

Preliminary seismic microzonation of Sivas city (Turkey) using microtremor and refraction microtremor (ReMi) measurements

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Abstract Sivas city, located in the inner east part of Anatolia (Turkey), is far from seismic sources. However, the city is under risk owing to strong earthquakes occurring around the area, and different soil conditions that can produce variation in the ground motion amplification. Microzonation of cities provides a basis for site-specific hazard analysis in urban settlements. In particular, seismic microzonation can be achieved by means of detailed seismic assessment of the area, including earthquake recordings and geological studies. In this paper, we propose a preliminary microzonation map for the city of Sivas, based on the variation in the dominant periods of the sediments covering the area. The periods are retrieved from microtremor measurements conducted at 114 sites, using the horizontal-to-vertical spectral ratio technique. The results of microtremor analysis were compared with those obtained from refraction microtremor measurements at two profiles crossing the studied area. According to the classification of dominant periods, Sivas area can be divided into four zones,

probably prone to different levels of seismic hazard. However, specific studies including analysis of weak earthquakes are required in the future to validate our microzonation map.

Keywords Sivas city · Microtremor · HVNSR · Microzonation · Refraction microtremor (ReMi)

1 Introduction

Sivas city is situated in inner East Anatolia (Turkey), near active tectonic areas where moderate and strong earthquakes occur (Fig. 1). Sivas has a population of more than 300,000 and is characterised by a low seismicity rate, although the city is surrounded by distant faults with high seismic activity. For the city of Sivas, no detailed studies on the vulnerability exist, but because of the recent construction of eight to ten floor buildings, the exposure seems to be high. The aim of this work was to prepare a preliminary seismic microzonation map of the city using microtremor measurements.

Analysis of microtremor measurements are a very convenient tool to estimate the effect of surface geology on ground motions in terms of resonant effects. The microtremor method measures ambient vibrations in the ground. Observation of the microtremors can be used to determine the dominant period of vibration and shake characterisation of the soil at a site. The measurements can be carried out using a single

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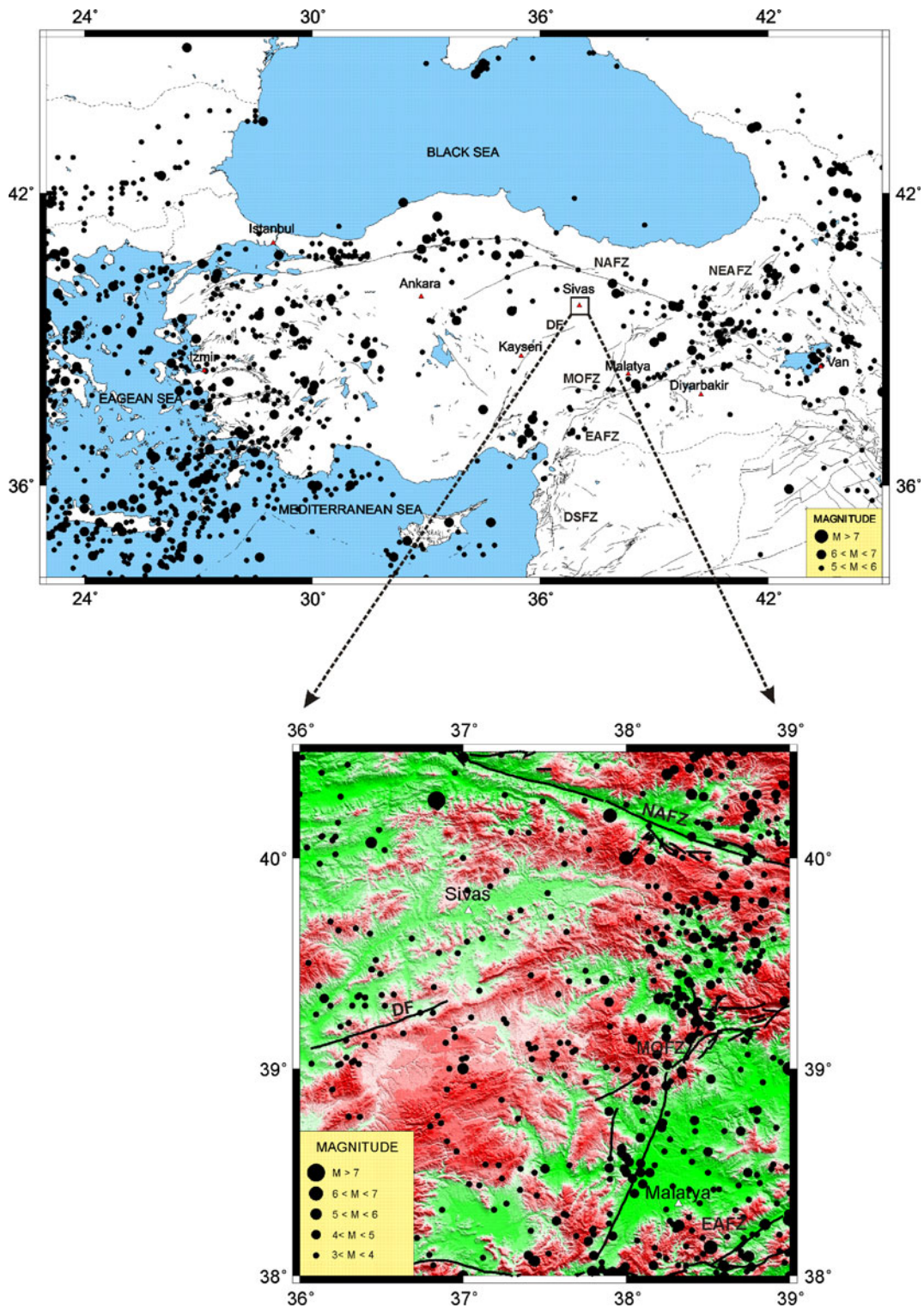


Fig. 1 Seismicity of Turkey between 1900 and 2011 for earthquakes with $M > 3$. The square shows the study area. *NAFZ* North Anatolian Fault Zone, *EAFZ* East Anatolian Fault Zone,

NEAFZ North East Anatolian Fault Zone, *MOFZ* Malatya-Ovacık Fault Zone, *DF* Deliler Fault

portable three-component seismic station, and then, routine spectral techniques such as Fourier spectrum and filtering can be easily applied to obtain estimates of the dominant frequency of vibration. The working area can then be classified according to its dominant period of ground vibration. Nakamura (1989) observed that the peak of the horizontal/vertical spectral ratio of microtremor data (HVNSR) often coincides with the S-wave transfer function between the ground surface and bedrock. The HVNSR, where H is the spectra of the horizontal component of ground motion and V is that of the vertical component, increases at the resonance frequency and thus would show a peak at that frequency. The Nakamura technique gives a reasonably good estimate of the resonance frequency and lower bound level of ground motion amplification of a site. However, it assumes site amplifications in the fundamental frequency range resulting from unconsolidated sediments below shallow subsurface crustal layers. The frequencies obtained at a higher frequency range than the fundamental one may represent the harmonics. The HVSNR technique is a very useful tool for microzonation and site response studies. The method is especially recommended in areas of low and moderate seismicity, owing to the lack of significant earthquake recordings (SESAME Project 2004).

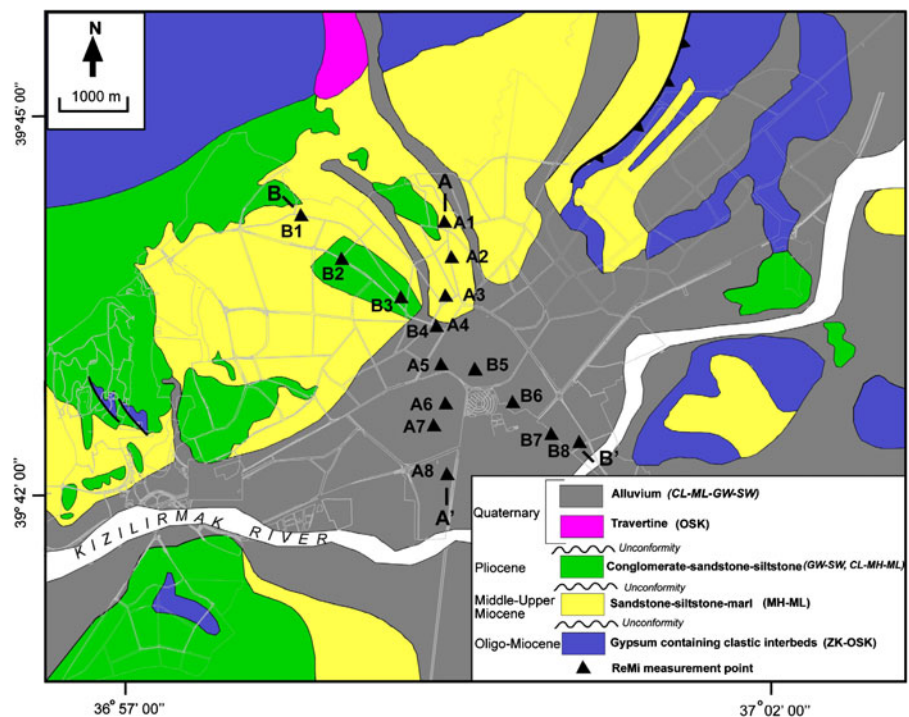
Guillier et al. (2008) reported significant influences on the H/V spectral ratios of ambient vibrations depending on the instrumentation and concluded, that all types of velocimeters are useful, but a careful choice of instruments and experimental setup are needed to obtain reliable H/V results. The microtremor H/V technique works very well on soft deposits underlain by hard bedrock or much stiffer sediments and is less efficient on stiff, thick deposits. With respect to earthquake data, the H/V method does not give a good estimation of the amplification at a site (Haghshenas et al. 2008).

Guidelines prepared by the SESAME Project team present a standard approach to estimate local site effects based on ambient noise records. However, this approach should be always combined with any available geophysical and geotechnical approaches to clarify local geological conditions (Atakan 2009).

Chatelain et al. (2008) tested different experimental conditions and suggested that unnecessary limitations, such as blocking streets to car and pedestrian traffic, be removed or that it is mandatory to perform recordings during quietest periods (night, weekends, etc.) or over the shortest possible time lag.

Some efforts were spent to propose a theoretical background, paying particularly attention to the nature

Fig. 2 Geological map of the region around Sivas (After MTA 1996). The black triangles are the REMI measurement points along the two profiles AA' and BB'



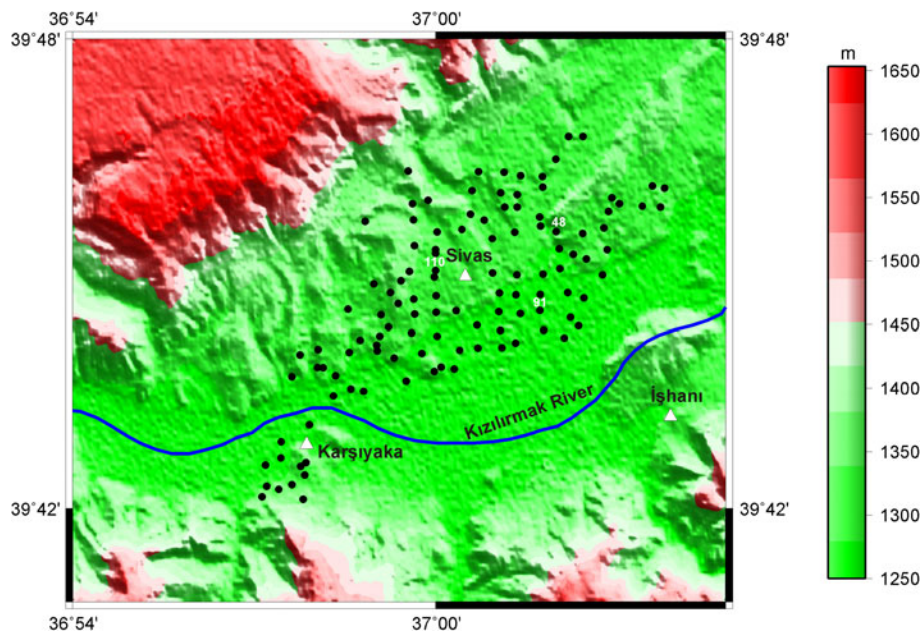
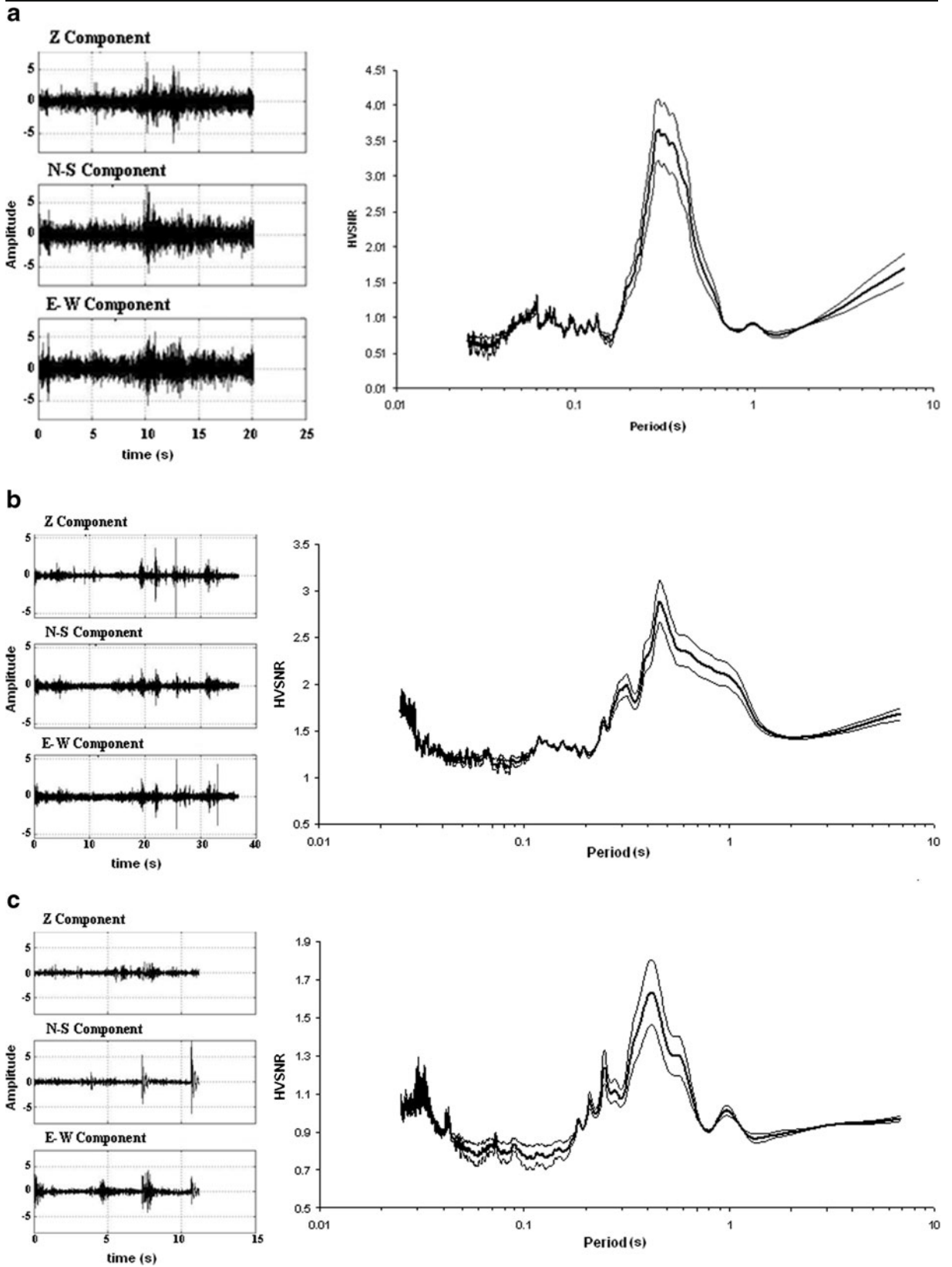


Fig. 3 Location of the microtremor measurements (*black dots*). 48, 91, 110 present locations of sample microtremor records

of microtremors (Fäh et al. 2001a; Malischewsky and Scherbaum 2004; Bonnefoy-Claudet et al. 2006). The state of art is that the Nakamura technique gives a reasonably good estimate of the resonant frequency of a site whenever the impedance contrast between the surface sediment and the underlined bedrock is high [see among others Bodin and Horton (1999) for the Mississippi Basin, Delgado et al. (2000) for the Segura River Valley (Spain), Giampiccolo et al. (2001) for Catania, Ibs-Von Seth and Wohlenberg (1999) for the Rhine Graben, Fäh et al. (2001b) for Basel and Parolai et al. (2002) for the Cologne area in Germany]. The risk is increased by the resonant period of the site and the presence of high-rise buildings, particularly susceptible to damage. Sivas is located far from important seismic sources, with sediments covering large sectors of the city and with high-rise buildings. Therefore, it has a potential hazard from distant earthquakes because of the ability of soft soils to amplify ground motion. Seismic zonation map has already been created for Turkey by the Ministry of Public Works and Settlement in 1996. After recent destructive earthquakes occurred in Turkey, such as Marmara ($M=7.4$) and Kaynasli earthquakes ($M=7.2$) in 1999, seismic microzonation of some cities started. However, at present, only a few of them are complete. For example, several studies were conducted in Istanbul after the Izmit (Kocaeli) earthquake in 1999. Ozel et al.

(2004) estimated S-wave velocity structure in the district of Avcilar–Istanbul using array microtremor measurements. A microzonation study has been conducted by Ansal et al. (2005) for Zeytinburnu, a working class suburb of Istanbul, as a part of the Zeytinburnu pilot project within the scope of the Earthquake Master Plan for Istanbul. They estimated the effects of site conditions dividing the area into cells and assigning several parameters at each cell using the available geotechnical and geological information. Finally, they produced zonation maps dividing the area into three zones with different variations for the parameters they used. Unfortunately, both the zonation proposed by the Turkish government and other studies do not cover the Sivas area, or they are not adequate to identify the earthquake hazards because of the local site effects in the city. In this paper, we propose the use of the dominant period of soils obtained through the HVNSR technique as the quantity to discriminate potential effects of local site conditions due to large distant earthquakes. The microzonation that we propose in this paper is very preliminary, and further studies such as analysis of earthquakes combined with analyses of geotechnical

Fig. 4 HVNSR of microtremors, **a** Station number: 48. **b** Station number: 91. **c** Station number: 110. The average curve (*thick line*) and the average \pm standard deviation curves (*thin lines*) are shown



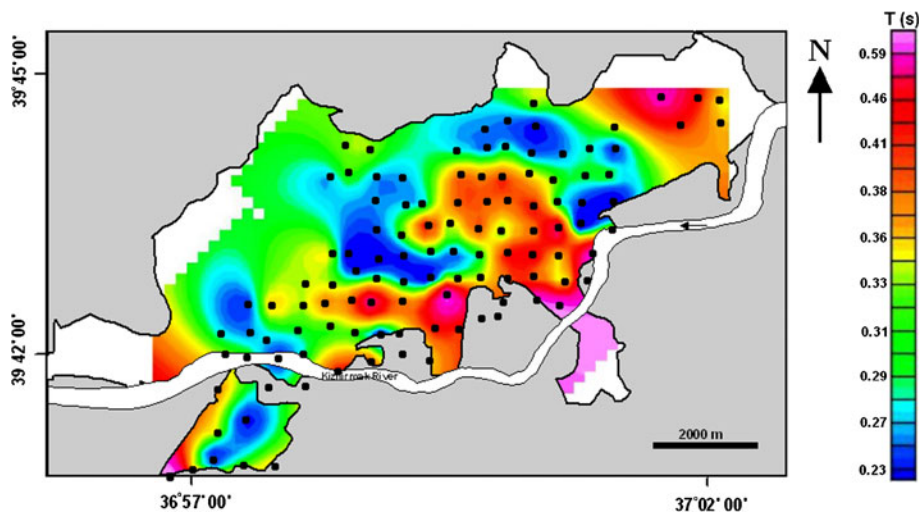


Fig. 5 Map of dominant periods obtained from HVNSR of microtremor measurements

data from boreholes are required to obtain sufficient knowledge of the area.

2 Geology and seismotectonics of the area

The major active faults associated with the North Anatolian Fault Zone (NAFZ) are located N and SE of Sivas city, at a distance between 100 and 300 km. Mainly, four seismic source zones in this region can be

identified as producing earthquakes. The NAFZ, north of Sivas, is an E–W-oriented structure (Fig. 1). In the last century, there were two destructive earthquakes originated from the NAFZ: the Niksar earthquake ($M_s=7.0$) in 1942 and the Ladik earthquake ($M_s=7.2$) in 1943. The East Anatolian Fault Zone (EAFZ) is NE–SW elongated and is located SE of Sivas. NAFZ and EAFZ cross each other at 400 km E of Sivas. The most destructive earthquakes associated to EAFZ were the 1939 Erzincan earthquake ($M_s=7.9$)

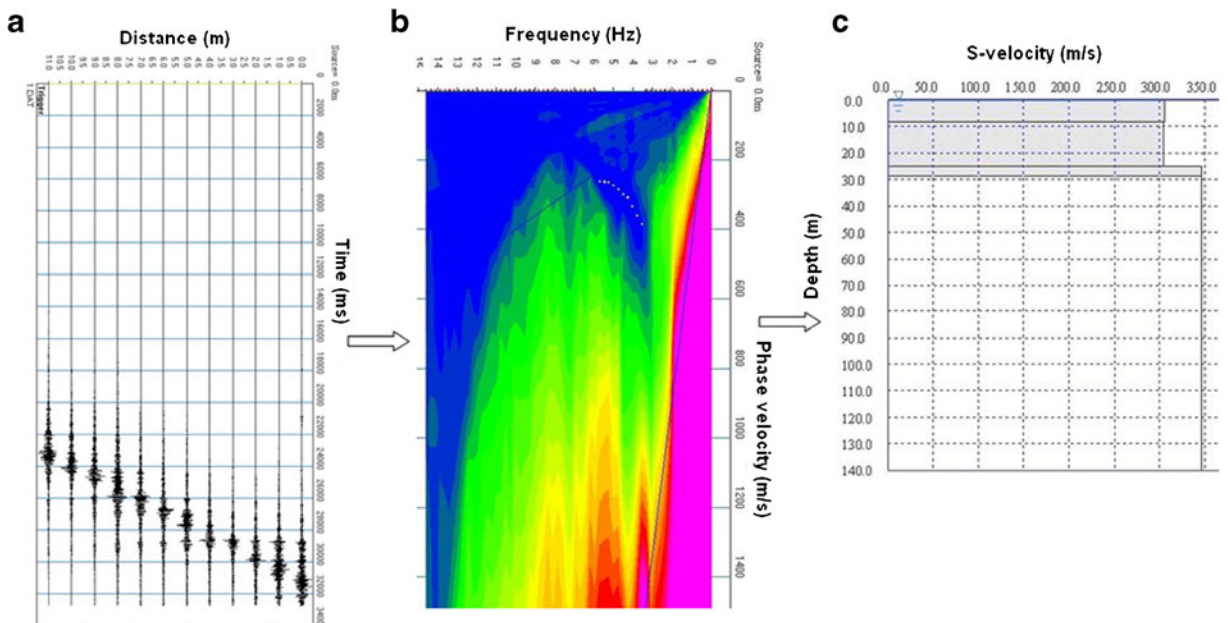


Fig. 6 Steps of ReMi processing. **a** ReMi record, **b** Rayleigh phase velocity dispersion picking, **c** Shear-wave velocity 1D modelling

and the 1992 Erzincan ($M_s=6.9$). Although there were no reports of large damage, these earthquakes caused panic in Sivas. Other important seismogenic zones are the Malatya–Ovacik Fault Zone (MOFZ), located S–SW of Sivas, and the Deliler Fault, located W–SW of Sivas, both producing earthquakes of magnitude less than $M=5.0$ (Fig. 1).

The study area is located at the northern margin of the Sivas Tertiary basin, approximately 80 km S of the NAFZ, known to be one of the main active faults of Turkey. The Sivas Basin is developed on a basement consisting of pre-Maastrichtian platform carbonates and metamorphic and ophiolitic rocks. In the Sivas basin, Maastrichtian–Palaeocene limestones unconformably overlie the basement. This unit passes upwards into Palaeocene basaltic lavas and Eocene clastic rocks. Lower Miocene clastic rocks or carbonates overlie older units with a local unconformity and pass upward into Middle Miocene playa gypsums with basaltic and continental clastic intercalation. Plio-Quaternary fluvial deposits and Quaternary alluvium, both candidates for amplification of seismic motion, unconformably overlie the Miocene rocks (Yilmaz and Yilmaz 2006) (Fig. 2). Soft sediments of Tertiary and Quaternary age that may strongly amplify seismic motion are present.

Urban area of Sivas is mainly composed of Oligocene sabkha gypsum, Lower Miocene basal conglomerate, marine limestone and continental to marine clastic rocks, Middle Miocene playa gypsum levels with clastic intercalation, Pliocene fluvial clastic deposits and Quaternary unconsolidated alluvium (Fig. 2).

3 Microtremor measurements and data analysis

Microtremor measurements were performed, following the SESAME project guidelines at 114 sites with a broadband three-component Guralp CMG-6TD sensor. The broadband seismometer has an eigenperiod of 30 s long-period corner frequency. The acquisition system consists of amplifiers, on board 24-bit A/D converter, and GPS time synchronization system. Each channel was sampled at 100 sps, and a laptop computer was used to control the system and store the data. Record duration was set to about 5 min. Measurements were repeated two times for each site to control the stability of the results. The recording site

distances ranged between 8,500 m in east direction and 4,500 m in north direction (Fig. 3).

Microtremor observations in this study were mainly carried out in parks, schools, mosques, and governmental offices during nighttime when there was no heavy traffic. Time series were generally divided in 20 s time windows (at least 10 segments) (Table 1 of SESAME H/V user guidelines 2004). We identified and removed the segments that showed transient disturbances; only the segments

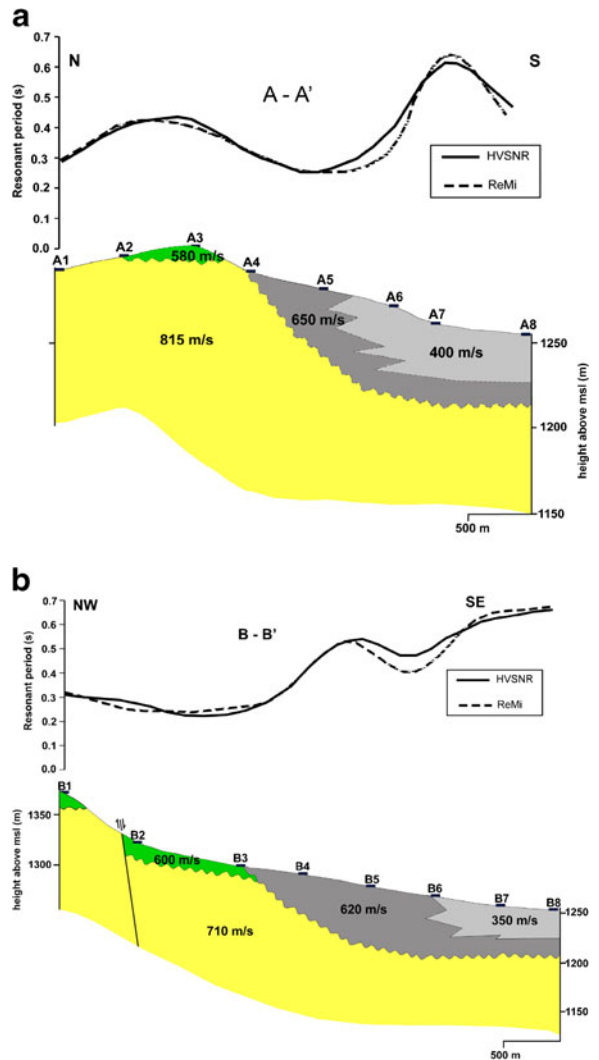


Fig. 7 Comparison of the geological reconstruction in terms of shear-wave velocity and thickness obtained with ReMi measurements with the dominant periods obtained from HVNSR and ReMi analysis. **a** A–A' profile (N–S direction), **b** B–B' profile (NW–SE direction). The heights are given respect to mean sea level (MLS) (m)

with no transient signals were maintained and processed. Whenever the number of segments did not reach 10, the length of time windows was reduced to 10 s.

The Fourier spectra were calculated for the selected segment using the FFT algorithm and then smoothed using a Parzen window. A computer program written in MATLAB by Cetinol (2003) was used to obtain the HVNSR spectra. The horizontal (NS and EW) components were merged with a geometric mean. HVNSR was obtained by dividing the mean horizontal spectrum by the vertical spectrum. Figure 4a–c shows examples of the HVNSR results for three selected sites. The dominant periods of the sites were determined from the HVNSR curves, delineated by the value of the main peak.

The variation in the dominant periods in Sivas is shown in Fig. 5. In this map, dominant periods change between 0.16 s and 0.7 s. Especially, with respect to the northern part of Sivas, the dominant periods recorded in the S and NE of the city are higher. The southern part of the town is located in a basin filled with heterogeneous alluvial Quaternary sediments in which site effects due to soft sediments are expected. The microtremor HVNSR method was therefore applied in order to assess the fundamental frequency of the sediments. The iso-dominant period map of sediments shows a distribution in a range of 0.4–0.7 s. The

observed periods can be related to the total thickness of Quaternary sediments (sand and gravel) in this part of the investigation area.

4 Refraction microtremor measurements

Refraction microtremor (ReMi) measurements were carried out at the same location of microtremor measurements to estimate the S-wave velocity profiles up to a depth of 100 m. Geometrics S-12 Smartseis 12 channel signal enhancement digital refraction seismograph capable of storing up to 24,000 samples per channel, and vertical geophones with frequency of 4.5 Hz were used to record surface wave data. At each station, the recording time was 20 s, and the measurement was repeated 20 times. Data processing was carried out using SeisImager/SW software package. Shear-wave velocity profiles were estimated along transects (A–A' and B–B', see Fig. 2) using the ReMi method. There are three steps in ReMi processing (Fig. 6a–c):

- Velocity spectral analysis
- Rayleigh phase-velocity dispersion picking
- Shear-wave velocity modelling.

The results of the dominant periods from microtremors can be correlated with the information on

Fig. 8 Distribution of HVNSR peak values overlaying the geological map of Sivas. A is the maximum value of HVNSR peaks

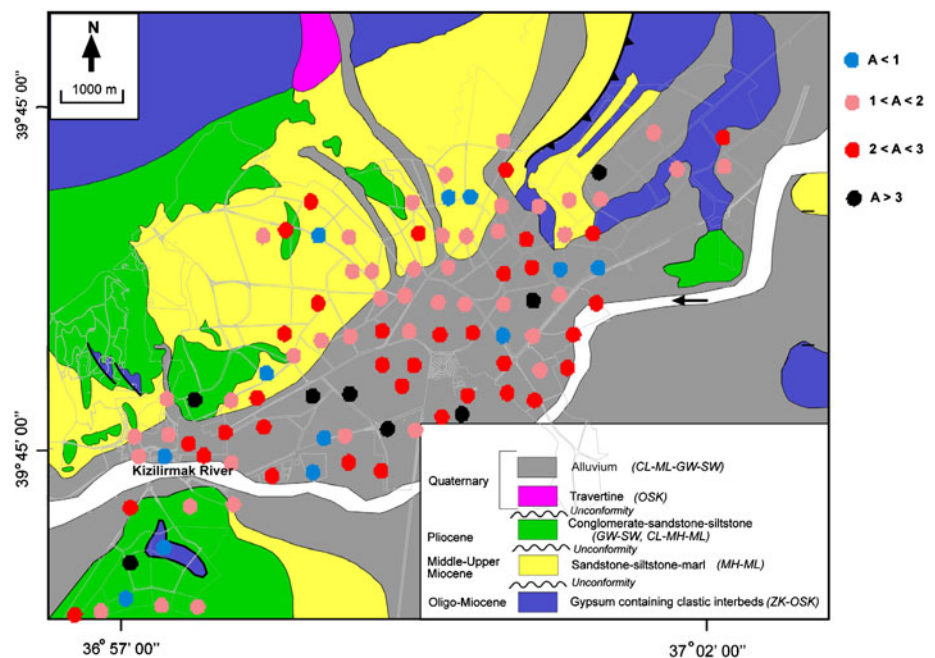
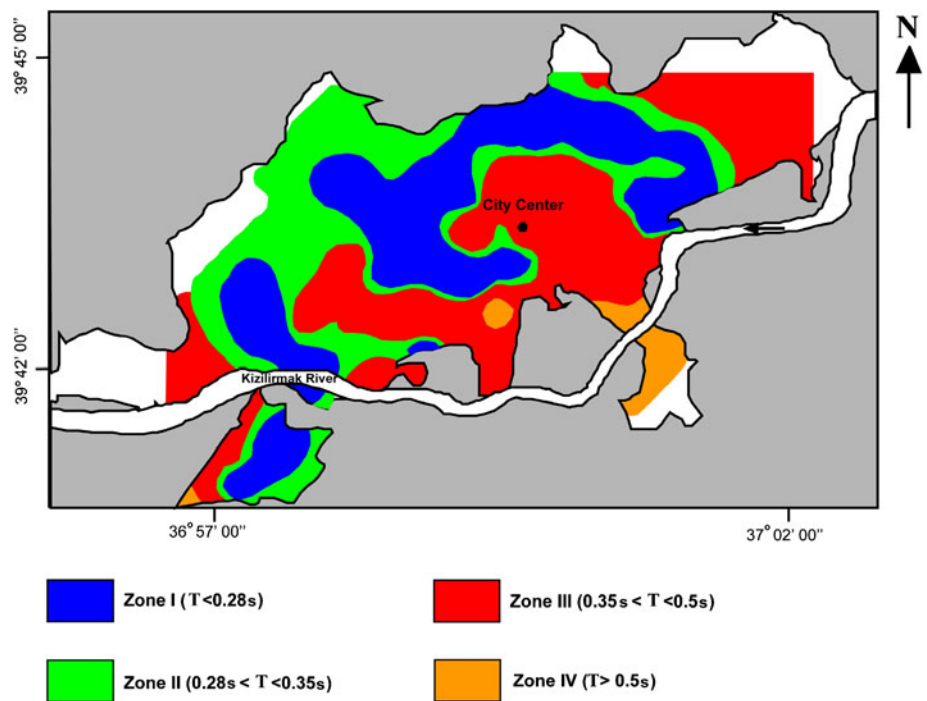


Fig. 9 Microzonation map based on the dominant period retrieved from microtremor measurements



shear-wave velocity and thickness of the sediments of the area. Joining the shear-wave profiles along A–A' and B–B' lines, we obtained two 2D-velocity sections, which can be correlated with the microtremor dominant periods found in the points adjacent to A–A' and B–B' lines (Fig. 7a, b). The comparisons explain quite well the reason for low and high periods in the study area. Rock sites have a flat HVNSR curve, while soft soil sites exhibit a peak defining their fundamental period. The boundary between rock and sediment can be clearly inferred from the change in fundamental period. The thicker the clay layer or unconsolidated soils are, the higher the dominant period is. Along the Kizilirmak River, the dominant period reaches a value of 0.7 s. With the aim to correlate dominant periods obtained from HVNSR and shear-wave velocity (V_s) and thickness of the sediments (H) retrieved from ReMi, we use Eq. (1) to estimate the resonant period from ReMi results (T_{ReMi}).

Soil classification results show that some parts of the region, especially located in the alluvial basin, have low shear-wave velocity values. These values are within the range of $350\text{--}400\text{ ms}^{-1}$ and thus fall into the D1-C according to NEHRP classification. Some parts located on the hilly and transition zone have better soil condition B and C categories with high shear wave velocities in the range of 580 and 650 m

s^{-1} , respectively. Bedrock of the region has B class with velocities in the range of $710\text{--}815\text{ ms}^{-1}$.

$$T_{REMI} = \sum \frac{4H}{V_s} \tag{1}$$

The sites located in the north and northwest parts of the city have short dominant periods (0.16–0.34 s). Close to the Kizilirmak River sediments and some older river sediments, the period ranges from 0.36 and 0.7 s. The dominant periods increase gradually towards the south of Sivas.

5 Discussion and conclusions

The purpose of this study was to develop a preliminary microzonation map for Sivas using the HVNSR technique. HVNSR gives a good estimate of the resonant frequency of a site. An appropriate ensemble of carefully selected windows of microtremors, as can be seen from the comparison with spectral ratios obtained from earthquakes and explosions, provides the estimates of the site response similar to those obtained from the HVNSR of seismic events (Zaslavsky et al. 2003). The complete database of dominant period for Sivas city includes 114 measurement points. The

period range is approximately 0.16 s–0.7 s. However, the recording interval was set to 5 min. This means that the minimum frequency is about 2 Hz (a period of 0.5 s) in the studied area. In order to investigate the lower frequency behaviour of the site, according to the presence of high-rise buildings that, in agreement with the empirical relation that connects the number of floors (8–10) at the resonance period of the building, is between 0.8 and 1 s, slightly greater than the maximum limit of 0.7 s.

The distributions of dominant periods are generally in good agreement with the surface geology. The periods increase up to 0.7 s along Kizilirmak River and decrease below 0.36 s in the north and northwest of Sivas (Fig. 5). The HVNSR amplitude distribution shows mostly low values in the north and northwestern part of the area, where a typical geological section consists of sandstone–siltstone and gypsum. At the sites with alluvial sediments, the maximum value of HVNSR peaks reaches up more than a factor of 3 along the Kizilirmak River and northeastern part of Sivas City (Fig. 8). High HVNSR values are observed in the north and northeast part of the study area, composed of sandstone–siltstone and gypsum, owing to alluvial materials belonging to ancient rivers. According to the variation in the dominant period of the ground, we propose to classify Sivas city into four zones as follows (Fig. 9):

- (a) Zone I— $T < 0.28$ s
- (b) Zone II— $0.28 \text{ s} < T < 0.35$ s,
- (c) Zone III— $0.35 \text{ s} < T < 0.50$ s,
- (d) Zone IV— $T > 0.50$ s

The distribution of the zones according to the dominant period retrieved through microtremor measurements agrees with the surface geology. The long-period ground vibration (between 0.5 and 0.7 s) happens especially in the areas near the Kizilirmak River. This could cause severe damage to the long period structures between five- and seven-story buildings in the occurrence of strong earthquakes. Hence, special attention should be given to the seismically resistant design of such structures.

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