Geomechanics and Engineering, *Vol. 16, No. 4 (2018) 435-448*
DOI: https://doi.org/10.12989/gae.2018.16.4.435

Linear and nonlinear site response analyses to determine dynamic soil properties of Kirikkale

Yetis Bulent Sonmezer[1a], Selcuk Bas[*2], Nihat Sinan Isik[3b] and Sami Oguzhan Akbas[4b]

[1]*Department of Civil Engineering, Faculty of Engineering, Kirikkale University, 71450 Kirikkale, Turkey*
[2]*Department of Civil Engineering, Faculty of Engineering, Bartin University, 74100 Bartin, Turkey*
[3]*Department of Civil Engineering, Faculty of Technology, Gazi University, 06500 Ankara, Turkey*
[4]*Department of Civil Engineering, Faculty of Engineering, Gazi University, 06500 Ankara, Turkey*

(Received July 20, 2018, Revised August 1, 2018, Accepted August 7, 2018)

Abstract. In order to make reliable earthquake-resistant design of civil engineering structures, one of the most important considerations in a region with high seismicity is to pay attention to the local soil condition of regions. It is aimed in the current study at specifying dynamic soil characteristics of Kirikkale city center conducting the 1-D equivalent linear and non-linear site response analyses. Due to high vulnerability and seismicity of the city center of Kirikkale surrounded by active many faults, such as the North Anatolian Fault (NAF), the city of Kirikkale is classified as highly earthquake-prone city. The first effort to determine critical site response parameter is to perform the seismic hazard analyses of the region through the earthquake record catalogues. The moment magnitude of the city center is obtained as M_w=7.0 according to the recorded probability of exceedance of 10% in the last 50 years. Using the data from site tests, the 1-D equivalent linear (EL) and nonlinear site response analyses (NL) are performed with respect to the shear modulus reduction and damping ratio models proposed in literature. The important engineering parameters of the amplification ratio, predominant site period, peak ground acceleration (PGA) and spectral acceleration values are predicted. Except for the periods between the period of T=0.2-1.0 s, the results from the NL are obtained to be similar to the EL results. Lower spectral acceleration values are estimated in the locations of the city where the higher amplification ratio is attained or vice-versa. Construction of high-rise buildings with modal periods higher than T=1.0 s are obtained to be suitable for the city of Kirikkale. The buildings at the city center are recommended to be assessed with street survey rapid structural evaluation methods so as to mitigate seismic damages. The obtained contour maps in this study are estimated to be effective for visually characterizing the city in terms of the considered parameters.

Keywords: local soil condition, site response analysis, soil amplification, peak ground acceleration, spectral acceleration, seismic hazard

1. Introduction

Ground motion from earthquakes can be directly affected from the soil conditions of a region considered. Hence, determining the distribution of local site parameters is of great importance for the estimation of the effects of earthquake on civil engineering structures. The hypocenter characteristics, seismic wave travelling and local site conditions affect all parameters related to ground motion. To illustrate, based on the structural and geotechnical field reconnaissance, 1985 Michoacan and 1989 Loma Prieta earthquakes indicated the need for considering local site conditions due to unpredicted earthquake-related damages on structures. Due to high thickness of soft clay in the site, high soil amplification values obtained from 1985 Michoacan earthquake led to great damage on the structures and even totally collapse of many buildings. Detailed studies on the local site behavior, which were performed especially after the 1985 Michoacan and 1989 Loma Prieta earthquakes, showed that local site conditions had a significant impact on the peak ground acceleration, amplitude and periods of response spectra (Kramer 1996).

In various recent investigations in literature, the importance of identifying dynamic soil characteristics of earthquake-prone settlements is underlined to make more realistic design of structures under seismic excitation. Akin *et al.* (2016) studied on site response estimation of seismically active city of Erbaa, Tokat located on the North Anatolian Fault. They revealed with distributive results that the region of the southern part of the city had high amplification ratio and predominant site frequency. Similar study was conducted by Isik (2010) for Saruhanlı town of Manisa at the Aegean Region to evaluate soil amplification ratio and pre-dominant periods of the region. He estimated that the building with more than ten storeys could be severely damaged due to high amplification ratio and lower predominant site period of the region. For the region of Adapazari seriously affected from 1999 Kocaeli earthquake, Silahtar *et al.* (2016) and Firat *et al.* (2016) made an investigation to determine the site properties and soil amplification factor of the region. Silahtar *et al.* (2016) concluded a general remark that geological properties and topographies had significant effect on the shear wave

∗Corresponding author, Ph.D., Assistant Professor
E-mail: selcukbas@itu.edu.tr or sbas@bartin.edu.tr
[a]Assistant Professor
[b]Professor

http://www.techno-press.org/?journal=gae&subpage=7 ISSN: 2005-307X (Print), 2092-6219 (Online)

velocity (V_s) and site amplification factor of the studied region of Adapazari. Performing one dimensional site response analyses with SHAKE2000 software for the estimation of amplification ratio of the Adapazari province, Firat *et al.* (2016) indicated that the use of design spectra given in seismic codes could not be suitable for the region with soft alluvial soil deposit due to amplified site response of Adapazari area. They also concluded that high amplification response was obtained in the high predominant periods for soft alluvial site deposits. In an effort to reduce the uncertainties relevant to earthquake resistant design of buildings in the city Babol, Iran, the dynamic site response analysis was performed by Tavakoli *et al.* (2016) using experimental and numerical methods. These analyses demonstrated that amplification ratio was greater than one in all regions of the city. The numerical analysis of one dimensional site response and the experimental microtremor testing were obtained to be closure agreement with each other for the subterraneous alluviums conditions. The effects of the local site condition on civil engineering structures are also investigated by Sisi *et al.* (2018), Gautam *et al.* (2016) and Fatahi *et al.* (2014). The influence of local site condition of Eastern Turkey on building fragility curves was investigated by Sisi *et al.* (2018) incorporating structural variability of the structures. Based on the site-specific uniform hazard spectrum analysis of this region, building structures located on soft soil were determined in this study to be more vulnerable to earthquake motion than those on stiff soil. In order to pertain the effects of local soil behavior with the observed structural damages, Guatam *et al.* (2006) carried out a study using equivalent-linear and nonlinear seismic site response analyses in certain five critical points of Kathmandu Valley, Nepal. For better damage estimation on the studied region in this study, the non-linear site response analysis was obtained to give more realistic results in terms of the acceleration response spectra and soil amplification ratio. A parametric numerical study on the site effect and soil-structure interaction (SSI) was made by Fatahi *et al.* (2014). Considering tall buildings with different story on soft soil, they concluded that site effects should be included in the non-linear response history analysis not excluding SSI so as to better understand earthquake response of building structures.

Turkey is an earthquake vulnerable country surrounded with active faults, such as North Anatolian Fault Zone (NAFZ) is the most important one with a total length of 1600 km (Allen 1969, Şengör *et al*. 1985, Bozkurt 2001). Seismic activity of the NAFZ fault generated 1999 Izmit (M_w=7.4) and 1999 Düzce (M_w=7.1) earthquakes leading to death of thousands. As of 1999 Izmit earthquake, many studies have been conducted on investigation of local site conditions effects in literature. Some of these studies on local soil conditions are Tezcan *et al.* (2002) for Avcilar region, Kılıç *et al.* (2006) for Zeytinburnu region, Ulusay and Kuru (2004) for Adana-Seyhan region, Selçuk and Çiftçi (2007) for the city of Van, (Kolat *et al*. 2012) for the city of Bursa, (Büyüksaraç *et al.* 2013) for the city of Sivas and (Akin *et al.* 2013) for the city of Tokat.

All of these studies aim to conduct seismic hazard analysis with respect to some of the factors, such as soil amplification, predominant site period, shear wave velocity distribution, liquefaction and landslide potential. Kirikkale is an earthquake-prone city in Turkey and is classified as Seismic Zone 1 according to surrounding zones of Seyfe Fault, Karakeçili Fault and Kirikkale-Sungurlu Fault (AFAD 2016). The Seyfe Fault 50 km away from the city of Kirikkale, was the source of 1938 Akpınar earthquake (M_w=6.4) which is a good example for the seismic activity in the region (Parejas and Pamir 1939). In an attempt to improve the structural quality, to develop new confidential settlement plans, and to conduct reliable investigation, it is indispensable to properly realize the influences of the local site condition on earthquake behavior of structures.

The main aim of the present study is to determine the dynamic soil properties of the city center of Kirikkale. For this aim, considering the fault systems of Kirikkale and the results obtained from the field tests of multichannel analysis of surface waves (MASW) method and standard penetration test (SPT), the 1-D equivalent linear (EL) and nonlinear (NL) site response analyses are performed for the city through SHAKE2000 (Ordonez 2012) and DEEPSOIL (Hashash *et al.* 2016) software. Thus, the parameters of amplification ratio, predominant site period, peak ground acceleration and spectral acceleration maps for the periods between T=0.2 s and T=1.0 s are estimated characterizing the site behavior of the settlement areas of Kirikkale.

2. Study region

2.1 Description of site

As shown in Fig. 1, Kirikkale is a city of the Central Anatolian Region, which is located on 70 km away from the capital city of Turkey, Ankara. The city has a population of 188000 and is positioned at 700 m altitude above sea level. The city also has a critical function to be a center in the transportation networks of Turkey. Moreover, the city plays a critical role for Turkey to host some important industries/plants, such as National Mechanical and Chemical Industry with the aim of manufacturing military products, and several steel, brass and gunpowder manufacturing plants as well as and the Central Anatolia Refinery owned by TUPRAS. Therefore, comprehensive investigation on the determination of dynamic soil parameters of the city of Kirikkale needs to be made to reduce seismic risk of the city and to accurately predict required measures before earthquake hits.

2.2 Geology

The bottom soil layer of the city of Kirikkale was formed with marble layer. Above this formation, the ground of the region was covered with another formation consisting of microgabbro diabase, basalt and volcano-sedimentary with the thickness of less than 5.0 m (Ketin 1955, Erkan 1975, Seymen 1982). General layout for the formation of the study region is given in Fig. 2.

All these formations were also covered heterogeneously with gravel, sand and clay (alluvion) units of quaternary strata (Birgili et al. 1975). Additionally, thickness of the bedrock at these regions was determined as almost 120 m with drilling efforts of DSI (General Directorate of State Hydraulic Works) for water extraction.

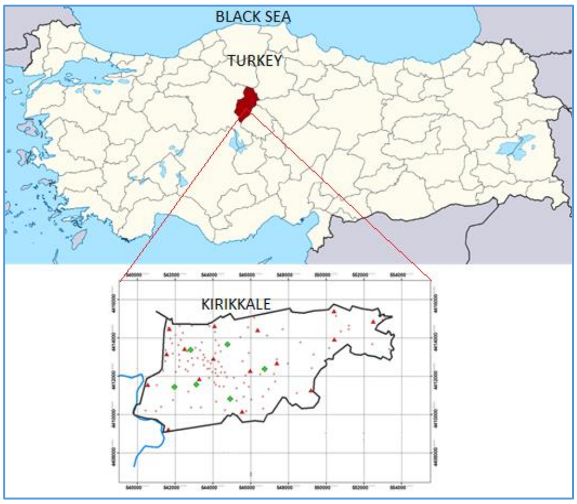

Fig. 1 Location of the city of Kirikkale

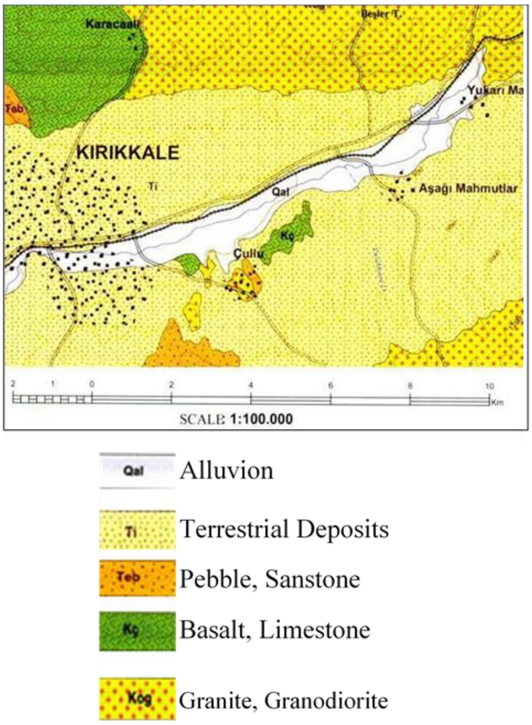

Fig. 2 Geological formation of the city of Kirikkale

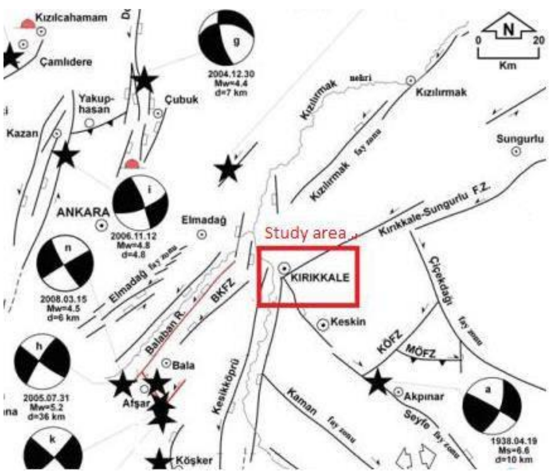

Fig. 3 Fault systems at the city of Kirikkale

2.3 Tectonics and seismicity

The most important fault mechanism affecting the city of Kirikkale is the North Anatolian Fault (NAF) with 1600 km length and 1110 km width (Rojay and Koçyiğit 2012). As depicted in Fig. 3, other significant fault systems are the Seyfe Fault (Kocyigit 2000) at the southeast of the city, the Kirikkale-Sungurlu Fault (Kocyigit 2008) at the east of the city, the Salt Lake and Keskin Fault at the south of the city, and the Bala and Karakeçili Faults (MTA 2015) at the southwest of the city. Recent geological studies on the Anatolian Plate on which the majority part of Kirikkale is located proved that two new neotectonic regimens were available in this plate and that in these regimens there were certain new active fault systems with the ability to generate destructive earthquakes (Kocyigit 2008). Hence, the city of Kirikkale is considered to be under seismic risk according to the important fault systems and active plate tectonics.

One of the most significant earthquakes occurred in the city of Kirikkale is the 1938 Akpınar Earthquake (M_s: 6.8) with an epicenter on the northern line of the Seyfe Fault Zone and 14 m away from the Akpınar Fault Segment lying between Akpinar and Taskovan provinces (Parejas and Pamir 1939).

3. Method

Seismic risk analysis allows to make probabilistic future estimation of the effect of earthquakes on structures in terms of local and global scale. The main goal of the seismic risk analyses is to calculate the expected peak ground acceleration (PGA) or spectral acceleration (S_a) of an interested site. Spectral acceleration is taken commonly used parameter into account to make effective structural design and damage estimation of civil engineering facilities. Developing a design spectrum for different types of soil such as rock, hard soil and soft soil is the conventional approach in earthquake engineering practices (Kramer 1996).

Seismic hazard analysis can be performed either deterministic method through the custom earthquake scenarios or probabilistic method considering the probability of occurrence of earthquake, its magnitude, its effect on structures and uncertainties related to interested site (Kramer 1996, Scawthorn and Chen 2002, Kramer 2009). All the seismic sources which may have an impact on the study region are considered in the probabilistic seismic hazard analysis (PSHA) that is performed according to defined probability of exceedance.

As a result of the seismic hazard analyses, a specific maps that present the potential of earthquake hazard of the study area can be obtained. In literature, many seismic hazard maps were prepared based on the seismic hazard analyses (Gülkan *et al.* 1993, Kijko and Graham 1998, Kayabali and Akin 2003, Das *et al.* 2006, Kalkan *et al.* 2009). These maps identify the uncertainties in the magnitude and location of earthquakes and the results of ground mo tions that can affect on specific area. Cornell (1968) and Algermissen and Perkins (1976) developed seismic risk maps for horizontal peak ground acceleration

(PGA) and velocity (PGV) based on the 10% probability of exceedance in 50 years using seismic risk principles. These maps were used for the design response spectra given in the American Association of State Highway and Transportation Officials (AASHTO) Bridge Design Specification, 13th edition (1983).

For the seismic risk estimations of Turkey, the responsible institution of Bogazici University, Kandilli Observatory and Earthquake Research Institute has made many investigation and project studies. According to the United Nations International Decade for Natural Disaster Reduction (IDNDR) activities, Global Earthquake Hazard Assessment Program (GSHAP) and the European Union-Mediterranean Region Earthquake Hazard Assessment Project (SESAME), certain researches conducted many studies and the peak acceleration (PGA)-based probabilistic earthquake hazard estimations were made based on the Poisson model for 10% probability of exceedance in 50 years. All these important works were performed in compliance with international design codes and paying attention to compatibility of them to neighboring regions (Erdik *et al.* 1999, Bommer *et al.* 2002). Within the scope of the TEFER project in Turkey supported by the World Bank (TEFER 2000, Bommer *et al.* 2002), many risk maps for the PGA values corresponding to 10% probability of exceedance in 50 years, spectral acceleration of T=0.2 s S_a (0.2) and T=1.0 S_a (1.0) were prepared using the SESAME project microzoning to invite the people to make registration to Turkish National Catastrophe Insurance Pool.

In the concept of performance-based design, earthquake levels are defined as the probability of exceedance of spectral acceleration. Generally, these are low intensity earthquake with 70% (43 years return period) and 50% (72 years return period) probability of exceedance in 50 years, design earthquake with 10% (475 years return period) probability of exceedance in 50 years and max. earthquake with 2% (2475 years return period) probability of exceedance in 50 years (Sitharam and Anbazhagan 2007, Sucuoglu 2015).

In the present study, probabilistic seismic hazard analysis (PSHA) of the city of Kirikkale is performed considering 10% (475 years return period) probability of exceedance in 50 years and using historical earthquake data. Utilizing magnitude obtained from the PSHA and local soil parameters of the city, a target acceleration response spectrum is generated through different attenuation relationships, and then soil behavior analyses of the study region are performed with the scaled new earthquake records according to the obtained target spectrum. From these efforts, ground motions parameters, such as peak ground acceleration (PGA) and spectral acceleration (S_a) for T=0.2 s and T=1.0 s periods, and soil amplification factor are determined and these values are shown distributively in the maps for the study region.

3.1 Seismic hazard analysis

One of the main and most important inputs for seismic hazard analyses is the historic earthquake data. This step is now accurately carried out with the help of developed effective local and global databases, such as PEER (Pacific Earthquake Engineering), USGS (US Geological Survey) etc. In the current study, earthquake data necessary for the seismic hazard analysis is obtained from the different databases of Republic of Turkey Prime Ministry Disaster and Emergency Management Authority (AFAD 2016), Bogazici University Kandilli Observatory and Earthquake Research Institute-Regional Earthquake-Tsunami Monitoring Center (BDTİM 2015), United States Geological Survey (USGS 2016).

Due to the limited number of severe earthquakes in the city of Kirikkale, the probabilistic approach is selected in this study instead of the deterministic approach. It is a

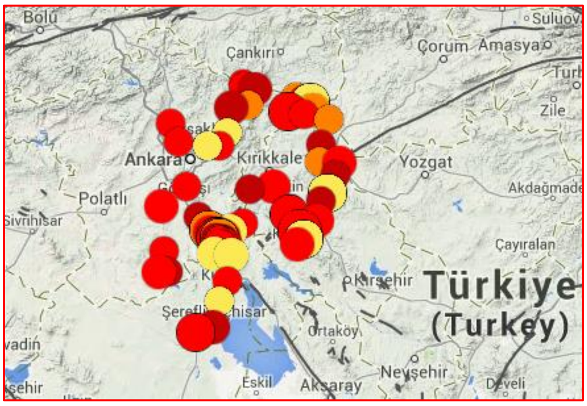

Fig. 4 Earthquakes in the circle with radius of 100 km in the study area

Table 1 Earthquakes used in the seismic hazard analysis

No	Date	Latitude	Longitude	Depth (km)	Magnitude (Mw)
1	06/09/1919	40.68	33.89	10	5.3
2	10/04/1928	40.22	33.67	10	5.8
3	09/04/1930	39.70	34.00	30	5.3
4	28/06/1933	39.30	33.20	30	4.9
5	07/12/1935	40.60	33.60	10	5.3
6	19/04/1938	39.44	33.79	10	6.4
7	27/04/1938	39.89	34.10	10	4.8
8	21/05/1958	40.65	33.36	10	4.8
9	20/01/1965	40.50	34.00	33	4.7
10	19/02/1973	40.28	33.86	22	5.0
11	27/04/1973	38.65	32.92	29	4.9
12	22/09/1975	40.36	33.40	3	4.9
13	04/07/1978	39.45	33.19	23	4.9
14	04/21/1983	40.65	33.36	36	4.8
15	04/06/1985	39.55	32.93	5	4.5
16	08/05/1990	40.23	33.88	17	4.7
17	24/08/1999	39.61	32.62	8	4.8
18	08/12/2001	40.22	33.81	10	4.5
19	30/07/2005	39.42	33.11	1	5.4
20	20/12/2007	39.42	33.07	7	5.5
21	31/01/2008	40.24	33.20	5	5.0
22	15/03/2008	39.46	33.01	12	5.2

common consideration for the estimation of probability of occurrence of an earthquake to make separate analysis for each earthquake source considered. Due to the lack of earthquake events with magnitude of higher than M_w=4.5 on the fault systems of the Karakeçili, Seyfe, Keskin and Kirikkale-Sungurlu, the PSHA analysis of the city is performed taking into account the earthquakes occurred in the circle with 100 km radius of the study region as shown in Fig. 4. The earthquakes with different magnitude scales of M_b (body magnitude), M_L(local magnitude), M_d (time dependent magnitude) and M_s (surface wave magnitude) are converted into one type of scale of M_w (moment magnitude) scale using the empirical expressions proposed by Deniz and Yucemen (2010) to provide the consistency of the properties of earthquake data.

The commonly used model of the Poisson is based on that the earthquakes occurred independently in terms of site and time parameters. In order to provide the independency condition of the Poisson model, it is necessary to eliminate the foreshocks and aftershocks in earthquake databases determining earthquake groups to be considered in the analysis (Yucemen 2011). Based on the studies of Van Dyck (1985), Utsu *et al.* (1995), Savage and Rupp (2000), Kagan (2002) and (Deniz 2006) determined the limitation of framework in the aspects of time and site of the study area for aftershocks within the scope of the studies mentioned above. He defined the limitations of distance window for aftershocks according to the outcomes from the four studies stated above, and the limitations of the time window averaging the results obtained from the studies of Gardner and Knopoff (1974) and Savage and Rupp (2000).

$$logn(M) = a - b \cdot M \tag{1}$$

where, *n (M)*: the number of earthquakes with a magnitude greater than or equal to *M* in a duration and in a certain region, *a*: the average annual seismic activity index parameter, *b*: the parameter accounting for the character of seismic activities in the region and *M*: magnitude.

In light of the previous investigations, the earthquake data to be used in the probabilistic earthquake hazard analysis of Kirikkale are specified considering the recommended time and distance window by Deniz (2006) for foreshocks and aftershocks. These earthquakes are listed in Table 1. The relationship between earthquake magnitude and frequency is commonly used to estimate the probability of an earthquake in a specific area. For this aim, the empirical formula of Eq. (1) proposed by Gutenberg and Richter (1942, 1944, 1956), and Richter (1958) is utilized in this study.

In exploring the effect of earthquakes on structures, it is aimed to define the round movements with highest risk throughout the life span of a structure. This ground motion corresponds to the earthquake with 10% probability of exceedance in 50 years service life span of structures (475 years return period). The probabilistic seismic hazard analysis performed using the earthquake data obtained from catalogues as listed in Table 1 gave the cumulative frequency and number of occurrence of the earthquakes.

Thus, the relationship between magnitude and number of occurrence is determined as indicated in Fig. 5. According to the PSHA analysis, the moment magnitude

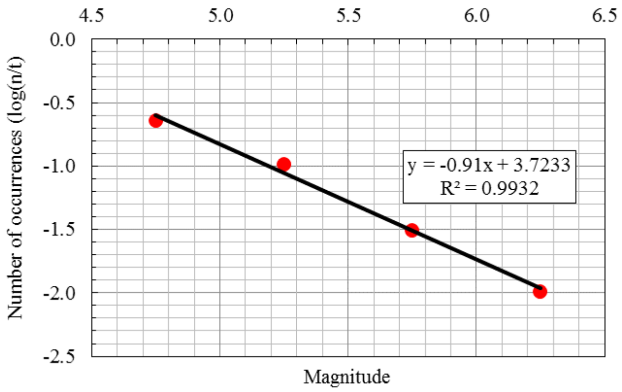

Fig. 5 Earthquake magnitude and number of occurrences relationship

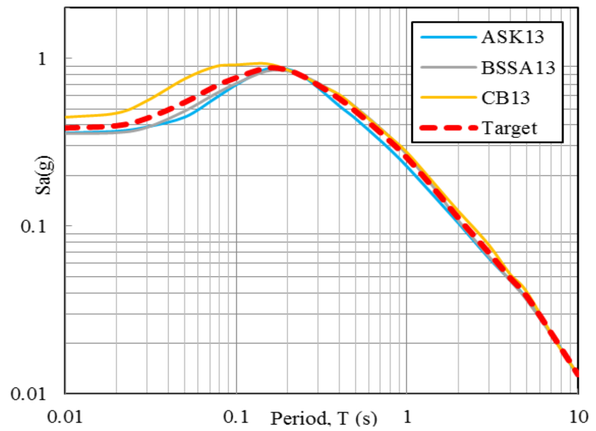

Fig. 6 The target spectra for the bedrock level at the study site

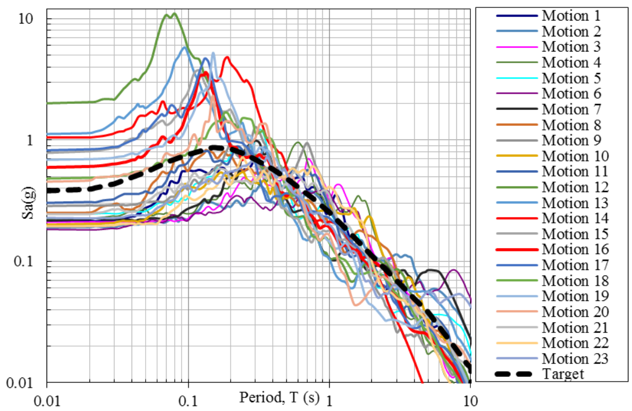

Fig. 7 Target spectrum and acceleration spectrum of selected records

(M_w) for the city of Kirikkale is estimated as M_w=7.0 considering 10 % probability of exceedance in 50 years.

Structures built in earthquake zones are exposed to different levels of earthquake effects. The ground motion parameters necessary for earthquake-resistant structural design of structures can be defined with different attenuation relationship (Kramer 1996). The relationships that consider local site condition, fault mechanism and distance to earthquake source of interested region are developed with the regression analysis using real

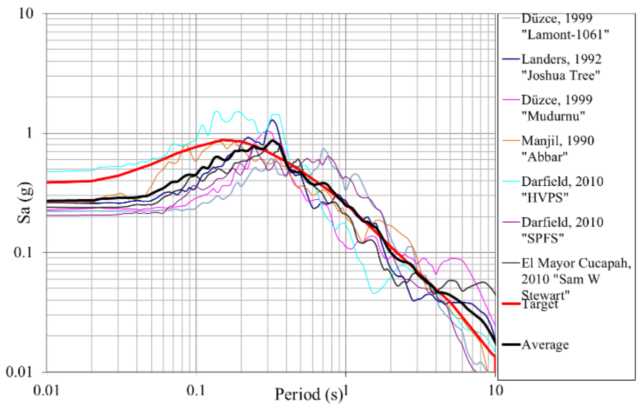

Fig. 8 Target spectrum and acceleration spectrum of scaled seven records

Table 2 MSE, *f* and V_{S30} values of scaled earthquakes

EQ	Station	M_w	MSE	Scale factor (*f*)	V_{S30} (m/s)
Landers 1992	Joshua Tree	7.2	0.254	0.87	379
Düzce 199	Lamont1061	7.1	0.105	2.37	481
Duzce 199	Mudurnu	7.1	0.292	2.66	535
Manjil 1990	Abbar	7.3	0.052	0.54	723
Darfield 2010	Heathcote Valley Primary School	7.0	0.238	0.9	422
Darfield 2010	SPFS	7.0	0.189	1.38	389
El Mayor-Cucapah, 2010	Sam W. Stewart	7.2	0.174	3.26	503

earthquake records at the vicinity of study region (Akın 2009).

In literature, the attenuation relationships of ground motion were obtained with many researchers considering region specific properties of study region (Joyner and Boore 1981, Campbell 1989, Ambraseys and Bommer 1991, Akkar and Bommer 2007). Using the strong ground motion records collected in Turkey, certain attenuation relationships were proposed for Turkey from Özbey *et al.* (2004) and Gülkan and Kalkan (2002). Since the proposed relationships were developed based on the earthquake records solely obtained from 1999 Kocaeli earthquake, seismic hazard was estimated lower than conventional ones. The main reason for obtaining lower risk from them is directly related to one earthquake consideration rather than tectonic and geology. Instead of one-earthquake dependent local attenuation relationships, a number of earthquake motions recorded not only at Turkey, Europe but also at the US are adopted in the present study to develop attenuation relationship for the city of Kirikkale. For this aim, a new generation attenuation relationship modified by Abrahamson *et al.* (2013) (ASK), Booret *et al.* (2013) (BSSA) and Campbell and Bozorgnia (2013) (CB) within the scope of the PEER project entitled "Next Generation Attenuation WEST2 (NGA-West2)" is adopted in the present study.

The final target spectrum to be used for obtaining and scaling the earthquake records is determined by averaging the spectra obtained from the ASK, BSSA and CB attenuation relationships and is shown in Fig. 6. The site is located 5.0 km from the Karakecili fault, and 10 km from the Kirikkale-Sungurlu and Keskin fault zones as shown in Fig 3. In defining the target spectrum, the distance is set to be 5.0 km in accordance with the worst scenario and the magnitude is taken as M_w=7.0 as found in the seismic hazard analysis for 50-year life span and 10% probability of exceedance.

Earthquake ground motions have been measured and recorded with the invention of recording devices since 1970. In the selection of earthquake records to be used in soil behavior analyses, scaled earthquake records according to the earthquake scenario obtained from the deterministic or probabilistic seismic analysis are recommended from (Kramer 2009). Based on these considerations, the required earthquake records to specify dynamic soil characteristics of the study region are selected from the PEER database according to M_w=7.0 obtained from the PSHA, the shear wave velocity range of 360 m/s<V_{s30}<760 m/s in the height of 30 m determined from the site investigations, 5 km distance to the fault and strike-sleep fault system of the NAFZ. Thus, a total number of 23 records selected and their acceleration spectrums are depicted in Fig. 7.

Spectrum-compatible scaling of earthquake records for soil behavior analysis consists of consideration of a number of earthquake records and scaling method (Naeim *et al.* 2004, Kramer 2009). Generally, three scaling methods of earthquake records were summarized by Fahjan and Ozdemir (2008) as follows:

a. Time domain
b. Frequency domain
c. Spectral matching in time domain.

In this study, time domain spectral matching is considered, which is changing only amplitudes of the selected earthquake records. In order to check the compatibility of the scaled earthquake records to given target spectrum, the error function of "Mean Squared Error (MSE)" as given in Eq. (2) is utilized in the present study.

$$MSE = \frac{\sum_i w(T_i)\left(\ln[S_A^{target}(T_i)] - \ln[f \times S_A^{record}(T_i)]\right)^3}{\sum_i w(T_i)} \quad (2)$$

where, *MSE*: mean squared error, S_A^{target}: target spectral acceleration, S_A^{record}: spectral acceleration of selected earthquake, *w*: weighting function (for general case $w(T_i)$ =1.00) and *f*: scale factor

Scale factor, *f*, provides to be a minimum difference between target spectra and spectra of selected earthquake within the specific period range. Its value is computed with Eq. (3)

$$\ln f = \frac{\sum_i w(T_i)\ln\left(S_A^{target}(T_i)/S_A^{record}(T_i)\right)}{\sum_i w(T_i)} \quad (3)$$

According to the results obtained from the scaling, seven out of 23 selected earthquakes that are in closest compatibility with the target spectra are considered to obtain the local spectrum. As shown in Fig. 7, the spectral values of some of the earthquakes are far from those of the target spectra. The acceleration spectrum graphs of the selected records are shown in Fig. 8, and the mean square error and scale factor values are given in Table 2. Similar approach was adopted in the study of (Akın 2009).

3.2 Dynamic soil properties

Cyclic behavior of soil is estimated with dynamic soil properties, such as damping, predominant site period, soil amplification etc. Damping properties and rigidity of the soil can be used in the assessment of earthquake-related problems (Kramer 1996). Changes in the soil rigidity due to deformation are found using the damping ratio (D) and shear modulus decay (G/G_{max}) curves. The damping ratio and shear modulus of soils are considered as functions of the amplitude of shear unit deformation under cyclic loading. The damping ratio and shear modulus decay curves are the main parameters of soil response analyses performed using both nonlinear and equivalent linear techniques (Hanumantharao and Ramana 2008). In literature, many investigations on damping ratio and shear modulus decay curves were made for different types of soils (Seed *et al.* 1986, Sun *et al.* 1988, Vucetic and Dobry 1988, Darendeli 2001). In this study, the 1D equivalent linear site response analysis necessary for developing the maps that demonstrate the distribution of dynamic soil properties of the city of Kirikkale is carried out based on the proposed model of Darendeli (2001) which incorporates the plasticity index (PI) and confining pressure. Thus, the shear modulus decay and damping curves are obtained for the city of Kirikkale. In the 1D equivalent linear and nonlinear site response analyses for example soil profile of the city, the model of are compared.

Shear wave velocity (V_s) is commonly used in the characterization of soil behavior. When the V_s is not determined from the field tests, this parameter can be estimated with correlation between the V_s and/or G_{max} standard penetration test (SPT), plasticity index (PI) and grain-size distribution (Kramer 1996). In literature, a number of research studies were made focusing on the relationship between SPT blow count and V_s (Seed and Idriss 1981, Iyisan 1996, Hanumantharao and Ramana 2008, Dikmen 2009). The empirical equation of Eq. (4) developed by Iyisan (1996) is adopted so as to estimate the shear wave velocity of soils of Kirikkale using SPT values.

$$V_s = 51.5 \cdot N^{0.516} \tag{4}$$

where, V_s: Shear wave velocity (m/s) and N: SPT blow count

4. Site response analyses

One of the main aims of the present study constitutes of a database including geotechnical properties of soils of the city of Kirikkale. Geotechnical data of the study area are obtained for a number of borings, Multichannel Analysis of Surface Waves (MASW) and Seismic Refraction tests. Eliminating the boring tests with the lack of SPT data, total number of 108 borings with the depth of 10-30 m are utilized in the analysis. Based on the Seismic Refraction tests, the shear wave velocity (V_s) is determined as 350 $<V_s<$481 m/s in the study region. According to the

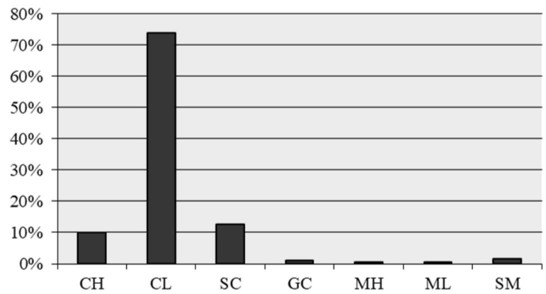

Fig. 9 Percentage distribution of the study region

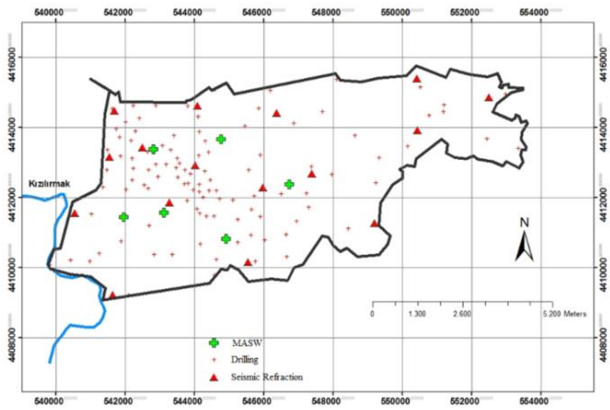

Fig. 10 Locations of the field tests at the study

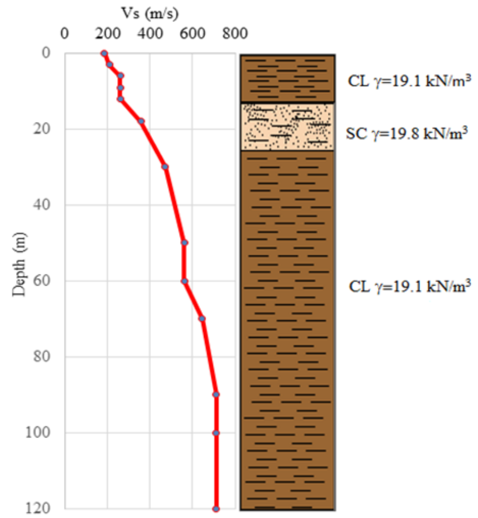

Fig. 11 Example soil profile of the study area

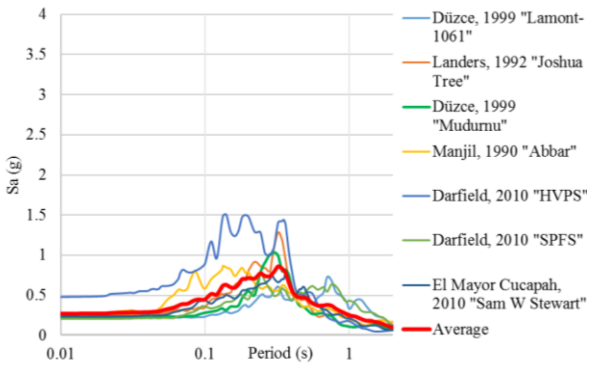

Fig. 12 Acceleration spectra of the scaled earthquakes at the bedrock level

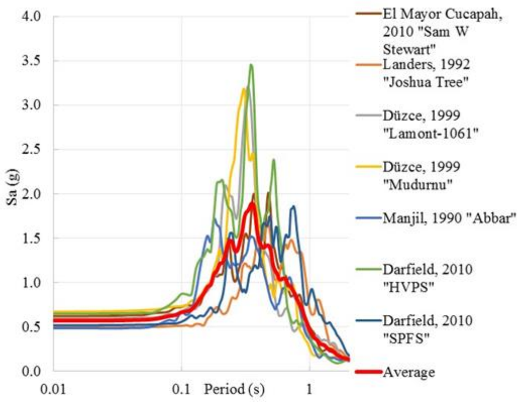

Fig. 13 Surface acceleration spectra of the scaled earthquakes from the EL analysis according to Darandeli (2001) model

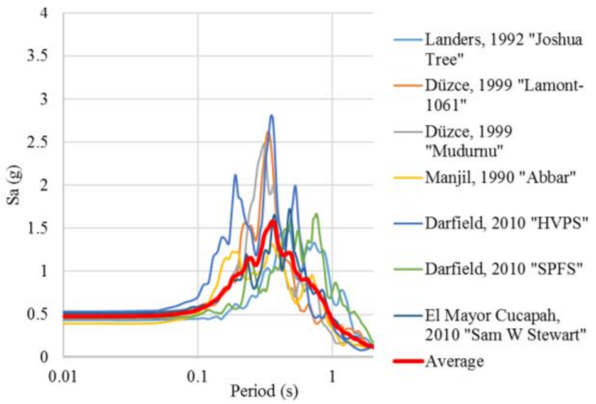

Fig. 14 Surface acceleration spectra of the scaled earthquakes from the EL analysis according to Vucetic and Dobry (1991) model

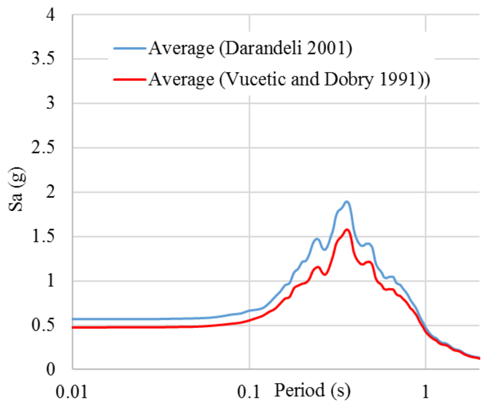

Fig. 15 Surface acceleration spectrum comparison of the EL analysis of Darandeli (2001) model with Vucetic and Dobry (1991) model

provisions of NEHRP-BSSC (2003), soil class of the city can be regarded as NEHRP very dense soil class of C. In addition, the new Turkish Seismic Code (AFAD 2018) classified the soil of Kirikkale as C (360 <V_s<760 m/s) and D (180<V_s<360 m/s at different locations of the city according to its V_s value. The soil of residential part of Kirikkale province consists of mostly CL (Clay) and less often CH and SC (Sand-Clay). Accordingly, the soil type of CL can be considered to be homogeneously distributed for the city of Kirikkale. The percentage distribution of the soils in the study region is given in Fig. 9.

In order to obtain shear wave velocity (Vs), 6 Active Multichannel Analysis of Surface Waves (MASW) and 15 Seismic Refraction applications are performed at the field and the SPT tests are carried out at 108 drilling points. Locations of the field tests at the study area are depicted in Fig. 10. The Vs is calculated using the formula given in Eq. (4) based on the SPT-N value up to 15-20 m depth in the soil profile as part of the soil behavior analyses. For depths greater than 20 m down to the bedrock, shear wave velocity however is calculated based on the results of MASW and seismic refraction tests.

The example soil profile, given in Fig. 11, is based on the average layer thickness values from the field tests of the study area. The undisturbed samples, obtained from the borings of the study site, indicated that the main ground layer was a clay layer (CL) and a clayey-sand layer with a thickness in the range of 3-8 m and an average of 5 m, which was located at approximately 5 m below the clay layer. The average thickness of the clay layer was about 120 m, based on the data from the deep borings conducted by the State Water Supply Administration (DSİ) of Turkey. In establishing the layer thicknesses in the typical soil profile (Fig. 11), these average values were considered. Eq. (4), proposed by İyisan (1996), was used for determining the shear wave velocity values from the SPT blow counts of the region.

The 1D Equivalent Linear (EL) site response analyses are performed using Shake2000 software (Ordonez 2012) on the example soil profile created using the drilling results obtained for the Kirikkale province. A total number of seven earthquake records are used and then scaled with the target spectrum defined using the attenuation relationships of the ASK, BSSA and CB. Fig. 12 shows the bedrock acceleration spectra of the selected records and Fig. 13 shows the surface acceleration spectra obtained using site response analyses based on the shear modulus decay curves and damping ratio suggested by (Darendeli 2001). Fig. 14 shows the surface acceleration spectra obtained using the shear modulus decay curves and damping ratio suggested by (Vucetic and Dobry 1991). Taking into account the confining pressure and plasticity index, (Darendeli 2001) model resulted in higher spectral acceleration values when compared to those obtained from (Vucetic and Dobry 1991) model shown in Fig. 15. This outcome is estimated to be related the effect of changing confining stress with depth on the soil behavior.

In this study, nonlinear site response analysis (NL) is also carried out using the Deepsoil software (Hashash *et al.* 2016) on the example soil profile as shown in Fig. 11. The NL analyses give more realistic and more accurate results when compared to 1D Equivalent Linear (EL) method. In the EL method, shear modulus and damping ratio are constant during loading while they are variable during loading in NL method (Kaklamanos *et al.* 2015). The shear modulus decay curves and damping ratio models recommended by EPRI (1993), Vucetic and Dobry (1991) and Darendeli (2001) are commonly used in soil behavior analyses in order to represent the dynamic soil behavior.

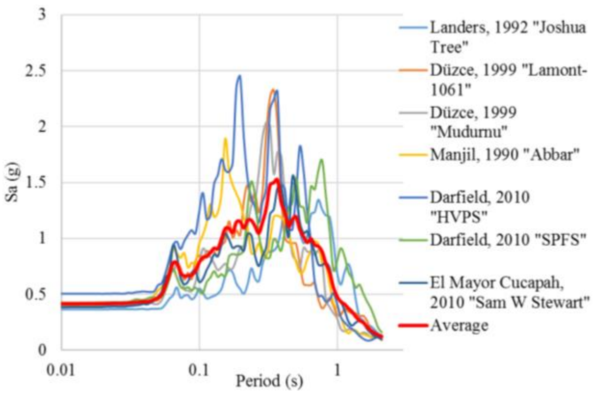

Fig. 16 Surface acceleration spectra from the NL analysis according to Vucetic and Dobry (1991) model

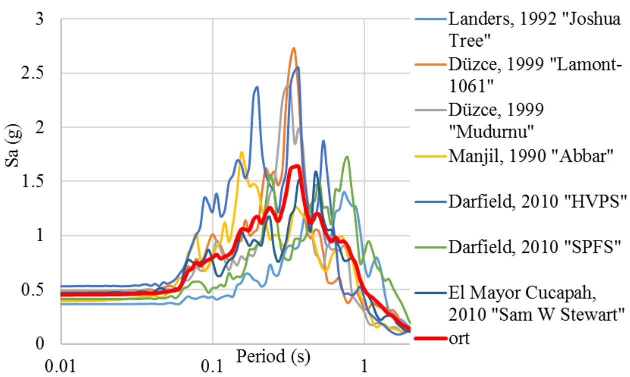

Fig. 17 Surface acceleration spectra from the NL analysis according to Darandeli (2001) model

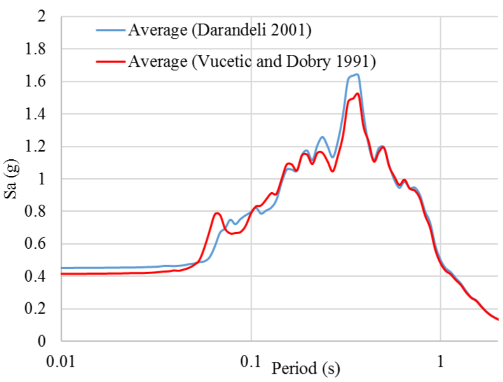

Fig. 18 Comparison of Darandeli (2001) model with (Vucetic and Dobry 1991) model in the NL analysis

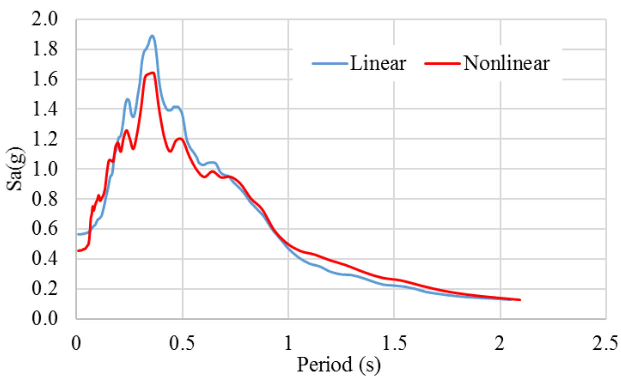

Fig. 19 Comparison of EL with NL according to the model Darandeli (2001).

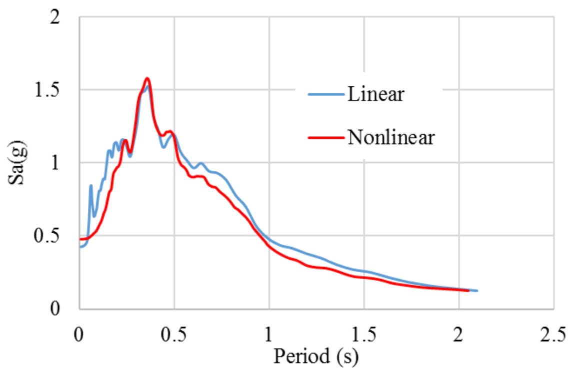

Fig. 20 Comparison of EL with NL according to the model Vucetic and Dobry (1991) model

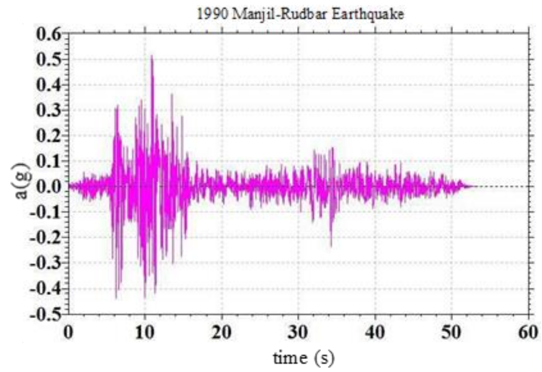

Fig. 21 1990 Manjil-Rudbar Earthquake record at the Abbar station (Iran)

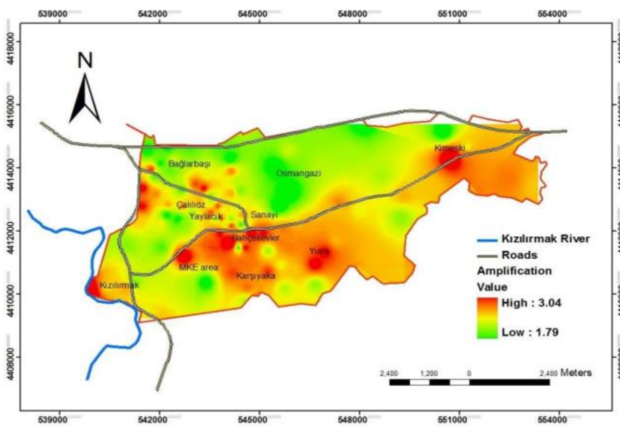

Fig. 22 Soil amplification map for the city center of Kirikkale

These models are applied to the shear modulus and damping ratio reference curves as a function of shear strain. However, these models are able to represent the small unit deformation sufficiently while being insufficient in the case of large unit deformation, allowing unrealistic shear stresses for increasing strains. This problem is attempted to be eliminated using models such as Modified Kondner-Zelasko (Matasovic 1993) and General Quadratic/Hyperbolic (Groholsk *et al.* 2015). The Deepsoil software performs analyses using appropriate shear modulus decay and damping ratio curves produced with Modified Kondner-Zelasko (Matasovic 1993) and General Quadratic/Hyperbolic (Groholsk *et al.* 2015).

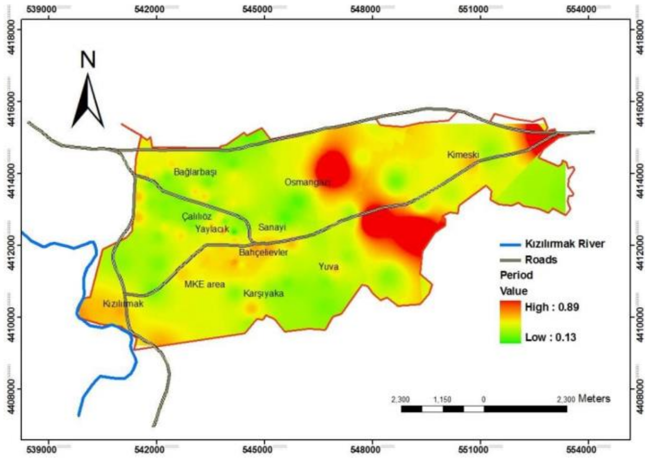

Fig. 23 Predominant site period map for the city center of Kirikkale

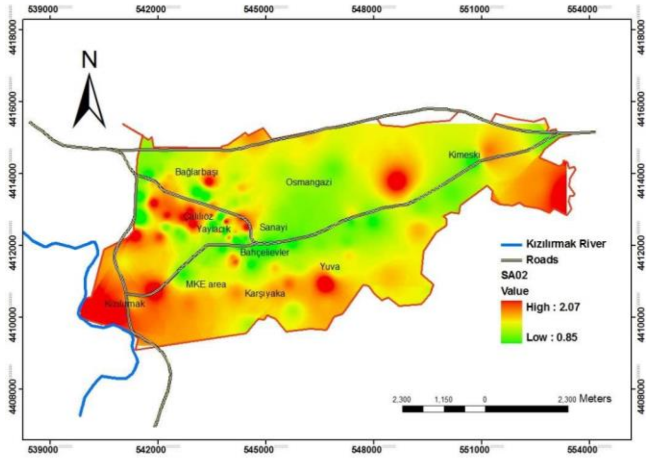

Fig. 25 Spectral acceleration map of the city center of Kirikkale for T=0.2 s period

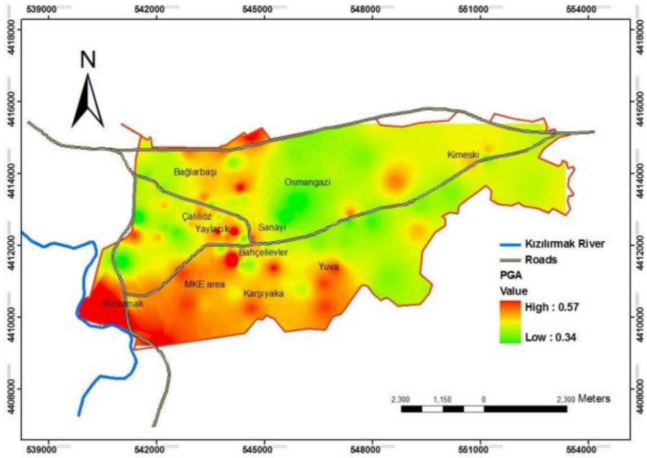

Fig. 24 Peak ground acceleration (PGA) map for the city center of Kirikkale

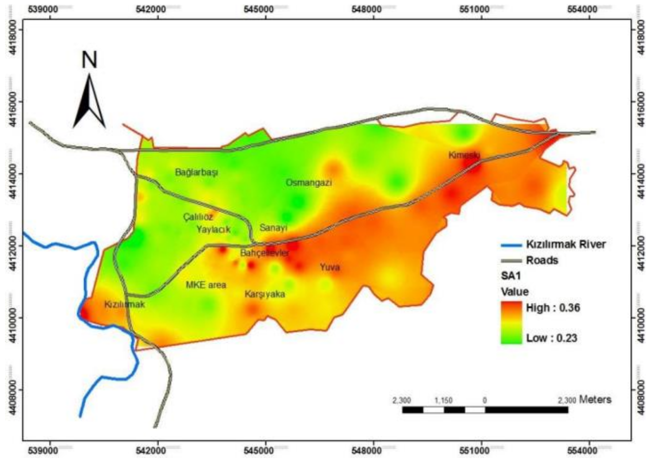

Fig. 26 Spectral acceleration map of the city center of Kirikkale for T=1.0 s period

Using Modified Kondner-Zelasko model in the NL analysis in this study, it is possible to produce curves complying with Darendeli (2001) and Vucetic and Dobry (1991) models are generated, and the analyses are performed. A total number of seven earthquake records are used in nonlinear site response analyses as it is the case for equivalent linear analysis. Figs. 16-17 show the surface acceleration spectra obtained using Darendeli (2001) and Vucetic and Dobry (1991) models, respectively, in nonlinear analyses. Fig. 18 shows a comparison of the results obtained from Darendeli (2001) and Vucetic and Dobry (1991) models. Darendeli (2001) model produced a higher spectral acceleration results when compared to those of Vucetic and Dobry (1991) model. Fig. 19 shows the comparison of the Equivalent linear analyses with the nonlinear analysis results obtained using Darendeli (2001) model. The equivalent linear analysis produced results similar to those of nonlinear analysis with the exception of 0.2 - 0.5 s periods; and the EL results are higher for this period range. Fig. 20 shows the comparison of the equivalent linear analysis with the nonlinear analysis results obtained using Vucetic and Dobry (1991). The NL analysis results are higher than EL analysis results for periods smaller than T=0.25 s while both results are comparable to other periods.

Figs. 22-26 indicate the amplification ratio, predominant site period, peak ground acceleration (PGA), and spectral acceleration maps for T=0.2 and T=1.0 s based on the site response analysis performed on 108 drilling locations, respectively. In order to create the maps, the record from "Abbar" station in Iran for the 1990 Manjil-Rudbar Earthquake (M_w=7.37) is used in site response analyses as this earthquake is more comparable to the target spectrum and offered the lowest mean-square error. In Fig. 21, the acceleration-time history of the earthquake used in the analyses is given.

Acceleration spectra reflect the maximum acceleration response of single degree of freedom system with different periods under a specific earthquake history. Specific part of the acceleration spectra refers to spectral acceleration (S_a). Developing a map with maximum values of surface acceleration spectra obtained from site response analyses is not useful due to the fact that the period corresponding to acceleration value is not known. However, the short period of T=0.2 s and the long period of T=1.0 s are considered as important specific periods in many design codes and studies in literature for reliable spectral analysis. Therefore, these specific periods ae taken into account in this study to develop maps that present the distribution of dynamic soil characteristics of the study region.

Amplification ratios in the study region are shown in Fig. 22 to change with the range between 1.79 and 3.04, and the highest amplification ratios are observed in the MKE province, and the neighboring regions of Karşıyaka, Yuva, Bahçelievler and Kimeski provinces. The other dynamic soil parameter of predominant site period varies between 0.13 s and 0.9 s in the study region. While the periods of MKE province and the neighboring regions of Kızılırmak, Karşıyaka, Yaylacık, Osmangazi, Yuva and Kimeski provinces are obtained in the maximum range between 0.50 and 0.89 s, the periods of other locations are in the range between 0.13 se and 0.50 s as depicted in Fig. 23 with the contour maps.

As shown in Fig. 24, peak ground acceleration (PGA) values are found to change between 0.34 g and 0.57 g. The maximum PGA values are observed in the MKE province and the neighboring region of Kızılırmak, Bahçelievler, Karşıyaka, and Yuva provinces. According to Fig. 25, the short period (T=0.2 s) spectral accelerations are found in the range between 2.07 g and 0.85 g, and the long period (T=1.0 s) spectral accelerations are found in the range between 0.23 g and 0.36 g as indicated in Fig. 26

In the light of this data, although high amplification ratios are obtained from the MKE province, and the neighboring regions of Kızılırmak and Bahçelievler where relatively longer periods are observed, the spectral acceleration values found from these locations are in lower range between 0.23 g and 0.36 g. Moreover, the neighboring regions of Bağlarbaşı, Çalılıöz and Sanayi provinces where short periods (T=0.20 s) are effective are identified to have medium level of amplification (2.0-2.5), yet the spectral acceleration values (0.85-2.07 g) obtained in these locations are higher when the short period (T=0.20 s) spectral acceleration map is analyzed.

5. Conclusions

In this study, it aimed at determining the dynamic soil characteristics of the city center of Kirikale based on results obtained from the seismic hazards analysis and surface acceleration response spectrum due to high seismicity of the Kirikkale province. For this aim, a number of field tests including SPT tests on the drilling points, Multichannel Analysis of Surface Waves (MASW) and Seismic Refraction tests are conducted on the study area. Based on the tests, the soil profile of the study region is obtained to be used in the site response analysis. Considering these findings as inputs, the 1D equivalent linear (EL) and nonlinear site response analyses are performed to identify the dynamic soil parameters of the earthquake-prone city of Kirikkale. The values of the parameters are given in a distributive manner with developed contour maps. Depending on the outcomes from these efforts, the following key points are obtained in the study.

• According to the probabilistic seismic hazard analysis performed for the city center of Kirikkale, the magnitude of a possible earthquake is found to be M_w=7.0 with respect to 50-year building life span and 10% probability of exceedance.

• Darendeli (2001) model results in higher spectral acceleration values both in 1D equivalent linear analyses (EL) and nonlinear analyses (NL) when compared to the Vucetic and Dobry (1991) model.

• The results from the equivalent linear analysis (EL) are obtained to be similar to those of the nonlinear analysis (NL) with the exception of 0.2-0.5 s periods and the EL results are higher for this period range. The equivalent linear analysis using Vucetic and Dobry (1991) model results in lower acceleration values at periods smaller than 0.25 s when compared to the nonlinear analysis (NL). For other periods, the results are comparable to the EL results.

• Although high amplification ratios are obtained from the MKE province and the neighboring region of Kızılırmak and Bahçelievler provinces where relatively long periods are observed, spectral acceleration values obtained in these locations are in a lower range between 0.23 and 0.36 g.

• The neighboring regions of Bağlarbaşı, Çalılıöz and Sanayi provinces where short periods (T=0.20 s) are effective are identified to have medium level of amplification (2.0-2.5), but the spectral acceleration values (0.85-2.07g) obtained in these locations are higher when the short period (T=0.20 s) spectral acceleration map is analyzed.

• The south-west region of the city is estimated under more risk than other regions according to the PGA and spectral acceleration values for the short period of T=0.2 s. The higher values of these parameters are seen for the long-period of T=1.0 s to extend to the southern part of the city as depicted in Fig. 26. Therefore, the buildings to be built at the regions are estimated to be affected more from earthquake motion.

• It is also estimated that the buildings with high modal periods will be exposed to low S_a (0.23-0.36 g) while the buildings with low modal periods will be exposed to higher S_a (0.85-2.07 g). From this conclusion, construction of high-rise buildings with modal periods higher than T=1.0 s are obtained to be suitable for the city of Kirikkale.

• The city center is seen to be more vulnerable to seismic load in terms of all engineering parameters. Particularly, the high values of the amplification ratio and PGA in the city center depict that the greater part of existing building stock is under high seismic risk and thus, the buildings at the city center should be assessed with street survey rapid structural evaluation methods so as to mitigate seismic damages.

• The obtained contour maps in this study are estimated to be effective for visually characterizing the city in terms of the considered parameters.

Acknowledgements

The research described in this paper was financially supported by Kirikkale University Scientific Research Projects (BAP) Coordination Unit (Project No: 2014/54). The authors would like to thank Kirikkale University BAP Coordination Unit.

References

Abrahamson, N.A., Silva, W.J. and Kamai, R. (2013), “Update of the AS08 ground-motion prediction equations based on the NGAWest2 data set", Research Report, Pacific Earthquake Engineering Research Center (PEER), University of California, Berkeley, California, U.S.A.

AFAD (2016), *Earthquake Zone Map of Turkey*, Republic of Turkey Prime Ministry Disaster and Emergency Management Authority, Ankara, Turkey.

AFAD (2018), *Turkish Earthquake Code for Buildings*, Disaster and Emergency Management Directorate, Ankara, Turkey.

Akın, M. (2009), "Seismic microzonation of Erbaa (Tokat-Turkey) located along eastern segment of the North Anatolian Fault Zone (NAFZ)", Ph.D. Dissertation, Middle East Technical University, Ankara, Turkey.

Akin, M.K., Kramer, S.L. and Topal, T. (2016), "Dynamic soil characterization and site response estimation for Erbaa, Tokat (Turkey)", *Nat. Hazards*, **82**(3), 1833-1868.

Akin, M.K., Topal, T. and Kramer, S.L. (2013), "A newly developed seismic microzonation model of Erbaa (Tokat, Turkey) located on seismically active eastern segment of the North Anatolian Fault Zone (NAFZ)", *Nat. Hazards*, **65**(3), 1411-1442.

Akkar, S. and Bommer, J.J. (2007), "Empirical prediction equations for peak ground velocity derived from strong-motion records from Europe and the Middle East", *B. Seismol. Soc. Am.*, **97**(2), 511-530.

Algermissen, S.T. and Perkins, D.M. (1976), "A probabilistic estimate of maximum acceleration in rock in the contiguous", Research Report, United States Geological Survey.

Allen, C.R. (1969), "Active faulting in northern Turkey", Research Report, Caltech Division of Geological Sciences, Pasadena, California, U.S.A.

Ambraseys, N.N. and Bommer, J.J. (1991), "The attenuation of ground accelerations in Europe", *Earthq. Eng. Struct. Dyn.*, **20**(12), 1179-1202.

BDTİM (2015), *Regional Earthquake-Tsunami Monitoring Center*, Boğaziçi University Kandilli Observatory and Earthquake Research Institute, Istanbul, Turkey.

Birgili, Ş.R.Y. and Ünalan, G. (1975), "Geological poperties of Çankırı-Çorum and is potential for petroleum production", Research Report, MTA, Ankara, Turkey.

Bommer, J., Spence, R., Erdik, M., Tabuchi, S., Aydinoglu, N., Booth, E., del Re, D. and Peterken, O. (2002), "Development of an earthquake loss model for Turkish catastrophe insurance", *J. Seismol.*, **6**(3), 431-446.

Boore, D.M., Stewart, J.P., Seyhan, E. and Atkinson, G.M. (2013), "NGA-West2 equations for predicting response spectral accelerations for shallow crustal earthquakes", Research Report; Pacific Earthquake Engineering Research Center (PEER), University of California, Berkeley, California, U.S.A.

Bozkurt, E. (2001), "Late Alpine evolution of the central Menderes Massif, western Turkey", *Int. J. Earth Sci.*, **89**(4), 728-744.

Büyüksaraç, A., Bektaş, Ö., Yılmaz, H. and Arısoy, M.Ö. (2013), "Preliminary seismic microzonation of Sivas city (Turkey) using microtremor and refraction microtremor (ReMi) measurements", *J. Seismol.*, **17**(2), 425-435.

Campbell, K.W. (1989), "The dependence of peak horizontal acceleration on magnitude, distance, and site effects for small-magnitude earthquakes in California and Eastern North America", *B. Seismol. Soc. Am.*, **79**(5), 1311-1346.

Campbell, K.W. and Bozorgnia, Y. (2013), "NGA-West2 Campbell-Bozorgnia ground motion model for the horizontal components of PGA, PGV, and 5%-damped elastic pseudo-acceleration response spectra for periods ranging from 0.01 to 10 sec", Research Report, Pacific Earthquake Engineering Research Center (PEER), University of California, Berkeley, California, U.S.A.

Cornell, C.A. (1968), "Engineering seismic risk analysis", *B. Seismol. Soc. Am.*, **58**(5), 1583-1606.

Darendeli, M. (2001), "Development of a new family of normalized modulus reduction and material damping curves", Ph.D. Dissertation, University of Texas at Austin, Austin, Texas, U.S.A.

Das, S., Gupta, I.D. and Gupta, V.K. (2006), "A Probabilistic Seismic Hazard Analysis of Northeast India", *Earthq. Spectra*, **22**(1), 1-27.

Deniz, A. (2006), "Estimation of earthquake insurance premium rates for Turkey", M.Sc. Thesis, Middle East Technical University, Ankara, Turkey.

Deniz, A. and Yucemen, M.S. (2010), "Magnitude conversion problem for the Turkish earthquake data", *Nat. Hazards*, **55**(2), 333-352.

Dikmen, Ü. (2009), "Statistical correlations of shear wave velocity and penetration resistance for soils", *J. Geophys. Eng.*, **6**(1), 61.

EPRI (1993), *Guidelines for Determining Design Basic Ground Motions*, Electric Power Research Institute, U.S.A.

Erdik, M., Biro, Y.A., Onur, T., Sesetyan, K. and Birgoren, G. (1999), "Assessment of earthquake hazard in Turkey and neighboring regions", *Annal. Geophys.*, **42**(6), 1125-1138.

Erkan, Y. (1975), "A petrological analysis of the regional metamorphism available in the Kırşehir segment of Central Anatolia massif", Assoc. Prof. Dissertation, Hacettepe University, Ankara, Turkey.

Fahjan, Y. and Ozdemir, Z. (2008), "Scaling of earthquake accelerograms for non-linear dynamic analyses to match the earthquake design spectra", *Proceedings of the 14th World Conference on Earthquake Engineering*, Beijing, China, October.

Fatahi, B., Far, H. and Samali, B. (2014), "Soil-structure interaction vs site effect for seismic design of tall buildings on soft soil", *Geomech. Eng.*, **6**(3), 293-320.

Firat, S., Isik, N.S., Arman, H., Demir, M. and Vural, I. (2016), "Investigation of the soil amplification factor in the Adapazari region", *Bull. Eng. Geol. Environ.*, **75**(1), 141-152.

Gardner, J.K. and Knopoff, L. (1974), "Is the sequence of earthquakes in Southern California, with aftershocks removed, Poissonian?", *B. Seismol. Soc. Am.*, **64**(5), 1363-1367.

Gautam, D., Forte, G. and Rodrigues, H. (2016), "Site effects and associated structural damage analysis in Kathmandu Valley, Nepal", *Earthq. Struct.*, **10**(5), 1013-1032.

Groholski, D., Hashash, Y., Musgrove, M., Harmon, J. and Kim, B. (2015), "Evaluation of 1-D non-linear site response analysis using a general quadratic/hyperbolic strength-controlled constitutive model", *Proceedings of the 6th International Conference on Earthquake Geotechnical Engineering*, Christchurch, New Zealand, November.

Gülkan, P. and Kalkan, E. (2002), "Attenuation modeling of recent earthquakes in Turkey", *J. Seismol.*, **6**(3), 397-409.

Gülkan, P., Kocyigit, A., Yucemen, S., Doyuran, V. and Basoz, N. (1993), "Earthquake zoning map of Turkey based on most recent data", Research Report, METU Earthquake Engineering Research Center, Ankara, Turkey.

Gutenberg, B. and Richter, C. (1942), "Earthquake magnitude, intensity, energy, and acceleration", *B. Seismol. Soc. Am.*, **32**(3), 163-191.

Gutenberg, B. and Richter, C. (1944), "Frequency of earthquakes in California", *B. Seismol. Soc. Am.*, **34**(4), 185-188.

Gutenberg, B. and Richter, C. (1956), "Magnitude and energy of earthquakes", *Ann. Geophys.*, **9**(1), 1-15.

Hanumantharao, C. and Ramana, G.V. (2008), "Dynamic soil properties for microzonation of Delhi, India", *J. Earth Syst. Sci.*, **117**(2), 719-730.

Hashash, Y.M.A., Musgrove, M.I., Harmon, J.A., Groholski, D.R., Phillips, C.A. and Park, D. (2016), *DEEPSOIL 6.1, User*

Manual, Board of Trustees of University of Illinois at Urbana-Champaign, Champaign, Illinois, U.S.A.

Işık, N.S. (2010), "Assessment of the site amplifications and predominant site periods for Saruhanlı, in an earthquake-prone region of Turkey", *Bull. Eng. Geol. Environ.*, **69**(2), 309-319.

Iyisan, R. (1996), "Correlations between shear wave velocity and penetration experiments in soils", *IMO Tech. Periodical*, **7**(32), 1187-1199.

Joyner, W.B. and Boore, D.M. (1981), "Peak horizontal acceleration and velocity from strong-motion records including records from the 1979 Imperial Valley, California, earthquake", *B. Seismol. Soc. Am.*, **71**(6), 2011-2038.

Kagan, Y.Y. (2002), "Seismic moment distribution revisited: I. Statistical results", *Geophys. J. Int.*, **148**(3), 520-541.

Kaklamanos, J., Baise, L.G., Thompson, E.M. and Dorfmann, L. (2015), "Comparison of 1D linear, equivalent-linear, and nonlinear site response models at six KiK-net validation sites", *Soil Dyn. Earthq. Eng.*, **69** 207-219.

Kalkan, E., Gülkan, P., Yilmaz, N. and Çelebi, M. (2009), "Reassessment of probabilistic seismic hazard in the Marmara Region", *B. Seismol. Soc. Am.*, **99**(4), 2127-2146.

Kayabali, K. and Akin, M. (2003), "Seismic hazard map of Turkey using the deterministic approach", *Eng. Geol.*, **69**(1), 127-137.

Ketin, İ. (1955), "Geological properties of Yozgat and its environs and the tectonic status of Central Anatolia Massif", *Turkish Geol. Bull.*, **6**(1), 1-40.

Kijko, A. and Graham, G. (1998), "Parametric-historic procedure for probabilistic seismic hazard analysis part i: Estimation of maximum regional magnitude Mmax", *Pure Appl. Geophys.*, **152**(3), 413-442.

Kılıç, H., Özener, P.T., Ansal, A., Yıldırım, M., Özaydın, K. and Adatepe, Ş. (2006), "Microzonation of Zeytinburnu region with respect to soil amplification: A case study", *Eng. Geol.*, **86**(4), 238-255.

Kocyigit, A. (2000), "General neotectonic characteristics and seismicity of Central Anatolia", Research Report, Turkish Petroleum Geologists, Ankara, Turkey.

Kocyigit, A. (2008), "Seismicity of Ankara and the origins of 2005-2007 Afşar (Bala-Ankara) earthquake", *MTA Nat. Resour. Econ. Bull.*, 1-7.

Kolat, C., Ulusay, R. and Suzen, M.L. (2012), "Development of geotechnical microzonation model for Yenisehir (Bursa, Turkey) located at a seismically active region", *Eng. Geol.*, **127**, 36-53.

Kramer, S. (1996), *Geotechnical Earthquake Engineering*, Prentice Hall, Upper Saddle River, New Jersey, U.S.A.

Kramer, S. (2009), *CEE 526 Geotechnical Earthquake Engineering Lecture Notes*, University of Washington, Seattle, Washington, D.C., U.S.A.

Matasovic, N. (1993), "Seismic response of composite horizontally-layered soil deposits", Ph.D. Dissertation, University of California, Los Angeles, Los Angeles, California, U.S.A.

MTA (2015), "Active fault map of Turkey Kırşehir (NJ 363) plat", Research Report, General Directorate of Mineral Research and Exploration, Ankara, Turkey.

Naeim, F., Alimoradi, A. and Pezeshk, S. (2004), "Selection and scaling of ground motion time histories for structural design using genetic algorithms", *Earthq. Spectra*, **20**(2), 413-426.

NEHRP-BSSC (2003), *NEHRP (National Earthquake Hazard Reduction Program) Recommended Provisions for New Buildings and Other Structures (FEMA 450)*, Building Seismic Safety Council, National Institute of Building Sciences, Washington, D.C., U.S.A.

Ordonez, G. (2012), *Shake2000: A Computer Program for the 1-D Analysis of Geotechnical Earthquake Engineering Problems*, GeoMotions, LLC, Washington, D.C., USA

Özbey, C., Sari, A., Manuel, L., Erdik, M. and Fahjan, Y. (2004), "An empirical attenuation relationship for Northwestern Turkey ground motion using a random effects approach", *Soil Dyn. Earthq. Eng.*, **24**(2), 115-125.

Parejas, E. and Pamir, H.N. (1939), "Nisan 1938 Orta Anadolu yer deprenmesi—Le tremblement de terre du 19 Avril 1938 en Anatolie centrale)", *Inst. Geol. Pub. ns*, **5**(3/4), 1-21.

Richter, C. (1958), *Elementary Seismology*, W.H. Freeman and Company, San Francisco, California, U.S.A.

Rojay, B. and Koçyiğit, A. (2012), "An active composite pull-apart basin within the central part of the North Anatolian Fault System: The Merzifon-Suluova Basin, Turkey", *Turk. J. Earth Sci.*, **21**(4), 473-496.

Savage, M.K. and Rupp, S.H. (2000), "Foreshock probabilities in New Zealand", *New Zealand J. Geol. Geophys.*, **43**(3), 461-469.

Scawthorn, C. and Chen, W.F. (2002), *Earthquake Engineering Handbook*, CRC Press, Boca Raton, Florida, U.S.A.

Seed, H. and Idriss, I. (1981), *Evaluation of Liquefaction Potential Sand Deposits based on Observation of Performance in Previous Earthquakes*, in *ASCE National Convention (MO)*, U.S.A., 481-544.

Seed, H., Wong, R., Idriss, I. and Tokimatsu, K. (1986), "Moduli and damping factors for dynamic analyses of cohesionless soils", *J. Geotech. Eng.*, **112**(11), 1016-1032.

Selçuk, L. and Çiftçi, Y. (2007), "Microzonation of the Plio-Quaternary soils: A study of the liquefaction risk potential in the Lake Van Basin, Turkey", *Bull. Eng. Geol. Environ.*, **66**(2), 161-176.

Şengör, A.M.C., Görür, N. and Şaroğlu, F. (1985), "Strike-slip faulting and related basin formation in zones of tectonic escape: Turkey as a case study", *SEPM Society for Sedimentary Geology*.

Seymen, I. (1982), "Geology of Kırşehir massif with a vicinity to Kaman", Assoc. Prof. Dissertation, Istanbul Technical University, Istanbul, Turkey.

Silahtar, A., Budakoğlu, E., Horasan, G., Yıldırım, E., Serdar Küyük, H., Yavuz, E. and Çaka, D. (2016), "Investigation of site properties in Adapazarı, Turkey, using microtremors and surface waves", *Environ. Earth Sci.*, **75**(20), 1354.

Sisi, A., Erberik, M.A. and Askan, A. (2018), "The effect of structural variability and local site conditions on building fragility functions", *Earthq. Struct.*, **14**(4), 285-295.

Sitharam, T.G. and Anbazhagan, P. (2007), "Seismic hazard analysis for the Bangalore region", *Nat. Hazards*, **40**(2), 261-278.

Sucuoglu, H. (2015), "Performance-based earthquake engineering", *Proceedings of the 3rd National Conference on Earthquake Engineering and Seismology*, Izmir, Turkey, October.

Sun, J., Golesorkhi, R. and Seed, H. (1988), "Book chapter: Dynamic moduli and damping ratios for cohesive soils", Research Report, Earthquake Engineering Research Center, Berkeley, California, U.S.A.

Tavakoli, H., Amiri, M., Abdollahzadeh, G. and Janalizade, A. (2016), "Site effect microzonation of Babol, Iran", *Geomech. Eng.*, **11**(6), 821-845.

TEFER (2000), "A probabilistic seismic hazard assessment for Turkey", Research Report, Prime Ministry Treasury and Foreign Trade Undersecretariat-General Directorate of Insurance, Ankara, Turkey.

Tezcan, S.S., Kaya, E., Engin Bal, İ. and Özdemir, Z. (2002), "Seismic amplification at Avcılar, Istanbul", *Eng. Struct.*, **24**(5), 661-667.

Ulusay, R. and Kuru, T. (2004), "1998 Adana-Ceyhan (Turkey) earthquake and a preliminary microzonation based on liquefaction potential for Ceyhan Town", *Nat. Hazards*, **32**(1), 59-88.

USGS (2016), *U.S. Geological Survey Earthquake Search*, United

States Geological Survey, U.S.A.

Utsu, T., Ogata, Y. and Matsuura, R.S. (1995), “The centenary of the Omori formula for a decay law of aftershock activity”, *J. Phys. Earth*, **43**(1), 1-33.

Van Dyck, J.F.M. (1985), “Statistical analysis of earthquake catalogs”, Ph.D. Dissertation, Massachusetts Institute of Technology, Cambridge, Massachusetts, U.S.A.

Vucetic, M. and Dobry, R. (1988), “Degradation of marine clays under cyclic loading”, *J. Geotech. Eng.*, **114**(2), 133-149.

Vucetic, M. and Dobry, R. (1991), “Effect of soil plasticity on cyclic response”, *J. Geotech. Eng.*, **117**(1), 89-107.

Yucemen, M. (2011), “Probabilistic seismic hazard analysis: Overview and considerations in statistical modeling”, *Proceedings of the 1st Turkish Earthquake Engineering and Seismology Conference*, Ankara, Turkey, November.

CC