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ORIGINAL RESEARCH PAPER

Mapping the thickness of sediments in the Ljubljana Moor basin (Slovenia) using microtremors

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Abstract The Ljubljana Moor basin is characterized by moderate bedrock topography and thicknesses of Quaternary lacustrine and fluvial sediments ranging from 0 to 200 m. More than 65 boreholes which reached the bedrock were drilled in the area, but their distribution in the basin is very uneven and some data from the boreholes uncertain. There are also no data on S-velocity distribution within the basin, but seismic refraction measurements pointed out a rather uniform increase of P-velocity with depth, great impedance contrast with the bedrock and relatively small lateral velocity variations. The microtremor horizontal-to-vertical spectral ratio (HVSR) method was therefore applied as a complementary tool to seismic refraction survey to map the thickness of sediments. First, microtremors were measured at the locations of boreholes which reached the bedrock and the resonance frequencies determined. The inverse power relationship between the resonance frequency and the thickness of sediments was then determined from 53 data pairs. The quality of the correlation is moderate due to possible heterogeneities in sediments and possible 3D effects in some minor areas, but the obtained parameters correspond well to the values obtained in six other European basins. Secondly, a 16 km-long discontinuous seismic refraction profile was measured across the whole basin, leaving uncovered some larger segments where active seismic measurements were not possible. Microtremors were then measured at 64 locations along the same profile, using 250 m point spacing, without leaving any gaps. The frequency–thickness relationship was used to invert resonance frequencies to depths. These were first validated using the results of the seismic refraction survey, which showed good agreement, and finally used for interpolation in the segments of missing refraction data to obtain a continuous depth profile of the

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bedrock. The study has shown that the microtremor method can be used as a complementary tool for mapping the thickness of unconsolidated sediments also in areas characterized by moderate bedrock topography. As the input data are always to some extent uncertain, it is important to have a sufficiently large number of borehole data to establish a frequency–thickness relationship, as well as some additional independent geophysical information for its validation.

Keywords Microtremors · Horizontal-to-vertical spectral ratio · Frequency–thickness relationship · Seismic refraction · Mapping sediment thickness

1 Introduction

The microtremor HVSR method (horizontal-to-vertical spectral ratio of ambient noise recordings) has in the last decade been widely used for seismic microzonation and site effect studies (e.g. Lermo and Chavez-Garcia 1994; Bard 1999) in sedimentary basins. The main condition for its successful application is a high impedance contrast between unconsolidated sediments and the rocky basement, but 3D effects and strong heterogeneities can preclude its application. The advantages of the HVSR method are estimate of the fundamental sediment resonance frequency without knowing the geological and S-velocity structure of the underground, and simple, low-cost measurements. On the other hand, if a sufficient number of boreholes drilled down to the bedrock in the study area exist or results of geophysical investigations are available, a direct relationship between resonance frequency and the thickness of sediments can be established without revealing the S-velocity to which both parameters are related. Using this relationship, the microtremor method can then be used as an exploration tool to map the thickness of sediments (e.g. Ibs-von Seht and Wohlenberg 1999).

The Ljubljana Moor basin is a young tectonic basin situated south of Ljubljana, the capital of Slovenia (Fig. 1). It is characterized by moderate bedrock topography and thicknesses of sediments ranging from 0 to 200 m. The basin is filled with unconsolidated lacustrine and fluvial Quaternary sediments composed of clay, gravel, sand, silt and chalk. The basement is built of Palaeozoic sandstones, conglomerates and shales, as well as Mesozoic carbonates. It is cut by several faults, which separate different blocks. The differential subsidence of tectonic blocks resulted in moderate bedrock topography. Data on the thickness of sediments in the basin is needed for hydrogeological and geotechnical studies, seismic microzonation and land-use planning. So far, more than 65 boreholes have been drilled in the basin down to the bedrock, but their distribution in the basin is very uneven.

To assess the capacity of the microtremor method to map the thickness of sediments in the Ljubljana Moor basin, we performed two sets of measurements. First, we measured microtremors at the locations of all boreholes with known depth to the bedrock. Based on this data set, we established the relationship between resonance frequency and the thickness of sediments. Secondly, we conducted seismic refraction measurements and microtremor measurements along a 16 km-long profile across the whole basin. Seismic refraction measurements were discontinuous in some larger segments due to obstacles in the field. The depth to the bedrock inverted from microtremor resonance frequencies using the previously established relationship was first validated using the depth determined by seismic refraction at the overlapping segments. Finally, the results of microtremor measurements were used

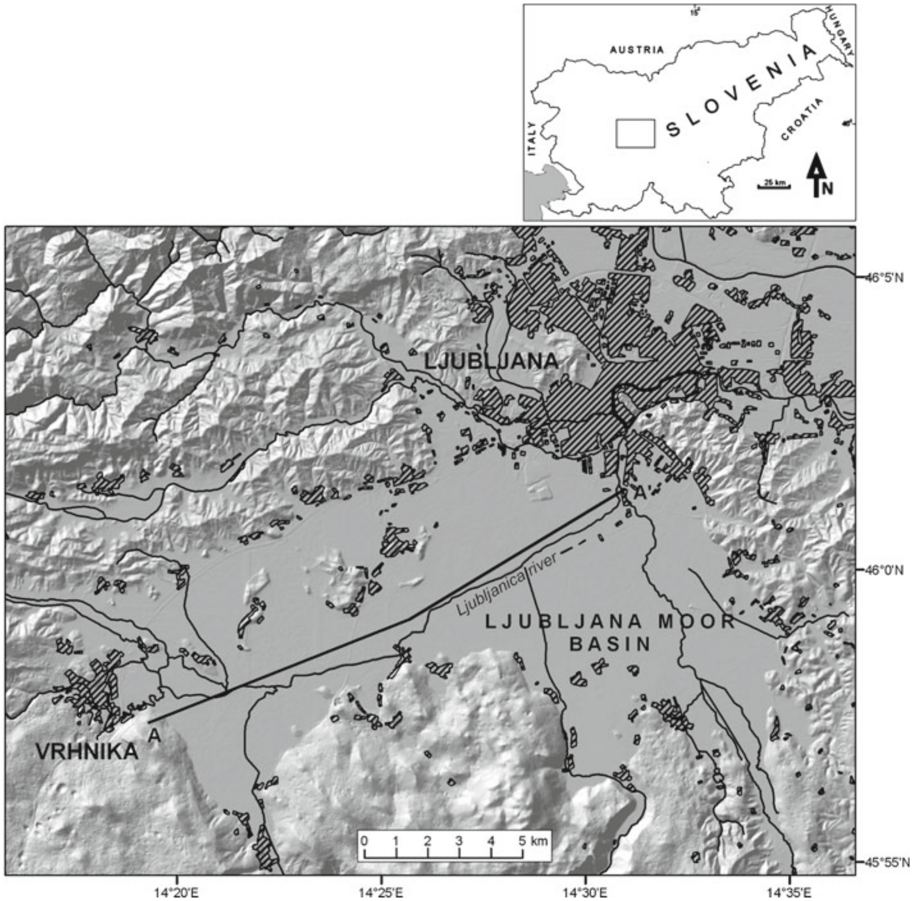

Fig. 1 Shaded relief map of the Ljubljana Moor basin with position of geophysical profile. Hatched areas represent urban areas

to interpolate the depth to the bedrock in the segments where seismic refraction data are missing.

2 Methodology

Recently, some studies (Ibs-von Seht and Wohlenberg 1999; Delgado et al. 2000a; Parolai et al. 2002; Hinzen et al. 2004; Garcia-Jerez et al. 2006; Motamed et al. 2007; D'Amico et al. 2008) have shown that resonance frequency obtained from microtremor measurements can be used to map the thickness of sediments. This method initially requires a sufficiently large number of points with known sediment thickness in the basin. These are normally borehole data, but can also be geophysical data from vertical electrical sounding or seismic refraction and reflection surveys. It is important that the depth range of input data extends over the full range of depths we intend to map later with microtremors. Microtremor measurements are first conducted at the locations of all boreholes and resonance frequencies derived from

HVSR peaks. Based on the frequency (f) – thickness (z) plot, the parameters (a, b) of the inverse power relationship

$$z = af^b \tag{1}$$

are established (Ibs-von Seht and Wohlenberg 1999) using one of the best-fitting techniques. The above equation (Eq. 1) represents a simplification of the problem, because both variables (f and z) are related to the S-velocity (Vs). Vs increases with the confining pressure, which is on the other hand proportional to the depth of the sediment burial, if there are no strong lateral variations. Average Vs is therefore related to soil thickness according to the expression (Delgado et al. 2000b)

$$\mathrm{Vs} = Az^B \tag{2}$$

By introducing this expression (Eq. 2) into the equation for a 1D model of a single layer

$$f = \mathrm{Vs}/4z \tag{3}$$

the frequency (f)–thickness (z) relationship (Eq. 1) can be derived.

Ibs-von Seht and Wohlenberg (1999) have studied both parameters (f and z) and demonstrated that it is possible to establish a direct functional relationship between them without knowing Vs. In this relationship (Eq. 1) it is assumed that the properties of sediments do not vary in the study zone. In areas where the geological characteristics of sediments are highly variable, the quality of the correlation will necessarily be low (Delgado et al. 2000a).

Although the microtremor method has been widely used in microzonation studies in the last decade (e.g. Mucciarelli and Monachesi 1998; Gallipoli et al. 2004; Panou et al. 2005; Gosar 2007), only a few studies on mapping sediment thickness using microtremors have been published in the same period. The established parameters of the f–z relationship (Eq. 1) of these studies are summarized in Table 1 and the corresponding functions shown in Fig. 2.

Ibs-von Seht and Wohlenberg (1999) studied the western part of the Lower Rhine Embayment (Germany) to the north of Aachen, which is covered with Tertiary and Quaternary sediments overlaying Palaeozoic bedrock. Data from 34 boreholes in a depth range from 15 to 1,257 m were used and the parameters $a = 96.0$ and $b = -1.388$ obtained.

Delgado et al. (2000a) and Delgado et al. (2000b) studied the shallow Segura basin (SE Spain), where the sediments consist of late Miocene-to-Pleistocene conglomerates, marls and sandstones which cover Triassic to Cretaceous carbonate rocks. At the top, coarse alluvial fan sediments were deposited during the late Pleistocene-to-Holocene. Data from 27

Table 1 Parameters of inverse power frequency– thickness relationship for seven sedimentary basins from literature and for Ljubljana Moor basin

Basin	Reference	a	Δa	b	Δb
Lower Rhine-west (Germany)	Ibs-von Seht and Wohlenberg (1999)	96.0	4.0	−1.388	0.025
Segura river (Spain)	Delgado et al. (2000a)	55.1		−1.256	0.048
Cologne (Germany)	Parolai et al. (2002)	108.0	7.0	−1.551	0.108
Lower Rhine-east (Germany)	Hinzen et al. (2004)	137.0		−1.190	
Zafarraya (Spain)	Garcia-Jerez et al. (2006)	194.6		−1.140	
Bam (Iran)	Motamed et al. (2007)	135.2		−1.979	
Florence basin (Italy)	D'Amico et al. (2008)	140.0		−1.172	
Ljubljana Moor (Slovenia)	This study	**105.5**	**18.7**	**−1.250**	**0.150**

Correspondent standard errors are shown if available

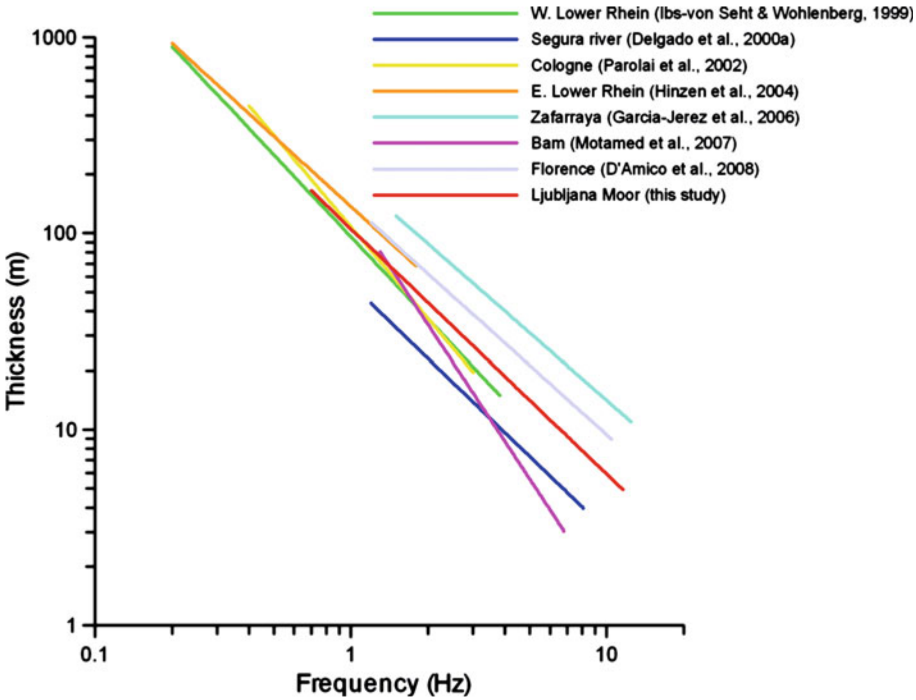

Fig. 2 Comparison of relationship between the resonance frequency and the thickness of sediments for Ljubljana Moor basin with relationships published for different sedimentary basins. Each line is shown in a depth range which was used in particular basin to derive a relationship. Relevant parameters are shown in Table 1

boreholes with a depth range from 4 to 44 m were used and the parameters $a = 55.1$ and $b = -1.256$ obtained (Delgado et al. 2000a). They found that the thickness of the sediments can be estimated with an error margin of less than 15%. Delgado et al. (2000b) derived only slightly different parameters ($a = 55.6$ and $b = -1.269$) for the same basin.

Parolai et al. (2002) studied the Cologne area (Germany), where sediments of Tertiary and Quaternary age cover Devonian bedrock. Data from 32 boreholes with a depth range from 20 to 402 m were used and the parameters $a = 108.0$ and $b = -1.551$ obtained.

Hinzen et al. (2004) studied the eastern part of the Lower Rhine Embayment (Germany) close to Cologne, where Palaeozoic bedrock is covered with Tertiary sands and clays overlaid by Pleistocene gravel. Data from 50 points derived from a geological profile with a depth range from 70 to 1,250 m were used. After microtremor measurements were performed the resonance frequencies were perturbed by adding normally distributed noise. Finally, the best fitting curve was derived with parameters $a = 137.0$ and $b = -1.190$.

D'Amico et al. (2004) studied Le Piane basin (Southern Italy) where Quaternary sediments cover carbonate and terrigeneous bedrock. Since only three of boreholes drilled in the area reached the bedrock, a seismic refraction and MASW survey were performed to derive S-wave velocity profile. Thickness of sediments was thus estimated from resonance frequency and S-wave velocity profile, but they did not present the parameters of f–z relationship.

Garcia-Jerez et al. (2006) studied the Zafarraya basin (Spain), a large karstic depression in Mesozoic carbonates covered with clay, silt, sand and conglomerates. Data from 17 geoelectrical soundings with a depth range from 11 to 125 m were used and the parameters $a = 194.6$ and $b = -1.140$ obtained.

Motamed et al. (2007) studied the Bam area (Iran), covered with shallow alluvial sediments. Data from 4 geotechnical boreholes and 25 refraction seismic investigations with a depth range from 3 to 80 m were used and the parameters $a = 135.2$ and $b = -1.979$ obtained.

Gueguen et al. (2007) studied the Grenoble Valley (France), characterized by a small apex ratio (width/thickness). The basin is filled with Quaternary sediments overlying Jurassic limestone. The maximum depth is more than 900 m. Resonance frequencies were compared to the thickness of sediments deduced from a microgravimetric survey and to the 1D theoretical assessment of site response, but they did not present the parameters of *f*–*z* relationship. They found that 2D and 3D effects can considerably disturb the resonance frequency determined with the microtremor method, especially close to the edges of this narrow basin.

D'Amico et al. (2008) studied the Florence basin (Italy) filled with Plio-Quaternary fluvio-lacustrine sediments overlaying calcareous and sandstone bedrock. Data from 23 boreholes with a depth range from 9 m to 115 m were used and the parameters $a = 140.0$ and $b = -1.172$ obtained.

Comparison of published relationships (Table 1, Fig. 2) shows similarity of the b values with the exception of the Bam case, while a is more variable. This may be an indication that the parameter b has in general lower variability, while a would actually be a characteristic parameter for each region. This was proposed already by Delgado et al. (2000a), but they compared only two quite similar basins. It should be considered also that parameter b has more influence on frequency–depth relation as there is an exponential dependency whereas the dependency for parameter a is only linear. Both case studies in the Lower Rhine Embayment (Ibs-von Seht and Wohlenberg 1999; Hinzen et al. 2004) were performed in more than 1,000 m-deep basins, and the Cologne area study (Parolai et al. 2002) in a 400 m-deep basin, while the other four studies considered very shallow, up to 125 m-deep basins. It seems the different depth range considered in these sedimentary basins has no direct influence on the two parameters. In any case, the number of surveyed basins with different geological settings is still too low for more general conclusions.

3 Geological setting

The Ljubljana Moor basin is situated in central Slovenia, south of the city of Ljubljana (Fig. 1). It is 23 km long and up to 12 km wide and occupies an area of 120 km^2. The surface of the basin is almost flat, with an average elevation of 290 m. Several hills above this flat surface represent outcroppings of the bedrock. The basin is filled with lacustrine and fluvial Quaternary sediments. The bedrock is built in the northern part of Carboniferous and Permian sandstones, conglomerates and shales, and in the central and southern part of Triassic dolomite and Jurassic limestone (Grad and Ferjančič 1974; Mencej 1989).

The tectonic subsidence of the basin in the form of tectonic graben started at the transition between Pliocene and Pleistocene. It was most intensive in the middle and upper Pleistocene, but it continues to recent times. It is related mainly to several faults striking in the NW-SE direction, while the faults striking in the NE-SW and E-W direction are less important. These faults cut the bedrock into several blocks. Differential movements of blocks have resulted in moderate bedrock topography. The depth to the bedrock ranges from 0 to 200 m and is greater in the eastern part of the basin (Premru 1982; Mencej 1989).

The deeper parts of the basin were first filled by fluvial sediments (mainly gravel and sand) deposited by streams from nearby hills. On the other hand, the Ljubljanica River as the main stream in the basin has karstic springs and therefore deposits only clay. Due to tectonic subsidence, the water outflow was later significantly reduced, and a lake was formed in the Pleistocene in which lacustrine sediments were deposited. These are composed of clay, silt and lacustrine chalk. The uppermost layers (the top 30 m) are composed of very soft Holocene clays of lacustrine and marsh origin. At the surface there used to be a layer of peat a few metres thick, but this has been mostly removed by now. The deep layers of porous gravel and sand protected from the top by impermeable clay represent an important source of fresh water for the city of Ljubljana (Mencej 1989).

There is no data on S-velocity distribution within the basin, but preliminary seismic refraction measurements pointed out a rather uniform increase of P-velocity with depth, great impedance contrast with the bedrock and relatively small lateral velocity variations. Although the Quaternary sediments are rather heterogeneous, it seems that variations of geomechanical properties and thus seismic velocities are more influenced by the depth of burial and related confining pressure than by lithological changes.

4 Relationship between thickness of sediments and resonance frequency

4.1 Borehole data

For the Ljubljana Moor basin, data for 74 boreholes which were drilled down to the pre-Quaternary bedrock were found in the archives of Geological Survey of Slovenia. The distribution of boreholes inside the basin is very uneven (Fig. 3). The majority of boreholes were drilled in the northern part within the urban area of Ljubljana. These are mainly shallow geotechnical boreholes. The density of boreholes with medium depth to the bedrock is also relatively high in the southern part of the basin. These are mainly hydrogeological boreholes. On the other hand, the number of boreholes in the central-eastern part, where the basin is the deepest, is quite low. Nine boreholes located close to the margin of the basin, where the depth to the basement is smaller than 5 m, were not considered, because it was revealed by tests that the microtremor method does not give reliable results in these areas, presumably due to the rather steep slopes of the basement. For the 65 considered boreholes, the range of depths to the basement is therefore 5 to 168 m.

The quality of the information available for each borehole is very different. In general, for a relatively small number of them the complete log of the geological column is available. For most of them only the depth to the bedrock is known, without any information on how accurate the data are. Nevertheless, we decided to keep in the database all the boreholes with a specified depth to the bedrock, but the uncertainty of the data cannot be neglected. The second problem is related to the location of each borehole with respect to the topography of the bedrock. Some boreholes might be located in areas where sediment thickness is variable—on the basement slopes, close to the slope or in depressions. One of the basic assumptions of the microtremor method—a nearly flat boundary between sediments and the bedrock—may in this case be violated and some 2D and 3D effects might take place, but they are limited to minor areas of the whole basin only. Since the topography of the bedrock is not known in details from an independent source (e.g. a geophysical survey), it was not possible to assess in advance which borehole locations were problematic. However, the bedrock topography is definitely not so extreme as, for instance, the case of narrow, deep valleys (e.g. Gueguen et al. 2007), which would preclude application of the microtremor method as a mapping tool, because the basin is relatively shallow (max. depth is 200 m) and most depressions within the basin are relatively wide compared to their depths.

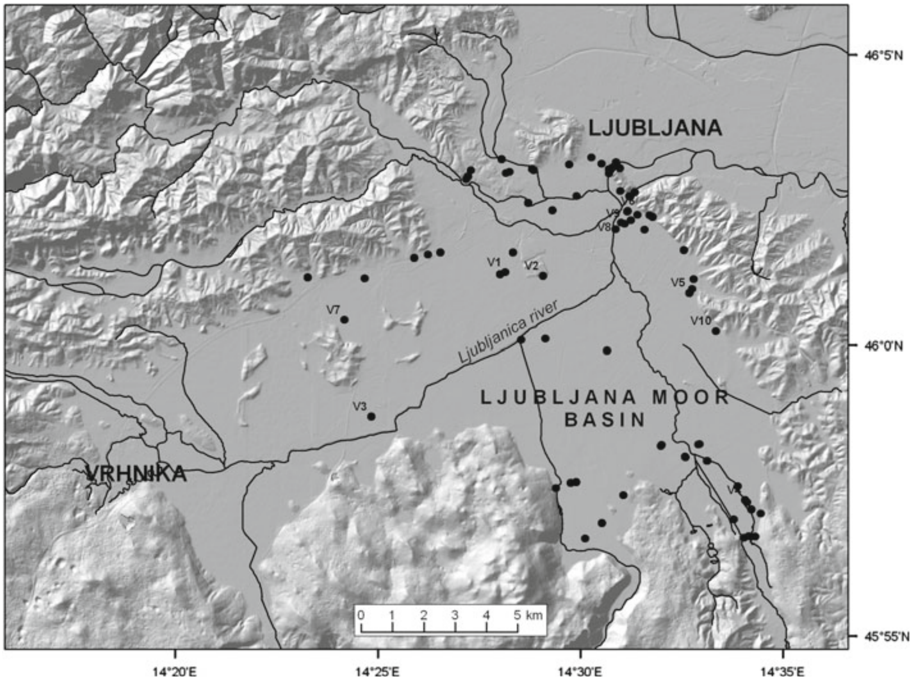

Fig. 3 Position map of boreholes in the Ljubljana Moor basin which reached the pre-Quaternary bedrock. Microtremor measurements were performed at locations of all boreholes. Labels indicate selected measurements shown in Fig. 4

4.2 Microtremor measurements

Microtremor measurements were performed in the vicinity of 65 boreholes using the portable Tromino seismograph (Micromed 2005) composed of three orthogonal electrodynamic velocity sensors, a GPS receiver, digitizer and recording unit with flash memory card. All parts are integrated in a common case to avoid the electronic and mechanical noise that can be introduced by wiring between equipment parts. The self-noise of the seismograph is in the frequency range 0.1–10 Hz much lower compared to the standard seismic noise models of the Earth (Micromed 2005). Before we started to use this type of seismograph, we performed a parallel test with a force-balanced broad-band seismometer which showed that Tromino can reliably sample the noise wavefield at least down to 0.5 Hz, which is below minimum frequency of interest in our study.

Good ground coupling of the seismograph on soft soils was obtained using long spikes mounted at the base of the instrument. The sampling frequency was 128 Hz and the recording length 20 min, which is recommended for spectral analysis at least down to 0.5 Hz (SESAME 2004). Several boreholes are located in the urban area of Ljubljana, where the traffic noise (transients) is constantly high during the daytime. Therefore, measurements were performed in this area during the night. This has considerably improved the quality of the data. On the other hand, in the rural areas it was proved that wind has the highest influence on the quality of recordings, but only close to trees. Therefore, we avoided taking measurements on windy days.

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. HVSR was computed as the geometric average of both horizontal component spectra divided by the vertical spectrum for each window. From the colour-coded plot of HVSR functions for all 40 windows, the windows including strong transient noise were identified in order to be excluded from further computation. On average 90% of all windows were used for computation. However, the effect of transient seismic noise on HVSR analysis is still debated. Parolai and Galiana-Merino (2006) have shown that transients have no or very little effect on the HVSR. At the end, the average HVSR function with a 95% confidence interval was computed.

Analysis has shown that clear HVSR peaks were obtained at 53 locations out of 65. Criteria for a clear peak defined by SESAME (2004) were used. At the remaining 12 locations the level of industrial or traffic disturbances was too high, or a near-flat response was obtained. We didn't find any systematic distribution of points with a near-flat response. Disturbances of industrial or traffic origin affected mostly the lower frequency band of the spectrum. The results of measurements (HVSR plots) at 10 selected borehole locations are shown in Fig. 4. The range of the depths to the basement for these examples is from 6 m (V10) to 168 m (V1). The amplitudes of HVSR peaks are in general high (from 4 to 20). This indicates a strong impedance contrast between sediments and the bedrock. In only a few cases is there a single sharp peak which is rather symmetrical (V6 and V9). More common is an asymmetrical peak shape (V2, V3 and V7) or a shape which includes an additional side peak, making the peak broader (V4, V5, V8 and V10). The amplitude of this side peak is usually considerably lower than the amplitude of the main peak. Its appearance is strongly dependent on the level of smoothing applied. The side peak is an indication of a more complex structure which includes not only the main impedance contrast with the bedrock, but also additional impedance boundaries within sediments. In some cases one or two additional peaks, well separated from the main peak (V1) but with considerably smaller amplitudes, were obtained.

4.3 Thickness–frequency relationship

The plot of the thickness of sediments vs. resonance frequency obtained from microtremor measurements for 53 data pairs is shown in the log-log scale in Fig. 5. The range of drilled sediment thickness was from 5 to 168 m, and the corresponding frequency range of HVSR peaks from 9.0 Hz to 0.8 Hz. The points are rather scattered and not well aligned. However, the fitting of the inverse power function in the least squares sense has given the thickness (z)–frequency (f) relationship

$$\mathrm{z} = 105.53\,\mathrm{f}^{-1.250} \tag{4}$$

which is also shown in Fig. 5. Correspondent standard errors $\Delta a = 18.7$, $\Delta b = 0.150$ and the coefficient $R^2 = 0.576$ indicates a relatively low quality of determination. There are several reasons for this:

- the quality of input borehole data is partly uncertain,
- the bedrock topography might cause in some minor areas of the basin 2D and 3D effects, and
- sedimentary fill can be heterogeneous in some parts.

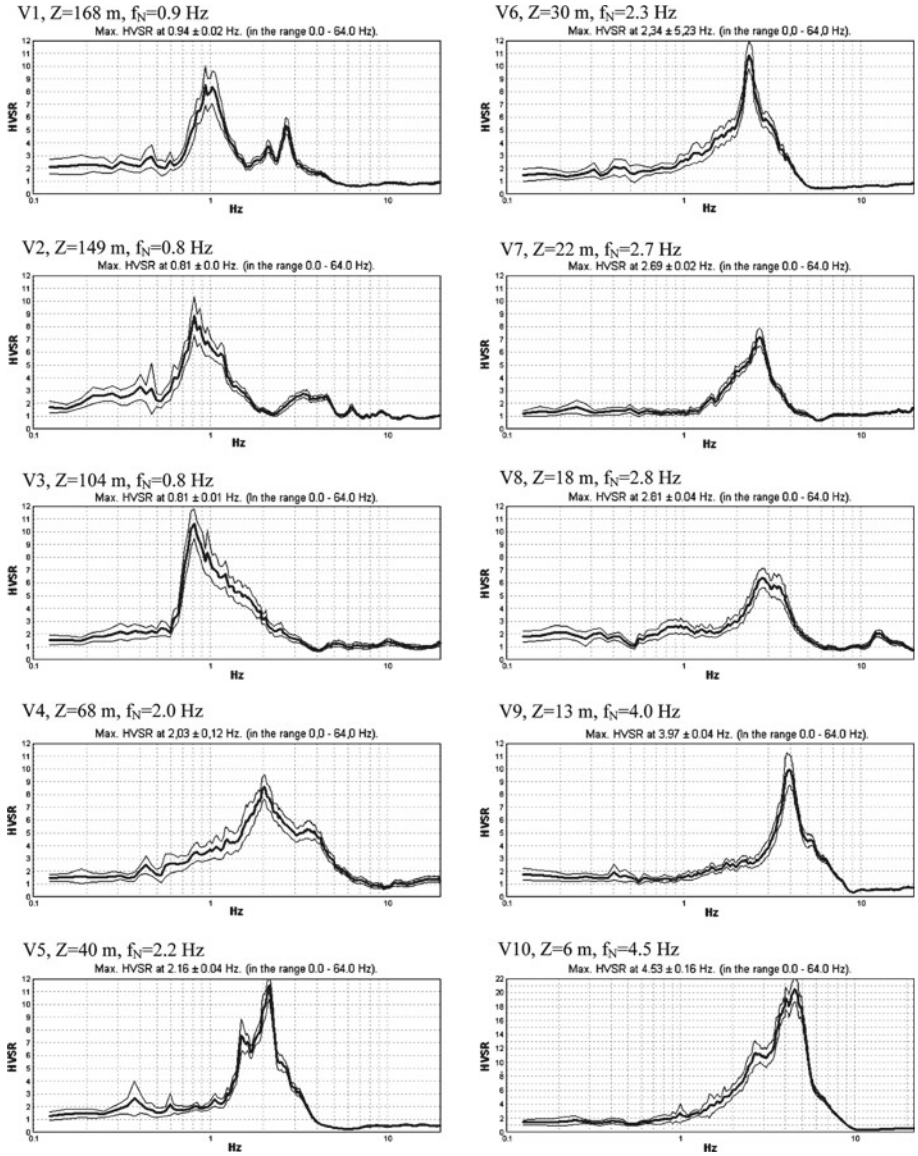

Fig. 4 Selected results (HVSR analyses) of microtremor measurements performed at borehole locations. Indicated is the thickness of Quaternary sediments. Measurement V10 has different scale due to larger amplitude of the peak

Experimental conditions (sensor–ground coupling, water saturation, weather, nearby structures, underground structures and transient noise) might also influence microtremor HVSR results to some extent. They are discussed further in conclusions.

In general, the resonance frequencies are in the deeper parts of the basin ($z > 80$ m) systematically lower than the established relationship. The examples of three boreholes in Fig. 4 (V1, V2 and V3) also show that different thicknesses of sediments ($z = 104$–168 m) are not reflected in a decrease of resonance frequency (0.8–0.9 Hz). This can be explained by the fact

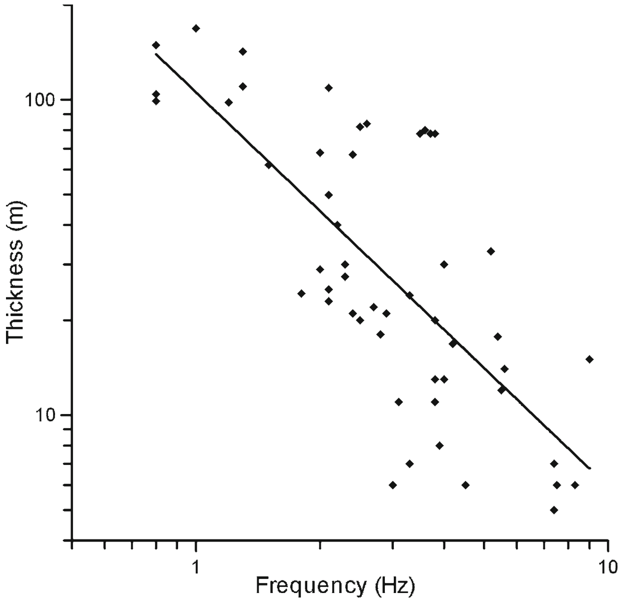

Fig. 5 Resonance frequency from microtremor measurements plotted versus thickness of sediments. The solid line is the best fit to the data points (Equation 4)

that some deeper parts of the basin are relatively wide depressions located between elevated blocks. It is therefore possible that the microtremor method does not detect the deepest part of a depression, but rather the nearby slopes. Less probable is that a shallower boundary inside heterogeneous sediments (e.g. a clay–gravel boundary) was detected, but this cannot be totally excluded. On the other hand, in the shallowest part of the basin ($z = 5$–$10\,\mathrm{m}$) the microtremor frequencies are systematically lower than the established relationship, but we did not find an explanation for this.

Comparison of the inverse power relationship for the Ljubljana Moor basin with published relationships for seven other basins (Fig. 2, Table 1) shows that parameter *b* is very similar to the values obtained in all investigated European basins (for the Bam basin [Iran], parameter *b* differs significantly). Although parameter *a* is in general more variable, its value for the Ljubljana Moor basin is very close to the average value of all other European basins. In spite of the fact that a lower quality of determination was obtained at borehole locations, the similarity of both parameters with the values published for other basins convinced us to still apply the microtremor method as a complementary tool to map the thickness of sediments. But we decided to first validate the relationship with the results of geophysical measurements.

5 Geophysical profile across the basin

A 16 km-long geophysical profile was measured in a WSW-ENE direction across the central part of the Ljubljana Moor basin (A-A′ in Fig. 1) to reveal the major structural features of the pre-Quaternary bedrock. The profile is characterized by moderate topography of the bedrock, with variations of its depth from 20 to 170 m. The investigations comprised seismic refraction and microtremor measurements.

Table 2 Layers of different P-velocity interpreted from seismic refraction investigations

Layer	P-velocity (m/s)
1	450–800
2	1050–1500
3	1500–1750
4	1800–2150
bedrock	4100–5200

5.1 Seismic refraction investigations

Seismic refraction measurements were performed along 16 layouts of 24 geophones (their location are shown in Fig. 9). In the NE part eight continuous layouts were deployed, but in the central and SW parts continuous measurements were not possible due to several obstacles, including agricultural fields, very dense vegetation and marsh areas. Therefore the gaps between individual layouts are quite big in these areas.

For data acquisition we used a 24-channel seismograph, 4.5 Hz geophones and small explosive charges as a seismic source. The spacing between geophones was 20 m. For each layout there were 5–7 shotpoints: direct and reverse at the two ends of the geophone layout, one in the middle, and at least two distant shots to determine the velocity in the bedrock.

After picking the first arrivals and plotting time-distance graphs, data were interpreted using the intercept time and generalized reciprocal methods (Palmer 1980). In the deeper part of the basin (80–170 m), five layers with different P-velocity were interpreted (Table 2), but in the NE and central part of the profile, where the depth to the bedrock is less (20–30 m), only three or four layers were revealed. Two examples of refraction seismograms with interpretation of five velocity layers are shown in Fig. 6. Within sediments the P-velocity gradually increases with depth, from the surface value of 450–800 m/s to 1,800–2,150 m/s close to the bottom of the basin (Table 2), without strong contrasts between individual layers. Lateral velocity variations inside layers are in general small. Together with the rather uniform increase of P-velocity with depth, this indicates that confining pressure related to the depth of burial has a larger influence on velocity than the heterogeneity of sediments. There is a strong velocity contrast (factor 2 or more) between sediments and the bedrock, which is characterized by P-velocity in the range 4,100–5,200 m/s. According to the geological map of the basin bedrock (Mencej 1989), only Triassic dolomite is expected along this profile, because the trust contact with Carboniferous and Permian rocks is located north of the profile location. Inside the bedrock some isolated areas of lower velocity were revealed, which are related to fractured fault zones. Most prominent faults striking in a NW-SE direction separate downthrown and elevated blocks in the NE part of the profile.

5.2 Microtremor measurements

Microtremor measurements were performed along the profile with 250 m spacing between points (Fig. 7). Altogether 64 measurements were taken using the same equipment and recording parameters as described in Sect. 4.2. The quality of the data was in some parts diminished by the very soft soil, which influenced the ground coupling of the instrument. Since some regions include marsh areas, the measurements were performed in the driest period (summer) of the year. To avoid wind as the main source of noise disturbance, all measurements were

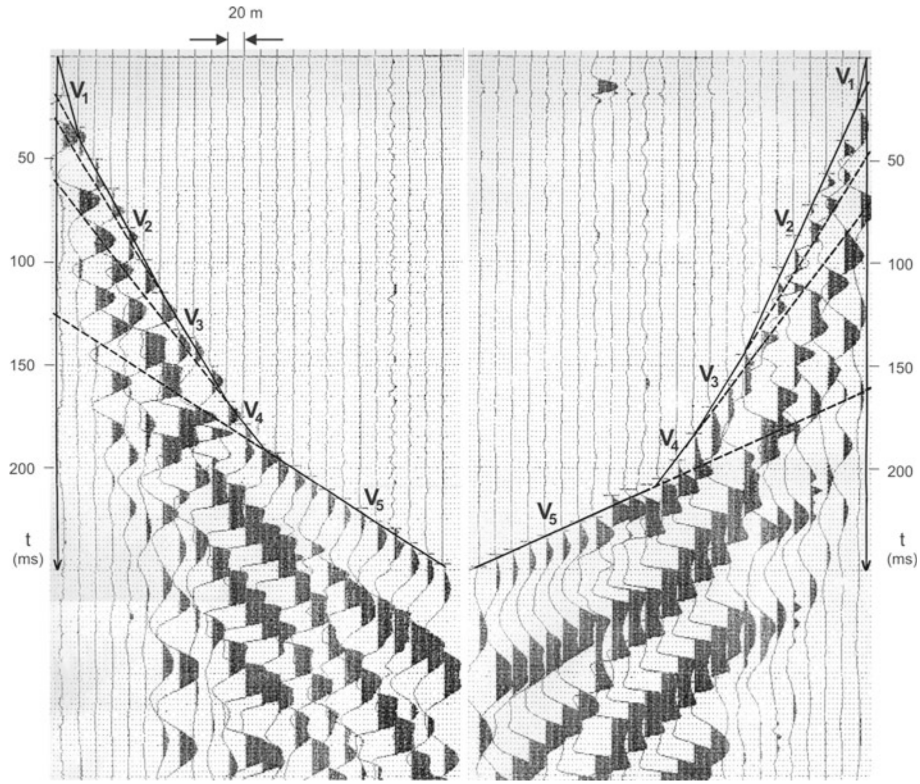

Fig. 6 Two examples of refraction seismograms with interpretation of five velocity layers

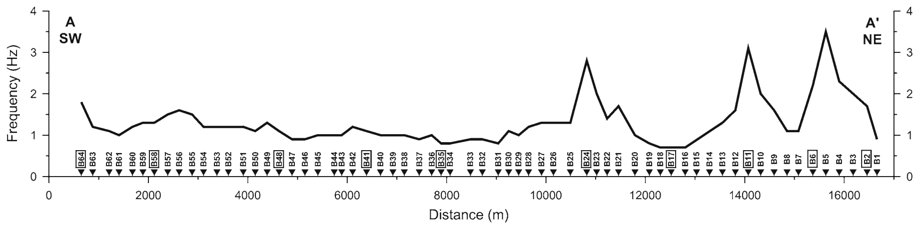

Fig. 7 Microtremor measurements along the profile A-A′ across the Ljubljana Moor basin with the plot of resonance frequency of sediments derived from HVSR analyses. The location of the profile is shown in Fig. 1. Boxed labels indicate measurements shown in Fig. 8

performed on days with little or no wind. Due to soft ground in some parts we observed high sensitivity of measurements to wind close to trees.

Measurements were analysed using the same procedure as described in Sect. 4.2. The variation of sediment resonance frequency along the profile is shown in Fig. 7, and selected results of measurements in Fig. 8. The frequency is in the largest part of the profile within the range 0.7–1.5 Hz; only in the NE part are there three peaks with frequencies between 2.7 Hz and 3.6 Hz (Fig. 7), which are related to elevated bedrock blocks. Only in few cases was a single sharp HVSR peak (B64 and B58 in Fig. 8) obtained. Most spectral ratios (B48, B41,

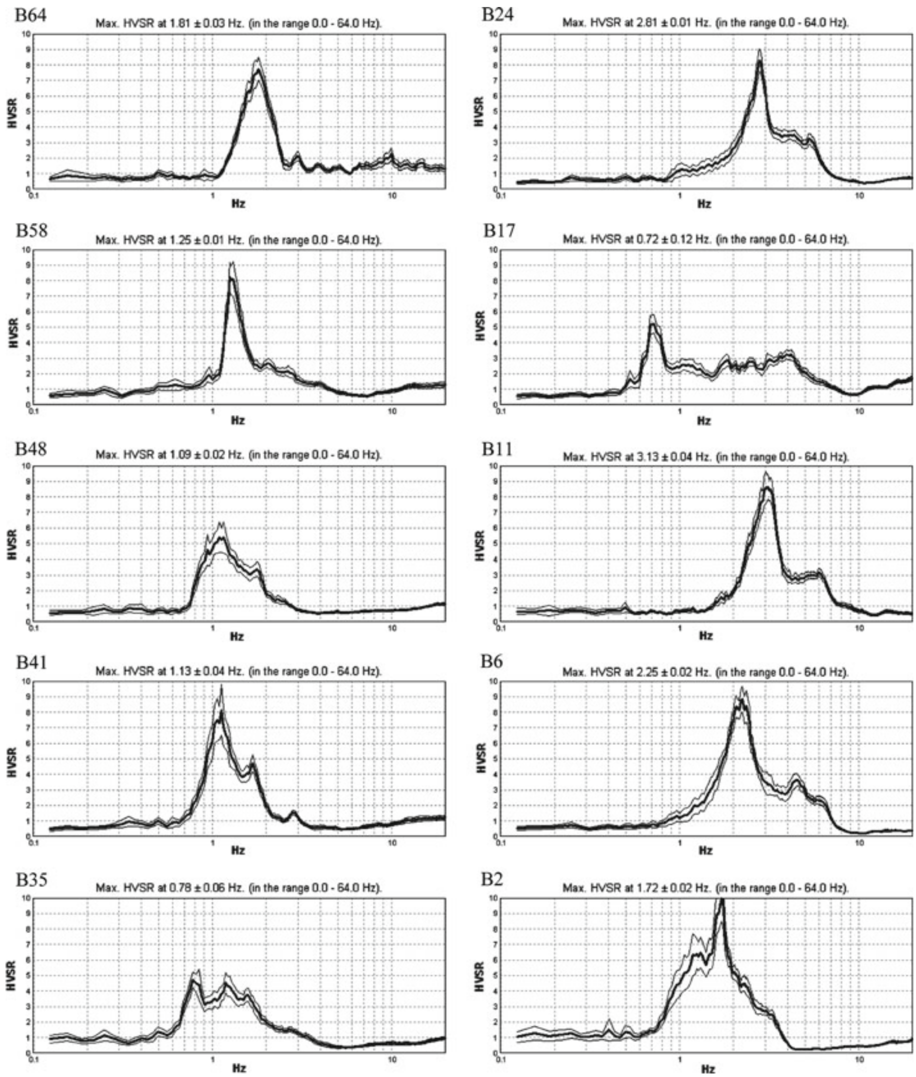

Fig. 8 Selected results (HVSR analyses) of microtremor measurements along the profile across the basin

B24, B11 and B6) have additional peaks at a higher frequency, which presumably indicate the presence of shallower velocity boundaries within the sediments (Micromed 2007). The amplitude of these side peaks is in most cases considerably lower than the amplitude of the main peak; only at point B35 are the amplitudes comparable. This confirms that impedance contrasts within sediments are much smaller compared to the contrast with the bedrock, as also follows from seismic refraction survey. In very few cases (B2 in Fig. 8) the side peak appears at a lower frequency than the main peak. Therefore, it is quite certain that at most locations the main peak corresponds to the strongest impedance contrast between sediments and the bedrock.

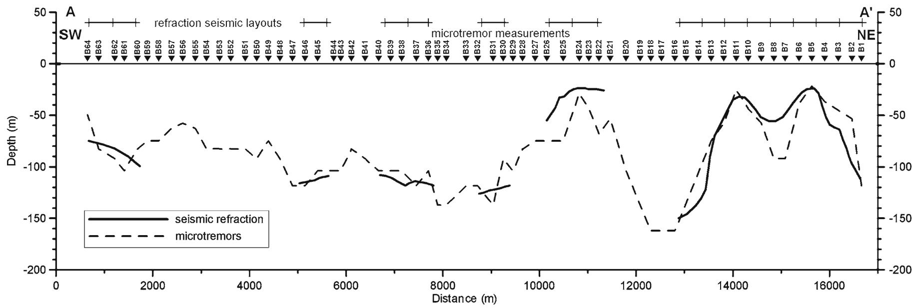

Fig. 9 Depth to the bedrock along the geophysical profile. Solid line represents results of seismic refraction survey, and dashed line results of microtremor measurements. Vertical scale is 20 times exaggerated

5.3 Bedrock depth profile

Resonance frequencies obtained from microtremor measurements along the profile were inverted to thicknesses of sediments using the derived relationship (Eq. 4). The bedrock depth profiles derived from seismic refraction survey and from microtremor measurements are shown together in Fig. 9. The vertical scale on this profile is 20 times exaggerated with respect to the horizontal scale to emphasize the bedrock topography. In sections where seismic refraction and microtremor data overlap, the correspondence of the bedrock shape and the depth obtained with both methods is very good. The discrepancy is slightly higher in the central part, but this part was surveyed with only two refraction layouts. The definition of two ridges in the eastern part with both methods is very similar, but the depth of the depression in between is different. However, the instance of a depression is also difficult for seismic refraction survey, which under such conditions tends to smooth the topography of the refractor.

Correspondence of the bedrock depth profile obtained with both methods at overlapping segments is good enough that the results of microtremor measurements can be used with confidence to interpolate the shape of the bedrock in segments of the profile where seismic refraction data are missing (Fig. 9). Some low smoothing should perhaps be applied to bedrock topography to remove spikes which result from individual measurements and obtain more realistic topography. Moreover, after validation of the frequency–thickness relationship obtained at borehole locations with the results of independent seismic refraction survey, we think that microtremors alone can be used in the wider basin area to get a reliable estimate of the bedrock topography.

6 Conclusions

The study performed in the Ljubljana Moor basin has shown that the microtremor method can be used as a complementary tool for mapping the thickness of unconsolidated sediments also in areas characterized by lithologically heterogeneous sedimentary fill, if lateral velocity variations are small, and by moderate bedrock topography, as long as the impedance contrast between sediments and bedrock is high enough. As the input data are always to some extent uncertain, it is important to have a sufficiently large number of borehole data to establish a reliable frequency–thickness relationship, and some additional independent geophysical information for its validation. The parameters of the frequency–thickness relationship established for the Ljubljana Moor basin are in good agreement with the parameters obtained in six other European basins, although the quality of the determination was lower. On the other hand, in the Ljubljana Moor basin a larger number of boreholes (53) was available to derive the relationship than in the compared basins (17–34). The lower quality of determination can be accounted to possible 3D effects in some minor areas of the basin and/or to possible heterogeneity of sediments in some parts. Additional evaluation of frequency–thickness relationship would be possible, if S-wave velocity distribution in sediments will be available. Investigations with Multichannel Analysis of Surface Waves (MASW) method (Park et al. 2007) are therefore recommended as a further step.

The results of mapping the thickness of sediments in the basin will be used in hydrogeological and geotechnical studies, for seismic microzonation and for land use planning. The large urban area of Ljubljana (45 km^2) has already been surveyed with a dense grid of microtremor measurements (200 m spacing) for microzonation purposes (Gosar et al. 2009). The map of sediment resonance frequency produced in this study can also be used in the southern part of the city, which is built on Ljubljana Moor basin sediments, to map the thickness of sediments.

There are some advantages of microtremor measurements with respect to seismic refraction and other established geophysical methods. Microtremor measurements can be easily performed in almost any environment and conditions. On the other hand, the seismic refraction method is difficult to apply in agricultural fields, marsh areas, areas of dense vegetation and in the built urban environment. If explosives are used as a seismic source, there are even further restrictions and possible danger for underground communications. The seismic refraction method is also limited in depth penetration. A target depth of 200 m, as is the case in the Ljubljana Moor basin, is at the upper limit to keep acquisition costs reasonable. For deeper targets it should be replaced with the much more expensive reflection method. On the other hand, the microtremor method can also be applied in more than 1,000 m-deep basins without increasing the cost. The method has its most serious limitation in the case of very pronounced bedrock topography (small ratio between width and depth of depressions). In this case, the 2D and 3D effects of basin geometry can not be neglected (Gueguen et al. 2007). The Ljubljana Moor basin is not in this category because it is shallow and most of the depressions within the basin are relatively wide compared to their depths. Possible influence of experimental conditions on microtremor HVSR results was extensively studied in the last years (e.g. Chatelain et al. 2008). They include sensor-ground coupling, water saturation, weather, nearby structures (trees, buildings), underground structures and transient noise (mainly traffic). For conditions in the Ljubljana Moor basin the sensor-ground coupling in case of very soft ground can be problematic. According to Chatelain et al. (2008) poor ground coupling may result in higher peak amplitude and an artificial peak at higher frequencies. The water in the top most layer of the ground can be expected in the basin and also have some influence on HVSR curves. Mucciarelli et al. (2003) and Chatelain et al. (2008) observed in this case a slight shift of the frequency peak towards smaller values. Influence of water saturation was observed also in our measurements (Gosar et al. 2009). The disturbance of HVSR from the wind is usually not related to the influence of the wind itself on the instrument (Mucciarelli et al. 2005) but to the excitation of a nearby structures or trees (Chatelain et al. 2008). This was observed also in our measurements close to trees. There is no agreement on the influence of transients on HVSR results yet (Parolai and Galiana-Merino 2006), but generally it is recommended to remove stronger transients in data processing (Chatelain et al. 2008). Underground structures were not problematic in the largest part of the Ljubljana Moor basin, but we think that some poor results in the urbane area of Ljubljana are related to them.

Although the microtremor method is today widely used in seismic microzonation studies, its application for mapping the thickness of sediments is still relatively limited, at least as far as results have been published. Results from only seven basins were found in the surveyed literature (Ibs-von Seht and Wohlenberg 1999; Delgado et al. 2000a; Parolai et al. 2002; Hinzen et al. 2004; Garcia-Jerez et al. 2006; Motamed et al. 2007; D'Amico et al. 2008). Comparison of the frequency–thickness relationship from these sedimentary basins has shown a relatively small variability of the *b* parameter, while parameter *a* seems to be more characteristic of each region. Good agreement of parameters obtained in any newly surveyed basin with those obtained in other similar basins can therefore be a valuable validation of the results. Thus, it would be important to continue with investigations to increase the number of sedimentary basins with an established frequency–thickness relationship.

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