Creating infrastructure for seismic microzonation by Geographical Information Systems (GIS): A case study in the North Anatolian Fault Zone (NAFZ)

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Although there are many studies for seismic microzonation in the literature, these studies have not covered the whole seismic microzonation processes. Moreover, they have not sufficiently focused on the important subjects, such as significance and use of aerial photos in seismic microzonation studies, data types used for seismic microzonation, and integrating these data by GIS.

This study suggests a GIS-based model that can be used for all settlements that are at risk of natural disaster, with a view to taking necessary measures against such natural disasters (especially earthquakes). This model was applied so as to take the measures needed for the town of Erbaa located on the western part of the eastern segments of the North Anatolian Fault Zone (NAFZ), a settlement with earthquake risk on the NAFZ. During creation of the system, geological, geotechnical data and data produced from aerial photos were integrated and assessed on a GIS environment. The infrastructure for seismic microzonation was created using this model. The potential areas for soil liquefaction were detected in the study area. Thus, the results were produced to assist in seismic microzonation.

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1. Introduction

Humankind has experienced and been involved in problems caused by disasters since ancient times. As cities have expanded and become crowded, the impact of disasters on urban areas has increased accordingly. Losses of both lives and money have been incurred around the world due to natural disasters such as earthquakes, landslides, floods, etc. (Turk, 2009). The application of technology required to control the effects of natural hazards comprises three significant elements, such as prediction, monitoring and safeguarding (Alexander, 1995). In the recent years, different technologies have been developed showing possibilities for a wide range of disaster management and hazard mitigation (Yılmaz, 2009). GIS can be used as a tool to minimize the damage resulting from these disasters (Lee and Talib, 2005; Köhler et al., 2006; Pal et al., 2007; Inel et al., 2007; Thierry et al., 2007; Lantada et al., 2007; Galderisi et al., 2008; Turk, 2009; Yılmaz, 2009; Mancini et al., 2010; Bednarik et al., 2010).

Microzonation studies solve problems resulting from natural disasters such as earthquakes and landslides. It is highly difficult to perform such studies by means of classical methods. Therefore, a GIS is needed to respond to these questions accurately and quickly (Kolat et al., 2006; Kienzle et al., 2006; Nath, 2005; Papadimitriu et al., 2008; Turk, 2009). In recent years, GIS has emerged to be a powerful computer-based technique that integrates spatial analysis, database management, and geographical visualization capabilities. For geotechnical purposes, GIS-based information systems have been developed and used to forecast and plan for natural hazards such as landslides or earthquakes (Kiremidjian, 1997; Anastasiadis et al., 2001). Particularly, in geotechnical earthquake engineering, there has been a number of research studies on GIS technology. This technology has been widely used in increasing numbers of seismic zonations for the prediction of earthquake-induced hazards (Kolat et al., 2006; Sun et al., 2008; Grasso and Maugeri, 2009).

Reliable data is the most important component in GIS studies. They are obtained from different geographical data sources, such as aerial photos, satellite images, laser scanning, the Global Positioning System (GPS), terrestrial measuring, and digitizing from existing maps. Since aerial photos and satellite images allow quick, accurate, and up-to-date geographical data, they are more preferred than other geographical data sources. The data-collection process is one
of the longest and most costly stages in the system realization phase. The necessary data flow must be provided so as to operate the created system properly (Turk, 2009).

In a natural disaster period, disaster and risk analyses of a region can be performed by showing the difference between the previous and current status of urban settlements by means of aerial photographs and satellite images of the area. In recent years in particular, natural disasters such as earthquakes, landslides, and floods can be extensively monitored using remote-sensing techniques (Altan, 2005; Li et al., 2005; Casson et al., 2005; Nichol et al., 2006; Hong et al., 2007; Tsai et al., 2010). Moreover, designation of safe settlements prior to natural disasters is directly related to land-use management. All of these processes can easily be carried out by GIS (Hong et al., 2007; Turk, 2009; Mancini et al., 2010; Tsai et al., 2010).

As natural disasters occur at any geographical location, they can be analyzed using GIS. The damage caused by an earthquake is inevitable. However, it can be possible to reduce or eliminate damage by measures taken before and after the disaster. Large numbers of seismic microzonation studies have been managed in earthquake-prone areas of the world, and they are continuously being executed with and without the use of GIS (Jimenez et al., 2000; Nath, 2005; Kılıç et al., 2006; Kolat et al., 2006; Kienzle et al., 2006; Sun et al., 2008; Papadimitriou et al., 2008; Grasso and Maugeri, 2009; Mhaske and Choudhury, 2010). These studies need to be supported by comprehensive multi-disciplinary contributions (Antoniou et al., 2008). Seismic microzonation studies can be performed easily by integration of data such as aerial photos, satellite images, geological data, geotechnical data and geodetic data by query-analysis of these data on GIS environments in cities (Jimenez et al., 2000; Nath, 2005; Altan, 2005; Kienzle et al., 2006; Kolat et al., 2006; Lantada et al., 2007; Sun et al., 2008; Galderisi et al., 2008). This provides a great contribution to disaster and risk management in the period before and after natural disasters (Bogazici University, 2003; General Directorate of Disaster Affairs of Turkey (GDDA) and World Institute for Disaster Risk Management (DRM), 2004; Altan, 2005; Sun et al., 2008; Antoniou et al., 2008; Grasso and Maugeri, 2009). Therefore, GIS and remote-sensing data must be used for handling problems resulting from natural disasters in the important active fault zones.

This study aims to create a GIS-based model in order to reduce or eliminate existing risks in urban areas before natural disasters, to create the infrastructure for seismic microzonation studies, and to realize easy, quick, and effective land-use planning studies. During the creation of this model, the growth direction of the town was ascertained by producing building data from aerial photos for two different periods in the study area. Thus, the produced data can be used to assist land-use planning in the area. In addition, the produced data, geotechnical, and geological data of the study area (faults, geological formations, microtremor, and borehole) were integrated and assessed in the GIS environment. As a result of these studies, the infrastructure of seismic microzonation studies in the study area was established. Potential areas

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**THE GIS BASED MODEL PROPOSED FOR SEISMIC MICROZONATION**

**VECTOR DATA**
- Administrative Data (City Boundary etc.)
- Geodetic Data (Geodetic Reference Point etc.)
- Geological Data (Fault, Geological Formation, Borehole, Earthquake Catalogue, Landslide Area etc.)
- Geotechnics Data (Microtremor, Seismical etc.)
- Fundamental Data (City Block, Building, Section of Map Index etc.)
- Topographical Data (Contour, River etc.)

**TABULAR DATA**
- Address Data
- Population Data
- Other Related Data

**RASTER DATA**
- Aerial Photo
- Satellite Image
- Digital Orthophoto

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![Fig. 1. GIS-based model proposed for seismic microzonation.](image-url)
for soil liquefaction were detected in the study area. Finally, information related to the earthquake risk of the study area was revealed by this model. The GIS-based model is suggested, so that it can be used in all settlements with earthquake risk.

2. Methodology

This study suggests a GIS-based model that can be used to create the infrastructure of seismic microzonation studies on cities that have a risk in terms of natural disaster, particularly earthquake (Fig. 1). In addition, a relational database was designed to cope with the damage resulting from natural hazards for this study.

In a GIS-based model, the database creation method should be explained. Object-oriented approaches are preferred today in the design of databases, and model-oriented systems are recognized as the standard. The Unified Modelling Language (UML) is recognized by the International Organization for Standardization (ISO) as a conceptual modelling language standard. UML is a diagram-drawing and relational-modelling language. It allows easy and comprehensible modelling of world objects in computer environments. Therefore, it is also efficiently used for spatial database design and ensures clear emphasis on the relationship between geographical and non-geographical data. Thus, an efficient, controllable, and productively operating spatial database can be designed by UML (Turk, 2004). Hence, UML class diagrams were used for the database design of the created system.

During creation of the system, aerial photos related to the town were evaluated by applying process steps such as interior, exterior orientations, stereo digitizing, and orthophoto production (using Zeiss Imaging and Erdas Imagine software). As a result, geographical layers of buildings and an orthophoto of the town were produced to determine the land use of the town of Erbaa. Some geological data (faults, geological formations) were obtained from the General Directorate of Mineral Research and Exploration of Turkey (Aktimur et al., 1989). In addition, geotechnical investigations and studies in different locations of Erbaa were performed as a part of the research project (Tatar et al., 2010). On the other hand, microtremor measures were also performed in different locations of the study area (Tatar et al., 2010). In the created relational database, borehole, and microtremor sites are composed of attributes such as borehole depth, number of blows, sample type, geotechnical description, strength, weathering, fracture, rock quality in each of depth of any borehole site, microtremor research depth, P wave velocity, S wave velocity, shear velocity in each of depth of any microtremor site. Afterwards, the collected data were integrated in a GIS environment (using ESRI ArcGIS 9.2 software). Finally, potential areas for soil liquefaction were revealed in the study area.

A user-interface program is a tool that allows for interaction between the user and the computer. Although many processes are performed for complex spatial analysis and queries in GIS software, these processes can be executed by means of pressing a button in developed user-interface programs. Thus, GIS software can easily be used widely by many users (Turk, 2009). In this study, the user-interface programs were developed to determine appropriate settlement in cities having an earthquake risk, and to ascertain easily high-risk buildings (ArcObject Programming Language and Model Builder). These programs have handled automated processes, such as borehole queries, geological formation queries, fault buffer analyses, the creation of thematic maps, and documentations.

Model Builder enables graphical modelling capability for configuration of spatial analysis processes, work flows, and scenarios. Additionally, it is used for creating and designing complicated spatial analysis process models. It is possible to find out, via an interface program, which zones in a settlement with earthquake risk have been affected, after the epicenter of the earthquake has been determined. In addition to performing a buffer-zone analysis related to the earthquake, the program can also be used in the realization of any scenario requiring buffer-zone analysis.

"Fault Buffer Analysis" was developed for such studies. It creates a buffer zone around the geographical layer, which is initially identified by the user and in the distance determined again by the user. Then, the process is realized by overlapping this buffer-zone layer created with the geographical layer, which can be evaluated in terms of risk. This program can perform full automatically multiple complicated spatial analysis processes via "Model Builder" on ESRI ArcGIS 9.2 software (Fig. 2).

3. Application in the City of Erbaa

3.1. Location and major geological features of the study area

The dextral NAFZ is one of the major continental strike-slip faults in the world, extending from Karliova in the east to the Gulf of Saros in the west, with a length of 1200 km (Barka, 1996). Both...
historical and instrumental records indicate that major earthquakes took place in many regions of Turkey in the past. The two most serious earthquakes that have taken place on this fault in the past century are the Erzincan earthquake ($M = 7.9$) in 1939 and the Kocaeli earthquake ($M = 7.4$) in 1999 (Sengör et al., 2005). There are important settlements in the area, such as Erbaa, Susehri, Koyulhisar, Reşadiye, and Niksar, which are located on or near the NAFZ (Eyidogan et al., 1991).

The town of Erbaa on the NAFZ, being at risk of earthquakes, was selected as the study area for this study. The geographical location of the Erbaa town is shown in Fig. 3. As geological features, alluvial deposits and Pliocene sediment widely crop out around the study area (Fig. 4). According to Yilmaz (1998), six different rock units in the study area range from Late Jurassic–Early Cretaceous to Quaternary in age. Canik and Kayabali (2000) divided the Quaternary alluvials, Pliocene sedimentary rocks and terrace sediments deposited in two different levels in Erbaa and its neighbours. While, alluvial deposits are mostly observed in the northern part of Erbaa, Pliocene clay, silt, pebble and sandstone levels are cropped out in the southern part of the town. Lithologically similar Pliocene deposits were also named Çerkeş formation by Aktimur et al. (1989). Alluvial deposits around the town of Erbaa generally include pebbly, sandy and silty clay levels. These deposits were divided as old and recent alluvial deposits by Canik and Kayabali (2000).

The basement rocks in the study area are composed of Permo-Triassic metamorphics of Turhal group. This basement is overlain by Upper Eocene volcano-sedimentary sequence, Pliocene continental and alluvial deposits. The rock units in the study are composed of Permo-Triassic metamorphic rocks, Lower–Middle Jurassic volcano-sedimentary sequence, Upper Jurassic–Lower Cretaceous limestones, Upper Cretaceous flysch deposits, limestones, volcano-sedimentary rocks and ophiolitic melange, Eocene turbiditic flysch and volcanics, Pliocene pebble and sand deposits and Plio-Quaternary young volcanic rocks from bottom to top. The neotectonic activity of the North Anatolian Fault Zone has resulted in the formation of pull-apart basins in the region and this tectonic regime is still active (Aktimur et al., 1992).

In this study, a user interface program was developed for geological formation query. It presents information on geological formations, such as formation name, rock class, formation age, ground type, and geological environment related to the area of inquiry by user identification. In the case of submitting a query according to a geological formation name, the geological formation
is selected on the map window, and information related to that formation is shown on the form window. It is possible to make queries according to criteria such as formation age, base type, and geological environment. In addition, records of geological formation selected can be exported as Microsoft Excel files by pressing the “Export to Selected Records” button (Fig. 5).

3.2. Seismological data

Erbaa city is one of the most active seismological places in Turkey. The earthquakes that occurred in 1939, 1942 and 1943 severely affected the area around Erbaa (Table 1). One of them, which occurred on 20 December 1942 ($M=7.0$), killed 3000 people and damaged 30,000 buildings. Detailed geological studies performed after the earthquake in 1943 confirmed that the town centre was on an active fault. Afterwards, the town of Erbaa was re-located towards the south (Erbaa Municipality, 2008).

In order to put forth the seismic danger potential in the study area, historical earthquakes on the North Anatolian Fault Zone have been taken into account. It has been deemed suitable to determine the seismic parameters by taking into account the features of the 1999 Kocaeli earthquake, which is the most prominent and most destructive of the possible earthquake scenarios that might take place with the same mechanism and similar magnitude. Hence, the condition of an earthquake with a magnitude of 7.2 and maximum horizontal ground acceleration value of 0.45 g ($a_{max}=0.45$ g) was taken into account. This possible earthquake scenario has been taken into account for the possible seismic danger situations in analyses.

### Table 1

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<th>Magnitude</th>
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<td>37.36</td>
<td>10</td>
<td>4.9</td>
</tr>
</tbody>
</table>

3.3. Geotechnical data

In this study, drilling operations have been carried out at 36 different locations. During the drilling of each borehole, a Standard Penetration Test (SPT) was carried out at one metre intervals starting from the first and a disturbed sample was taken. Furthermore, again starting from the first 1.5 m of the borehole, an undisturbed sample was taken at one metre intervals using a thin walled sampler (Shelby) with a diameter of 89 mm. In addition to field studies, a CPT (Conical Penetration Test) with 30 seismic conical tips and pore fluid pressure metre was carried out. A maximum depth of 10 m was attained in these measurements due to gravelly levels.

The effects of local ground conditions on earthquakes have been studied for quite a while. The first and foremost related data were obtained from some measurements that were taken from various locations during the 1957 San Francisco earthquake (Idriss and Seed, 1968). The damage that occurred during the 1985 Mexico Michoacan earthquake ($M_s=8.1$) has put forth the effect of local ground conditions on seismic behaviour. The maximum bedrock acceleration value that is generally smaller than 0.04 g has caused an amplification of almost five times in the thick clay stone layers of an old river bed and has resulted in severe damage to buildings with periods close to the ground period. The microtremor measurement results taken from 517 different locations in order to determine the ground amplification values in the study area were evaluated within the scope of the project. According to Nakamura method, the dominant period and seismic amplitude amplification coefficient maps along with ground amplification maps were taken into account during analyses (Carniel et al., 2006). In addition, $V_s$ values were obtained for locations at which measurements using MASW (Multi-station Analysis of Surface Waves) and ReMi (The Refraction Microtremor) methods were carried out.
When preparing the liquefaction map, a great deal of different data such as the distance of the residence area to the fault, slope map, aspect map, borehole operations, ground amplification values obtained from microtremor measurements and the geological map of the study area were used.

Borehole studies were performed in different locations around the town of Erbaa by General Directorate of State Hydraulic Works (1971). The results of them show that the alluvium thicknesses are between 120 and 150 m. The alluvium deposit is thick in the north of the Kelkit River while it is thin in the south of the river. The alluvium thickness is 135 m on an average in the study area.

In this study, the condition of an earthquake with a magnitude of 7.2 and maximum horizontal ground acceleration value of 0.45 g ($a_{\text{max}} = 0.45 \text{ g}$) was considered. The samples taken from boreholes in different locations of the town of Erbaa were evaluated and the liquefaction analysis method of Youd et al. (2001) was applied. Sieve analysis and tests on determination of Atterberg limits were performed for ground classifications. As a result of this analysis, the ground classes such as SM (mixed-sand-silt), CL (clay-low), GW (gravel-weighted) and SC (sand-clay) were detected. Finally, the areas which have FS (factor of safety) value of liquefaction smaller than one were determined as potential-high liquefaction areas.

The user interface program was developed for borehole query. It shows the information related to boreholes, such as borehole location, latitude, longitude, groundwater level, borehole number, sample number, borehole depth, and borehole date. In case of making a query according to borehole number, the borehole is selected on the map window, and information related to that borehole is shown on the form window. On the other hand, the log file of the borehole can be obtained by pressing the “Show Borehole Log” button (Fig. 6).

If user interface-programs are required to perform different purposes in seismic microzonation, they can also be developed to handle these functions.

### 3.4. Input parameters and other thematic maps

Designed geographical layers for the suggested model, their attributes and geometrical types are given in Table 2. Table 3 shows the data input–output in the system, data needed, and data produced for determining the measures taken against potential damage to cities at risk of earthquake.

Thematic maps are a visual interaction tool. In this study, thematic maps such as a geological map, an urban growth direction map and potential soil liquefaction map were produced using GIS. In addition, a digital elevation model (DEM), an orthophoto, a slope map, and an aspect map of the study area were produced by means of GIS and evaluating stereo aerial photos (Table 3). These outputs help to reveal the existing situation of the study area in the natural disaster process. Conclusively, the GIS-based model suggested in this study provides great assistance in seismic microzonation studies.

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**Table 2**

<table>
<thead>
<tr>
<th>Geographical layer name (Type)</th>
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<td>Fault (Polyline)</td>
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</tr>
<tr>
<td>Microtremor (Point)</td>
<td>Survey ID, Station Name, Survey Date, Ground Type, Latitude, Longitude, Seismic Amplification, Ground Vibration Period, Explanation</td>
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<tr>
<td>Borehole (Point)</td>
<td>Borehole ID, Borehole Place, Depth, Borehole Number, Sample Number, Groundwater Level, Borehole Date, Explanation</td>
</tr>
<tr>
<td>Geological formation (Polygon)</td>
<td>Formation ID, Formation Name, Rock Class, Formation Age, Environment, Ground Type, Ground Class, Symbol, Explanation</td>
</tr>
<tr>
<td>Building (Polygon)</td>
<td>Building ID, Name, People Number, Type, Floor Number, Height, Construction Date, Explanation</td>
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<tr>
<td>City block (Polygon)</td>
<td>Block ID, Function, Explanation</td>
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<tr>
<td>Population (Standalone Table)</td>
<td>City ID, City Name, Year, Population, Explanation</td>
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<td>Seismical parameter (Standalone Table)</td>
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<tr>
<td>SPT parameter (Standalone Table)</td>
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</tr>
</tbody>
</table>

*Fig. 6. User interface program developed for borehole query.*
3.5. Results

A general census was performed in Turkey in 1970 and 2007 by the Turkish Statistical Institute (TurkStat, 2008). According to these data, the urban population of Erbaa in 1970 was 15,606. It increased up to 56,810 in 2007. However, when the numbers of buildings produced from aerial photos in both periods are taken into consideration, it seems that the number of buildings, which was 1798 in 1972, also increased to 8395 by 2006. It was found that the population of the town indicated a growth of 264% in the period between these two dates, with an additional 41,204 persons. Moreover, there seems to be an increase in the number of buildings (6,597 buildings) at a rate of 367%.

In this study, the urban growth direction of the study area was ascertained by building data from aerial photos for the years 1972 and 2006. As a result of this process, it was found that a considerable amount in the increase of settlements was realized towards the active fault (Fig. 7).

Geologically, the town of Erbaa is located on an alluvium deposit of Quaternary age. On the other hand, the borehole and microtremor studies show that soil liquefaction can occur in the study area. While the potential soil liquefaction may happen in the red coloured area, it may not occur in the green coloured areas at Fig. 8. Results of the spatial query indicate that the number of buildings on potential soil liquefaction areas (in red coloured area at Fig. 8) in the study area is 1182. It shows that 14% of the total buildings could be at risk.

To minimize the risk of earthquakes, it is recommended that high-risk areas be avoided as much as possible when building residences and infrastructure facilities. In this study, several spatial analysis processes were executed. Buildings at distances of 15, 50 and 100 m from an active fault were automatically

<table>
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<td>Digital</td>
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<td>Aspect map</td>
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<td>Orthophoto</td>
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<td>SPT parameter</td>
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Fig. 7. Urban growth direction of the town of Erbaa.
determined for detecting optimum settlement and revealing the earthquake risk in the town by the developed user-interface program. As a result of the spatial analysis; 60, 134 and 243 out of 8395 buildings remained within these areas. These buildings constitute approximately 0.7%, 1.6% and 2.9% of all the buildings (Fig. 9).
4. Conclusions

In case of considering the population of the town and the number of buildings, these indicators reveal that there is a dense urbanization in the study area. In addition, it shows increasing earthquake risk in the town. Furthermore, some of the industrial facilities in the town are located almost on the active fault. If these industrial facilities and buildings were not built by considering the existing ground conditions, they could be damaged in an earthquake. Building up to the period prior to the earthquake on 20 December 1942 in Erbaa (M=7) was very close to the Kellit River. After the earthquake, the town almost disappeared off the map. Following the earthquake in 1943, the central administration took a decision to move the city’s settlement towards the south. However, it was found upon evaluation of aerial photographs from 1972 and 2006, and integration of these data with GIS, that a considerably dense urbanization has once again developed towards the fault. Furthermore, potential areas for soil liquefaction were detected in the study area. New buildings will be constructed which should be built according to the existing geotechnical and geological conditions in the study area.

Natural disasters are directly related to geographical location. Therefore, geographical data before and after a natural disaster are needed to reduce or eliminate the damages resulting from natural disasters. Accurate and quick acquisition of these data has a direct impact on the success of plans for the future. In such cases, aerial photographs and satellite images have been accepted as indispensable geographical data sources. Thus, necessary measures can be taken within the shortest time and with the greatest efficiency by integrating aerial photographs, satellite images, and orthophotos with geological and geotechnical data on a GIS environment in a natural-disaster process (especially during an earthquake).

In this study, geological (faults, geological formations and horizons), geotechnical (microtremor), data (DEM, orthophoto) obtained from aerial photographs (providing accurate, up-to-date, and quick geographical data), and other data (slope map, aspect map) were integrated on a GIS environment. Thus, a sustainable GIS-based model was revealed to assist in seismic microzonation studies so that damage resulting from natural disasters such as earthquakes, landslides, and floods can be minimized or eliminated. This model is recommended for use in all cities that are at risk in terms of natural disaster, primarily earthquake, on the North Anatolian Fault Zone. Additionally, it can be used to reduce the risks caused by earthquake not only in the study area selected but also in any settlement located in an active fault zone.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.cageo.2011.10.006.

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