 and 22.7 Hz. The temporal stability of the signal was moderate. In general 95 % confidence interval of average curves is narrower at higher frequencies and wider at lower frequencies. This is mainly due to the low-frequency industrial and traffic noise which could not be completely removed by exclusion of windows which include stronger transients. In most cases there is a sharp peak in the HVSR which is rather symmetrical (L6, L15 and L36 in Figure 5). An asymmetric shape with an additional small side peak is also common (L2, L8 and L68 in Figure 5). Sometimes the presence of a small side peak is only slightly indicated (L53 and L70 in Figure 5), but this depends also on the level of applied smoothing. In general the amplitude of the side peak is lower then the amplitude of the main peak, but there are some exceptions as L2 and L68 in Figure 5. Some measurements, as L20 in Figure 5, show more complex shape with several peaks, indicating more complex subsurface structure.

The amplitudes of the HVSR peaks are mainly in the range 3-6, only in few cases they reached the values between 8 and 11. The amplitude of the peak is related to the impedance contrast between sediments and the bedrock, but in principle it can not be used for quantitative estimation of the contrast or site amplification.

The data from 57 measuring points were used to prepare the iso-frequency map showing resonance frequencies of sediments (Fig. 7). The map was drawn using GIS software and natural neighbour interpolation algorithm. The fundamental frequency of sediments shows a distribution in a range of 4.4-22.7 Hz. Very high frequencies (above 16 Hz) are limited to small, isolated areas. They can not be related to the total thickness of Quaternary sediments, but can indicate the presence of a stiffer layer inside them, located at shallow depth. Most probably this is a lens of conglomerate inside the gravel, which is common in given geological environment. Similar conditions were observed in the Ljubljana basin (Gosar et al., 2010), where conglomerate bodies of irregular shape inside the Sava river deposits were confirmed also by drilling.

For a rough numerical estimate of the thicknesses (h) which correspond to the sediments fundamental frequencies (f_0), a single layer fundamental mode case relation (f_0=Vs/4h) can be used. In the Ljubljana basin which has similar geological setting, seismic shear wave velocity (Vs) of sand-gravel sediments was estimated by the joint modelling of microtremor array measurements and HVSR data on 300-600 m/s (Rošer and Gosar, 2010).

If we take the average Vs=450 m/s, we obtain for the frequency range of 4.4-16.0 Hz the corresponding thickness of 25.6-7.0 m. This is a reasonable estimate of the sediments thickness for a Litija basin, which is situated in a relatively narrow valley. This prevents the formation of a deeper sedimentary basin.

BUILDINGS MAIN FREQUENCIES AND SOIL-STRUCTURE RESONANCE

One of the principle applications of sediments iso-frequency map is the assessment of the possible occurrence of soil-structure resonance in the case of an earthquake. During the field measurements, we surveyed also the building typology in the area. We realized that buildings with the height in the range from two to three floors (including ground floor) prevail and that the building typology (masonry with RC floors) is very similar to the buildings in other Slovenian towns. Since in the last years microtremor site effects and soil-structure resonance studies were performed also in four other towns (Bovec, Kobarid, Ilirska Bistrica and Brežice) where the seismic hazard is increased, we decided to consider larger building stock in which microtremor measurements were conducted to derive fundamental resonance frequencies (Gosar and Martinec, 2009; Gosar, 2009; Gosar, 2010; Gosar, 2012). In the Bovec basin it was proved by the microtremor method that soil-structure resonance has enhanced the damage related to the 1998 Mw=5.6 earthquake (Gosar, 2007). Statistical analysis on a large data set of buildings provided a necessary insight into distribution of dynamic parameters which can be used in any soil-structure resonance study in wider region (Gosar, 2012).

Microtremor measurements were performed in totally 45 buildings with two or three floors. At each floor the Tromino instrument was placed as close as possible to the mass centre of the building and close to the inner wall. The two horizontal components were oriented one in the longitudinal and one in the transverse directions of the building. Short spikes mounted at the bottom of the seismograph were used to enable precise levelling, but to avoid vibration of the unit. The sampling frequency was 128 Hz and the recording length 10 minutes. Microtremor measurements have proved to be an effective tool for assessment of building fundamental frequencies. Such experimental approach is very valuable, as analytical seismic evaluation of an existing building is usually very difficult, even if the project documentation of the building is available, which is usually not the case for older buildings (Gosar, 2012).

Statistical analysis of the resonance frequency vs. number of floors (height) was performed to generalize identification of potential soil-structure resonance (Table 1 and Fig. 8). The frequency difference between both horizontal directions is usually small, because most buildings have a rather symmetrical shape. On the other hand the difference in average resonance frequency is very clear between buildings with two and three floors. The average value of both horizontal components for two-floor buildings is 9.11+/–1.94 Hz and for three-floor buildings 7.03+/–1.46 Hz (Gosar, 2012). To assess the possible occurrence of soil-structure resonance in general, a comparison of the average values for these two building heights +/– one standard deviation is therefore a reasonable approximation, which gives the range 5.6–11.1 Hz (Gosar, 2012). The possible occurrence of soil-structure resonance should be therefore sought especially in this frequency range which was compared to the free-field sediments iso-frequency map (Fig. 7). This comparison shows that the danger of soil-structure resonance is a serious issue in the Litija basin and indicates higher hazard, especially in the central and south-eastern part of the town. If we consider the total area of free-field measurements in Litija, 37 % of the surveyed town area is occupied by the 5.6–11.1 Hz frequency range.

CONCLUSIONS

Sediments main resonance frequency (f_0) derived from microtremor HVSR measurements has two basic applications in the seismic microzonation. It can be used directly, together with the data on the building fundamental frequencies, to assess the possible occurrence of soil-structure resonance. Secondly, it can be a complement to the average shear wave velocity in the upper 30 m ($Vs_{,30}$) as proposed by Pitilakis (2004) and Luzi et al. (2011). Most of the seismic codes make use of the $Vs_{,30}$ to discriminate soil categories, although some doubts exist about the capability of $Vs_{,30}$ to predict actual amplification of sediments. Luzi et al. (2011) showed that there is a significant reduction of the standard deviation associated to the ground motion prediction when the classification is based on the couple of variables $Vs_{,30}$-f_0.

The main result of this study is a new soft covers iso-frequency map of the Litija basin. The advantage of the applied microtremor HVSR method is a straightforward estimate of the resonance frequency of sediments without knowing their thickness and shear waves velocity. Such approach is considerably cheaper than evaluation of site amplification based on results of drilling and/or geophysical investigations. Comparison of the free-field iso-frequency map with the fundamental frequency range of buildings which prevail in the area has shown that the possible occurrence of soil-structure resonance is a serious issue, which should be considered in a seismic risk assessment. Soil-structure resonance issues for low-rise buildings are frequently overlooked, because most of the large urban areas (major cities) are located in rather deep sedimentary basins characterized by low frequencies of soft covers, which can pose a hazard only for a high-rise buildings. On the other hand, smaller towns are frequently located in shallow basins along the rivers, whereas low-rise family houses represent here the major part of the building stock.

Table 1 Results of statistical analysis of building's main frequencies for buildings with two and three floors in Slovenia (after Gosar, 2012).

No.of floors	N	Resonance freqency (Hz)											
		longitudinal				tranverse				average			
		AVG	STD	MIN	MAX	AVG	STD	MIN	MAX	AVG	STD	MIN	MAX
2	25	9.44	2.15	4.0	13.0	8.77	1.93	3.9	12.0	9.11	1.94	4.0	12.0
3	20	6.87	1.50	3.7	9.8	7.19	1.66	3.6	10.1	7.03	1.46	3.7	10.0

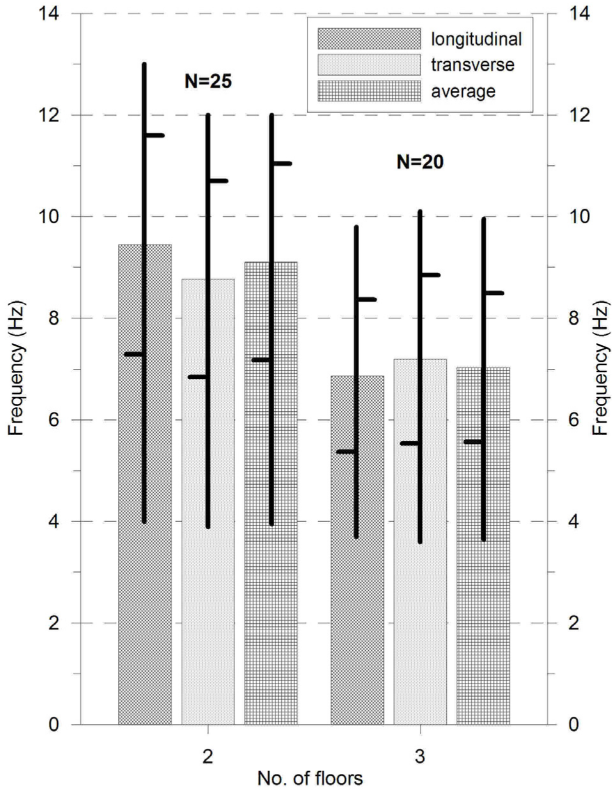

Fig. 8 Results of statistical analysis of building fundamental frequencies for 45 examined two and three floors buildings in Slovenia: bars – average value for longitudinal and transverse direction and for their average, vertical line – range of values, two short horizontal lines – average +/– one standard deviation (modified after Gosar, 2012).

Therefore, soil-structure resonance related risks should not be neglected, because majority of the population is living in these buildings.

ACKNOWLEDGEMENTS

The study was realized with the support of the research program P1-0011 financed by Slovenian Research Agency.

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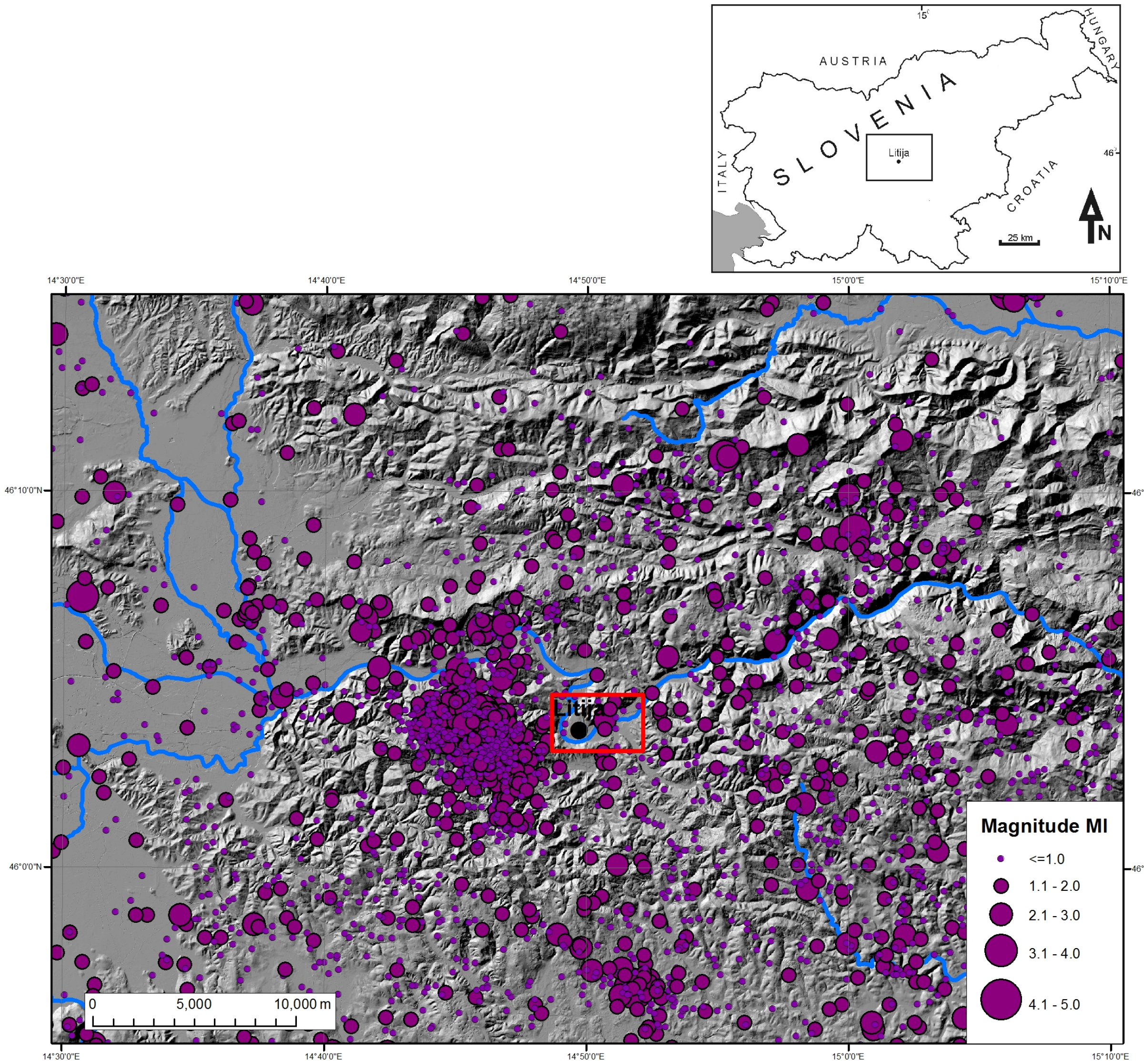

Fig. 1 Seismicity map of the wider Litija area for period 1977-2009 from EARS (2010) catalogue. A rectangle indicates the study area shown in Figures 2 and 7.

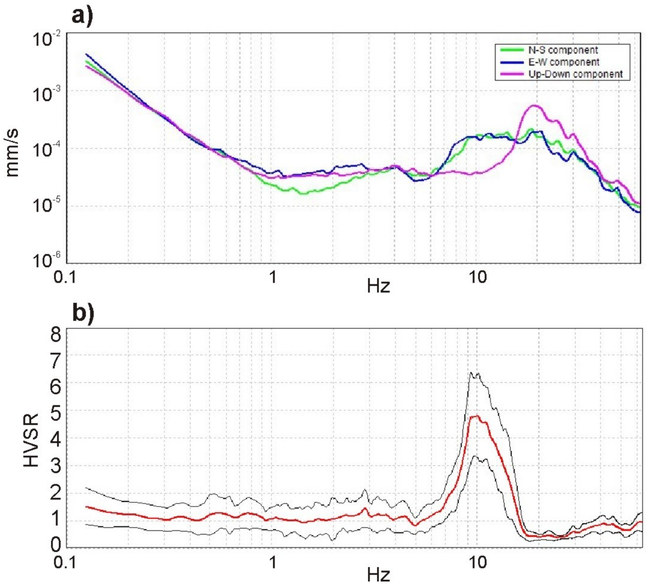

Fig. 3 An example of microtremor analysis. Amplitude spectral curves (a) shows the difference between both horizontal and the vertical component in a narrow frequency range. This difference results in a clear peak on the Horizontal-to-Vertical Spectral Ratio (HVSR) curve (b).

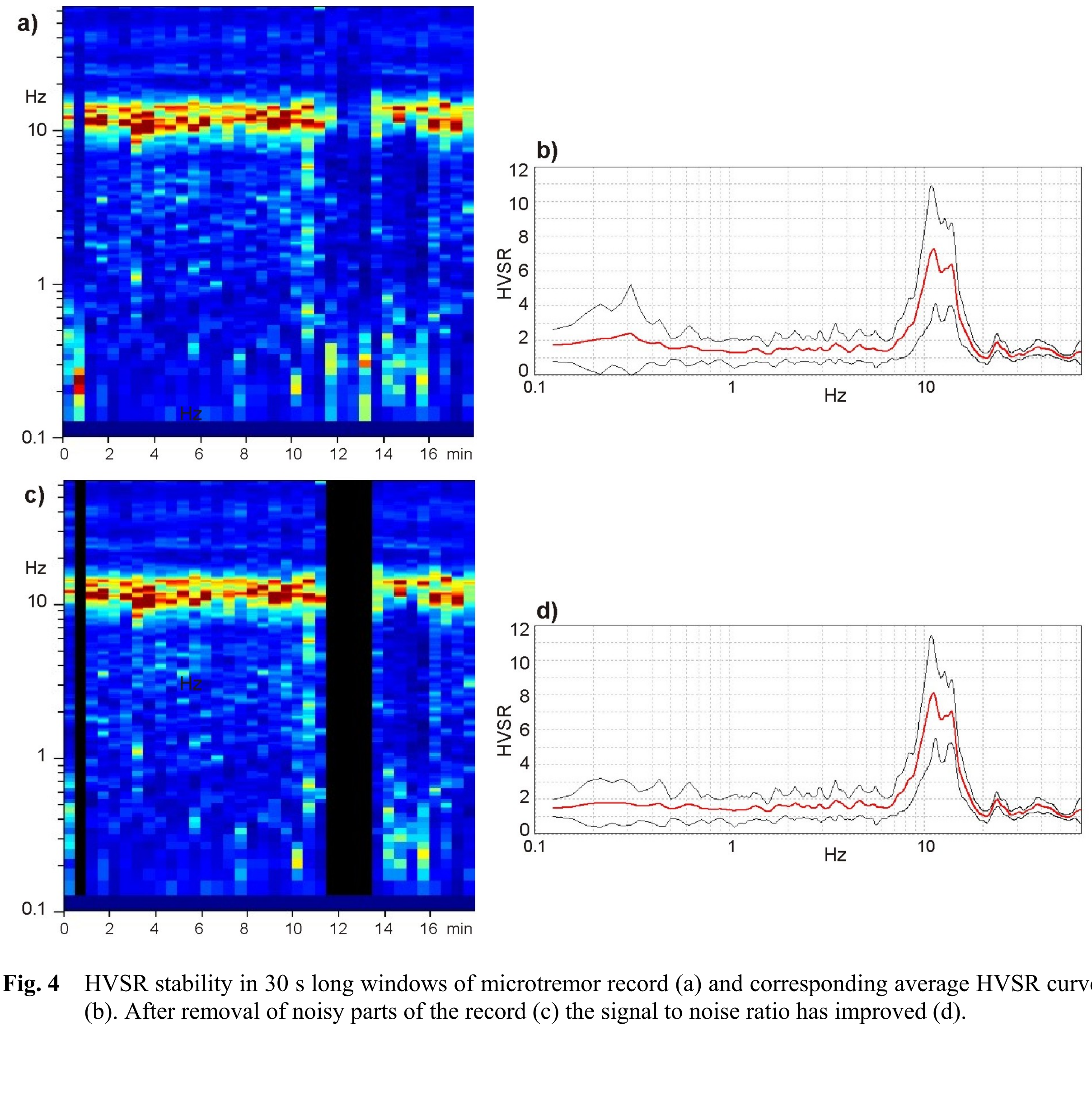

Fig. 4 HVSR stability in 30 s long windows of microtremor record (a) and corresponding average HVSR curve (b). After removal of noisy parts of the record (c) the signal to noise ratio has improved (d).

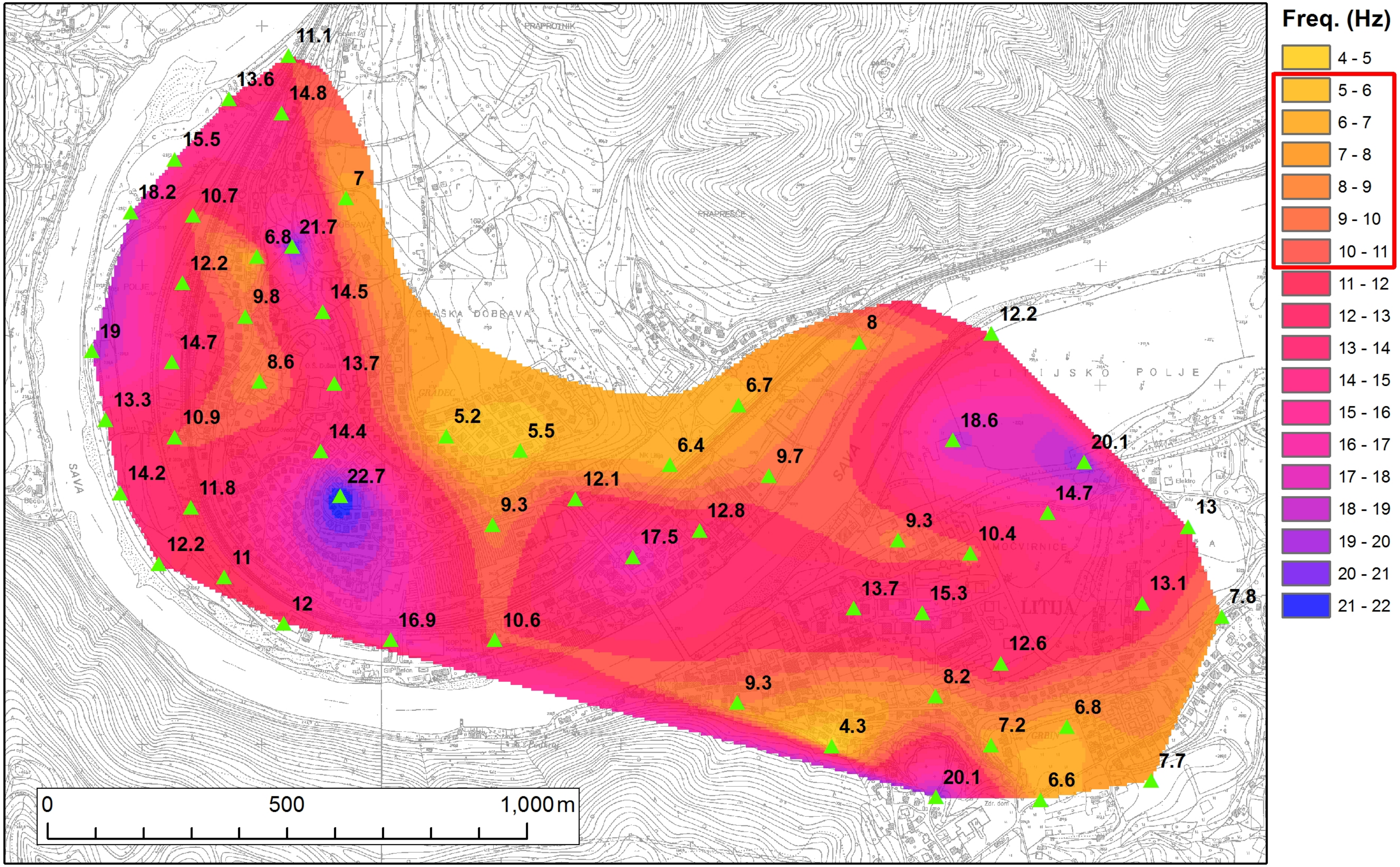

Fig. 7 Map of the sediments main resonance frequency derived from microtremor measurements in the Litija basin. Triangles indicate points of free-field measurements; labels indicate the frequency of the HVSR peaks. 37 % of the surveyed urbane area is characterized by a frequency range (red rectangle in legend) of the possible occurrence of soil-structure resonance.