Determining the site effects of 23 October 2011 earthquake (Van province, Turkey) on the rural areas using HVSR microtremor method

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A magnitude of 7.1 Mw earthquake struck Van city on October 23, 2011. Although, construction practices of all rural housing units are similar in the region, the earthquake caused massive damage to villages located on soft soils in northern region of the city. In this study, the effects of soil conditions on damaged housing units were determined by conducting horizontal to vertical spectral ratios of microtremor (HVSR) measurements. The level of damage in the villages that are settled on lacustrine and stream sediments has verified that the damage correlates well with comparatively high HVSR peak period and HVSR peak amplitude values in the range of 0.2–1.6 s and 4–10, respectively. The HVSR peak period and HVSR peak amplitude levels on rock units are in the range of 0.1–0.2 s and 1.5–2, respectively. It is important to note that hillside effect is found to be another key factor that increased the level of damage to the housing units in some villages.

1. Introduction

A destructive earthquake with a moment magnitude (Mw) of 7.1 occurred on October 23, 2011 at 13:41 local time, in the 20 km northern side of Van, Turkey (Kandilli Observatory and Earthquake Research Institute (KOERI), 2011). The earthquake primarily affected urban areas of Van and Erciş in Turkey, caused 644 casualties and also destroyed many buildings.

The structural damages caused by Van earthquake, have shown the importance of the quality of construction as well as the seismic wave phases, earthquake source properties and local geotechnical conditions. Seismic waves cause a variety of incidents such as liquefaction, seismic amplification, strength reduction, etc., while passing through the layers of soil. From this perspective, the effect of soil conditions on the structure under dynamic loads can be one of the key factors that will greatly affect the level of damage caused by earthquakes. Regional geology, tectonic and topographical conditions can cause varying degrees of damages in close proximity when exposed to the same seismic motions by changing the properties of the earthquake waves (Ansal 1999a, b).

HVSR microtremor technique, known as Nakamura's technique, has received great attention from all over the world with its simplicity together with quick information about dynamic characteristics

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of ground and structures. HVSR technique has been used by many other researchers (Lermo and Chavez-Garcia 1993, 1994; Lachet and Bard 1994; Field and Jacob 1995; Gitterman *et al.* 1996; Theodulidis *et al.* 1996; Bard 1998; Konno and Ohmachi 1998; Mucciarelli 1998; Zaslavsky *et al.* 2000; Fah *et al.* 2001; Dikmen and Mirzaoglu 2005; Asten 2006; Bonnefoy-Claudet *et al.* 2006; Hasancebi and Ulusay 2006; Eskişar *et al.* 2013; Asten *et al.* 2014; Akkaya 2015). Although several researchers claimed that the theoretical background of this technique is not clear, there have been many successful experimental studies performed (Nakamura 2008). In the past decade, Nakamura method is widely used for estimation of site effect under seismic waves. Lermo and Chavez-Garcia (1993, 1994) applied the HVSR method to estimate the empirical transfer function in Mexico. Their results showed that the HVSR can estimate the dominant frequency at a site based on earthquake data. Field and Jacob (1995) applied the HVSR method in Flushing Meadows, New York. The results suggested that the HVSR is an effective and reliable tool to calculate the fundamental frequency of a layered sedimentary basin. The research done by Suzuki *et al.* (1995) in Hokkaido, Japan showed that the dominant frequency obtained from HVSR was in good agreement with the predominant frequency estimated from the thickness of an alluvial layer. Dikmen and Mirzaoğlu (2005) used this method to determine seismic microzonation of Yenisehir–Bursa which is located at the northwestern part of Turkey. Ozel *et al.* (2004) estimated S-wave velocity structure in the district of Avcilar–Istanbul using array microtremor measurements. Eskişar *et al.* (2013) utilized Nakamura's method in the northern coast of İzmir Bay, Turkey. Fundamental period map obtained from H/V spectral ratio method illustrated the characteristics of weak soil conditions and the presence of bedrock level under thick alluvial soils. Their results showed that the microtremor investigations have proved to be an effective tool for assessment of local soil conditions in case of thick soft sediments in the northern coast of Izmir Bay.

The HVSR has been studied to explain its strengths and limitations by many researchers (Bonnefoy-Claudet *et al.* 2006; Bard 2008; Pilz *et al.* 2009; Lunedei and Albarello 2010). Usually, the HVSR reveals the site dominant frequency, but the amplitude of the HVSR is not well understood (Pilz *et al.* 2009). In order to overcome the limitations of Nakamura's method, SESAME (2004) published HV User's Guidelines. Therefore, HVSR analysis in this study was performed following the rules outlined in SESAME (2004).

Within the scope of this study, the effect of soil conditions on damaged buildings was determined by conducting horizontal to vertical spectral ratio of microtremor (HVSR, ambient noise) measurements in the villages affected by the Van earthquake. For this purpose, HVSR measurements with a 10–30 min data record were conducted at 80 locations in the villages of Van during the period of June–July 2013. These villages are as follows: Bardakçı, Topaktaş, Arısu, Zeve, Çitören, Çakırbey, Ermişler, Gedikbulak, Şahgeldi, Tabanlı, Dağönü, Guveçli, Göllü, Ağartı, Gülsünler, Yumrutepe, Mollakasım, Alaköy, Tevekli, Özkaynak, Hıdır, Ocaklı, Yemlice, Akçaören, Koçköy, Yalnızağaç, Kasımoğlu, Adıgüzel (figure 1). After performing the proper data-processing steps based on HVSR microtremor records taken from the villages, peak frequencies/periods and peak amplitude values (amplification) of HVSR were calculated. The results were checked with the level of damage in the buildings considering regional tectonics, geological and geophysical conditions.

2. Geology of the region

Many different types of rocks, from Paleozoic period to the current period have been found around Lake Van basin (figure 2). The basin generally consists of Oligocene–Lower Miocene aged marine sediments called Van Formation (MTA 2007). Bitlis massive metamorphic rocks are mainly observed on the surface from southern to the eastern part of the basin (Ternek 1953; Ketin 1977; Yılmaz *et al.* 1981; Göncüoğlu and Turhan 1984). Volcanoclastic deposits are found around Nemrut and Süphan volcanoes located in the western side of the region. In addition, lavas extending from Etrüsk and Tendürek volcanoes are found in the northern and northeastern parts of the region (Güner 1984; Yılmaz *et al.* 1987). Clastic ophiolitic units are derived from Yüksekova Complex and settled on Upper Cretaceous–Paleocene, while sedimentary rocks are observed in the southern and southeastern parts of the basin (Acarlar *et al.* 1991). Lacustrine sediments and fluvial deposits from Pliocene period outcrop in the eastern and northeastern parts of the basin.

The villages included in this study are generally located on Quaternary-aged terrestrial sediments composed of Van Formation (composed of Oligocene–Lower Miocene aged sandstone, conglomerate, siltstone, claystone, calcarenite rock types), Adilcevaz limestone (composed of Lower Miocene reef limestone), Aktaş Formation (composed of Middle Miocene conglomerate), Kurtdeliği Formation (composed of Upper Miocene aged Yağlık basalt, Upper Miocene aged gypsum, sandstone, conglomerate, siltstone, claystone and Miocene-aged rock formations), respectively (MTA

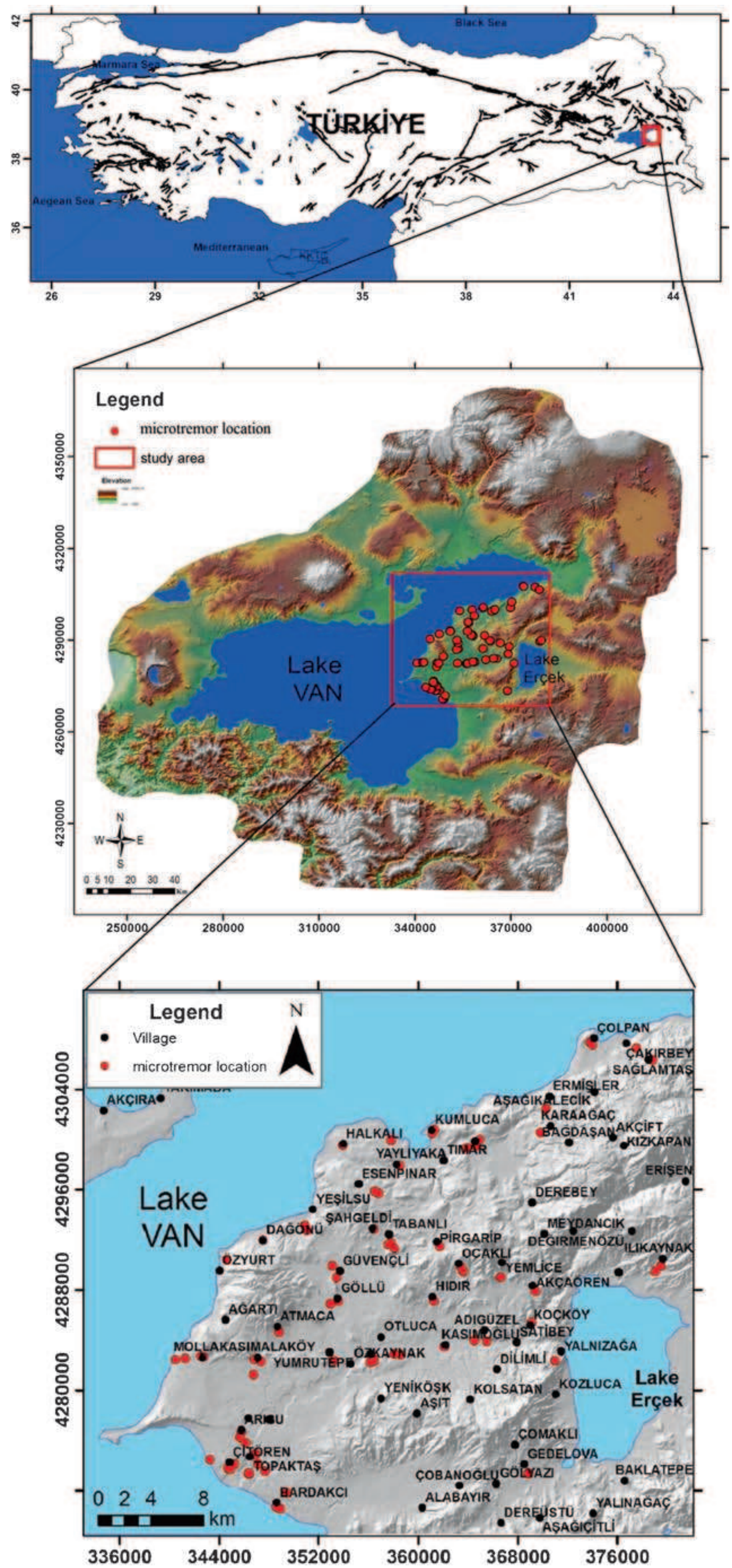

Figure 1. Location map of the study area.

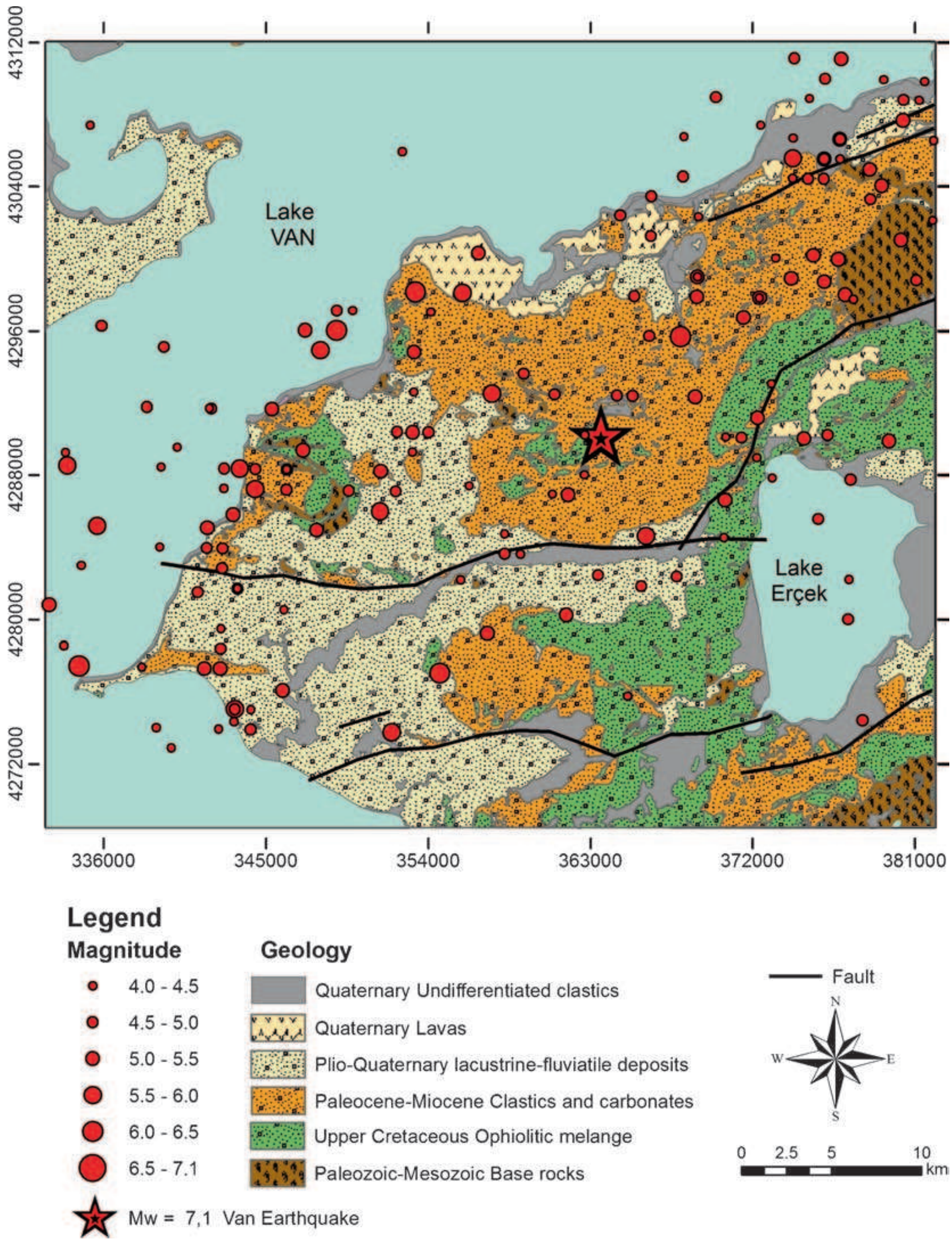

Figure 2. Geological map of the study area (modified from MTA 2008).

2007, 2008). Additionally, sedimentary and volcanic formations of Plio-Quaternary period dominated by fluvial and lacustrine environments outcrop along the villages investigated in the study. It is known that the water level of Lake Van was at its highest point 16,000 years ago; however, the water level dramatically dropped down to its current level over the last 10,000 years (Degens *et al.* 1978). As a result of this movement in the water level, alluvial fan deposits, lacustrine sediments and fluvial deposits, alluviums, current lacustrine and fluvial sediments, talus deposits have become the most common soil types in the geology of the region, which are commonly called Plio-Quaternary deposits (MTA 2007, 2008).

Some of the villages that were severely affected by the earthquake (Çitören, Arısu, Mollakasım, Alaköy, Yumrutepe, Atmaca, Göllü, Güveçli, Tabanlı, Dağönü, Şahgeldi, Yeşilsu, Ocaklı, Pirgarip, Hıdır, Aşağıgölalan, Esenpınar, Sağlamtaş, Çakırbey) were located on Oligocene–Miocene clastic rocks composed of sandstone, siltstone and conglomerate, and marl sequences. In these villages, soil is composed of stiff-to-loose talus deposits. Other severely affected villages were located in the flood plain on Karasu River (Bardakçı, Topaktaş, Özkaynak, Gülsünler, Kasımoğlu, Satıbey and Koçköy) which overlies on Quaternary alluvial deposits and terraces. Volcanic deposits are situated on Halkalı, Timar (Gedikbulak), Çolpan, Karaağaç and Yaylıkaya regions. Kumluca village is situated on volcanic deposits and coastal sediments.

3. Seismicity of the region

The study area is located in the northern side of Bitlis–Zagros suture zone that caused the neotectonic period of eastern Anatolia region. Bitlis–Zagros suture zone was developed as a result of Arabian–Eurasian collision. Bitlis ocean's closure produced Çüngüş Basin by the Late Miocene Period (Şengör and Kidd 1979; Koçyiğit *et al.* 2001). Eastern Anatolia region had new

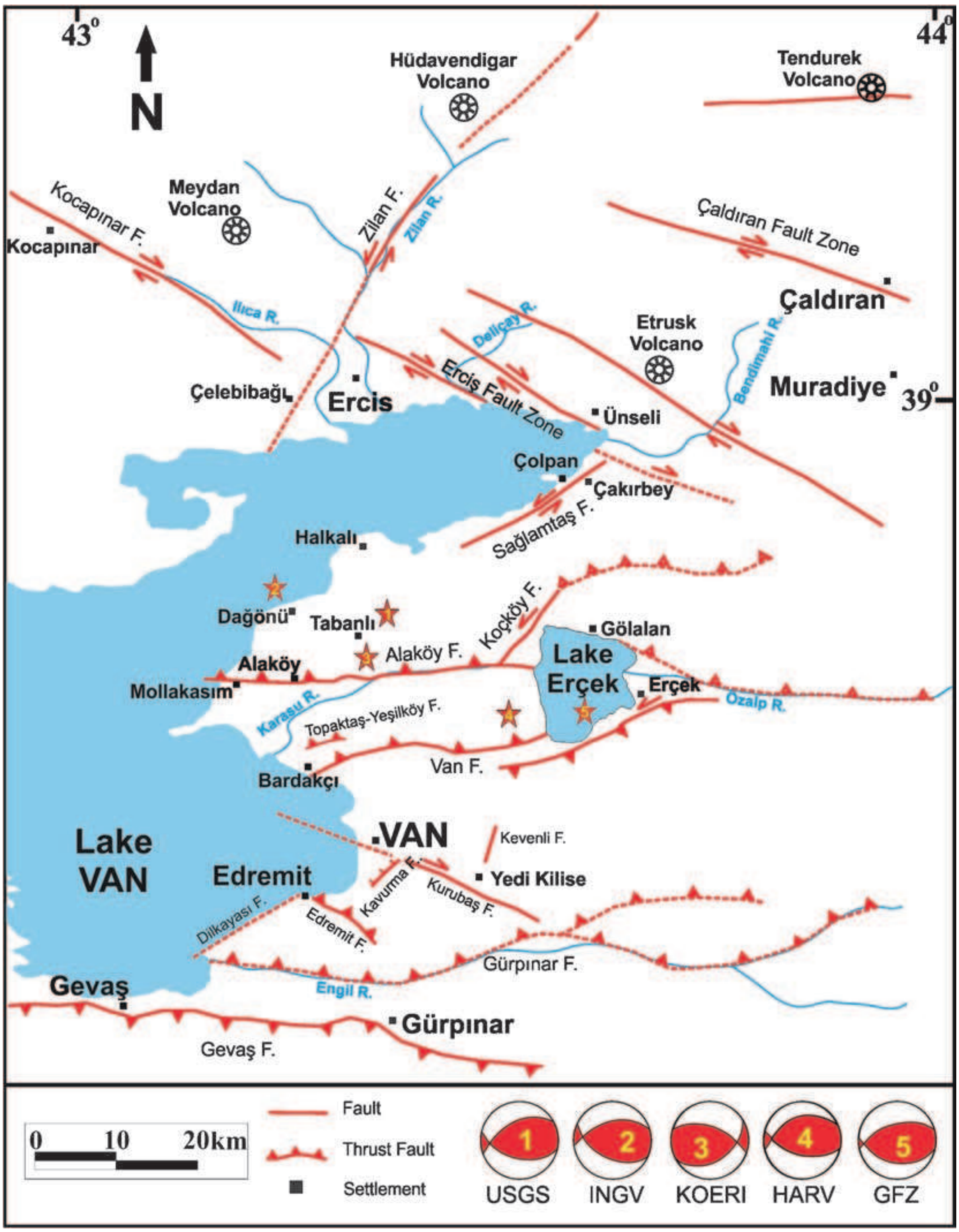

Figure 3. Major active faults in eastern part of Lake Van and epicenter of the main shock that occurred on October 23, 2011. Beachballs are showing focal mechanism solutions of different institutions. TF: thrust fault, RL: right-lateral strike slip fault, LL: left-lateral strike slip fault, NF: normal fault. Ruptured faults of 23 October 2011 are Van and Topaktaş faults (modified from Poyraz *et al.* 2011).

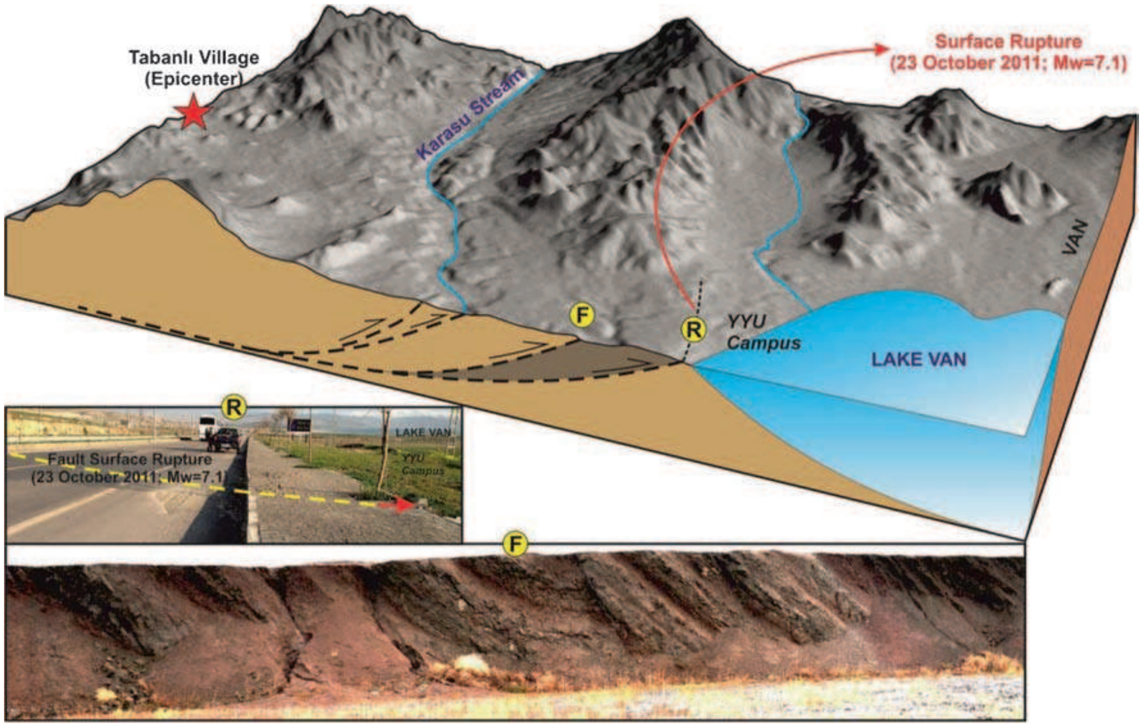

Figure 4. Block diagram showing main thrust zones in the region and ruptured faults after Van earthquake (R: surface rupture, F: Van Thrust Fault).

morphological characteristics followed by this collision (Şaroğlu and Güner 1981).

Fault plane solutions, which were obtained by various institutions, display that the earthquake is activated by thrust fault mechanism (figure 3). According to the Disaster and Emergency Management Presidency of Turkey (AFAD), approximately 12,000 aftershocks between the magnitude values of 2.0 and 5.0 were recorded in this region (AFAD 2011).

Lake Van and its surrounding area comprise seismically-active fault systems (strike-slip fault, normal fault and reverse fault) with diverse magnitudes and properties (Aksoy and Tatar 1990; Koçyiğit *et al.* 2001; Akkaya and Köse 2002; Çiftci *et al.* 2004; Özvan *et al.* 2005). These fault systems are as follows: Çaldıran fault zone, Erciş fault zone, Süphan fault zone, Muş fault zone, Güzelsu fault zone, Başkale fault zone, Van fault zone, Özalp fault zone, Gevaş fault zone and other individual faults (Bulanık fault, Malazgirt fault, Kuşcu fault, Çakırbey fault, Alabayır fault, Erçek fault, etc.) (Koçyiğit *et al.* 2001). Özalp and Gevaş fault zones are in the form of E–W trending reverse fault; whereas Çaldıran and Erciş faults are in the form of NW–SE trending right lateral strike-slip fault zones; whereas Süphan and Başkale fault zones are in the form of NE-trending left lateral strike-slip fault zones, respectively (Koçyiğit *et al.* 2001) (figure 3). Van earthquake that occurred on October 23, 2011 was recorded to be the most destructive earthquake resulting from the movement of reverse faults in Turkey (Koçyiğit *et al.* 2011). Earthquake-induced surface fault rupture and block diagram can be seen in figure 4. Especially after 2000, the region had relatively higher seismic activities.

The earthquake happened in Van on October 23, 2011 which was recorded by 22 different accelerometer stations, were located on different types of soils, of the National Strong Ground Motion Observation Network of Prime Ministry Disaster and Emergency Management Presidency (AFAD) in Turkey. According to the nearest station (Muradiye) located 42 km away from the epicenter of this earthquake, the peak ground acceleration values are recorded as 178.5 cm/s^2 in the north–south direction, 168.5 cm/s^2 in the east–west direction and 75.5 cm/s^2 in the vertical direction, respectively (AFAD 2011).

4. Microtremor measurements and data analysis

One of the most important problems in the studies aiming to identify earthquake-induced damages depending on soil condition is determining the dynamic properties of soil layers. The statistical studies related to earthquake damages in these regions, where equal seismic intensities were observed, show different levels of earthquake damages in almost identical structures. HVSR technique, known as Nakamura's technique, which was introduced by Nakamura (1989), is used for determining HVSR peak frequencies or periods and HVSR peak amplitude values (amplification) based on recording the ambient seismic noise (generally in the range 0.1–1 micron) and microtremor (between 0.005 and 2 s) (Kanai and Tanaka 1954, 1961). HVSR method is based on the spectral ratio of the horizontal *vs.* vertical components of microtremors observed at the same site. After Nakamura (1989), this technique was tested

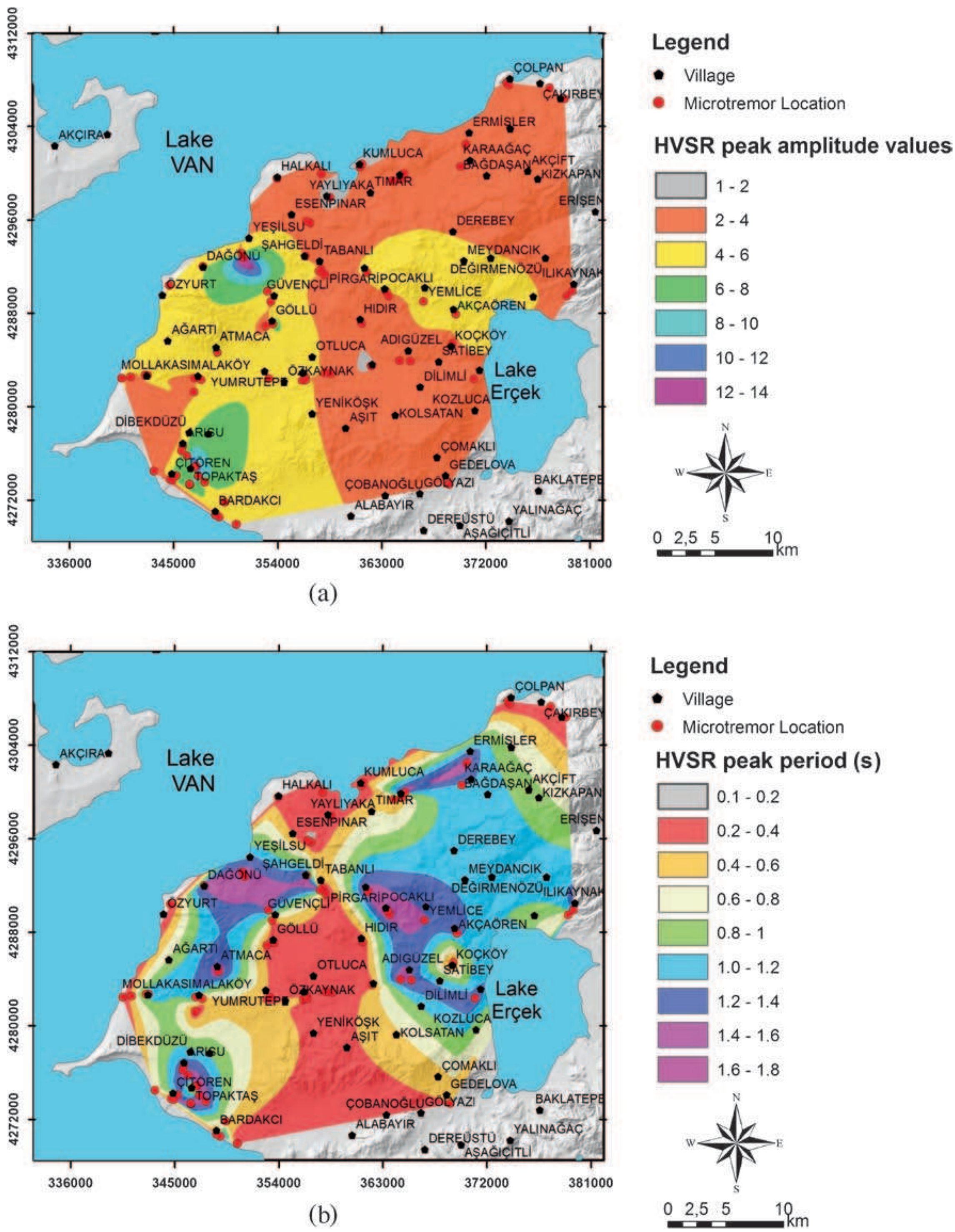

Figure 5. HVSR measurements obtained from the records of HVSR peak amplitude values **(a)** and HVSR peak period values **(b)**.

Table 1. *Comparison of HVSR peak values, local soil conditions and final damage assessment results of Governorship of Van.*

Village name	HVSR peak period	HVSR peak frequencies	HVSR peak amplitude	Soil type	Damage type	Damage (%)				
						No damage	Minor	Moderate	Heavy	Collapse
Adıgüzel	1.40	0.71	3.94	Plio-Quaternary sediments	Moderate	4	17	79	0	0
Alaköy	1.12	0.89	5.46	Plio-Quaternary sediments	Heavy	2	13	0	28	57
Akçaören	1.28	0.78	4.13	Ophiolitic melange	Minor	8	38	28	23	3
Arısu	1.33	0.75	5.28	Alluvium	Heavy	6	16	4	74	0
Atmaca	1.56	0.64	4.30	Plio-Quaternary sediments	Moderate	7	40	1	52	0
Bardakçı	0.54	1.84	4.60	Plio-Quaternary sediments	Moderate	8	38	0	46	8
Çakırbey	0.20	4.91	2.84	Alluvium-clastic rocks	Moderate	7	19	0	74	0
Çitören	1.58	0.63	4.87	Plio-Quaternary sediments	Heavy	2	2	1	80	15
Çolpan	0.21	4.70	2.13	Alluvium-volcanic unit	Minor	23	37	30	10	0
Dağönü	1.49	0.67	6.57	Alluvium	Heavy	0	0	0	100	0
Ermişler	1.15	0.87	3.14	Clastic rocks	Moderate	2	28	18	37	15
Esenpınar	0.17	5.87	2.22	Alluvium-volcanic unit	Moderate	9	24	55	12	0
Göllü	0.32	3.09	6.85	Plio-Quaternary sediments	Heavy	0	11	0	69	20
Güveçli	1.28	0.78	6.88	Plio-Quaternary sediments	Heavy	0	0	0	100	0
Halkalı	0.29	3.34	2.95	Alluvium-volcanic unit	Heavy	0	10	1	37	52
Hıdır	1.51	0.66	2.73	Clastic rocks	Moderate	5	41	0	54	0
Ilıkaynak	1.36	0.73	3.49	Alluvium-ophiolitic melange	Moderate	0	35	0	60	5
Kumluca	0.19	5.11	2.04	Alluvium-volcanic unit	Heavy	0	1	4	95	0
Koçköy	0.42	2.38	2.03	Ophiolitic melange	Minor	78	5	0	17	0
Mollakasım	1.28	0.78	4.69	Alluvium	Heavy	8	7	0	85	0
Ocaklı	1.75	0.57	4.20	Clastic rocks	Moderate	21	18	0	61	0
Özkaynak	0.19	5.15	4.25	Plio-Quaternary sediments	Heavy	0	19	0	81	0
Özyurt	0.17	5.85	5.66	Alluvium	Heavy	1	0	4	95	0
Tabanlı	0.15	6.35	2.08	Clastic rocks	Moderate	0	9	77	14	0
Timar	0.30	3.28	4.96	Alluvium-volcanic unit	Heavy	2	3	1	94	0
Topaktaş	1.47	0.68	8.98	Alluvium-clastic rocks	Heavy	0	2	1	97	0
Yaylıyaka	0.25	3.90	1.94	Alluvium-volcanic unit	Moderate	0	3	27	70	0
Yemlice	1.42	0.70	4.69	Clastic rocks	Heavy	1	1	0	64	34
Yeşilsu	1.16	0.86	4.79	Alluvium-clastic rocks	Moderate	0	23	10	48	19
Yumrutepe	0.33	3.03	5.64	Plio-Quaternary sediments	Heavy	3	5	2	68	22

experimentally and theoretically at many sites by different researchers (Lermo and Chavez-Garcia 1993, 1994; Lachet and Bard 1994; Field and Jacob 1995; Gitterman *et al.* 1996; Theodulidis *et al.* 1996; Mucciarelli 1998; Konno and Ohmachi 1998; Zaslavsky *et al.* 2000; Fah *et al.* 2001; Dikmen and Mirzaoğlu 2005; Asten 2006; Bonnefoy-Claudet *et al.* 2006; Hasancebi and Ulusay 2006; Eskişar *et al.* 2013; Asten *et al.* 2014; Akkaya 2015). According to these studies, the HVSR method can

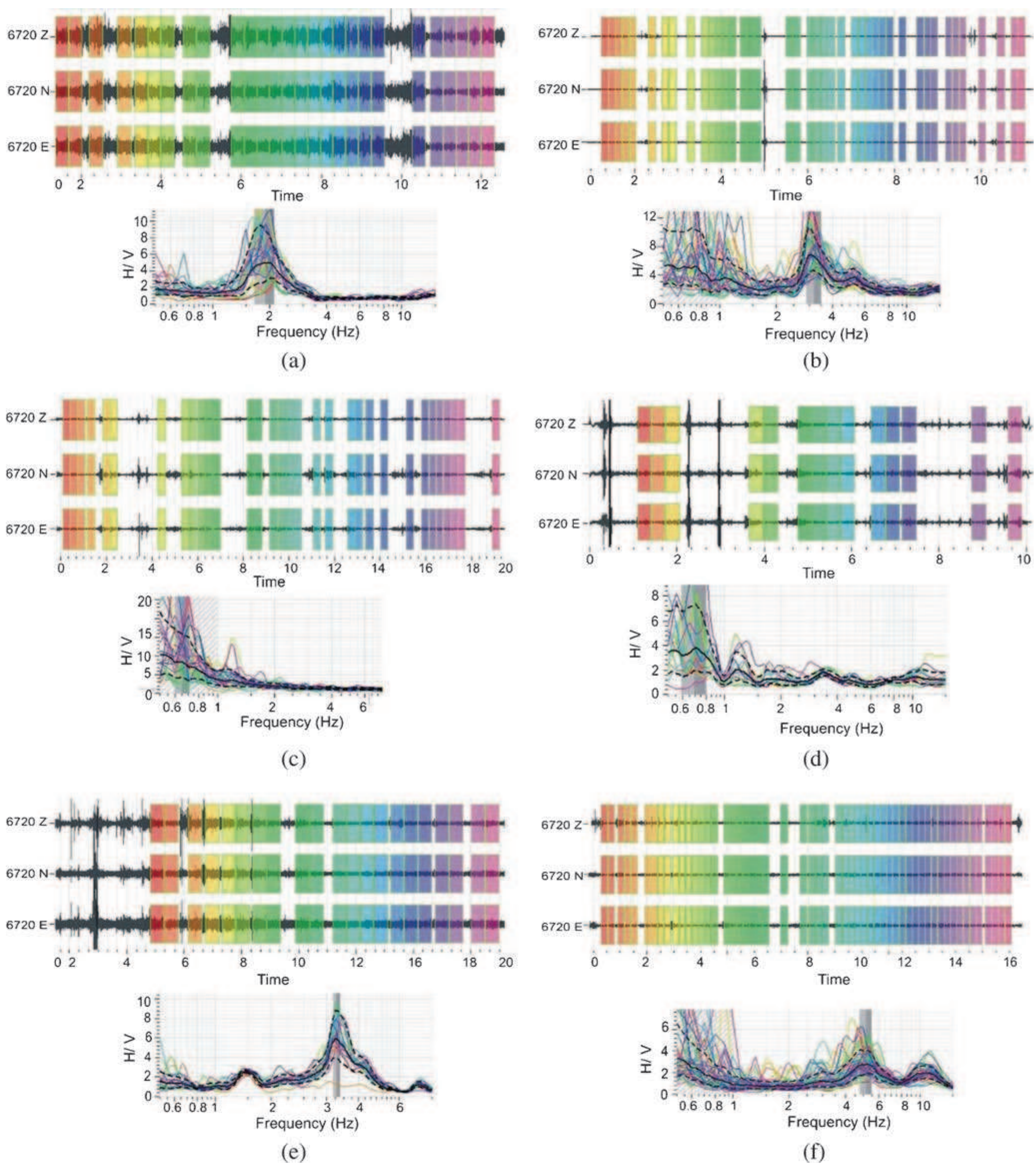

Figure 6. Interpretation of data obtained from the microtremor measurements in the study area; in the figure, there are two dotted lines above and below which is standard deviation for all values of the ratio of the resulting spectra. The line in the middle is the average value of the FFT analysis of the HVSR value, while the thin line is colourful curves HVSR of each window ((**a**)Bardakçı, (**b**) Göllü, (**c**) Dağönü, (**d**) Adıgüzel, (**e**) Timar (Gedikbulak), (**f**) Çolpan)).

generally provide a very good estimation of the fundamental frequency (peak frequency or period of HVSR) of the sites in terms of their soil properties.

HVSR measurements were recorded using a CMG-6TD model seismograph equipped with three components, which was designed by Güralp Systems. At each station, the HVSR measurements were recorded for a duration of 10–30 min at 80 different locations in order to identify the soil conditions. Measurements were recorded in accordance with Nakamura (1989) HVSR method. Peak frequency and peak amplitude values of HVSR for the villages were determined by following the conventional data processing steps by the data obtained from HVSR measurements. These measurements were recorded under suitable environmental conditions, where there is no wind and rain by means of stable installation of seismometer on the ground and controlling the accuracy of the level. HVSR analysis in this study was performed following the rules outlined in (SESAME 2004). Measurements were recorded within a sampling interval of 100 Hz (dt = 0.01 s). Each window is base-line corrected for anomalous trends, tapered with Hanning window and a Butterworth band-pass filtered from 0.1 Hz low-cut to 10 Hz high-cut frequencies. The data obtained for each component, between 10 and 30 s in window length, is used to calculate HVSR values. The Fourier amplitude spectra of each selected window are computed and smoothened after merging two horizontal components by applying their geometric means (Site EffectS assessment using AMbient Excitation (SESAME) 2004). FFT (Fast Fourier Transform) was applied to each window using frequency-domain analysis. A horizontal-to-vertical spectral ratio was calculated for each range and spectral ratio. The standard deviation referring to the measurement point was also calculated using the average of calculated spectral values. The spectra, which was obtained using Parzen-window method, was computed using a cosine taper with 10% smoothing and Konno–Ohmachi smoothing with a constant value of 40 (Konno and Ohmachi 1998). After smoothing the spectral ratio curves and processing the raw data as described above, the maximum HVSR peak

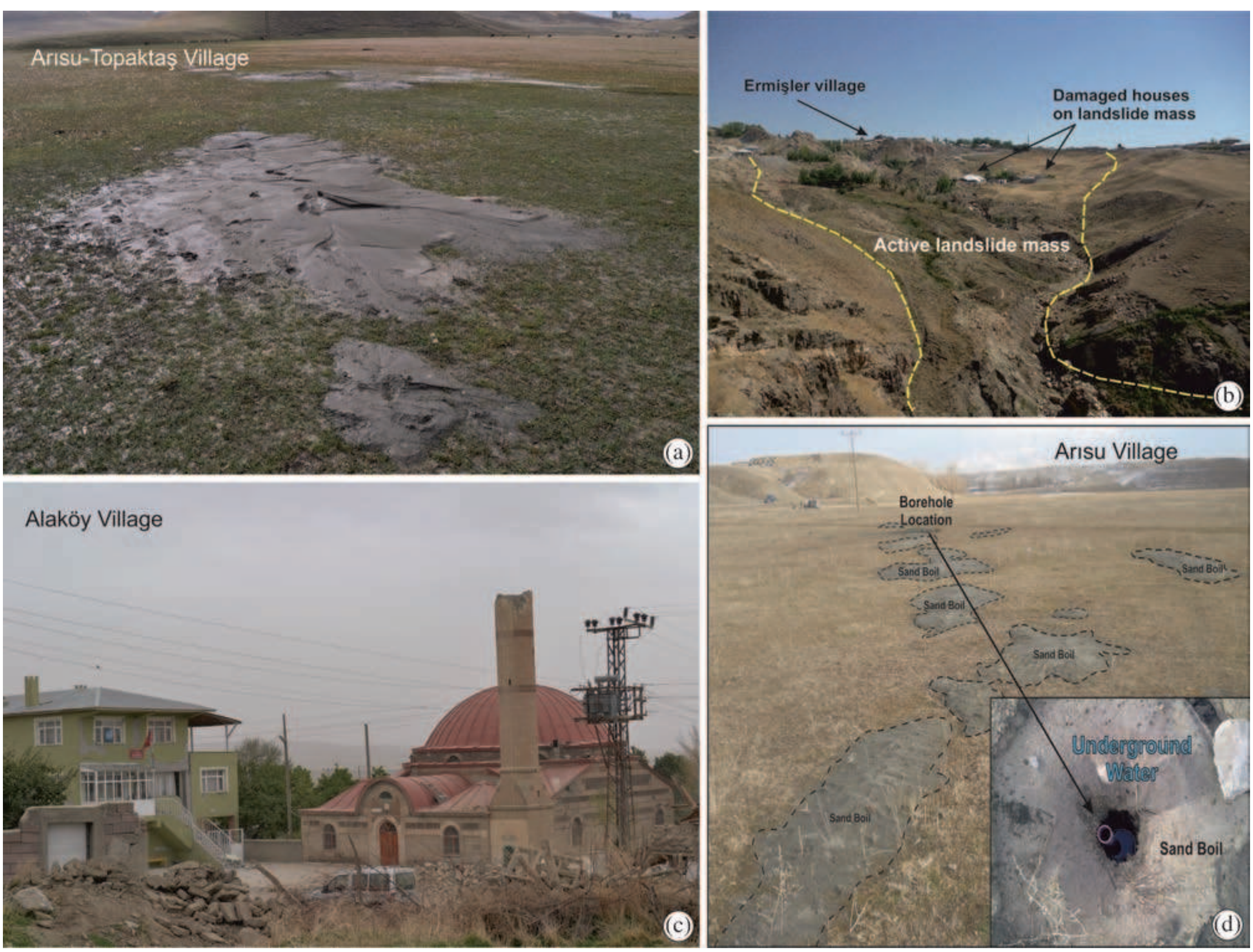

Figure 7. Earthquake-induced damages in the study area; **(a)** liquefaction, **(b)** landslide, **(c)** hillside effect, and **(d)** underground water effect.

period values and HVSR peak amplitude values were obtained by using the Nakamura method (figure 5, table 1). With the evaluation of the spectral curves obtained through the analysis, HVSR peak period and the corresponding increased rate in HVSR peak amplitude are determined (figure 6). The Geopsy software packages prepared by the SESAME were used in order to process the data obtained.

5. Results

HVSR method is applied to 80 microtremor measurements to provide information related to site response of the study area (figure 5). HVSR peak period values were found to be between 0.2 and 1.6 s and HVSR peak amplitude values were found between 4 and 10, respectively, in the villages that were severely damaged by the earthquake. HVSR peak period values of 0.1 s and HVSR peak amplitude values of 1.5–2 were obtained from the microtremor measurements, which were conducted in the villages that have minor damages caused by the earthquake (Çolpan, Çakırbey, Halkalı, Karaağaç, Sağlamtaş, Yaylıyaka). This location over the rock area shows quite smaller peaks at lower periods.

The level of damage in the villages that are settled on lacustrine and stream sediments (Arısu, Mollakasım, Alaköy, Bardakçı, Topaktaş, Özkaynak, Gülsünler, Kasımoğlu, Satıbey, Koçköy, Yumrutepe, Atmaca, Göllü, Güveçli, Tabanlı, Dağönü, Şahgeldi, Yeşilsu, Ocaklı, Pirgarip, Hıdır and Aşağıgölalan) has verified that the damage correlates well with comparatively high HVSR peak period values and HVSR peak amplitude values that were in the range of 1.0–1.6 s and 6–9, respectively. The probability of liquefaction (Akın *et al.* 2013) has increased in these villages (Arısu and Topaktaş villages) due to the shallow groundwater level and the sandy soil layer.

Other severely damaged villages (Çitören, Arısu, Mollakasım, Alaköy, Yumrutepe, Atmaca, Göllü, Güveçli, Tabanlı, Dağönü, Şahgeldi, Yeşilsu, Ocaklı, Pirgarip, Hıdır, Aşağıgölalan, Esenpınar, Sağlamtaş, Çakırbey) were located on the Oligocene–Miocene aged deposits. The values of mid-range HVSR peak period, obtained in these villages, are compatible with geological characteristics of the region (0.4–0.8 s). High HVSR peak period and HVSR peak amplitude values were obtained, correlating with occurrence of liquefaction, in the villages of Bardakçı, Topaktaş, Özkaynak, Gülsünler, Kasımoğlu, Satıbey and Koçköy (figure 7a).

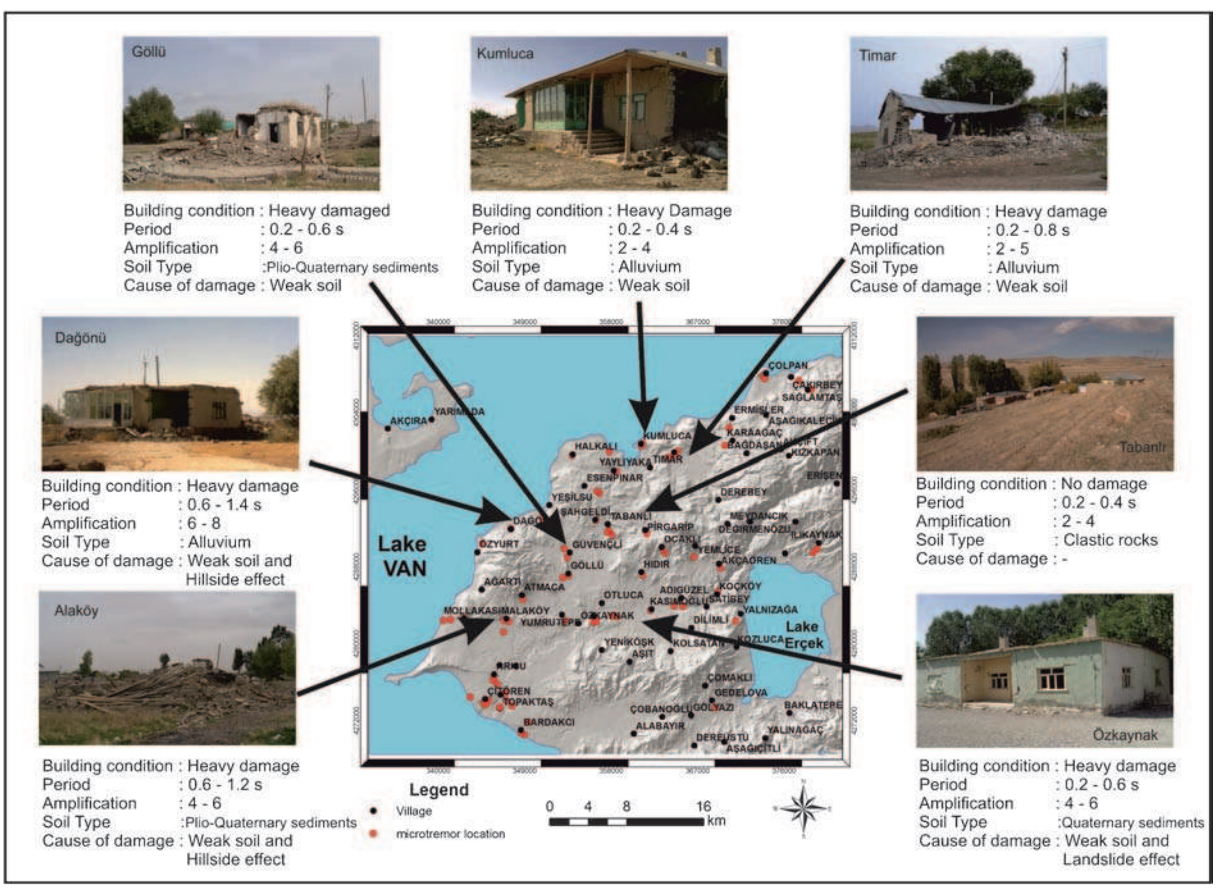

Figure 8. Different types of earthquake-induced structural damages in investigated villages.

For Halkalı, Çolpan, Çakırbey, Sağlamtaş, Karaağaç, Kumluca and Yaylıyaka villages located on volcanic units and lacustrine deposits, the HVSR peak period levels are in the range of 0.1–0.2 s and HVSR peak amplitude values are in the range of 1.5–2. In general, the level of damage is minor; however, it increases in some parts of the villages, where the housing units are generally located on the locally found lacustrine sediments.

The results of this study are compared with the results of the final damage assessment report prepared by Governorship of Van and the relation between the damage levels to the buildings and the regional tectonics, local geological and geophysical conditions are given in table 1. The results of this study are almost consistent with the results of the final damage assessment report prepared by Governorship of Van. However, it should be noted that the housing units severely damaged in villages located in volcanic areas, were constructed on locally found alluvial/lacustrine deposits (i.e., Halkalı, Yaylıyaka, Kumluca, Çolpan and Esenpınar villages). The damages in Satıbey, Ermişler and Özkaynak villages are mainly because of the landslides (figure 7b).

It was found that hillside effect, which is the translation of the body waves into surface waves in the edges of the basin, increased the amplitude value. The increase in the amplitude consequently resulted in higher levels of damages in housing units in Alaköy and Dağönü villages (figure 7c). Arısu and Güveçli villages are highly damaged due to underground water (figure 7d). Structural damages, which are related to the local soil conditions and the geological properties, are given in figure 8.

5.1 *Structural damages of housing units*

The structural damages were severe and widespread in villages located on soft soils. A great majority of the existing housing units are unreinforced masonry buildings in these villages. The walls of relatively older housing units are mostly constructed with adobe blocks and mud mortar, whereas the newer units are constructed with light-weight concrete blocks and cement mortar (Tapan *et al.* 2013). There are also many housing units built with combination of these two different types of blocks, sometimes together with wooden structural materials (Tapan *et al.* 2013).

Figure 9. Damages to unreinforced masonry buildings on weak soils in the study area.

The roofs of these housing units, particularly for relatively older ones, are built by woodwork and covered with a thick layer of clay for heat insulation. Although construction practice of all housing units are similar in the region, damages to the housing units located on strong soils such as rock units were relatively less than the damages of housing units located on weak soils (figure 9).

6. Conclusion

Reliable seismic hazard analyses require adequate consideration of local site effects. Experiences from the past earthquakes have revealed that soil conditions play an important role on seismic wave amplification phenomena and seen as one of the important parameters responsible for the level of damage. Good knowledge of local geotechnical features is required in order to consider local site effects (also known as the transfer function) in analyses. Therefore, determination of soil conditions constitutes a basic stage in earthquake engineering studies.

The structural damages caused by Van earthquake, have shown the importance of quality of construction as well as the seismic wave phases, earthquake mechanism, earthquake source properties, rupture direction, and local geotechnical conditions. Although, construction practices of all rural housing units are similar in the region, the earthquake caused massive damage to villages located on soft soils in northern region of the city.

The damage level of severely damaged villages that are settled on lacustrine and stream sediments was verified with comparatively higher HVSR peak period and peak amplitude values. It was also found that hillside effect, which is the translation of the body waves into surface waves in the edges of the basin, increased the amplitude values. The increase in the amplitude values consequently resulted in higher levels of damages in housing units.

HVSR peak period and peak amplitude values obtained in this study are almost consistent with the level of damage in housing units. However, this correlation seemed to be decreased in alluvial soils. Therefore, it is concluded that site characteristics (peak frequency of HVSR), wave amplification, and ground vulnerability are affected by sediment type, location, and thickness of sedimentary units.

Finally, this study shows that local soil conditions directly affect the level of damage in the structures after an earthquake. Therefore, it is important to consider dynamic properties of soil while designing the structures.

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