

A newly developed seismic microzonation model of Erbaa (Tokat, Turkey) located on seismically active eastern segment of the North Anatolian Fault Zone (NAFZ)

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Abstract A methodology to model seismic microzonation maps is required in the hazard mitigation decision plans of the earthquake prone areas. The stage of disaster preparedness for new residential places is of great importance for detailed seismic microzonation models. The effects of local geological and geotechnical site conditions were considered in order to establish site characterization as the initial stage of the models in this study. Dynamic soil properties based on the empirical correlations between shear wave velocity (V_s) and standard penetration test blow counts were taken into account in order to define representative soil profiles extending down to the engineering bedrock. One-dimensional site response analyses were performed to analyze earthquake characteristics on the ground surface. The layers for soil classification, geology, depth to groundwater level, amplification, distance to fault, slope and aspect, and liquefaction-induced ground deformation potential of the study area were prepared in seismic microzonation models. The study area, Erbaa, is placed along the seismically active North Anatolian Fault Zone. Final seismic microzonation map of the study area was evaluated applying different GIS-based Multi-Criteria Decision Analysis (MCDA) techniques. Two of the MCDA techniques, simple additive weighting and analytical hierarchical process (AHP), are considered during the evaluation step of the final seismic microzonation map. The comparison is made in order to distinguish two different maps based on these MCDA techniques. Eventually, AHP-based seismic microzonation map is more preferable for the seismic design purposes in this study.

Keywords Seismic microzonation · GIS · Simple additive weighting (SAW) and analytical hierarchical process (AHP) · Erbaa · Turkey

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1 Introduction

Seismic microzonation models are needed especially for city planning, disaster preparedness, and hazard mitigation decisions in earthquake prone areas. The most suitable residential areas can be determined using proper seismic microzonation models for each seismically active area. Preparation of the seismic microzonation maps is the main aspect for the evaluation of natural hazard-related effects. Seismic microzonation requires both multi-disciplinary contributions and combinations of the effects of earthquake generated ground motions on man-made structures (De Mulder 1996; Ansal et al. 2004; Pitilakis 2004; Dan 2005).

Seismic microzonation can be considered as understanding the procedure regarding the response of soils under earthquake ground motion using geological, geotechnical, and geophysical data. Additionally, geological and geotechnical data are crucial to identify, control, and prevent geological natural hazards (Bell et al. 1987; Legget 1987; Hake 1987; Rau 1994; Dai et al. 1994, 2001; GDDA 1996, 2000; Van Rooy and Stiff 2001; Ansal et al. 2001, 2004; Topal et al. 2003; Akin 2009).

Turkey is one of the most seismically active countries, and the northern part of Turkey is seismically controlled by the active North Anatolian Fault Zone (NAFZ) which has a dextral strike-slip movement with an approximately 1,600-km-long surface rupture (Allen 1969; Ketin 1969; Ambraseys 1970; Şengör 1979; Şengör et al. 1985; Barka 1992; Armijo et al. 1999; Bozkurt 2001). Erbaa (Tokat), located on the eastern part of the North Anatolian Fault segment as a study area, is in a critical place with respect to construction and potential development. After the disastrous 1942 ($M_s = 7.2$) and 1943 ($M_s = 7.6$) earthquakes (Tatar et al. 1990; Barka 1992; Barka et al. 2000), most subsequent development in the Erbaa region was moved to the hilly region toward the south of the Kelkit River (Fig. 1).

The aim of this study is to develop seismic microzonation models in terms of different site conditions containing a variety of geological, geotechnical, and geophysical data in order to determine the suitability of residential areas in Erbaa. Soil properties and dynamic soil behaviors are considered during the preparation of these models. Soil classification, geology, depth to groundwater level, amplification, distance to fault, slope and aspect, and liquefaction-induced ground deformation potential of the study area are evaluated in seismic microzonation models. Final seismic microzonation map of Erbaa is prepared applying different GIS-based multi-criteria decision analysis (MCDA) techniques. Throughout the study, ARCGIS 9 (ESRI 2011) is employed for the preparation of the seismic microzonation maps.

The produced seismic microzonation maps are established using different GIS-based MCDA techniques in this study. Simple additive weighting (SAW) and analytical hierarchical process (AHP), which are the two widely used MCDA methods, are considered for the production of seismic microzonation maps. The essential layers for the maps are prepared by means of GIS methodologies. The obtained seismic microzonation maps with respect to two different MCDA methods are compared in order to define the final seismic microzonation map of Erbaa.

2 Methodology for seismic microzonation models

Preparation of the seismic microzonation maps is valuable solutions for evaluating the effects of natural hazards in urban planning and earthquake-resistant design of

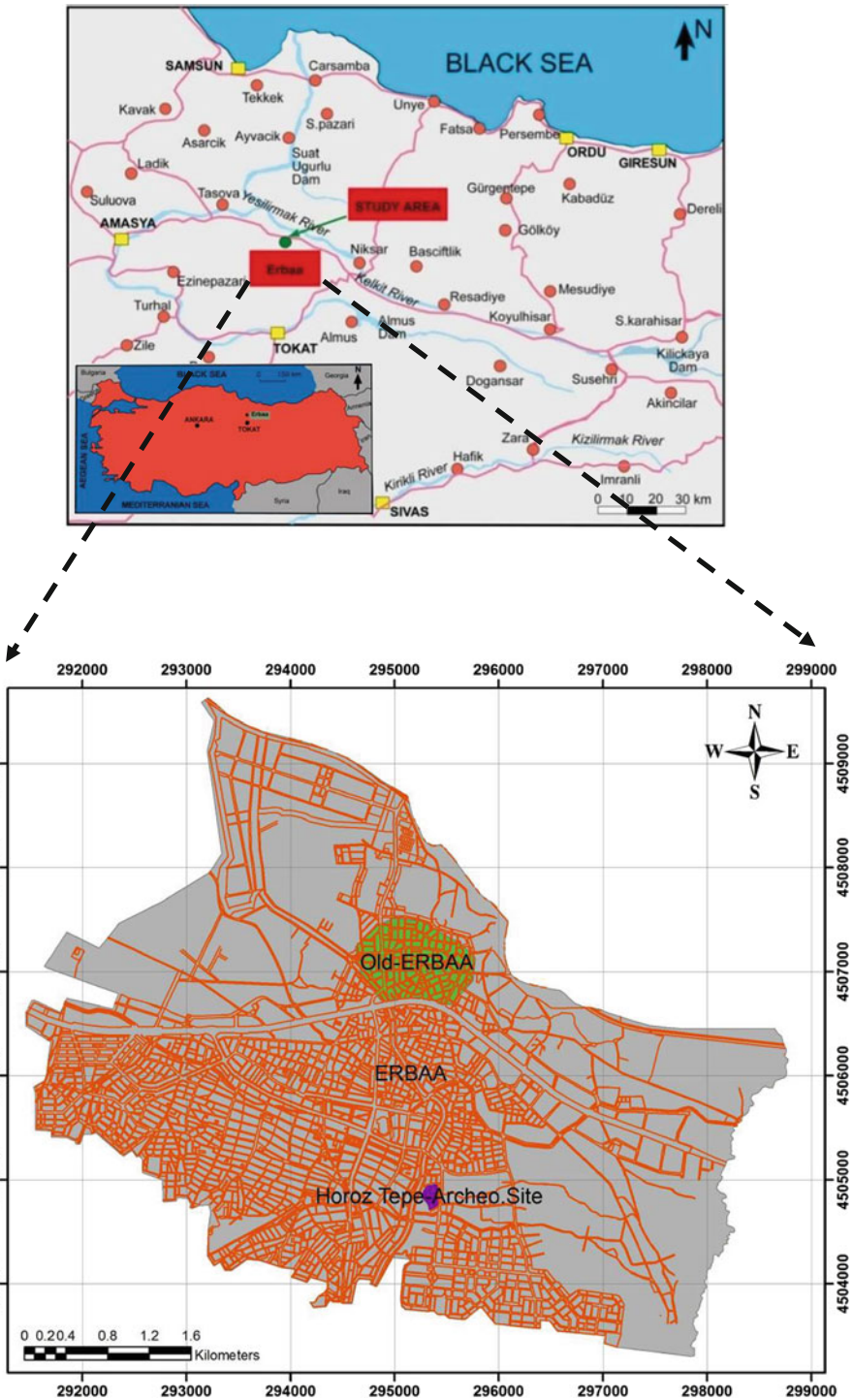


Fig. 1 Location map of the study area

constructions. Seismic microzonation is the procedure of the evaluation of soil/rock layers under earthquake loading conditions with ground motion properties. Seismic microzonation studies generally involve three stages according to İnce et al. (2008): (a) the assessment of seismicity and regional seismic hazard, (b) identification of geological structure and fault features, (c) the determination of the effects of local geotechnical conditions in the study area. In other words, the development of a hazard map is important to consider the source of an earthquake and evaluate the propagation of waves to the top of the bedrock with the determination of the effects of local soil profile to indicate the potential seismic hazards.

In this study, the first step is to adopt a grid system that divides the study area into cells (500 m × 500 m) according to the available geological and geotechnical data. Shear wave velocities obtained from geophysical tests and empirical correlations are considered in order to apply site-specific empirical relationships between V_s (m/s) and SPT- N_{30} . Besides, newly developed site-specific empirical relationships between V_s (m/s) and SPT- N_{30} are used in site response analyses (Akin et al. 2011). Site characterization is performed on the basis of boreholes and other relevant information by defining one representative soil profile for each grid cell with shear wave velocities extending down to the bedrock (shear wave velocity, $V_s \geq 760$ m/s). Site-specific earthquake characteristics on the ground surface for each representative soil profile are calculated using equivalent one-dimensional site response analyses by means of ProShake software (EduPro 1999). Additionally, the existent data obtained from previous boreholes with in situ and laboratory tests are also used in this study.

Secondly, in the site response analyses of Erbaa, input ground motions are considered using PGA values as given in the following sections. Afterward, the ratio is calculated on the basis of site amplification method using soil/bedrock ratio to obtain amplification factors (AF) for the study area.

As another stage, the liquefaction potential of Erbaa is evaluated using different empirical methods. The post-liquefaction effects are evaluated in terms of lateral spreading and vertical settlement. Finally, the produced lateral spreading and vertical settlement maps are re-evaluated by assigning different weights to each layer to obtain a final liquefaction-induced ground deformation map.

3 General properties, geology, and seismotectonics of the study area

3.1 General properties

The study area (Erbaa), located on the eastern part of the North Anatolian Fault segment, has a critical place in terms of the construction, and development aspects are in the Middle Black Sea Region of Turkey. Erbaa is one of the biggest towns of Tokat. The study area is bounded by the coordinates 4,504,000 N and 292,000 E in the southwestern edge and 4,506,500 N and 298,500 E in the northeastern edge in Universal Transverse Mercator (UTM) projection (Zone 37 N, European Mean Datum 1950) with an average altitude of 248 m. The study area is approximately 25 km² with a dimension of 6.5 km long and 4.1 km wide. The city center of Erbaa is located on the left embankment of the Kelkit River. After the disastrous 1942 ($M_s = 7.2$) and 1943 ($M_s = 7.6$) earthquakes, the settlement led to move to the south of old Erbaa. The authorities stated possible locations for new settlements are required due to the rapid increase in population of Erbaa. New and old settlements are shown in Fig. 1.

3.2 Geology

On a regional scale, metamorphic rocks and limestone of Permian to Eocene age can be observed as basement rocks. These rocks are overlain by Upper Eocene volcanics (basalt, andesite, agglomerate, and tuff) and alternating sandstone and siltstone layers. These units are covered by Pliocene deposits consisting of semi-consolidated clay, silt, sand, and gravel with an unconformity and a recent Quaternary alluvial unit (Aktimur et al. 1992) (Fig. 2). The alluvium, which includes gravel, sand, and silty clay, can be observed in the basement of Kelkit river valleys as well as in the northern part of the Erbaa basin. The Quaternary alluvial unit consists of heterogeneous materials derived from various older geological units in the vicinity. The Quaternary alluvial unit and Pliocene deposits broadly cover the study area. While the northern part of the settlement area is located on the alluvial unit, the Pliocene deposits dominate the southern part of Erbaa (Yilmaz 1998) (Fig. 3).

The Pliocene deposits consist mainly of uncemented gravel, sand, and occasionally uncompact sandstone layers. The groundwater level of Pliocene deposits is assumed to be deeper since some of 30-m-deep boreholes toward the hills opened during this study in Pliocene unit are all dry. Most of the study area is covered with alluvium. The thickness of the alluvium in the northern part (near the Kelkit River) is generally greater than that found in the southern part. The alluvium contains stratified materials of heterogeneous grain sizes, derived from various geological units in the vicinity. The alluvium in the Erbaa area consists of gravelly, sandy, silty, and clayey layers. The alluvium has a generally shallow (around 1 m below the surface) groundwater level, especially in the northern part of Erbaa toward the Kelkit River. Besides, the alluvial fans observed in the small river beds do not spread over a wide area in the Erbaa basin (Fig. 3).

3.3 Seismotectonics

Erbaa and its close vicinity are within a pull-apart basin formed by the tectonic activity of the NAFZ. The NAFZ is 1,500 km long, seismically active, right-lateral strike-slip fault that accommodates relative motion between the Anatolian and Black Sea Plates (Sengör et al. 1985). The NAFZ ruptured during six large, westward-propagating earthquakes with magnitudes greater than 7 and caused approximately 900-km surface break between 1939 and 1967 (Allen 1969; Ketin 1969; Ambraseys 1970). Erbaa is located on the eastern part of the NAFZ. Surface ruptures of the 1939 ($M_s = 8.0$), 1942 ($M_s = 7.2$), and 1943 ($M_s = 7.6$) earthquakes occurred in the Tasova-Erbaa and Niksar basins (Barka et al. 2000). The northern part of Erbaa is surrounded by the fault segments that ruptured in the 1942 and 1943 earthquakes (Fig. 4). The southern part is bounded by the Esencay fault which has a different morphological expression; however, no instrumental and/or historical earthquakes were mentioned in the study of Barka et al. (2000) related to this fault.

NAFZ is considered as the main/only source zone for Erbaa. There are no strong earthquakes recorded after 1942. A seismicity map produced by Taymaz et al. (2001) represents the seismicity of the eastern Mediterranean region for the period of 1964–2001 with magnitudes, $M > 4.0$ as given in Fig. 5. As can be observed in Fig. 5, there is no earthquake activity in the close vicinity of Erbaa in the period of instrumental recording, although it is seismically active.

Erbaa is in the First Degree Earthquake Zone of Turkey (<http://www.deprem.gov.tr/indexen.html>). It is one of the most important seismic areas on the NAFZ with past seismic activity. The 1942 and 1943 Niksar-Erbaa earthquakes are the most destructive

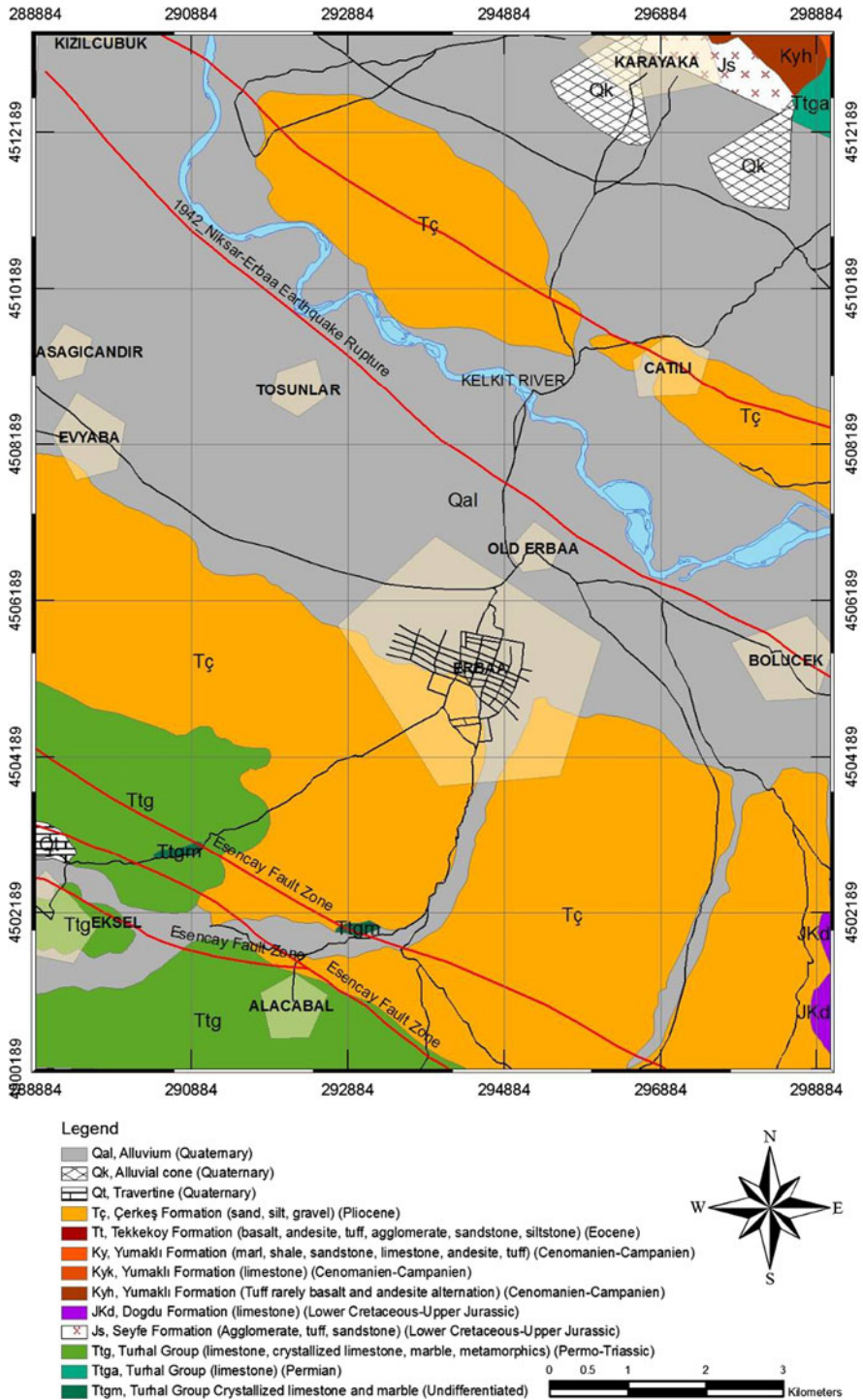


Fig. 2 General geology of the study area

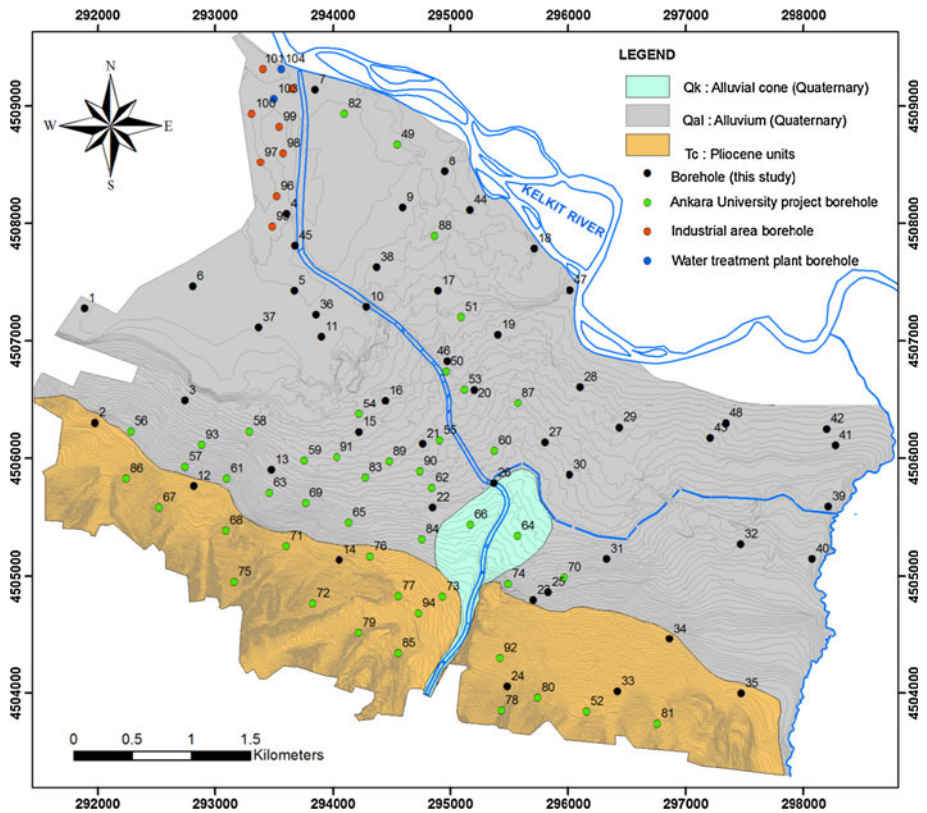


Fig. 3 Geology of the study area and distribution of the borehole locations in the study area

earthquakes for the region. No seismic activity with high magnitude has been recorded since 1942 Erbaa-Niksar earthquake in this area implying a seismic gap for this region. A summary of historical earthquakes in the vicinity of the study area is given in Table 1.

4 Database for seismic microzonation model of the study area

4.1 Geotechnical data

The existent geotechnical data which include 56 borings and laboratory test results (Canik and Kayabali 2000; Akademi 2002; Metropol Muh. 2005) obtained from previous projects (Ankara University project, Industrial area and Water treatment plant projects) were considered in this study. Forty-eight new boreholes with intended 30 m depths were drilled in the study area. Standard penetration tests carried out through new 48 boreholes were performed at every 1 m, and undisturbed samples (UD) are taken at every 1 m (where possible) to obtain a continuous soil profile. The total number of boreholes considered in this study is 104 with their laboratory test results. The locations of these boreholes are shown in Fig. 3. A total of 1,390 m of drilling, including 1341 SPT and 312 UD samples, was examined in this study. The depth of the ground water level (GWL) at the study area

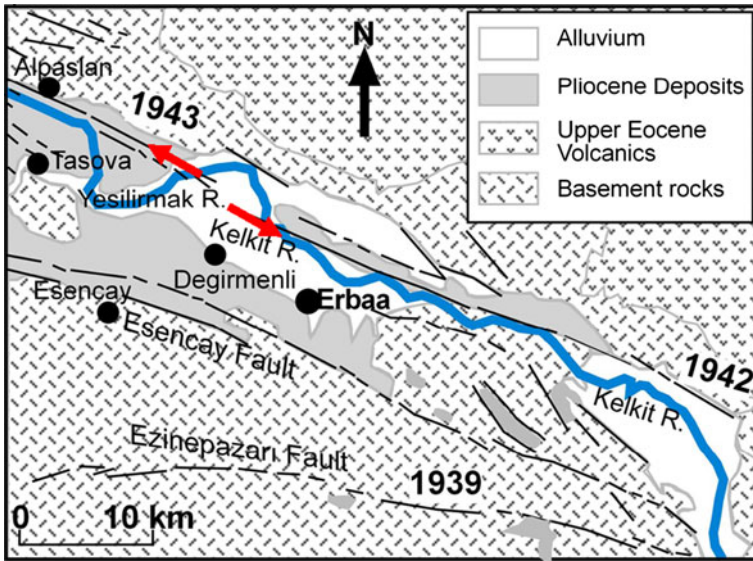


Fig. 4 Tectonic map of the study area and the close vicinity of the North Anatolian Fault System (Note: the red arrows represent the beginning of the surface rupture with the related earthquake)

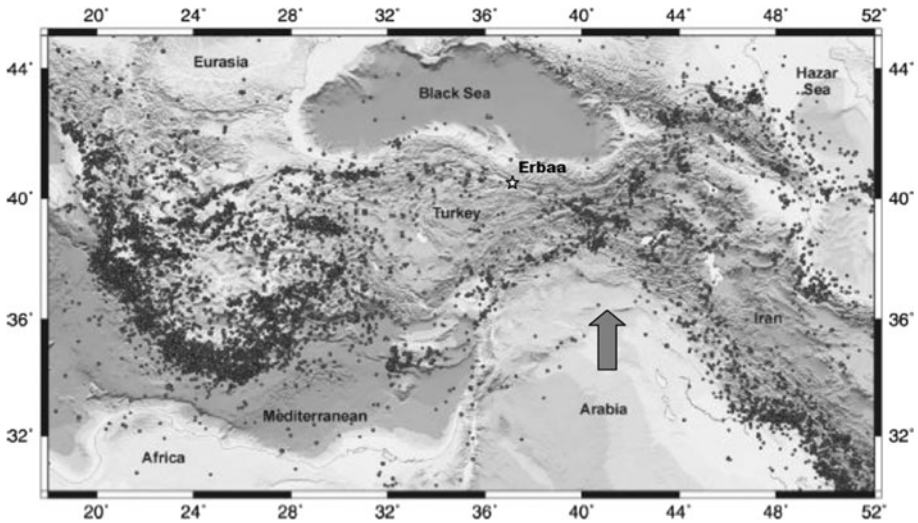


Fig. 5 A combination of topography, bathymetry, and earthquake epicenter distributions for Turkey, and its vicinity can be observed through the broad period (for the period of 1964–2001) with magnitudes, $M > 4.0$ (modified from Taymaz et al. 2001)

varies between 1 and 19 m depth. The alluvium unit has a very shallow GWL (1–2 m) with about one-half meter fluctuation in the dry season near the Kelkit River. SPT blowcount values from the boreholes are evaluated separately for the different geological units. The alluvial units has generally low SPT blow count values ($N < 20$) indicating a loose–medium dense sedimentation. Refusal SPT blow counts are mostly obtained in gravelly

Table 1 Historical earthquakes around Erbaa

Years	Location	Magnitude ($M \geq 5.5$)	Years	Location	Magnitude ($M \geq 5.5$)
1543 (1)	Tokat and Erzincan	Unknown	1939 (2)	Erzincan (325 km to Erbaa)	7.9
1688 (1)	Amasya-Niksar	Unknown	1940 (2)	Erbaa and its vicinity	6.2
1909 (2, 4)	Erbaa and its vicinity	6.3	1941 (2, 4)	Erbaa and its vicinity	5.7
1909 (2)	Erbaa and its vicinity	5.8	1942 (2)	Niksar-Erbaa	7–7.2
1909 (2, 4)	Erbaa and its vicinity	5.7	1943 (2, 3, 4)	Tosya-Ladik	7.2–7.3
1916 (2, 4)	Tokat	7.1	1943 (2)	Erbaa and its vicinity	5.6
1923 (2)	Erbaa and its vicinity	5.9	1944 (2)	Erbaa and its vicinity	5.5
1929 (2, 3, 4)	Erbaa and its vicinity	6.1	1960 (2, 4)	Erbaa and its vicinity	5.9
1935 (2, 3)	Erbaa and its vicinity	5.5	1992 (1, 2, 3)	Erzincan (325 km to Erbaa)	6.8
1939 (2)	Erbaa and its vicinity	5.7	1992 (2, 4)	Erzincan (325 km to Erbaa)	5.8

References: (1) Ambraseys and Finkel (2006), (2) Özmen et al. (1997), (3) Ayhan et al. (1984), (4) İnan et al. (1996)

layers of the alluvium. In addition, the Pliocene units mostly reveal refusal during SPT tests after 10–15 m depth. The evaluated boreholes, in situ and laboratory tests including Atterberg limits, sieve, and hydrometer analyses altogether integrated into the database.

Five cross-sections along the study area (Fig. 6) are investigated; one of the typical cross-sections (II–II') is mentioned in Fig. 7 including SPT blowcounts (N_{30} , is number of blows for 30 cm depth in SPT) for each borehole. Pliocene layers are exposed at topographically higher levels and the soil layers change as the ground surface slopes downward toward the Kelkit River.

Laboratory tests indicated that the average water content of the clay layers in the Pliocene units is lower than the layers in the alluvial areas. The water content of samples varies between 1.1 and 63.9 % for the alluvium, and between 4 and 31.6 % for the Pliocene unit. The soil classification is based on the Unified Soil Classification System (USCS), and sandy (SM and SP-SW) and clayey sand (SC) layers are observed in the alluvium. Based on Atterberg limits, the alluvial clay may be classified as low plasticity clay (CL). The Pliocene gravel unit contains clay particles. The clayey gravel unit (GC) is low-plastic. Furthermore, the sandy layers are represented by clayey sand (SC), and the clayey deposits (CL-CH) in Pliocene unit are also generally observed.

4.2 Geophysical data

Various in situ geophysical tests including microtremor measurements, seismic refraction and electrical resistivity, SPT-based uphole method, SCPTU measurements, and downhole surveys are performed in the study area. The number of each survey locations is summarized in Table 2, and some of the surveys are shown in Fig. 8. SPT-based uphole method applying the impact energy of the split spoon sampler during the SPT test as a vibration source which was previously introduced by Bang and Kim (2007) is also used in some boreholes. SPT-based uphole method, which is the modified version of the seismic uphole method, is the combination of both low- and high-strain tests. The SPT-based

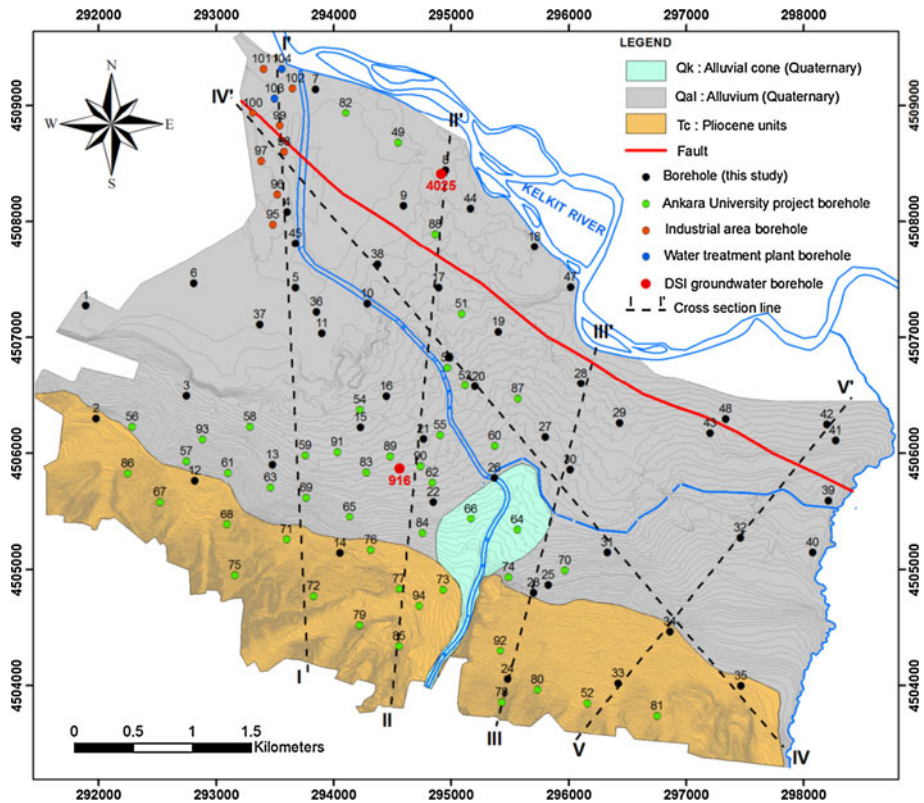


Fig. 6 A schematic diagram of cross-section lines in the study area

uphole test uses a number of receivers (geophones) inserted on the ground surface to obtain the shear wave velocity profile of a site. In this method, the shear waves are produced by SPT hammer impact without any additional explosives or mechanical sources. A total of 30 SCPTU measurements with varying depths are performed in accordance with ASTM D5778-95(2000) standards. The depths reached by the cone penetration test (CPT) apparatus at some locations are adversely affected by gravelly layers. The depths of the SCPTU applications range from 1 to 11.4 m.

5 Evaluation of the database for the seismic microzonation model

5.1 Dynamic soil properties used in site response analyses

Shear wave velocity values obtained from geophysical tests and empirical correlations are evaluated to obtain the shear wave velocity profiles for site response analyses as a part of microzonation study. Newly developed site-specific empirical relationships between V_s (m/s) and $SPT-N_{30}$ are considered in the study area (Akin et al. 2011). These proposed relationships based on uncorrected SPT blowcount values including the depth effect between V_s (m/s) and $SPT-N_{30}$ are likely to be useful for the shear wave velocity profile.

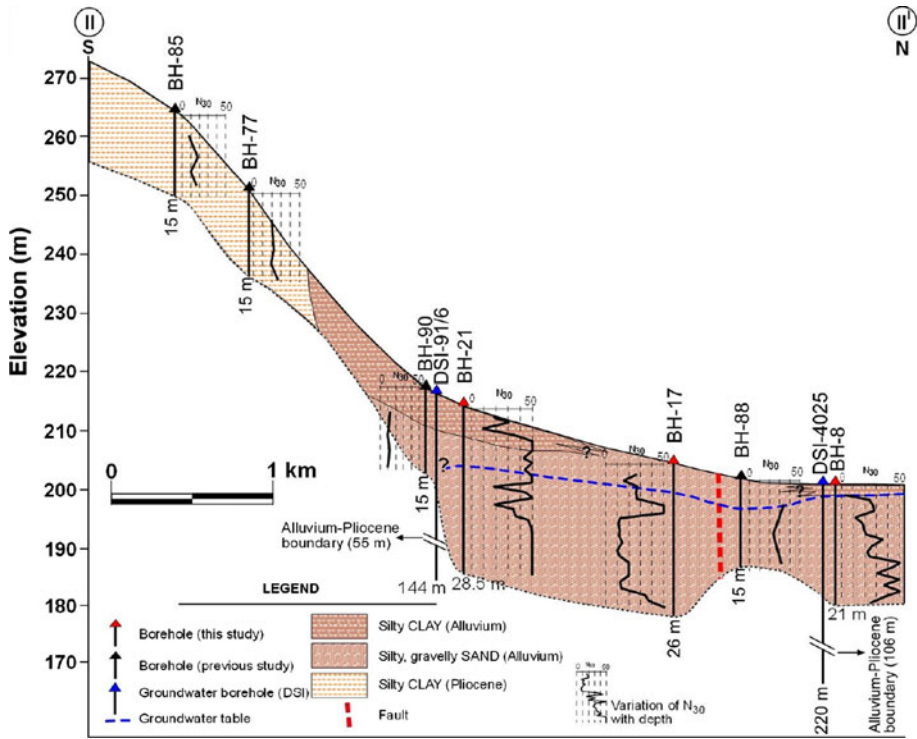


Fig. 7 One of the cross-sections of study area (II–II')

Table 2 The number of geo-physical tests applied in the study area

Tests	Number of locations
Resistivity survey	24
Seismic refraction	23
SCPTU (seismic cone penetrometer with pore water pressure)	30
SPT-based uphole surveys	In 10 boreholes
Downhole surveys	3
Microtremor measurements	517

The use of these equations for different soils will be applicable for the indirect estimations of V_s in Erbaa (Akin 2009).

In addition, the V_{s30} soil profiles are also evaluated in terms of National Earthquake Hazard Reduction Program (NEHRP) site classification category (NEHRP 2003). The NEHRP site classification based on equivalent shear wave velocities indicated that most of the investigated region could be designated as class D since the V_{s30} values in the study area range between 180 and 360 m/s representing D type soil which can be classified as stiff soils in accordance with NEHRP classification.

The data obtained from 104 boreholes are evaluated for site response analyses. The shear wave velocity profiles for each borehole are defined by dividing the soil profile into sublayers. Alluvial and Pliocene soil deposits are separately evaluated in four main soil groups: A1-clay

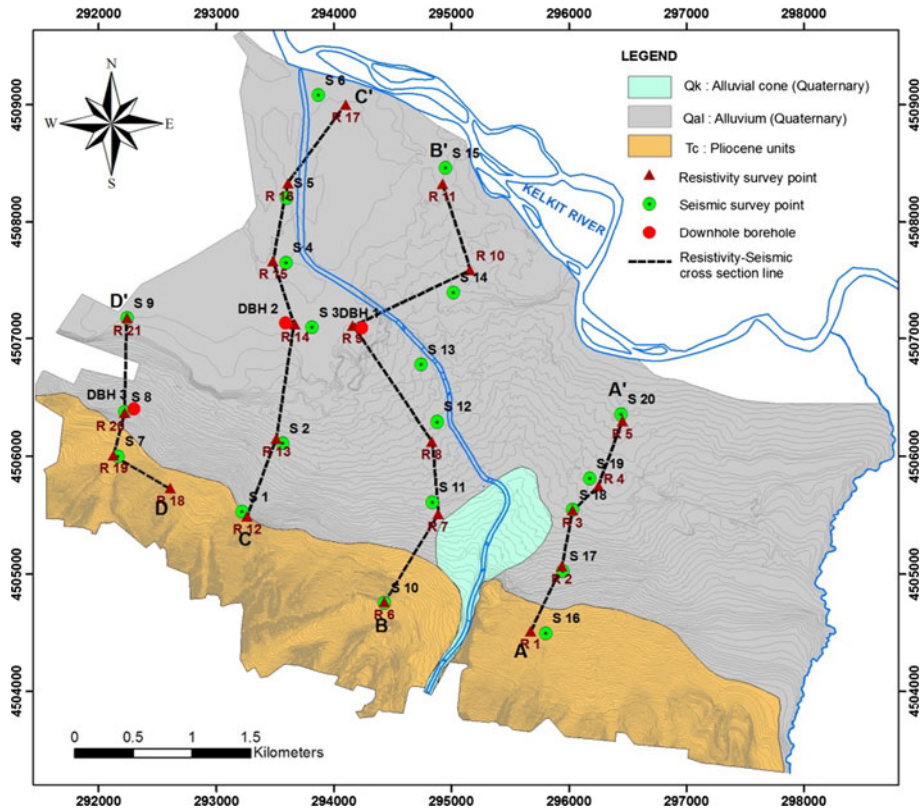


Fig. 8 The distribution of geophysical survey locations in the study area (*R* resistivity survey point, *S* seismic survey point, *DBH* downhole borehole)

(alluvium clay), A2-sand (alluvium sand), P1-clay (Pliocene clay), and P2-sand (Pliocene sand). Instead of using default models in the program, the essential modulus reduction and damping curves are calculated in order to model the conditions of the soil.

The modulus reduction (G/G_{max}) curve describes the manner in which the shear modulus varies with shear strain amplitude. The shape of modulus reduction curve indicates how nonlinear the material is. A linear material would have a horizontal modulus reduction curve, that is, the modulus reduction factor would be 1.0 at all strains. The plasticity index has also a considerable influence on modulus reduction curves (Vucetic and Dobry 1991). In general, soil nonlinearity increases with decreasing plasticity index. A number of investigators studied the modulus reduction behavior of different soils and proposed standard modulus reduction curves for those soils (e.g., Dobry and Vucetic 1987; Darendeli 2001). The modulus reduction curve can also be affected by effective confining pressure, void ratio, geologic age, and cyclic strain may cause (Dobry and Vucetic 1987; Kramer 1996; Darendeli 2001).

Modulus reduction and damping curves are established using the Darendeli model (Darendeli 2001) with an adoption of EPRI (Electric Power Research Institute) (EPRI 1993) curves to execute equivalent linear 1-D site response analysis. The Darendeli model is reformulated with different confining pressures, and the curves were similar to the EPRI curves. Therefore, site-specific soil models are established producing modified G/G_{max} -shear strain

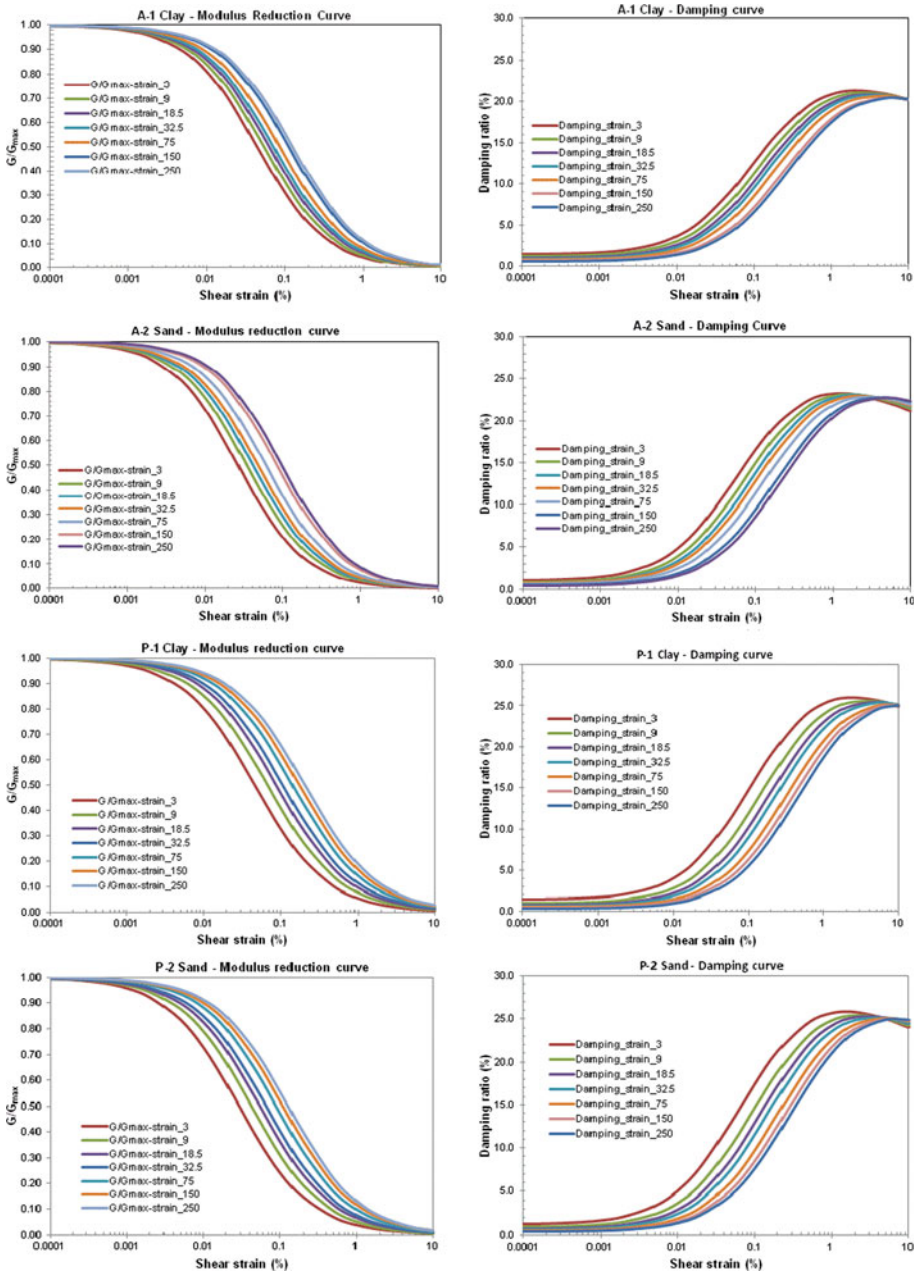


Fig. 9 Modulus reduction and damping curves for Alluvial and Pliocene soil deposits

curves in this study. The G/G_{max} -shear strain curves are created for the four previously defined soil groups (Fig. 9). As given in Fig. 9, the symbol of each curve (e.g., G/G_{max} -strain_3) indicates the representative depth in meters (e.g., 3 m) and the related confining pressure for the same depth.

5.2 Ground motions used for site response analyses

An earthquake magnitude of 7.2 with from 0 to 4 km rupture distance is accepted for the regional earthquake hazard analysis. The most important and destructive earthquake in the study area occurred in 1942 with a surface magnitude of 7.2 (Özmen et al. 1997; Tatar et al. 2006). Accordingly, 7.2 magnitude is accepted as the maximum credible earthquake (MCE) for the study area with respect to the important seismotectonic activities around Erbaa. The study area is divided into parallel zones with respect to the fault surface rupture considering a 2-km distance interval toward the seismic source (Fig. 10).

As earlier mentioned, no recorded strong ground motions from destructive earthquakes have been found in the Erbaa region since the destructive earthquakes occurred there in 1940s (Table 1). As a result, the peak ground acceleration (PGA) for Erbaa is estimated using expected magnitude and different attenuation relationships.

Peak ground acceleration (PGA) values are determined to obtain proper ground motion scenarios for Erbaa. The newly updated next generation attenuation (NGA) relationships (Power et al. 2008) are used to obtain target spectra for the study area. The main aim of PEER NGA project was to develop empirical ground motion prediction equations (GMPEs) to allow a range of interpretations. The source of strong ground motion data for the development of the GMPEs in that study was a comprehensive and consistent database compiled in the PEER NGA project. The Pacific Earthquake Engineering Research Center

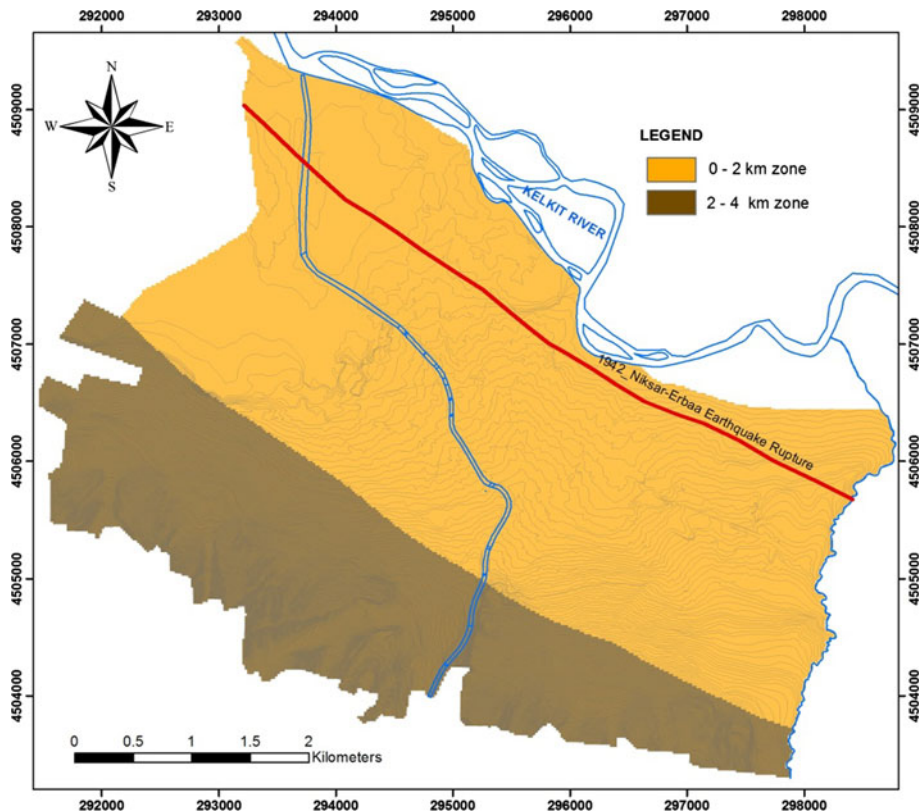


Fig. 10 Parallel zonation with respect to fault surface rupture in the study area

Table 3 Properties of the ground motions used in site response analysis

Associated number in this study	Earthquake name	Years	Magnitude	Peak ground acceleration (PGA) (g)
9	Imperial Valley-06	1979	6.5	0.37
10	Imperial Valley-06	1979	6.5	0.26
16	Imperial Valley-06	1979	6.5	0.43
19	Irpinia, Italy-01	1980	6.9	0.29
34	Loma Prieta	1989	6.9	0.38
40	Kobe, Japan	1995	6.9	0.71
42	Kocaeli, Turkey	1999	7.5	0.18

(PEER) ground motion database includes a very large set of ground motions recorded worldwide of shallow crustal earthquakes in active tectonic regimes. The database has one of the most comprehensive sets of metadata, including different distance measures, various site characterizations, and earthquake source data (Power et al. 2008).

A group of ground motions is identified and scaled to be constant with target response spectrum. In order to obtain the ground motions for the study area, the PEER (Pacific Earthquake Engineering Research Center) database (PEER 2009) and near fault ground motion databases (Baker 2007) are considered. The obtained motions are used in site response analyses (Table 3). The reason of the usage of NGA relationships for this study is that they have a broad and constant database of ground motions which are newly updated for the PEER project. Since the development of NGA models is based on the model building that uses seismological and geotechnical information, in addition to the empirical ground motion data, the NGA models are intended to begin the transition from simple empirical models to full numerical simulations for specific source-site geometries (Abrahamson and Silva 2008).

Ultimately, two different NGA relationships, Boore and Atkinson (2008) (BA08) and Campbell and Bozorgnia (2008) (CB08) models, are considered in this research to determine target spectra.

After selecting the process regarding suitable strong ground motions from the databases, the selected motions are not only compared but also scaled with the target spectra calculated from Boore and Atkinson (2008) (BA08) and Campbell and Bozorgnia (2008) (CB08) next generation attenuation relationships. The obtained rock PGA values from BA08 and CB08 NGA relationships for different distance zones are presented in Table 4. The graphics based on the BA08 and CB08 attenuation models are depicted in Fig. 11.

5.3 Site response analysis and amplification

Dividing a study area into grid cells is a common practice in seismic microzonation applications. Site characterization can be carried out based on grid system using the

Table 4 Calculated rock PGA values from NGA relationships for different distance zones in the study area

Distance to surface rupture (km)	PGA (BA08)	PGA (CB08)
0	0.549	0.481
2	0.445	0.457
4	0.361	0.402
6	0.316	0.345

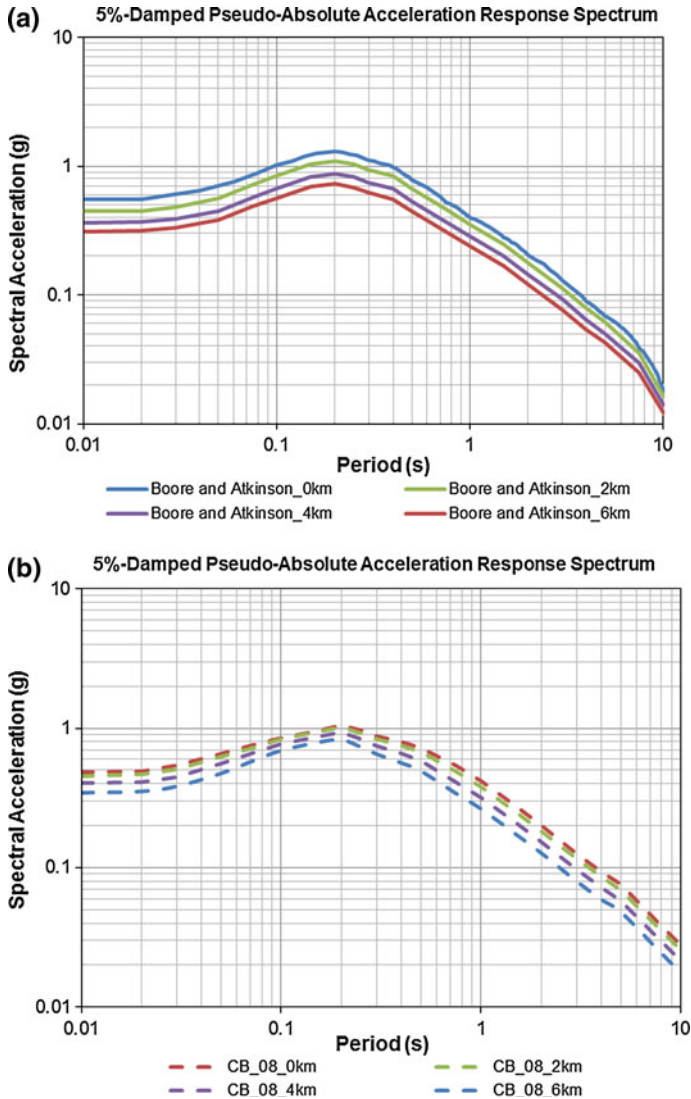


Fig. 11 **a** Boore and Atkinson (2008) (BA08) target spectrum model for different distances, **b** Campbell and Bozorgnia (2008) target spectrum model for different distances

available data for each cell (Matsuoka et al. 2006; Erdik et al. 2005; Ansal et al. 2006; Ansal and Tonuk 2007; Akin 2009). Erbaa settlement is divided into 500 m × 500 m grid cells, and seismic response analysis is performed for each cell. A total of 118 grid cells are obtained for the study area (Fig. 12). The results of representative soil profiles for each grid cell with shear wave velocities extending down to the bedrock (shear wave velocity, $V_s \geq 760$ m/s) are statistically extrapolated for the entire study area considering the change of geology and topography. Site-specific earthquake characteristics on the ground surface for each representative soil profile are calculated using one-dimensional site response analyses using ProSHAKE (v.1.12) software.

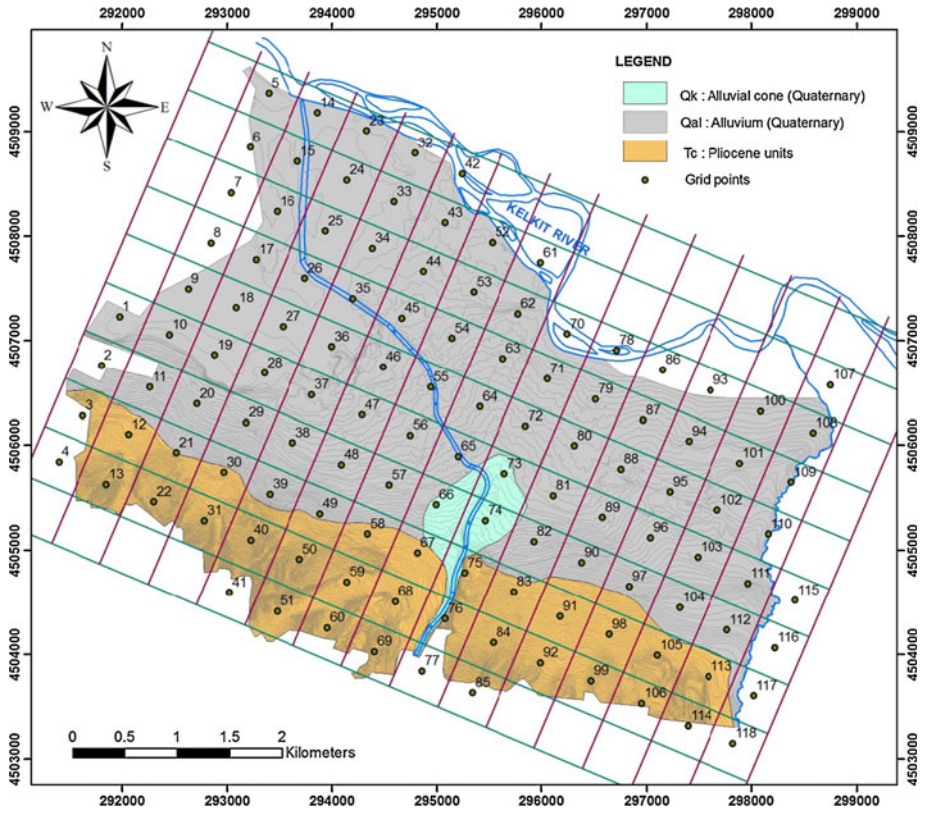


Fig. 12 Grid system used for site response analysis

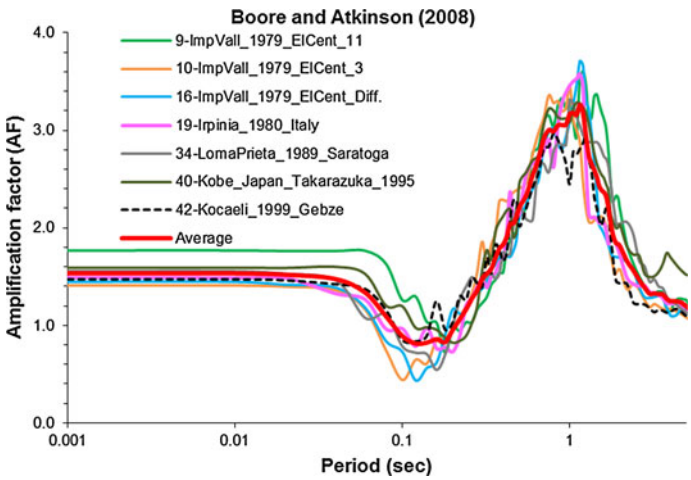


Fig. 13 Amplification ratio of BH-4 based on Boore and Atkinson (2008) model for 0-km distance zone

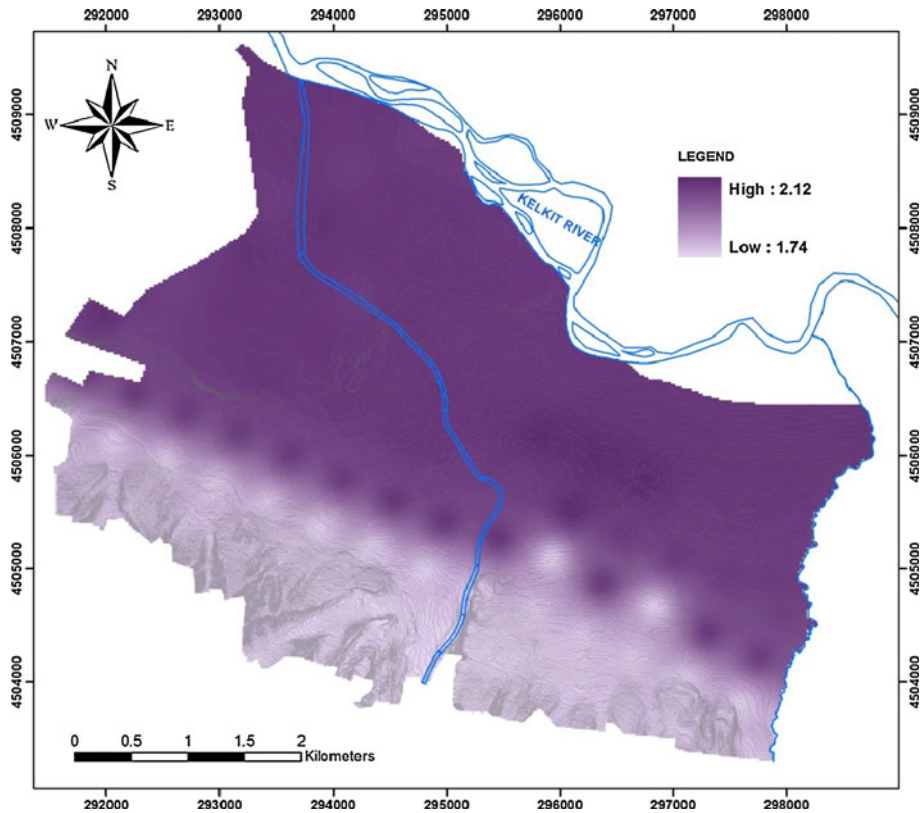


Fig. 14 Amplification map of study area

Input ground motions are considered using PGA values calculated from NGA relationships in the site response analyses of Erbaa. Site amplification ratio, the ratio between response spectra of ground surface motions computed from ground response analyses, is calculated to obtain amplification factors (AF) for the study area. The calculated amplification ratio for BH-4 is shown in Fig. 13 with respect to BA08 model.

Amplification factors are defined by different empirical approaches (from site response analyses, from Midorikawa 1987 equations and Stewart et al. 2003 approaches). The obtained values are compared with the measured microtremor results. Amplification factors from one-dimensional site response analyses and from different empirical approaches mostly vary within a range of approximately 1.5–2.5 in the study area. However, the microtremor measurements yield quite high amplifications up to 8.36. Besides, different period ranges should be taken into account for the design of structures.

The distribution of amplification values is also prepared to be considered in the final seismic microzonation map in order to account for site response effects in the study area. The amplification values determined by the geotechnical-based amplification factors model proposed by Stewart et al. (2003) are considered for the evaluation stage. The classification ranges and the amplification factor map are presented in Fig. 14.

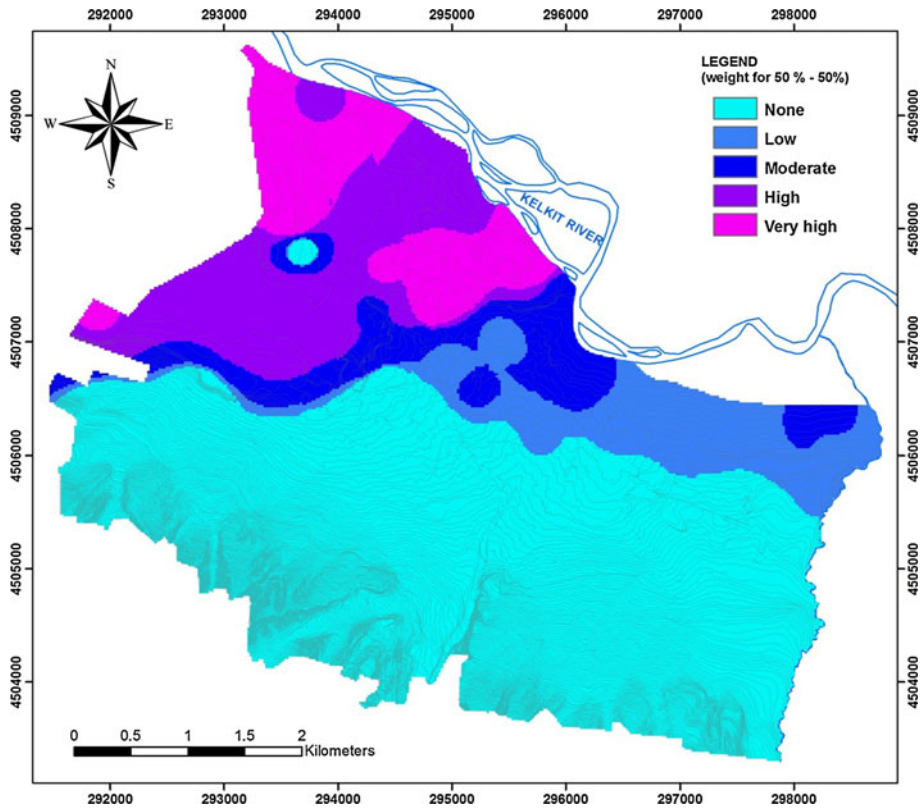


Fig. 15 Final liquefaction-induced ground deformation map of Erbaa

5.4 Liquefaction analysis

The liquefaction potential of Erbaa is evaluated applying different empirical methods and a newly proposed software called WSlq (Kramer 2008). Borehole specific PGA values are considered for liquefaction evaluations instead of using a constant PGA value for the whole study area since the PGA values were obtained from site response analyses. In general, Pliocene soils are not susceptible to liquefaction whereas loose alluvial units with shallow groundwater level dominantly expose liquefaction susceptibility. The susceptibility analyses indicate that the liquefaction-susceptible soils mostly cover the northern part of the study area. The liquefaction potential/severity index models based on Iwasaki et al. (1982); Sonmez (2003) and Sonmez and Gokceoglu (2005) designate a high liquefaction potential zone in the northwestern part of Erbaa especially in sandy alluvial deposits along the Kelkit River.

The post-liquefaction effects are evaluated in terms of lateral spreading and vertical settlement. The lateral spreading displacement can reach a maximum value of 5–10 m around the Kelkit River embankment. Moreover, the post-liquefaction vertical settlement is quite critical in the northwestern part of Erbaa. The settlement calculations indicated that a maximum vertical settlement may reach up to be 0.48–2.5 m. Finally, the produced lateral spreading and vertical settlement maps are re-evaluated by assigning different weights within the framework MCDA techniques to the each layer to obtain a final

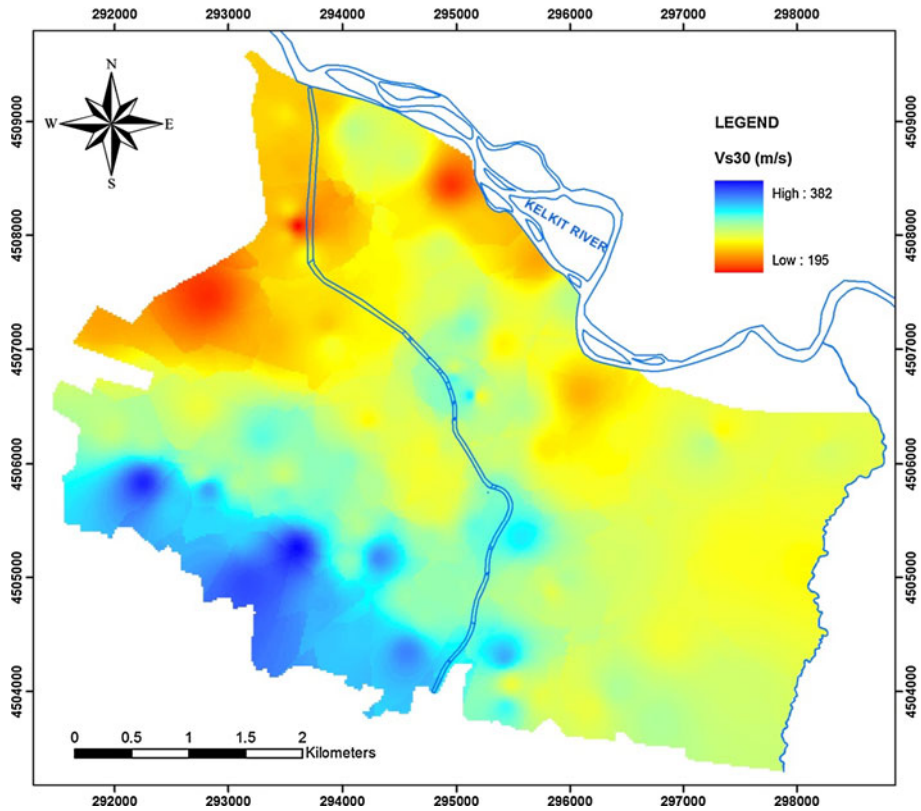


Fig. 16 V_{s30} map for soil classification of the study area

liquefaction-induced ground deformation map. The final map is the combination of the liquefaction potential, liquefaction-induced lateral spreading, and vertical settlement ground deformations for the study area (Fig. 15).

6 Production of seismic microzonation maps

In many site selection applications, the GIS-based MCDA procedures were preferably used to create appropriate predictions on various site conditions. (Kolat et al. 2006; Mohanty et al. 2007; Akin 2009). The evaluation process in MCDA includes preferences, determination of MCDA methods, calculation of rank and weight values, and preparation of the GIS-based microzonation maps. MCDA is a powerful tool for environmental decision-making for scientists and practitioners. The application of MCDA methods to environmental decision-making considerably improves the decision process in many engineering projects (Bello-Dambatta et al. 2009). The combination and utilization of the data vary in various MCDA approaches (Malczewski 2006). Simple additive weighting (SAW) and analytical hierarchical process (AHP), which are the two MCDA methods, are considered for the production of different seismic microzonation maps in this study.

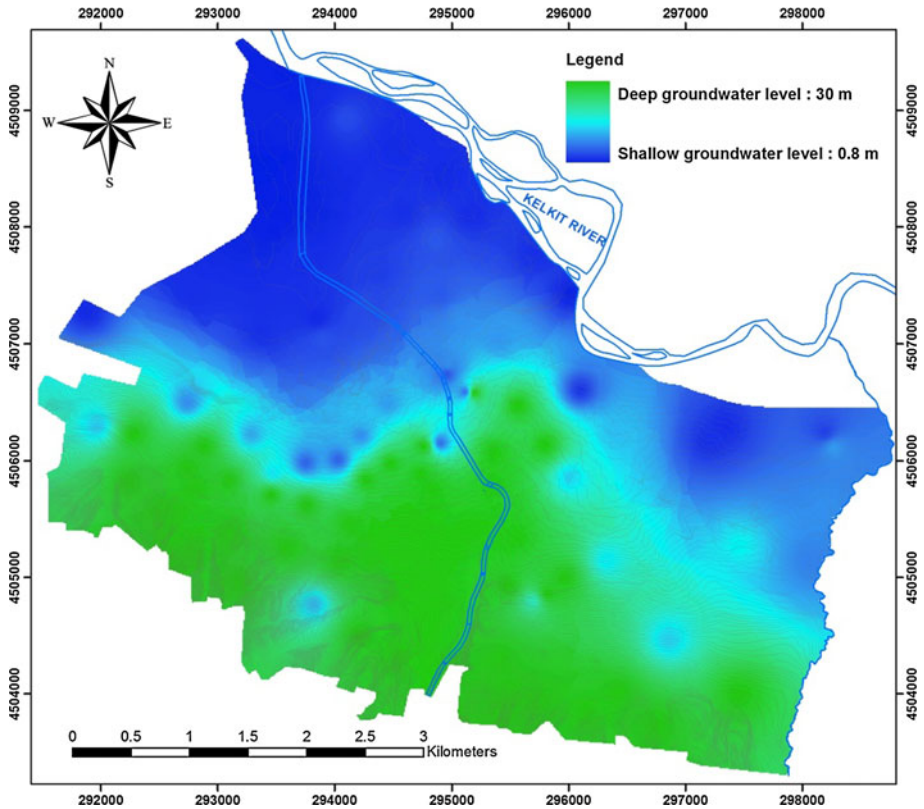


Fig. 17 Depth to groundwater level map of the study area

6.1 Prepared input maps

Geology (Fig. 3), distance to fault (Fig. 10), amplification (Fig. 14), liquefaction-induced ground deformation potential (Fig. 15), soil classification (Fig. 16), depth to groundwater level (Fig. 17), slope (Fig. 18), and aspect (Fig. 19) maps are considered as prepared input maps in this section.

6.2 Simple additive weighting-based (SAW) seismic microzonation map

The SAW method is broadly applied in environmental sciences in GIS and spatial processes (Malczewski 1999). Different weights are assigned to each thematic map layer with respect to its relative importance. SAW has the capability of weighing criteria on different scales (Bello-Dambatta et al. 2009).

The assigned weight and rank values for the layers/classes of the study area based on the engineering judgment are summarized in Table 5. The most important layer is affirmed as the liquefaction-induced ground deformation map. Ranking values vary between 1 and 5 indicating an importance increase toward 5. Though, weight values are grouped from 1 to 10 indicating an importance increase toward 10.

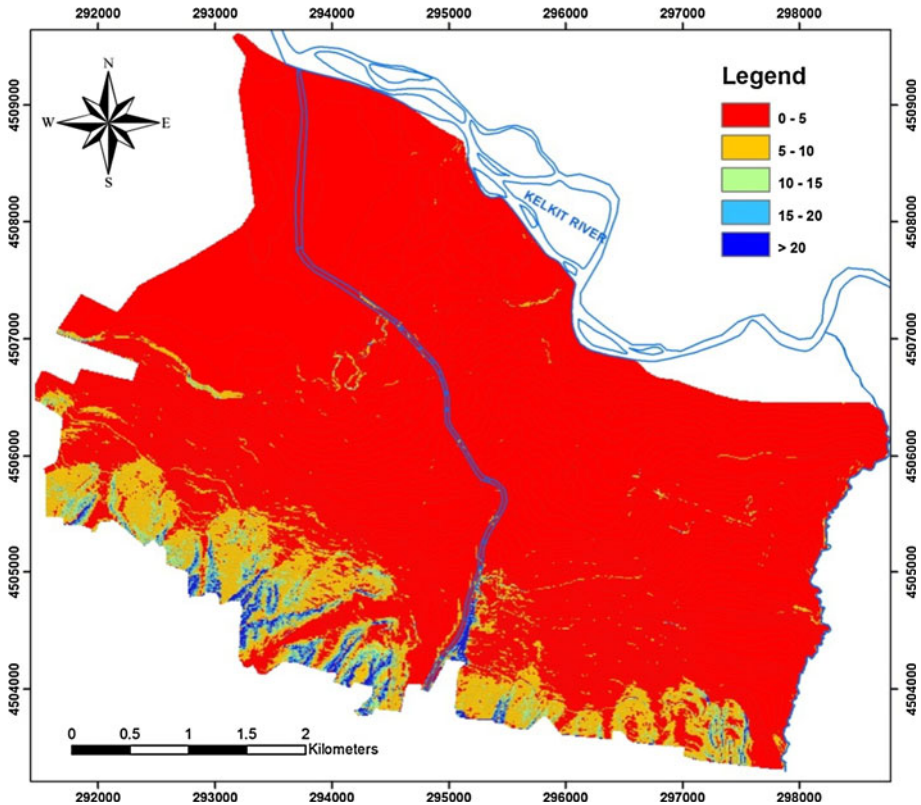


Fig. 18 Slope map of the study area (in degrees)

The highest weight value is implemented to the liquefaction-induced ground deformation layer in SAW method. The order of weight assigning extends with decreasing importance in the study area with respect to the seismic microzonation design purposes. The seismic microzonation map of the study area based on SAW method is given in Fig. 20.

6.3 Analytical hierarchical process-based (AHP) seismic microzonation map

The analytical hierarchical process (AHP) was firstly developed by Saaty (1977) to produce a ranking of decision alternatives with a mathematical structure. The main goal of AHP is to determine weights using pairwise comparisons of alternatives for each aspect (Marshall and Oliver 1995; Bello-Dambatta et al. 2009). In AHP, a complex decision problem is divided into simpler parts to form a decision hierarchy. Both qualitative and quantitative data are used to form ratio scales between decision elements at each hierarchical level by pairwise comparisons.

A pairwise comparison is executed for AHP method. The weight values assigned to each map are obtained from pairwise comparison. In contrast, AHP method does not suggest any technique for ranking the layers. Besides, Janssen (1992) states that the AHP method cannot only be used to assess weights but it can also be used to assess the performance of alternatives by pairwise comparison. Considering these assumptions, it is decided to apply the pairwise comparison for each separate layer to obtain ranking values.

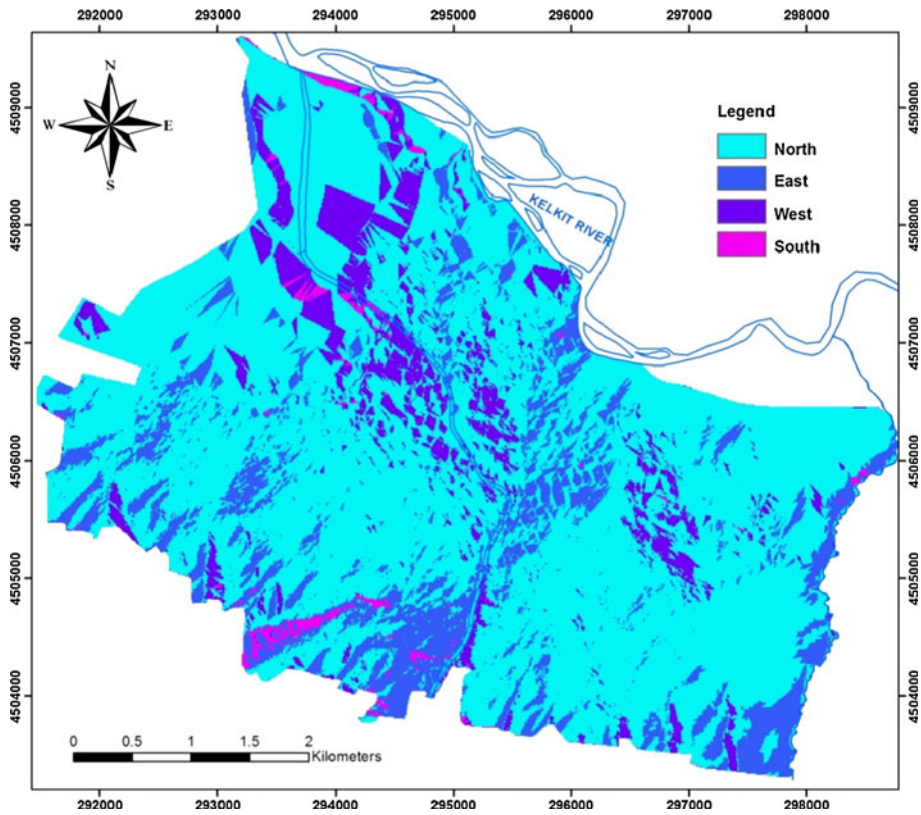


Fig. 19 Aspect map of the study area

The pairwise comparison matrix developed for eight criteria is presented in Table 6. The most important layer is referred as the liquefaction-induced ground deformation layer, followed by the distance to fault, lithology, amplification, soil classification (V_{s30} -based site classification), depth to groundwater table, slope, and aspect layers with decreasing importance as also mentioned in SAW method.

During the estimation of rank values, a similar pairwise comparison is executed for each layer separately. The rank values are assigned considering the comparison of layer classes. The obtained ranking values are presented in Table 7. The decision-maker’s inconsistency can be calculated by the consistency index (CI) in AHP method to understand whether decisions agree with the transitivity rule. A threshold value of 0.10 is accepted as consistency ratio (CR). If the CR value is higher than the threshold value of 0.10, the rankings in pairwise comparison matrix should be reconsidered and revised. Besides, the consistency ratios for each layer are summarized in Table 8. The seismic microzonation map of the study area based on AHP method is given in Fig. 21.

6.4 Evaluation of seismic microzonation maps

The SAW-based and AHP-based seismic microzonation maps are categorized into four zones according to the recommended subdivisions by the General Directorate of Disaster

Table 5 Assigned rank and weight values for the layers/classes in SAW method

Layers	Weighting	Classes	Ranking
Slope (°)	2	0–5	5
		5–10	4
		10–15	3
		15–20	2
		>20	1
Aspect	1	S	5
		W	4
		E	2
		N	1
Lithology	5	Pliocene	2
		Alluvium	1
Depth to groundwater table	4	>20 m	5
		10–20 m	4
		5–10 m	2
		0–5 m	1
Distance to fault	7	2,000–4,000 m zone	2
		0–2,000 m zone	1
Soil classification (V_{s30} -based site classification)	3	(360–380 m/s)-D type soils	2
		(180–360 m/s)-C type soils	1
Amplification	6	1.74–1.91	2
		1.91–2.10	1
Liquefaction-induced ground deformation	8	None	5
		Low	4
		Moderate	3
		High	2
		Very high	1

Affairs of Turkey (GDDA 2000). The general properties of recommended subdivisions of GDDA are as follows:

- (i) Suitable areas—normal residential developments can be planned without any further precautions.
- (ii) Provisional areas—development can take place provided certain precautionary measures against heave, excessive settlements, shallow water table, etc. are taken.
- (iii) Detailed geotechnical investigations required areas—conditions are such that individual investigations are required and prescribed standard precautions to be taken against very high heave, very high settlement, very shallow water table, liquefaction, flood, etc.
- (iv) Unsuitable areas—no settlement of any kind is allowed in areas where seismicity, landslides, floods, water table at the surface, steep slopes, etc. pose serious risks to residential development. Such areas may be used for recreational purposes.

The division of “detailed geotechnical investigation required area, provisional area, and suitable area” is performed with respect to the histogram of seismic microzonation map.

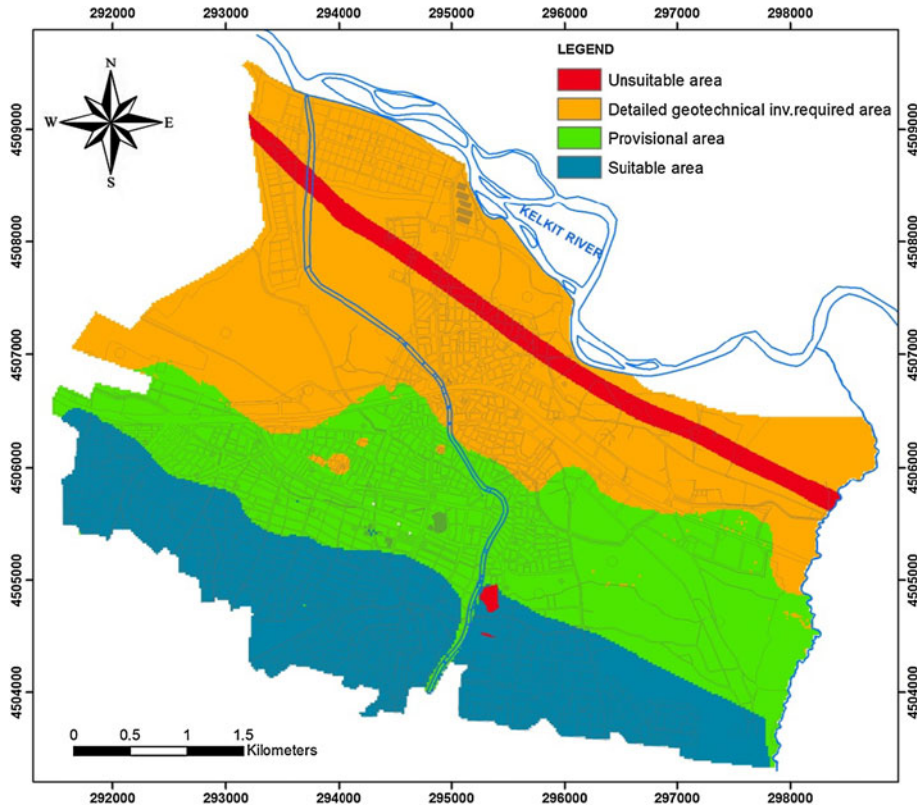


Fig. 20 SAW-based seismic microzonation map of the study area

The “unsuitable area” boundary is determined separately according to the buffer zone criterion.

6.5 Comparison of seismic microzonation maps

In order to compare these two seismic microzonation maps, re-classification is carried out for two raster maps. Afterward, the same values are assigned to the classes in two microzonation maps. The comparison is performed to interpret the differences between these maps. Hence, a resultant map showing the difference between two maps is generated (Fig. 22). In this resultant map, the red areas indicate non-overlapped areas of the two methods. Besides, the light yellow areas show the consistency of the two MCDA methods for the same area.

According to the comparison of two maps, the results are generally compatible with each other. The non-overlapping zones cover provisional and detailed geotechnical investigation required areas in both maps (Fig. 22). Besides, consistent results are found for suitable areas. Eventually, the seismic microzonation map based on AHP method is accepted to be the final seismic microzonation map of Erbaa as the AHP method is more objective than the SAW method with respect to logical judgment criteria and theoretical foundation (Zanakis et al. 1998). Moreover, the pairwise comparison matrix in AHP method provides interrelation assumptions between layers. However, the SAW method only considers the decision-maker’s assigned weights and is accepted to be more subjective.

Table 6 Comparison matrix developed for AHP-based seismic microzonation map

AHP calculation criterion	Liquefaction	Distance to fault	Lithology	Amplification	V_{s30} -based site classification	Depth to groundwater table	Slope	Aspect
Liquefaction	1	2	2	3	3	5	7	9
Distance to fault	1/2	1	4	2	4	5	8	9
Lithology	1/2	1/4	1	3	4	4	7	9
Amplification	1/3	1/2	1/3	1	2	4	7	9
Soil classification (V_{s30} -based site classification)	1/3	1/4	1/4	1/2	1	2	8	9
Depth to groundwater table	1/5	1/5	1/4	1/4	1/2	1	6	9
Slope	1/7	1/8	1/7	1/7	1/8	1/6	1	2
Aspect	1/9	1/9	1/9	1/9	1/9	1/9	1/2	1

Table 7 Assigned weight and rank values to the layers/classes in AHP method

Layers	Weighting	Classes	Ranking
Slope (°)	0.022	0–5	0.401
		5–10	0.258
		10–15	0.179
		15–20	0.123
		>20	0.040
Aspect	0.016	S	0.548
		W	0.281
		E	0.115
		N	0.056
Lithology	0.177	Pliocene	0.833
		Alluvium	0.167
Depth to groundwater table	0.067	>20 m	0.542
		10–20 m	0.248
		5–10 m	0.139
		0–5 m	0.070
Distance to fault	0.241	2,000–4,000 m zone	0.857
		0–2,000 m zone	0.143
Soil classification (V_{s30} -based site classification)	0.093	(360–380 m/s)-D type soils	0.833
		(180–360 m/s)-C type soils	0.167
Amplification	0.125	1.74–1.91	0.833
		1.91–2.10	0.167
Liquefaction-induced ground deformation	0.259	None	0.415
		Low	0.270
		Moderate	0.182
		High	0.106
		Very high	0.027

Table 8 Consistency ratios (CR) for each layer

Layers	Consistency ratio (CR)
Liquefaction-induced ground deformation	0.086
Distance to fault	0.010
Lithology	0.010
Amplification	0.046
Site classification (V_{s30} -based site classification)	0.010
Depth to groundwater table	0.096
Slope	0.088
Aspect	0.065

7 Conclusions

An appropriate settlement planning for urban areas, especially in the close proximity to seismic zones, requires detailed microzonation studies. Regarding the scope of this

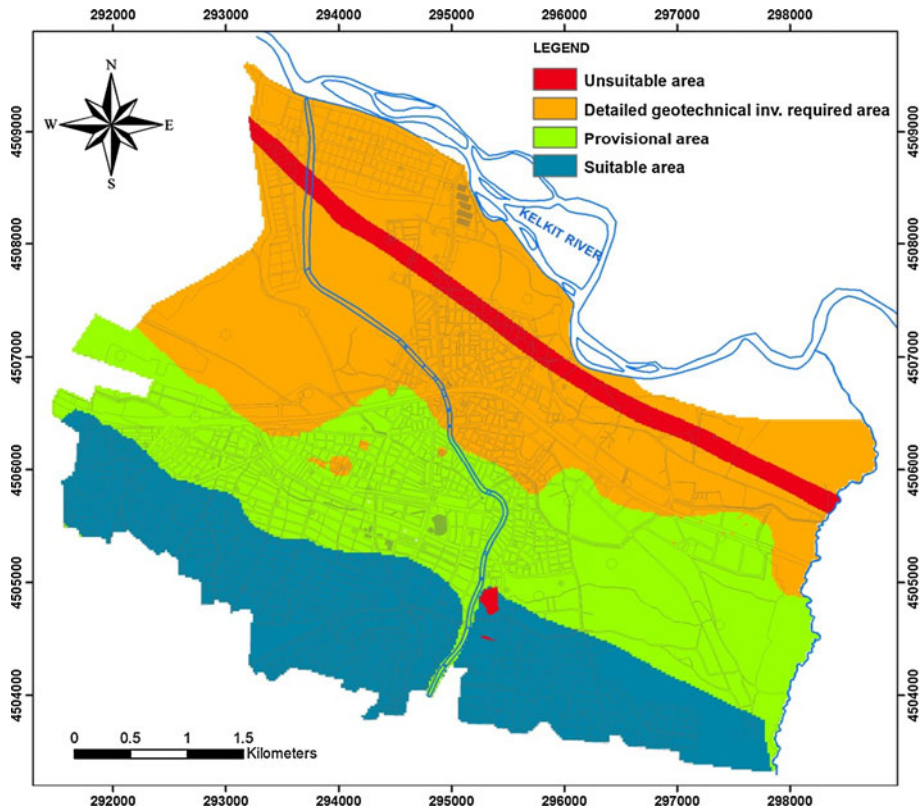


Fig. 21 AHP-based seismic microzonation map of the study area

research, it is aimed to propose a newly developed seismic microzonation model in order to determine the suitability of residential areas of Erbaa (Tokat, Turkey) which is in a seismically active region.

Site response analyses revealed that soil amplification assessment indicates superior amplifications which are dominant in the northern part of the study area. However, the amplification factors obtained from different methods do not reveal a certain distinction between alluvium and Pliocene deposits in the study area.

The alluvial units in the northwestern part of Erbaa are more susceptible to earthquake-related ground deformations than the other parts of the study area. According to liquefaction and post-liquefaction analyses, the damage may occur in the close vicinity of the Kelkit River which locates in the northern part of Erbaa.

In general, liquefaction-induced ground deformation map is accepted to be the most significant layer for seismic microzonation whereas aspect map is found to be the least effective. The MCDA is an efficient tool for site classification in seismic microzonation projects. The AHP methodology, being the most common MCDA technique, is exploited to obtain the final seismic microzonation map of Erbaa. The study area is categorized into four different zones with regard to the suitability of residential areas as follows: unsuitable areas, detailed geotechnical investigation required areas, provisional areas, and suitable areas. The final map shows that the southern part of the study area is suitable for settlement and that the northern part requires detailed geotechnical investigation.

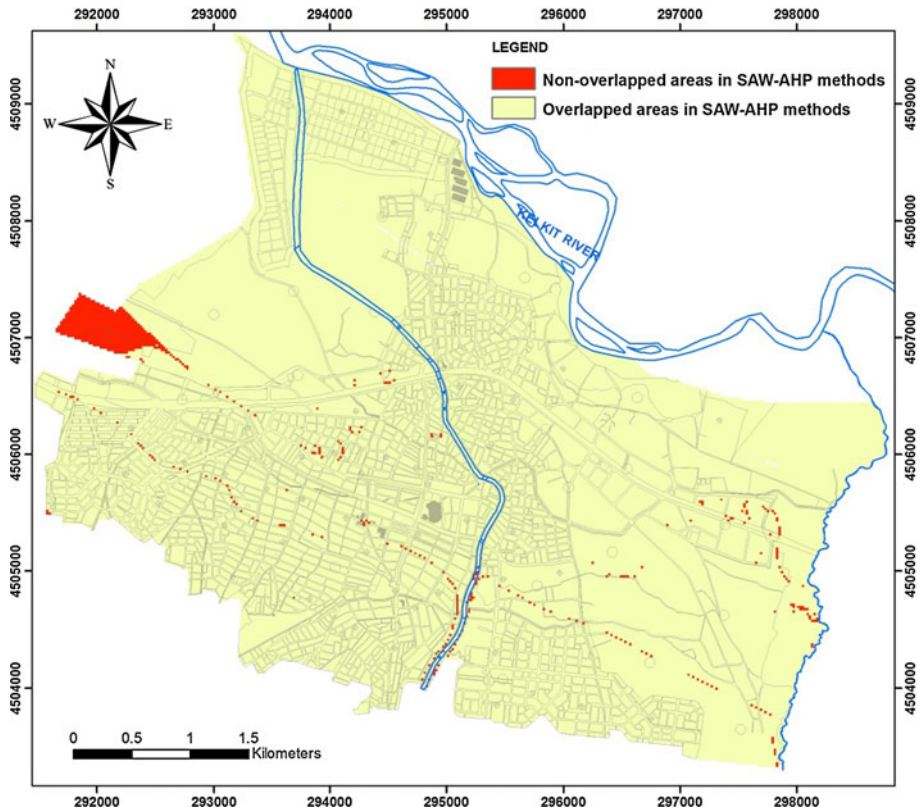


Fig. 22 Comparison map of SAW- and AHP-based seismic microzonation maps

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