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ORIGINAL PAPER

An integrated earthquake vulnerability assessment framework for urban areas

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Abstract In this paper, an integrated urban earthquake vulnerability assessment framework, which considers vulnerability of urban environment in a holistic manner and performs the vulnerability assessment for the neighborhood scale, is proposed. The main motivation behind this approach is the inability to implement existing vulnerability assessment methodologies for countries like Turkey, where the required data are usually missing or inadequate for the decision-makers in prioritization their limited resources for risk reduction in the administrative units from which they are responsible for. The methodology integrates socio-economical, structural, coastal, ground condition, vulnerabilities (fragilities), as well as accessibility to critical services. The proposed methodology is implemented for Eskisehir, which is one of the metropolitans of Turkey. In the implementation of the proposed framework, geographic information system (GIS) is used. While the overall vulnerabilities obtained for neighborhoods are mapped in GIS, the overall vulnerabilities obtained for buildings are visualized in 3D city model. The main reason behind using different mapping and visualization tools for vulnerabilities is to provide better ways for communicating with decision-makers. The implementation of the proposed vulnerability assessment methodology indicates that an urban area may have different vulnerability patterns in terms of structural, socio-economical, and accessibility to critical services. When such patterns are

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investigated, effective vulnerability reduction policies can be designed by the decision-makers. The proposed methodology well serves for this purpose.

Keywords Earthquake · Structural fragility · Socio-economic vulnerability · Accessibility to critical services · 3D visualization · GIS

1 Introduction

Urban earthquake vulnerability has increased over the years due to the increasing complexities in urban environments. The main reasons for high vulnerability of urban environments to earthquakes are the location of major cities in hazard prone areas, growth in urbanization and population, and rising wealth measures (Tucker et al. 1994; Kakhandiki and Shah 1998). In recent years, physical examples of these factors are observed through the growing costs of major disasters in urban areas which have stimulated a demand for in-depth evaluation of possible strategies to manage the large-scale damaging effects of earthquakes. Understanding and formulation of urban earthquake vulnerability requires consideration of a wide range of vulnerability aspects, which can be handled by developing an integrated approach. In such an integrated approach, an interdisciplinary view should be incorporated into the vulnerability assessment.

There have been several attempts for the development of vulnerability assessment methodologies and its use in earthquake risk assessment by considering various aspects of vulnerability, such as, physical, social, economical, etc. Moreover, the developed methodologies vary in scale, such as local, regional, national, international, etc. Examples of risk assessment incorporated with vulnerability analysis at various scales can be found in King and Kiremidjian (1994), Hewitt (1997), Davidson and Shah (1997), Mileti (1999), Radius (1999), FEMA-NIBS (1999), Alexander (2000), Dowrick (2002, 2003), Morales (2002), Plattner (2005), Mourouse and Brun (2006), and Karaman et al. (2008). Among these examples, Earthquake Disaster Risk Index (EDRI) presented by Davidson and Shah (1997) is one of the earliest models, which provided a multidisciplinary approach by considering several dimensions of risk and vulnerability. As EDRI has been developed for comparisons of relative risks of different cities, it does not allow comparisons to be made among the neighborhoods within a city, which is required for developing effective disaster risk reduction plans in detail. In later approaches, the value of geographic information systems (GIS) has been realized, and GIS is used for preparing urban earthquake risk and vulnerability maps at different scales. For example, in Radius (1999) project, earthquake risk for 27 cities selected from Asia, Europe, the Middle East, Africa, and Latin America is assessed by using GIS tools and considering mainly physical urban environment, such as buildings, infrastructures, etc.

HAZUS, which was developed by FEMA-NIBS (1999), considers economical and social aspects of urban earthquake risk as well as buildings, lifelines, and infrastructure. HAZUS also allows mapping of results by providing outputs compatible with GIS software. Although HAZUS methodology is one of the most sophisticated urban earthquake risk assessment approach, its application is limited to the United States as it is designed for the US conditions. Recognizing this fact, several initiatives in Europe have started for developing earthquake risk assessment and loss estimation methodologies across the Euro-Mediterranean region. The final products of these initiatives are usually software packages for assessing the seismic risk and earthquake losses.

Stafford et al. (2007) reviewed eighteen such packages in terms of their potential for effective rapid postearthquake response. Strasser et al. (2008) comparatively investigated five European seismic risk estimation methodologies, namely KOERILOSS, SELENA, ESCENARIS, SIGE-DPC, and DBELA. Strasser et al. (2008) stated that these five models have common inputs of ground motion and building stock data; however, the outputs vary due to variations in vulnerability functions. Moreover, none of these models considered the various aspects of urban environment vulnerability (social, economical, cultural, structural, etc.) as a whole, rather they concentrated on predicting loss of building stock and related indirect losses, such as number of fatalities and economic losses due to structural damages. However, when the urban environment is considered in a holistic manner, the predicted losses due to earthquakes will be much higher. The main reason is that earthquakes not only cause losses in building stock and fatalities but also result in destruction of urban environment's economy, cultural heritage, social structure, etc. Since the final products of urban earthquake risk assessment methodologies are crucial for decision-makers in developing effective risk reduction strategies, the components of urban environment such as ground conditions, buildings, infrastructure, social, economical, organizational structures, and accessibility to critical services have to be integrated in the overall vulnerability assessment. In addition to that, computed risk for an urban environment is time dependent as urban environments are changing in time and vulnerabilities of elements at risk are variable at different phases of an earthquake. Hence, the establishment of pre-, during, and post-disaster intervention plans requires holistic considerations of urban earthquake vulnerability. Another problem with the existing methodologies is the fact that they generally divide the urban environment under study into grids and risk is assessed for these grid units, whereas the grids may not have any physical meaning for decision-makers. The solution to this problem would be working in small grid sizes and aggregating these grids for administrative zones, which requires too detailed data collection and analyses.

In this paper, an integrated urban earthquake vulnerability assessment framework, which considers vulnerability of urban environment in a holistic manner and performs the vulnerability assessment for the smallest administrative unit, namely at neighborhood scale, is proposed. The main motivation behind this approach is the inability to implement existing vulnerability assessment methodologies for countries like Turkey, where the required data are usually missing or inadequate for the decision-makers for prioritization their limited resources in risk reduction in the administrative units from which they are responsible for. The methodology integrates socio-economical, structural, coastal, ground condition, vulnerabilities (fragilities), as well as accessibility to critical services. After giving the general overview of the proposed framework, its application for Odunpazari Municipality of Eskisehir, which is one of the metropolitans of Turkey, is presented. In the implementation of the proposed framework, the tools of the geographic information system (GIS) are used in order to establish the backbone of a spatial decision support system (SDSS) for decision-makers of the administrative units. The backbone of SDSS is supported by 3-D visualization/mapping techniques so that decision-makers can easily use and interpret the outputs.

2 The proposed integrated vulnerability assessment framework

The vulnerability components of an urban area can be considered in two main categories. In the first category (Type I vulnerability), the vulnerability is determined based on seismic hazard and fragility analysis of the structural elements of the urban area, such as buildings, infrastructure, lifelines, etc. On the other hand, in the second category (Type II Vulnerability), the urban elements are mainly vulnerable to any kind of natural disasters like socio-economic structure and accessibility to critical services. Hence, Type II Vulnerability is not dependent on the seismic hazard analysis. In the proposed methodology, the indexes of the Type I and Type II vulnerabilities are evaluated for the neighborhoods of the considered urban area. Then, Type I and Type II vulnerability indexes are combined in an overall urban vulnerability index according to a GIS-based multicriteria decision analysis (MCDA) for the urban area. In MCDA analysis, simple additive weighting (SAW) method is used, where the vulnerability indexes are given weights according to their importance. The overall vulnerability index (*V*) is computed by using Eq. 1.

$$V = w_1 v_s + w_2 v_{12} + w_3 v_{22} \tag{1}$$

where v_s = vulnerability index obtained for structural vulnerability (fragility) for a given neighborhood; v_{12} = vulnerability index obtained for socio-economical vulnerability for a given neighborhood; v_{22} = vulnerability index obtained for accessibility to critical services for a given neighborhood; w_i = weights of each vulnerability component for a given neighborhood, $i = 1, 2, 3$

$$\text{Note that} \sum_{i=1}^{3} w_i = 1$$

The computed overall vulnerability indexes as well as the individual vulnerability index values are mapped for each neighborhood in GIS. Moreover, the overall and individual vulnerability values for each building are visualized in a 3D urban environment in order to better convey the computed vulnerability information to the decision-makers. Figure 1 illustrates the overall structure of the proposed methodology.

As it can be seen from Fig. 1, in the most general context, the proposed framework has the following nine components:

- Seismic hazard analysis
- Soil response analysis
- Tsunami inundation analysis
- Structural vulnerability (fragility) analysis
- Socio-economic vulnerability analysis
- Vulnerability for accessibility to critical services
- Overall vulnerability assessment
- GIS-based mapping of vulnerabilities for neighborhoods
- Visualization of vulnerabilities in 3D virtual city model

The first three components (seismic hazard analysis, soil response analysis, and tsunami inundation analysis) are required prior to structural vulnerability (Type I vulnerability, v_{11}) analysis as v_{11} is dependent on the input from the first three components. (It is more proper to use the term fragility instead of vulnerability when the built environment is considered. However, in order to be consistent with the use of the term vulnerability for nonstructural elements involved in the framework, we preferred to use the term structural vulnerability).

The seismic hazard analysis can be performed either in a deterministic way or by using a probabilistic approach. Considering the aleatory uncertainties related to earthquake occurrences with respect to time, space, magnitude, and the additional epistemic uncertainties, probabilistic approach appears to be more appropriate. Also, recently, more attention is paid to the assessment of seismic hazard due to active faults. Accumulation of more data and information on the main characteristics of faults has also contributed to this. Accordingly, the new generation of seismic hazard maps should take into consideration the potential threat created by faults and should utilize the stochastic models consistent with

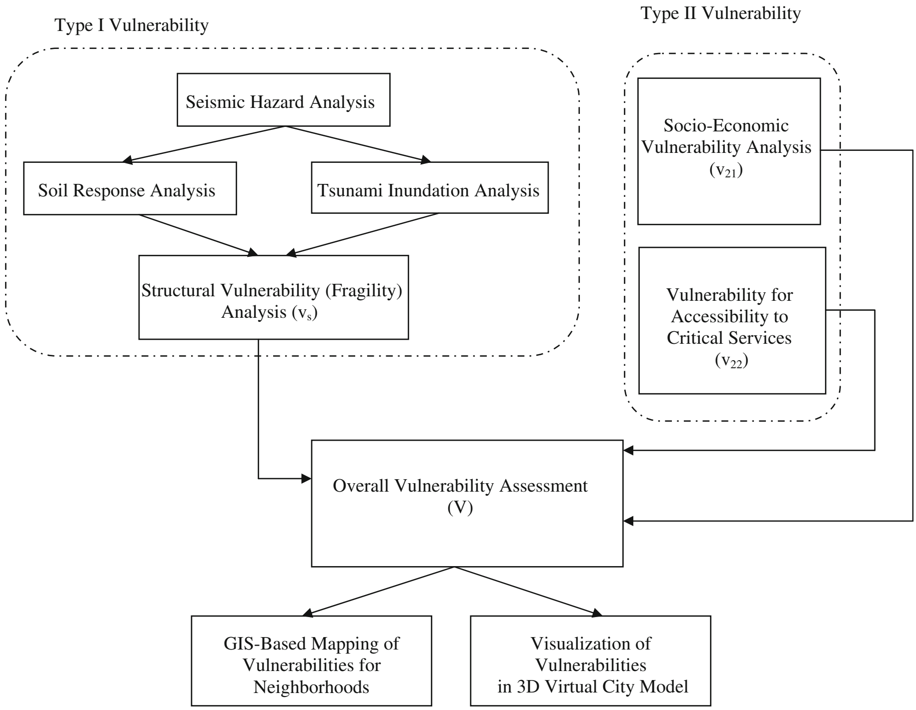

Fig. 1 Components of the proposed integrated vulnerability assessment framework

the available information on faults. However, this process requires time and is quite expensive if it is carried out for large regions. This fact is observed in the pilot study conducted for the development of the seismic hazard map of Eskisehir, where all seismic sources are defined as area sources. Besides, the results of the probabilistic seismic hazard analysis are used only to evaluate the distribution of seismic hazard all over the Eskisehir province at a macrolevel. In the case of the structural fragility analysis conducted at a microlevel for the municipality of Odunpazari, a deterministic seismic hazard analysis, based on a single critical scenario, is conducted.

The soil response analysis deals with the amplification of the seismic motions by the local site conditions. The seismic hazard analysis provides only the magnitude of the expected peak ground motion values on bedrock. During the propagation of earthquake waves from bedrock to surface, their characteristics change as they pass through different soil layers. Soil response analysis provides one of the basic inputs for structural fragility analyses. An earthquake site response analysis is traditionally carried out based on a one-dimensional wave propagation assumption unless there are strong evidences for 2-D or 3-D effects, such as when the site is close to the edge of a valley or it is located on a sharp topographical feature. To perform a soil response analysis for a site, typical data requirements are seismic hazard maps and site characterization consisting of soil stratification (type of soil, layering, and water table) and mechanical properties of the soil (most notably, the shear modulus and non-linear soil properties) at least in the top 30–40 m of the deposit. These data can be obtained by either in situ geotechnical investigations or geophysical site characterization methods or combinations of both. The soil response analysis results in a soil response map of the urban area to be used in the structural vulnerability analyses. The maps are prepared by using GIS tools with certain interpolation methods.

The tsunami inundation analysis is an optional component to be used for urban environment in coastal regions. Cummins et al. (2009) discuss the importance of site selection for housing in coastal areas and tsunami inundation mapping for estimating loss. Usually, numerical models are used to develop the inundation maps. The main inputs to these models are bathymetric and topographic data. Synolakis et al. (2008) reviewed the available numerical models for tsunami inundation maps. Hence, if the study area involves some coastal residential areas, it would be beneficial to obtain a tsunami inundation map in order to integrate it to the overall vulnerability assessment.

After carrying out seismic hazard, soil response, and/or tsunami inundation analysis, the next step is to perform structural vulnerability (fragility) analysis. Due to underlying uncertainties, seismic vulnerability of buildings has to be treated in a probabilistic manner. The vulnerability assessment involves the consideration of building characteristics and conditions. The earthquake damage can be presented and estimated in various ways. These can be classified as empirical/statistical methods, analytical/theoretical methods, and methods utilizing expert opinion.

A reliable data source for earthquake damage estimation is the damage data assessed based on field observations of buildings damaged during earthquakes, provided that personal biases in the damage evaluation are eliminated. This empirical data can be described based on a relatively old statistical method, which is proposed by Whitman (1973), and referred to as the damage probability matrix (DPM). A DPM is composed of probabilities that a certain damage state (DS) is observed when a certain type of structure is exposed to known earthquake intensity (say, I). The ratio of the cost of repairing the earthquake damage to the replacement cost of the building (excluding the value of land on which the building is constructed) is defined as the damage ratio (DR). This method gives an average value of the damage ratio for a group of buildings having similar structural systems and materials of construction and suitable for regional damage estimation rather than an individual building. A more sophisticated statistical method is proposed by Yucemen et al. (2004) who have used the discriminant analysis technique of multivariate statistics.

The analytical/theoretical methods involve structural analysis models that consider the dynamic characteristic of buildings and are generally used to forecast damage for a single structure. Their advantage is that the method correlates the seismic demand with typical physical parameters used in seismic design. However, the main drawback is the difficulties involved in model development and computational efforts. Lack of sufficient empirical data and incomplete knowledge may necessitate the use of expert opinion.

The structural vulnerability (fragility) of the building stock (v_{11}) for every neighborhood in the considered urban environment is evaluated and mapped by using GIS. In the proposed methodology, it is also possible to evaluate the fragilities of infrastructures (v_{12}) and of lifelines (v_{13}). The overall structural vulnerability (v_s) for the given neighborhood is given by Eq. 2:

$$v_s = \sum_{i=1}^{3} w_{1i} v_{1i} \tag{2}$$

where w_{1i} is the weight assigned to the ith structural vulnerability component for the given neighborhood, and the sum of w_{1i}s equals 1.

Once the Type I vulnerability is computed, the next step is to evaluate the socio-economic vulnerability (v_{21}). The vulnerability in socio-economic content is taken to be the ability to anticipate, resist, cope with, and respond to a hazard. Therefore, v_{21} is evaluated independent from the seismic hazard analysis. Socio-economic vulnerability can also apply to a particular group or social unit and to the structures and institutions—economic, political, and social—which govern human life. Instead of focusing solely on the risk of exposure to physical phenomena, the approach used in this study recognizes that such physical phenomena are embedded in and mediated by the particular human context (social, political, economic, and institutional) in which they occur.

Socio-economic vulnerability assessment refers to the analysis of various factors in order to establish the probability of certain outcomes from an uncertain event or suite of events; in this case, it is the earthquake hazard. Earthquake risk is specifically high in urban areas where a high concentration of people, buildings, infrastructure, economic and social activities, etc. can be found. It is to be noted that the aim is not to formulate a specific policy for earthquake risk management, but results of this study can provide insights for the policy makers to understand differential levels of vulnerability for the social groups and formulate effective risk prevention policies.

Differential socio-economic vulnerability analysis of different groups is discussed widely in the literature. For example, The Social Vulnerability Index (SoVI), created by Cutter (2003), examined the spatial patterns of social vulnerability to natural hazards at the county level in the United States in order to describe and understand the social burdens of risk. Social vulnerability stems from limited access to resources and political power, social capital, beliefs and customs, physical limitations of the population, and characteristics of the built environment, such as building stock and age, and the type and density of infrastructure and lifelines. Socio-economic vulnerability for different sections of the society is analyzed based on such characteristics as age, gender, health, welfare and wealth of households, and capability and coping strategies of social groups. Response to risk by children, elderly, sick, and the disabled may be quite different from that of young and healthy persons (Yiing-Jenq et al. 2004). Similarly, an individual's level of income, occupation, and family size are among characteristics that determine socio-economic position, which in turn determine the place of residence, its qualitative and quantitative features and infrastructure, which eventually determine the impact of risk (Evans and Kantrowitz 2002).

Physical accessibility is one of the most vital and important components of natural disaster preparedness. For this reason, emergency accessibility is a paramount factor for a decision-maker, who has to consider accessibility to/from critical services in a disaster situation and in the early stages of preparedness planning. In this study, vulnerability for the physical accessibility to/from critical services (ambulances, fire brigades, etc.) in an urban area (v_{22}) is described by using zone-based, isochronal-based, and raster-based models. These models are implemented in geographic information systems by considering accessibility of fire brigades (v_{221}), ambulances (v_{222}), etc. Moreover, the accessibilities to health services from each neighborhood of the urban area are evaluated by considering the capacity of the health services. The cumulative effects of accessibility in different parts of the urban environment are determined. Then, the overall vulnerability for accessibility (v_{22}) is computed by taking the weighted sum of the individual vulnerabilities for accessibility (v_{221}, v_{222},…).

$$v_{22} = \sum_{i=1}^{3} w_{2i} v_{22i} \tag{3}$$

where w_{2i} is the weight assigned to the ith accessibility to critical services vulnerability component for the given neighborhood, and the sum of w_{2i}s equals to 1.

After evaluating the Type I and Type II vulnerabilities, the overall vulnerability can be evaluated for each individual building or each neighborhood. In the proposed approach, in order to demonstrate the methodology, both are evaluated in the case study. While the overall vulnerabilities obtained for neighborhoods are mapped in GIS, the overall vulnerabilities obtained for buildings are visualized in 3D city model. The main reason behind using different mapping and visualization tools for vulnerabilities is to provide efficient ways for communicating with the decision-makers.

3 Implementation of the proposed framework for the Eskisehir metropolitan area

3.1 General information about Eskisehir

Eskisehir, with a population of 600,000, is one of the important centers of industry in Turkey. It is the main center of Eskisehir province. Eskisehir City Greater Municipality coordinates Odunpazari and Tepebasi Municipalities, which are the two administrative units dividing the Eskisehir City into two (Fig. 2). A number of dams and two universities are located within Eskisehir City boundaries. Due to its rapid development, Eskisehir has become a popular location for new investments. According to the current seismic zoning map of Turkey (Code 1997), the province of Eskisehir is located in Zones II–IV. The seismic zoning map of Turkey contains five zones, with Zone I being the seismically most active one. Odunpazari, which has a population of 350,000, is the largest municipality of Eskisehir and is selected as the region to illustrate the application of the proposed framework.

3.2 Seismic hazard assessment

The classical probabilistic seismic hazard analysis (PSHA) method is utilized for the assessment of seismic hazard for the Eskisehir province. Earthquake occurrences in the time domain are assumed to exhibit a Poisson process and magnitudes to be distributed exponentially. It was not possible to use the alternative characteristic earthquake and renewal process models due to the lack of sufficient data on the main parameters of the

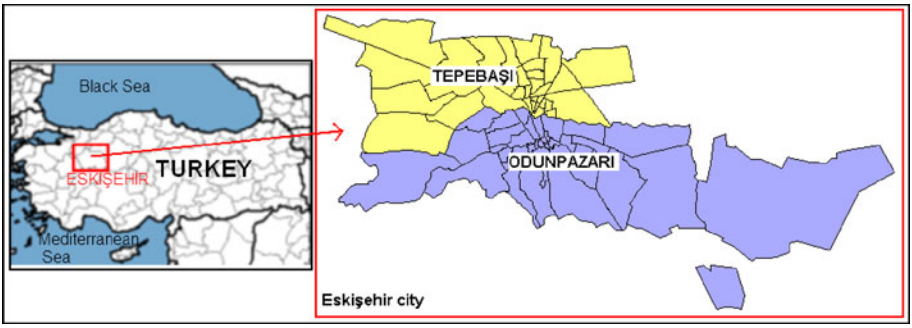

Fig. 2 Odunpazari and Tepebasi municipalities of Eskisehir greater municipality

faults, such as slip rates, magnitude and mean recurrence interval of characteristic earthquakes, time passed since the last characteristic earthquake, etc.

A comprehensive earthquake catalog, in which earthquakes in different scales are converted to a common scale, is compiled. Seismic source zones near the region are delineated, and different attenuation relationships are employed. Uncertainties related to the seismicity parameters and different assumptions are taken into consideration by using the logic tree procedure. Seismic hazard maps in terms of peak ground acceleration and MSK intensity, corresponding to a return period of 475 years, are developed for the Eskisehir province. The basic steps of the probabilistic seismic hazard analysis carried out for Eskisehir are summarized in the following subsections.

3.2.1 The earthquake database and modifications

A comprehensive seismic database, which contains the earthquakes that have occurred within 250 kms of the city center (coordinates: 30.489°E longitude and 39.774°N latitude) in the last century, is compiled. It is assumed that the seismic hazard for the Eskisehir province is due to the seismic activity occurring in a rectangular region bounded between 27.50° and 33.50°E longitudes and 37.50°–42.00°N latitudes. In preparing this seismic database, four different sources of seismicity data were utilized. These are the catalogs provided by the Earthquake Research Department of General Directorate of Disaster Affairs of Turkey (GDDA-ERD 2004), Kandilli Observatory and Earthquake Research Institute of the Bogazici University (KOERI 2004), International Seismological Centre (ISC 2004a, b), and United States Geological Survey (USGS 2004a, b). The data in these catalogs were provided in different magnitude scales, and it is necessary that they are converted to a single scale. All the magnitude scales used in the seismic database are homogenized and converted to the moment magnitude scale. The moment magnitude (M_w) scale is selected since in recent years, this scale has become the most preferred one. The minimum value of M_w is set to 4.5, and earthquake magnitudes reported in different scales are converted to M_w by using the empirical conversion equations developed by Deniz and Yucemen (2010) by applying the orthogonal regression procedure to earthquakes that have occurred in the last 100 years in Turkey.

In order to satisfy the assumptions of the Poisson process, it is necessary that earthquake clusters should be identified and dependent events (fore and after shocks) be eliminated from the seismic database (declustering). This is achieved by using the space and time windows specified by Deniz (2006), which were obtained based on an extensive literature survey. This way two alternative seismic databases containing all earthquakes and only main shocks are created.

The incompleteness in the earthquake catalogs is also taken into account. For this purpose, an analysis of catalog completeness is performed based on the method proposed by Stepp (1973). In view of this analysis, both databases (which contain all earthquakes and only main shocks) are assumed to be complete for earthquakes with magnitude greater than 5.0. However, the completeness is assumed to be valid since 1966 for earthquakes with magnitudes between 4.5 and 5.0. The resulting seismic database is referred to as the artificially completed catalog.

3.2.2 Delineation of the seismic source zones

Since the geographical location of seismic source zones depends highly on subjective judgment of experts, the number and the layout of seismic source zones change from study to study. In our study, the areal seismic source zones delineated by Bommer et al. (2002) are adopted with some local modifications (Kocyigit 2005) to take into account the recent findings. The resulting seismic source zones, which formed the basis for the seismic hazard analysis conducted in this study, are tabulated in Table 1. In the same table, the maximum earthquake magnitudes are also given. For the earthquakes that cannot be related to any one of the 13 seismogenic provinces, background seismicity regions (G1–G4) are defined. There exist background seismicity regions both inside and outside of the main seismic source zones as listed in Table 1. The configuration of seismic source zones is displayed in Fig. 3.

In order to quantify the seismicity parameters, information given in the two seismic databases that include whole events and only main shocks is considered. Considering the other alternative assumptions listed in Table 2, namely incomplete versus artificially completed catalog and standard least squares regression versus maximum likelihood method in the computation of the recurrence relationships, $2^3 = 8$ different combinations are possible. The earthquakes in the finalized seismic databases are distributed to these thirteen main and four background seismic source zones according to the location of their epicenters and are used to predict the seismicity parameters of each seismic source zone. For the estimation of the parameters of the Gutenberg-Richter linear magnitude–recurrence relationship (mainly β, the parameter of the exponential magnitude distribution), the least squares regression and maximum likelihood methods are applied both to the original (incomplete) and artificially completed data sets, creating four different combinations for each one of the alternative seismic databases that include whole events and only main shocks. Because of space limitation, here only the standard least squares (SLS) and maximum likelihood (ML) estimates of β computed for the case of artificially completed

Table 1 Seismic source zones, expected maximum earthquake magnitude values, observed mean annual rates, and the β values computed from the artificially completed earthquake catalog containing all earthquakes (*SLSE* standard least squares estimate, *MLE* maximum likelihood estimate)

Source number	Seismic source zone	$(M_w)_{\max}$	ν_{obs}	β_{SLSE}	β_{MLE}
1	North anatolian fault system—segment B	8.0	3.284	1.741	2.970
2	North anatolian fault system—segment C	7.4	2.400	1.699	3.062
3	North anatolian fault system—segment D	8.0	1.898	1.817	1.778
4	Bartin fault zone	6.8	0.202	1.099	2.556
5	Beypazari-Urus fault zone	5.4	0.100	3.182	3.182
6	Orta (Dodurga) fault zone	6.2	0.238	1.931	1.931
7	Inonu-Eskisehir fault zone	7.1	0.343	1.669	1.669
8	Tuz Golu fault zone	6.9	0.101	1.676	3.108
9	Kutahya fault zone	6.9	0.288	2.263	2.993
10	Simav-Aksehir fault zone	7.2	2.762	2.083	2.809
11	Alasehir-Izmir (Gediz) graben	7.2	2.188	2.326	2.395
12	Buyuk Menderes graben	7.1	0.430	1.516	3.454
13	Cameli-Burdur fault zone	7.1	1.013	2.053	2.125
G1	Background north	5.8	0.713	2.930	3.362
G2	Background inner 1	5.4	1.036	3.182	3.182
G3	Background inner 2	5.4	1.204	2.025	2.025
G4	Background inner 3	5.4	2.710	2.464	2.464

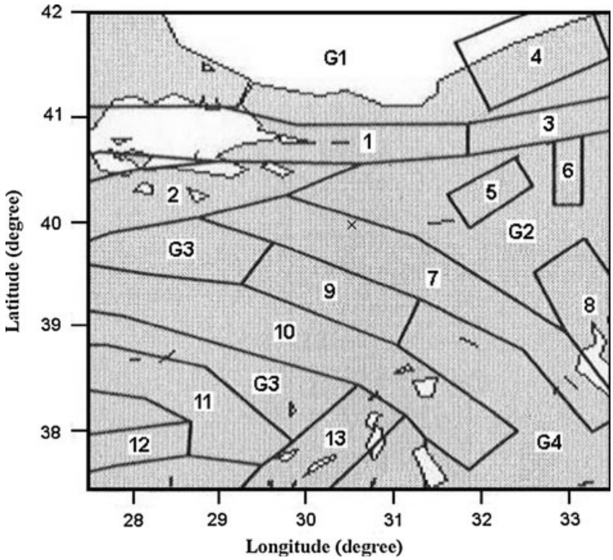

Fig. 3 Configuration of the seismic source zones listed in Table 1 (×: shows the approximate location of Eskisehir's city center)

Table 2 Alternative assumptions and the corresponding subjective probabilities

Alternative assumptions	Subjective probability
All earthquakes	0.5
Main shocks only	0.5
Incomplete catalogs	0.4
Artificially completed catalogs	0.6
Standard least squares regression in the computation of the recurrence relationships	0.4
Maximum likelihood method in the computation of the Recurrence relationships	0.6
If PGA is used	
Attenuation relationship of Gulkan and Kalkan (2002)	0.6
Attenuation relationship of Boore et al. (1997)	0.4
Attenuation uncertainty, $\sigma_{\ln\,Y} = 0.447$	0.1
Attenuation uncertainty $\sigma_{\ln\,Y}$ is equal to the reported value	0.6
Attenuation uncertainty, $\sigma_{\ln\,Y} = 0.707$	0.3
If intensity (MSK) is used	
Attenuation relationship of Musson (2000) in its original form	0.5
Attenuation relationship of Musson (2000) converted to M_w scale	0.5
Attenuation uncertainty, $\sigma_{\ln\,I} = 0.01$	0.15
Attenuation uncertainty, $\sigma_{\ln\,I} = 0.06$	0.60
Attenuation uncertainty, $\sigma_{\ln\,I} = 0.10$	0.25

catalog containing all earthquakes are given in Table 2, together with the values of the annual seismic activity rate, v, for earthquakes with $M_w \geq 4.5$.

3.2.3 Attenuation relationships

Peak ground acceleration and MSK intensity are selected as the earthquake severity parameters. In order to estimate earthquake hazard in terms of these parameters, the following attenuation relationships are employed. For the peak ground acceleration, the ground motion prediction equations given by Gulkan and Kalkan (2002) and Boore et al. (1997) for rock sites are adopted. These equations are, respectively, as follows:

$$\ln Y = -0.682 + 0.253 \times (M - 6) + 0.036 \times (M - 6)^2 - 0.562 \times \ln r + 0.202 \tag{4}$$

$$\ln Y = -0.242 + 0.527 \times (M - 6) - 0.778 \times \ln r + 0.301 \tag{5}$$

where $r = \sqrt{r_{cl}^2 + h^2}$; $Y =$ horizontal component of the peak ground acceleration (PGA) in g; $M =$ moment magnitude; $r_{\mathrm{cl}} =$ closest horizontal distance to the vertical projection of the rupture in km; $h =$ fictitious depth, computed by regression analysis as 4.48 and 5.57 km, respectively, for Eqs. 4 and 5. The standard deviation, $\sigma_{\ln Y}$, is reported as 0.562 and 0.520, for Eqs. 4 and 5, respectively. For intensity attenuation, the following equation proposed by Musson (2000) is used:

$$I = 1.063 + 1.522 \times M_s - 1.102 \times \ln R - 0.0043 \times R \tag{6}$$

where $I =$ intensity in MSK scale; $M_s =$ earthquake magnitude in the surface wave magnitude scale; and $R =$ hypocentral distance in kms. The standard deviation came out to be $\sigma_I = 0.486$ (or $\sigma_{\ln I} \approx 0.06$). The alternative assumptions considered for the attenuation relationships are summarized in Table 2. The use of an imported attenuation relationship as an alternative to a local one is due to the fact that the relationship given by Boore et al. (1997) has been used widely in many studies in Turkey (e.g., Erdik et al. 2004, Yucemen and Ozturk 2008). It is well known that the output of an attenuation relationship is quite sensitive to the value of the associated standard deviation. Accordingly, the epistemic uncertainty associated with this factor is taken into consideration by assuming alternative values for the underlying standard deviation with weights as shown in Table 2.

3.2.4 "Best" estimate of seismic hazard for Eskisehir city center

In order to reflect the influence of various assumptions discussed above and to account for the epistemic uncertainties in the values of seismicity parameters, the logic tree procedure is applied as described below. The alternative assumptions are listed in Table 2, together with the subjective probabilities assigned to them. These probabilities quantify the likelihood of each assumption being valid as compared to the alternative assumptions reflecting the subjective opinions of the authors. Seismic hazard computations are carried out for each one of the resulting $2^4 \times 3 = 48$ combinations, and the mean hazard values are obtained for each alternative case. By multiplying the mean seismic hazard results computed for each one of the 48 combinations by the corresponding joint probability (multiplication of the probabilities of the selected alternatives) of that combination and adding these values, a weighted average seismic hazard value is computed. The resulting seismic hazard curve in terms of PGA is called as the "best" estimate of seismic hazard for Eskisehir city center and is shown in Fig. 4a. The same procedure is repeated for the

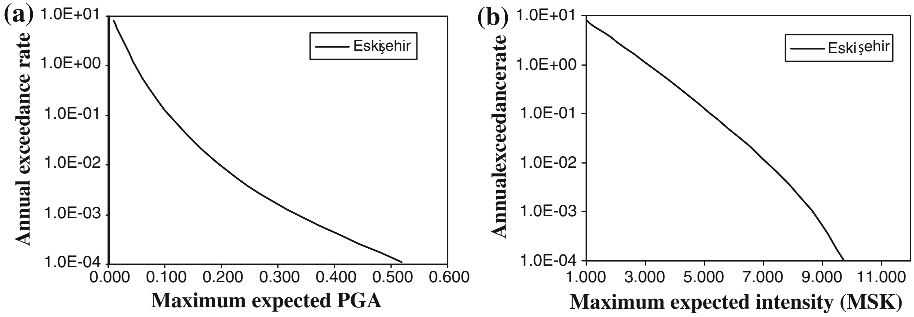

Fig. 4 "Best" estimate seismic hazard curves for Eskisehir city center. **a** In terms of peak ground acceleration (PGA in g); **b** in terms of intensity (MSK)

48 combinations resulted for MSK, and the "best" estimate seismic hazard curve in terms of MSK is obtained as shown in Fig. 4b. Based on these "best" estimate hazard curves and for a return period of 475 years, the PGA and MSK values are obtained as 0.28 g and 8.2 (MSK), respectively, for the city center of Eskisehir. It is to be noted that the term "best" estimate is used within the context of Bayesian statistics to reflect the fact that the weights are assigned subjectively.

Seismic hazard maps are also plotted for peak ground acceleration (PGA) and intensity (MSK) corresponding to a return period of 475 years (10% probability of exceedance in 50 years) considering the combination composed of the most likely assumptions. These maps are shown in Fig. 5. All of the seismic hazard calculations are carried out by using the software CRISIS 2003 (Ordaz et al. 2003).

3.3 Structural fragility analysis for Odunpazari municipality

The structural fragility (vulnerability) analysis is carried out only for the municipality of Odunpazari. According to the seismic hazard map given in Fig. 5b, the MSK intensity for a return period of 475 years is about 7.5 for Odunpazari municipality. Based on the damage probability matrices developed for Turkey by Yucemen (2005), "moderate" building damage is expected in Odunpazari for this level of hazard from a probabilistic point of

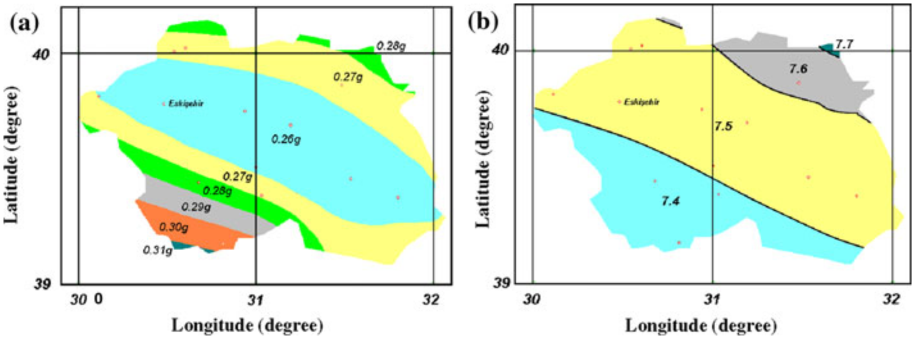

Fig. 5 Seismic hazard maps corresponding to a return period of 475 years obtained based on the combination of the most likely assumptions. **a** In terms of peak ground acceleration (PGA in g); **b** in terms of intensity (MSK)

view. However, it is not possible to distinguish finer levels of damage since the aim of the probabilistic seismic hazard analysis, consistent with the lack of sufficient information on active faults, is to evaluate the distribution of seismic hazard all over the Eskisehir province, which has larger spatial coverage than the city center of Eskisehir province, at a macrolevel. Accordingly, a deterministic analysis is carried out in order to quantify the level of damage for the 31 neighborhoods located in Odunpazari municipality by establishing a finer rating within the range of moderate damage. For this purpose, a more detailed damage analysis is carried out based on the characteristics of buildings located in these neighborhoods and by selecting a scenario earthquake.

Servi (2004) has compiled a database for the 27,904 buildings located in the 31 neighborhoods of the Odunpazari municipality based on the records kept officially by the municipality for the registered buildings. This database contains information on the location (longitude and latitude), number of floors, soil classification (Z1, Z2, Z3, Z4), apparent quality (very bad, bad, moderate, good), and type (reinforced concrete, masonry, wooden) of these buildings. The soil classification indicated above is according to the Turkish Seismic Code (Code 1997) as detailed in Table 3. In this table, V_S denotes the shear wave velocity.

Seismic Risk Analysis Software (SRAS) described in Yakut and Kucukcoban (2005) is used in order to assess the expected damage in these buildings due to the selected scenario earthquake. The software uses five data sets to start the damage estimation analysis. These are building inventory data, attenuation relationship data, scenario earthquake data, capacity curves for each building type, and the analysis method data. Reliable building inventory data are must to obtain realistic results for the defined scenario earthquake assuming that attenuation relationship and the analysis method yield dependable results (Yakut and Kucukcoban 2005). The calculation involves three parts, namely demand calculation, performance calculation, and damage estimation. Demand calculation part initially finds the shortest distance between each building in the considered region and the fault associated with the scenario earthquake and then generates smoothed acceleration response spectrum expected under each building. Subsequently, the performance calculation module computes performance using the generated demand curve and the provided capacity curve for each building. Finally, damage estimation module predicts the performance of each building under the scenario earthquake induced forces.

The building inventory data require the following information for each building: location, site soil classification, number of stories, type of construction, age, and apparent quality. It is to be noted that all the required building inventory data are provided

Table 3 Site soil classification scheme according to Turkish Seismic Code (Code 1997)

Class name	General description	Mean V_S (m/s)		
		Min.	Ave.	Max.
Z1	FIRM to HARD ROCKS (e.g., rock, very stiff clay, very dense sands)	700	850	–
Z2	GRAVELLY SOILS and SOFT to FIRM ROCKS (e.g., tuffs, agglomerate, stiff clays, dense sands)	400	550	700
Z3	STIFF CLAYS and SANDY SOILS (e.g., soft deposits, medium dense sand, stiff clay and silt)	200	300	400
Z4	SOFT SOILS (e.g., high water table + alluvial deposits, loose and soft clay and silt)	–	180	200

by Servi (2004), for the 27,904 registered buildings located in the 31 neighborhoods of the Odunpazari municipality as stated above. For more information on SRAS, the reader is referred to Yakut and Kucukcoban (2005).

Based on the past seismic activity and the seismic sources delineated in the region (Fig. 3), it is clear that the most important seismic threat to Odunpazari municipality is due to the Eskisehir Fault Zone. The 6.4 magnitude of the February 20, 1956, Eskisehir earthquake is taken as the magnitude of the scenario earthquake to be created from this fault. The attenuation equation of Gulkan and Kalkan (2002) is used.

The damage ratio (DR) obtained from the SRAS program for each building is used to find the mean damage ratios (MDR) for each neighborhood. Damage ratio is defined as the ratio of the cost of repair to the replacement cost of the building. The MDRs vary between 23.06 and 36.48% for the neighborhoods. The variation for the individual buildings is between 21 and 37%. The largest MDR of 36.48% is observed for the neighborhood of Sumer, which is a very small region. Here, it was only possible to evaluate 4 registered buildings. These are all high-rise reinforced concrete buildings of 9–10 floors, all located on Z3 soil class (see Table 3) and their apparent qualities are rated as very poor. As a result the highest MDR is observed in this small neighborhood. In earthquake damage evaluation, the damage ratios between 10 and 50% are rated as moderate damage based on the damage probability matrices developed for Turkey by Yucemen (2005). Accordingly, all of the neighborhoods of Odunpazari municipality are expected to experience moderate damage due to this scenario earthquake. This result is also consistent with the results of the probabilistic seismic hazard analysis conducted for the Eskisehir province as described in the previous sections. However, in order to distinguish the neighborhoods according to the expected mean damage ratio, a finer subdivision is established as follows: The neighborhoods with MDR less than 25% are classified as¨Light¨, those with MDR between 25 and 28% as “Light-moderate” and those with MDR > 28% as “Moderate”. The indicator variables 0 (zero), 1 (one), and 2 (two) are assigned, respectively, to these three groups. The results of this classification are shown in Table 4, and these will form the basis for the assessment of vulnerabilities in the following stage of the proposed integrated vulnerability assessment framework. When the values of Table 4 are mapped for neighborhoods of Odunpazari municipality, spatial distribution of structural vulnerability can easily be visualized (Fig. 6). Figure 6 shows that in Odunpazari, the northern neighborhoods have building vulnerability ranging from moderate to light-moderate, and the central to southern parts have light building vulnerability. In Odunpazari municipality, the central and southern parts constitute the older parts, with concentrations of many historic buildings. On the other hand, the northern part is the newly developed section of the municipality that has relatively high building vulnerability. This distribution of vulnerability is contradictory to the common observation that vulnerability increases with the age of buildings and is due to the fact that the newly developed section is located in a region where the soil conditions are poor and this problem is not taken into consideration adequately in the construction of these new buildings.

3.4 Socio-economic vulnerability analysis for Odunpazari

In this study, the major sociological dimensions of socio-economic vulnerability are defined by referring to such characteristics of individuals:

1. *Socio-demographic dimension* refers to population profile, age distribution, marital conditions, gender, race/ethnic composition, health status, migration, household size,

Table 4 The level of expected damage for the different neighborhoods of the Odunpazari municipality (*0* "Light"; *1* "Light-moderate"; *2* "Moderate")

Neighborhood	Mean damage ratio (MDR %)	Damage indicator	Neighborhood	Mean damage ratio (MDR%)	Damage indicator
Akarbasi	27.56	1	Huzur	23.65	0
Akcaglan	26.95	1	Istiklal	27.61	1
Akcami	25.20	1	Karapinar	23.06	0
Alanonu	24.66	0	Kirmizitoprak	27.95	1
Arifiye	28.12	2	Kurtulus	26.68	1
Buyukdere	24.13	0	Orhangazi	24.19	0
Cankaya	24.79	0	Orta	24.49	0
Cunudiye	23.60	0	Osmangazi	25.08	1
Dede	23.88	0	Pasa	24.41	0
Deliklitas	28.47	2	Sarkiye	23.70	0
Emek	24.56	0	Sumer	36.48	2
Erenkoy	23.44	0	Visnelik	28.96	2
Gokmeydan	26.89	1	Yenidogan	23.31	0
Goztepe	24.33	0	Yenikent	29.51	2
Gultepe	24.35	0	Yildiztepe	24.02	0
Gundogdu	23.62	0			

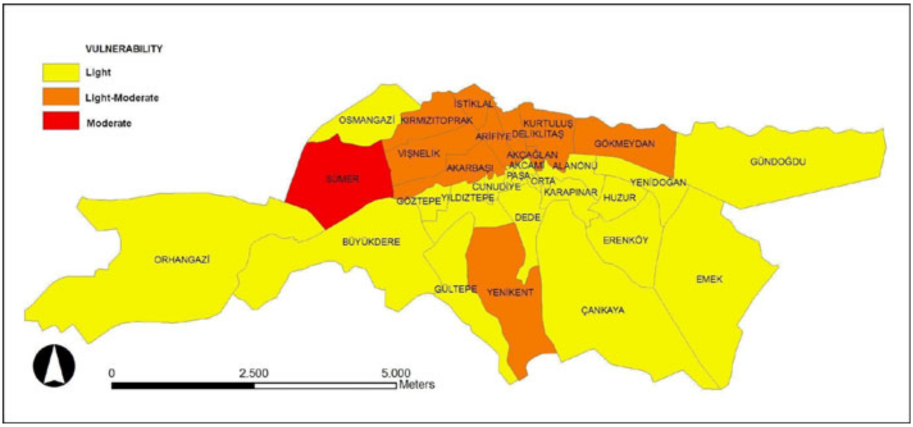

Fig. 6 Spatial distribution of building vulnerability (fragility) in Odunpazari

and number of dependent persons in the household like children under the age 15 and elderly over the age 65+.

2. *Socio-economic dimension* refers to level of education and skills, level of income, house and property ownership, employment status as self-employed or wage or salaried work, seniority in work, size of workplace and investment if self-employed, degree and nature of risks related to unemployment and/or specific job losses, access to welfare benefits, social networks—social solidarity and reciprocal ties among family, relatives, friends, neighbors as well as housing conditions, house ownership

status (owner occupied or rented), nature of physical infrastructure like roads, sanitation, access to clean water, etc.

3. *Social security dimension* refers to the degree and nature of social insurance and social security benefits for the population, access to retirement payments, access to health care, public provisions for population with special needs like disability, homeless, etc.
4. *Socio-spatial dimension* refers to regional differences, mainly urban/rural settlements.
5. *Political dimension* refers to the level of political participation of the people, as well as the policies and activities of the local governments toward reduction of all vulnerabilities and social risks.
6. *Behavioral dimension* refers to the level and nature of perceptions of risks in the population, attitudes toward all kinds of risks and specifically disasters and earthquake risks, political awareness and being organized as pressure groups to be effective on policies, the level of precautions taken by the population.

In fact, within the scope of sociological dimensions explained above, the socio-economic vulnerability is understood as an outcome of existing social inequalities in the society. Furthermore, some studies conducted so far show that ill health, disability and poverty are all closely associated with vulnerability. Additionally, social inequalities determine the space where individuals live and the nature of this living place. The vulnerability of the living space (including the dwelling, neighborhood and means and endowment of infrastructures in that neighborhood) is also effective in the determination of the socio-economic vulnerability in close association with the characteristics of the individual. The vulnerability of this living space is further increased by factors, such as the level of urbanization, population growth, and density. Consequently, it can be assumed that places where the poor live have poorer infrastructural services. This is the point where the space is interwoven with what is social. All these sociological and spatial features determine the levels at which individuals are affected before, during, and after the hazard and the time required for recovery.

Assessment of socio-economic vulnerability in Odunpazari municipality is carried out in terms of four stages: (a) sample selection and questionnaire development, (b) cluster and indicator development, (c) measurement analysis and indicator selection, and (c) index development.

3.4.1 Sample selection and questionnaire development

To develop a social vulnerability index, a representative database on the basis of neighborhoods and streets is needed. On the other hand, province-based data collected by the Turkish Statistical Office (TUIK) is not published as disaggregated by neighborhoods and streets. This causes researchers to face with difficulties in reaching relevant databases. In order to overcome this difficulty, in this study, a field research was conducted to reach representative and space-based data in terms of neighborhoods. The addresses required were obtained from the Eskisehir Greater Municipality database after signing a confidentiality agreement. Such a database was developed as “City Information System” by Eskisehir Greater Municipality which enabled “muhtars” (local administrators) to systematically follow any changes in the status of the registered households residing in their respective neighborhoods. From this database, 5% of addresses were randomly selected from the neighborhoods and streets of Odunpazari and used as the sample of the field research for the present study. Consequently, building numbers were determined from randomly selected streets in 31 neighborhoods of Odunpazari and its streets.

Later, however, considering that the focus of this study is to understand socio-economic vulnerability before and after an earthquake, the research team decided to modify the sample so as to give relatively more weight to addresses from the inner streets rather than main streets and boulevards. It was decided to interview only one household from each selected building (address). Determining which household this should be constituted the second stage of the sampling process. At the second stage, it was assumed that the number of stories in a building is an important indicator of earthquake vulnerability reviewing the previous earthquake casualties in Turkey. The death tolls were higher in lower stories. Accordingly, interviews were conducted with households living in:

Flat on the 1st storey in single storey buildings
Flat on the 2nd storey in two-storey buildings
Flat on the 2nd storey in three-storey buildings
Flat on the 3rd storey in four-storey buildings
Flat on the 4th storey in five-storey buildings, and
Flat on the 5th storey in six-storey buildings.

In cases where there were more than one flat in a storey, questionnaires were conducted with that household who accepted to be interviewed. Questionnaires were administered with one household member over the age of 18 and who was capable to answer the questions. The original sample consisted of 1,500 households, and interviews were conducted with 1498 of these. This high rate of realization stems from the fact that the sample included those households present in their homes at the time of the field research and were ready to take part.

The questionnaire was made up of 69 open- and close-ended questions under 8 sub-headings. In order to form the questionnaire, the above explained sociological dimensions have to be converted into relevant indicators to measure socio-economic vulnerability before and after an earthquake.

3.4.2 Cluster and indicator development

First, a broad literature review was made to find similar studies. In this review, the most relevant study was found to be by Cutter et al. (2003). In this study, property, income, employment, education, demography, social, politics, local government, attitude, and behavior of individuals were mentioned as relevant indicators of vulnerability involved in environmental hazards. However, all such mentioned indicators in the literature should be re-defined within the specific local conditions of the town/space under study and with respect to the conditions of an earthquake. Additionally, since this is the first study of this kind in Turkey, in terms of developing a single socio-economical vulnerability index for each neighborhood, other previous sociological researches on earthquakes conducted in Turkey (Kasapoglu and Ecevit 2001; Izmit Kent Kurultayi 2000; Akdur 2001; Adapazari Chamber of Industry and Commerce 2000) were also reviewed. Hence, the items of the questionnaire were derived from the findings of these studies, mainly conducted after the Marmara earthquake to assess the social, economical, and cultural impact on the households.

After the literature review, 9 clusters and 57 indicators of social vulnerability were decided to be used in the vulnerability assessment questionnaire. It decided to include a wide list of indicators as derived from the literature in order not to miss any significant findings. The Table 5 below displays the contents of the questionnaire prepared according to this wider perspective.

Table 5 Questionnaire form and content

Category	Parameters asked
A. General information	With respect to the household and its members: Age, sex, educational background, place of birth, work status, social security coverage, type and ownership of present dwelling, qualifications of the house, property, migration
B. Income	Subsistence income, subsistence, savings, ways of coping up with economic difficulties
C. Employment	Job dates for employment and unemployment, criteria for "good job", vocational training
D. Health	Health insurance coverage, access to health services and strategies in coping up with health problems, disability
E. Daily life	Politics, social participation, political activities, daily life
F. Values	Values related to disasters
G. Local government	Information about, participation to, assessment of and level of satisfaction in local government services
H. Disaster and disaster management behavior	Risks that may be confronted with, ideas about the causes of disasters, responsibilities in disaster situations, measures taken against disasters at individual level

After finalizing the questionnaire and training the interviewers, the field research was conducted under the supervision of the Sociology Department of Eskisehir Anadolu University. The field work was given start in August 2005, and it lasted until 1 December 2005. The method adopted was to start first from the outer and more remote neighborhoods of Odunpazari municipality, which was followed by covering the sample addresses in a circular way so as to get closer and closer to the centre to save time and to guarantee the consistency of the field research. After the field research, all data were coded and analyzed statistically by using the SPSS packet program. In the final stage of indicator development, statistical significance testing of the answers to the questions was made.

3.4.3 Measurement analysis and indicator selection

These clusters and items were analyzed by conducting a factor analysis and for internal consistency as well as total-item correlation scores. At the end of this process, clusters and each cluster's indicators according to high correlation and internal consistency were defined. Clusters and their corresponding indicators are as follows:

1. *The "proprietorship/ownership cluster"* comprises three indicators: "proprietorship of the house," "car ownership," and other "real estate ownership." Relationship of this triple content with vulnerability is set as follows: The proprietorship cluster is considered to be vulnerable if the household is living in a rented house, if they have no car and there is no real estate ownership.
2. *The "income cluster"* includes "monthly household income less than 500 TL (approximately 350 US dollars)"; "household can save nothing from monthly income"; "household income falls short of subsistence"; "household's frequent deferral of health care because of economic difficulties"; "household in need of assistance for the education of its children" and "food cuts comes first in case of economic difficultly."

3. *The "employment cluster"*: The household is deemed to be vulnerable in terms of employment in case "household head is unemployed" and if there is also "somebody else unemployed in the same household.
4. *The "education cluster":* Household is vulnerable if the "level of education of household head is below primary school", if the "level of education of the spouse of the household is below primary school," and if there is "no books in the house other than school textbooks."

A study conducted following the Marmara Earthquake revealed the importance of education as a leading parameter where rational behavior and attitude went hand in hand with higher levels of education and where education stood as one of the most important independent variables, as it is was in many other cases, that particularly determined request for support (Kasapoglu and Ecevit 2001; Adapazari Chamber of Industry and Commerce 2000).

5. *The "demographic cluster"*: Household size is taken as a major indicator. Households with 6 or more members are determined as demographically vulnerable. According to Poverty Survey by Turkish Statistical Office (2004), for all Turkey (including rural and urban), households with 7 or more members are found to be vulnerable to poverty. Since Eskisehir is an urban area and household size is lower than Turkey's average, researchers decided households with 6 or more members can be considered as vulnerable.
6. *The "migration cluster"* has three contents: Households with "duration of residence in Eskisehir shorter than 5 years", "duration of residence in the present neighborhood is 5 years or shorter" and "households with scant confidence in the house they are living" are considered vulnerable in terms of migration.
7. *The "politics cluster"*: It is assessed in terms of "daily taking of a national paper" and "holding a political opinion". Political vulnerability emerges if households do not follow daily papers regularly and state no political opinion. Again, in the previous studies about the coping strategies with the after effects of the earthquakes, it was found that households who have information about government decisions and policies can cope better.
8. *The "spatial cluster"* has two major indicators. In the questionnaire, the respondents were asked to assess 13 local government services with respect to the quality of these services and their level of satisfaction. In this cluster, however, the point was confined to level of satisfaction with respect to services related to disasters. Related questions included those on the type of dwelling, how heating is provided, features of the dwelling in terms of infrastructure (electricity, water, and sanitation) and household items owned. In this cluster, spatial vulnerability is determined by the evaluations of the respondents of the local government services under urgent action plans "in cases of disasters like earthquake, flood, and fire are insufficient." Also, households living in squatter housing areas and in such dwellings where heating is provided by stove are considered to be vulnerable.
9. *The cluster "disaster-related attitude/behavior/beliefs"*: In this cluster, 6 questions were forwarded under the heading attitudes/values/beliefs. These questions were to be responded within the framework of 5 scales (fully agree, agree, undecided, disagree, and fully disagree) in order to convert a somewhat subjective dimension into an indicator. Vulnerability indicators of this cluster were respondents' declarations in terms of citizenship responsibilities and payment of taxes. In that sense, opposing views to the statements "it is the responsibility of citizens to construct houses resistant

to earthquake, fire, and flood" and "I agree to pay more taxes for a cleaner and safer environment" were taken as heightening the risk of vulnerability from earthquakes. The inclusion of attitudes is again mentioned by previous studies who emphasized that the populations expecting everything from the state and not taking their own precautions due to such behavior are vulnerable. In sum, we have nine clusters accompanied by relevant indicators that increase social vulnerability as shown in Table 5.

After the determination of the nine clusters and related indicators, they were examined with respect to internal consistency and item-sum correlations. Then, each indicator was assigned a weight between 0 and 1 points. In the literature, it is common to assign weights to indicators in order to stress the relative importance of some indicators over the others. The arguments underlying this approach were considered; however, in the absence of an empirical justification for weighting, it was decided to treat each variable as having an equal weight. Cluster scores were obtained by adding up these 0–1 points. Hence, selected variables can be gathered under a single factor for each area. Furthermore, they yielded high correlation with the total and strengthen internal consistency.

In the factor analysis, when the indicators were checked for internal consistency and intercorrelations, it was seen that certain issues can be gathered under a single dimension that are related to each other. Hence, a total score to strengthen internal consistency was identified. Accordingly, nine clusters were reduced to four: namely proprietorship, income, education, and politics, which were found to constitute a coherent whole. Factor analysis showed that 45.81% of variance in total score could be explained by this four-variable structure. Weight values that these four variables assumed in the context of the first factor turned out as 0.61, 0.77, 0.66, and 0.66, respectively. Internal consistency coefficient, Cronbach alpha, (Cronbach 1951, Crocker and Algina 1986) was calculated as 0.77, and correlations of clusters with total score were found as 0.63, 0.74, 0.66, and 0.66, respectively.

Afterward, each cluster was transformed into Z scores with zero mean and standard deviation of 1, and vulnerability index was obtained by adding these up. This value, in turn, was transformed into T score with an average value of 250 and standard deviation of 10. The distribution of vulnerability index that ranges from 23.93 to 73.29 is shown in the chart below.

At the end of the analysis it was found that while households with vulnerability scores under 40 are considered to have "light vulnerability," those in the interval 40 and below 60 are considered to have "moderate vulnerability" and others with scores 60 and higher are considered to be "highly vulnerable." (See Table 6)

The statistical findings were also examined whether vulnerability scores differed with respect to neighborhoods. Since there were very few observations in some neighborhoods, the normality assumption of single direction variance analysis could not be satisfied, and instead, Kruskal–Wallis test, which is the nonparametric equivalent of the former, was applied. This test showed that with 95% confidence level, there are significant differences with respect to neighborhoods.

3.4.4 Index development

Finally, the socio-economical vulnerability indexes for the neighborhoods are mapped by using GIS. Figure 6 shows that in Odunpazari, the central and south eastern parts have high degree of social vulnerability, whereas the northern parts have light socio-economic

Table 6 Indicators that exacerbate social vulnerability

Cluster type	Variables	Condition of being vulnerable
Ownership	Owner of the house	Lessee
	Car	If no car
	Real estate	If none
Income	Monthly household income	If less than 500 TL
	Saving	If no saving
	Whether income is sufficient	If not sufficient
	Assistance for education	If none received
	Deferral to healthcare services because of economic difficulties	If frequently deferred
	What is cut in case of economic difficulty	If there is cut from food
Employment	Job of household head	If unemployed
	Any other unemployed household member	If there is one
Education	Education level of household head	If primary or lower
	Education level of spouse	If primary or lower
	Any book other than textbook	If none
Demography	Household size	If 6 or more
Migration	Duration of residence in the city	If 5 years or shorter
	Duration of residence in the neighborhood	If 5 years or shorter
	Confidence in house	If none
Politics	Following any daily paper	If none
	Political opinion	If none is stated
Space	Earthquake related local government services	If considered insufficient
	Type of dwelling	If squatter housing
	Any restoration in the house	If done
	Heating in the dwelling	If stove is used
Attitude/belief	Citizen responsibility	If not accepted
	Willing to pay higher taxes for earthquake-safe places	If not accepted

vulnerability levels. When the maps for building (Fig. 6) and socio-economic (Fig. 7) vulnerabilities are compared, it can be seen that socio-economically least vulnerable neighborhoods have structurally more vulnerable building stocks.

As can be seen from the results of socio-economic vulnerability analysis, differential socio-economic vulnerability of different groups is found as supported by the literature. In that sense, it can be argued that socio-economic vulnerability has the following characteristics:

1. It differs among different sections of the society based on age, gender, and health differences.
2. The most disadvantaged, poor, and dependent sections can usually be more vulnerable.
3. However, vulnerability may not necessarily depend on wealth or poverty as the level of fragility of buildings can vary. The most vulnerable people may not be found in the most vulnerable places: Poor people can live in resilient physical environments and be vulnerable because of the lack of resources and access to basic needs, and wealthy

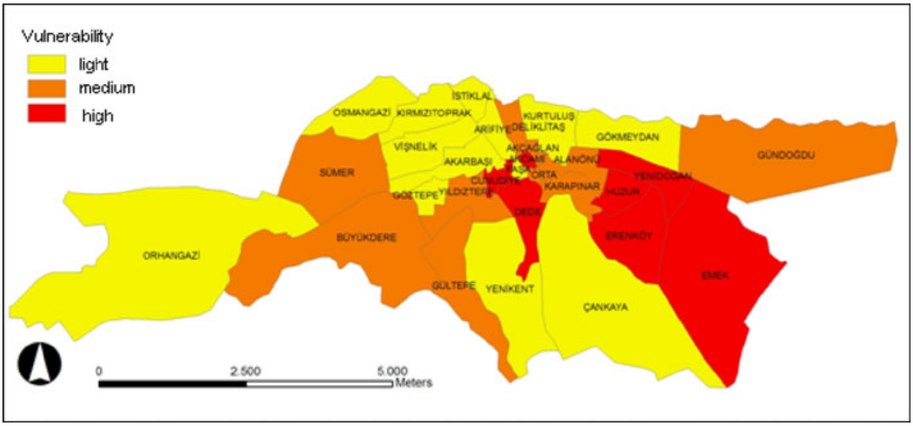

Fig. 7 Spatial distribution of socio-economic vulnerability in Odunpazari

people can be living in fragile physical environments and not vulnerable because they have more and stable access to resources, such as better precautions. In Eskisehir, as well as all over Turkey, the construction of the buildings is given to the private and single constructors. The system works such that a person who owns a piece of urban land can make an agreement with a constructor in return for a specified number of apartment flats for the land. The number of flats the land owner can get depends on the size of the land and its market value. Despite the fact that municipalities are responsible from license control checks and safety regulations, such a procedure was implemented with a very flexible understanding before the 1999 Marmara earthquake. So one can have luxury and modern apartment buildings on highly demanded and valuable urban land, mainly constructed for the well-off persons, but which may not be earthquake resistant. This finding of the research should be understood within this framework of the realities of construction sector in Turkey, including the private agreements between the constructor and the land owner, as well as the poor control policies of the municipalities before 1999.

4. It is dependent on the dynamic interaction of a range of economic, social, and physical processes, which influence the capacity of individuals, social groups, sectors, regions, and ecosystems to respond to various socio-economic and biophysical shocks.

From socio-economic vulnerability assessment point of view, it was also found that just as buildings do not face exactly the same risk in case of an earthquake, neither do individuals and households. In the case of any earthquake, interventions and actions may yield better results if decision-makers, particularly local government authorities, know well about priority areas and priority groups.

3.5 Accessibility to critical services

Physical accessibility is defined as being able reach an intended point or location in spite of the hindrances like transportation and reflects the ease for travelers. Accessibility can be assessed based on the measures of time, cost, distance, and population, and it is one of the most important variables in the early planning stages. Accessibility analyses basically serve for checking the benefits of plans as a planning control tool, and helping decision-makers to investigate the new locations of urban services, testing the benefits of the current locations of urban services, identifying thresholds about urban services, and finding out the capacity and service area of urban services (Kuntay 1990). When emergency accessibility is considered, physical accessibility basically reflects emergency organization's readiness to respond to an emergency in a coordinated, timely, and effective manner and helps to determine the extent to which a city is ready for any disaster. That is why, measurement and evaluation of physical accessibility of emergency services is one of the most vital components of disaster preparedness. A few seconds of delay by emergency response units may mean loss of human life, environment, and property. Measuring and evaluating emergency accessibility can help decision-makers to test the current emergency service response performance, to identify critical areas that have low or no accessibility, and to find out solutions in order to improve the response to these critical areas (Badri et al. 1996).

There are basically three accessibility measurement techniques: zone-based, isochronal-based, and raster-based. It is difficult to rate any one of these as the best measuring technique. Different situations and purposes demand different approaches (Makri and Folkesson 1999).

In zone-based accessibility, the accessibility evaluations are calculated and presented in zone-based units, such as administrative units, quarters, etc. Based on costs on a transportation network (usually time or distance), the accessibility values are calculated for each zone separately from zone centroid to related urban service or vice versa. The disadvantage of this technique is that the same accessibility result is obtained for the whole zone. It has an advantage of producing easily comparable results with other urban-based parameters.

One of the other accessibility measurement techniques is the isochronal technique, where the accessibility evaluations are calculated and presented in an isochronal logic. An isochrone is a line on a map that connects points of equal travel time away from a single reference point. If an origin is defined as the reference point, isochrones can be drawn connecting points in all directions that can be reached in a threshold time or distance. The isochrone is irregularly shaped because of the structure of transportation network. Routes make it possible to travel faster in some directions than in others. The representation of the accessibility results can be either total of polylines having similar accessibility costs (polyline-based representation) or simple polygons that connect the edges of related polylines (polygon-based representation). Polygon-based representation is mostly used to be able to perform GIS-based overlay analyses; on the other hand, polyline-based representation can also be chosen for visual representations. The basic disadvantage of this technique is that the details of the accessibility costs directly depend on the selected threshold intervals and the same accessibility value is obtained for the isochrones (Ertugay and Duzgun 2006).

The raster-based technique is similar to isochronal-based technique; however, in raster-based technique, equal travel time or distance from a reference point is represented by the value of pixels in raster environment instead of isochrones, which are lines in vector environment. An advantage of this technique is that more detailed costs (time or distance) can be obtained based on selected pixel size. The traditional methods of accessibility evaluation do not consider the whole territory and mainly based on node/arc logic, so accessibility evaluation can be done in raster environment in order to create a continuous model. The main disadvantage of it is that working in raster environment reduces the geometrical accuracy of the information (mostly preferred in regional studies, which does not necessitate high spatial accuracy) but opens a wide range of new analysis capabilities.

In this study, the three different accessibility measurement techniques (zone-based, isochronal-based, and raster-based) are used within GIS environment creating an accessibility vulnerability index. Four steps are followed: (a) data collection; (b) calculation of accessibility costs; (c) analysis of physical accessibility of emergency services based on three different accessibility measurement techniques (zone-based, isochronal-based and raster-based); (d) creation of emergency accessibility vulnerability indexes.

1. *Data collection*: The data used in the study are digital transportation network data, their hierarchies and average speeds, the location of emergency services of fire brigades and health services, and the administrative borders of neighborhoods, which are obtained from Eskisehir Great City Municipality.
2. *Calculation of accessibility costs*: In all of the three techniques, average speeds extracted from Eskisehir metropolitan municipality travel survey are reduced by 30%, assuming that in case of disaster emergency, the traffic speeds will be less than the normal ones and are used for calculating travel costs. In zone-based technique, the polygons of quarters are converted to centroids, and the costs (distance and time) among each emergency services and centroids are calculated. In isochrone-based technique, network analyst function of GIS is used to define the accessed networks from emergency services. In raster-based technique, the vector transportation network is converted to raster, and costs for each pixel are calculated based on average speed and pixel size (The 5 km/h speed accepted for average pedestrian speed and attached to unnetworked cells).
3. *Analysis of physical accessibility of emergency services:* There are two fire brigades in Eskisehir, one of which is the Tepebasi fire brigade located in the northern part of the city, the other one is the Odunpazari fire brigade located in the south. There are also a total of 36 hospitals in Eskisehir, 18 out of these 36 are local clinics.

The zone-based accessibility costs for fire brigades are calculated for single access (fire brigade to quarter). The zone-based accessibility costs for ambulances are calculated for three different cases that are single access cost (hospital to quarter), return access cost (hospital to quarter to hospital), and capacity constrained access cost (hospital to quarter to hospital with a constraint based on hospital capacity). The details of these calculations can be found from Ertugay and Duzgun (2006). The isochronal-based accessibility costs for fire brigades and health services are calculated for 0- to 5-min time intervals, as reaching an emergency case in 5 min is the critical threshold for emergency accessibility. Similarly, the raster-based accessibility costs for fire brigades and health services are calculated for each pixel continuously and classified 0–5 min time intervals.

4. *Creation of emergency accessibility vulnerability indexes:* The accessibility values obtained from each method and those for the considered emergency services are combined by using Eq. 3. Then, the vulnerability indexes are classified in a scale of 1–3; 1 being the least vulnerable, 2 being medium vulnerable, and 3 being highly vulnerable.

Figure 8 shows that in Odunpazari, the neighborhoods on the axis from north to south have least vulnerability in terms of accessibility to critical services. However, the neighborhoods on the periphery have the highest vulnerability. When the maps for building (Fig. 6), socio-economic (Fig. 7), and accessibility to critical services (Fig. 8) vulnerabilities are compared, it is observed that every component of urban vulnerability has a different spatial pattern.

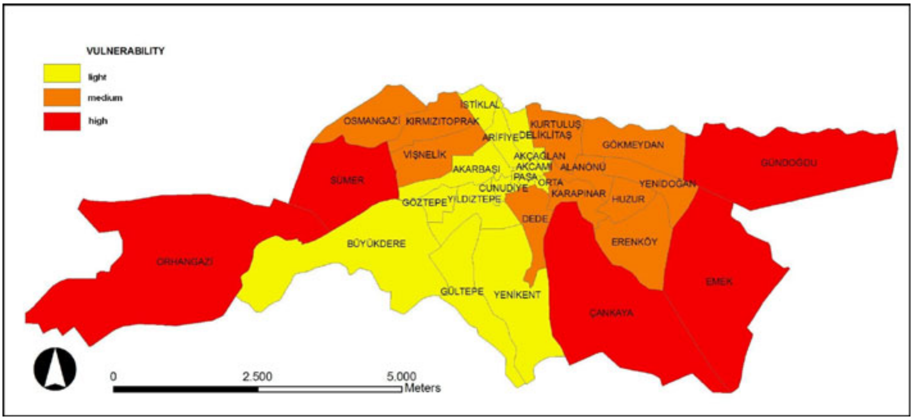

Fig. 8 Spatial distribution of accessibility to critical services in Odunpazari

3.6 GIS-based integrated vulnerability assessment

In this study, the different types of vulnerability indexes assessed for the Odunpazari municipality are combined by using Eq. 1. Here, simple additive weighting (SAW) method is used, where each one of the vulnerability indexes is given equal weights. It is also possible for decision-makers to assign different weights in order to analyze several earthquake scenarios at different disaster phases. For example, vulnerability due to accessibility to critical services can be given a higher weight during the response period of an earthquake as compared to the post-disaster phase. The spatial distribution of the overall vulnerability assessed for the Odunpazari municipality is displayed in Fig. 9. The overall vulnerability pattern of the neighborhoods in the Odunpzari municipality is subject to

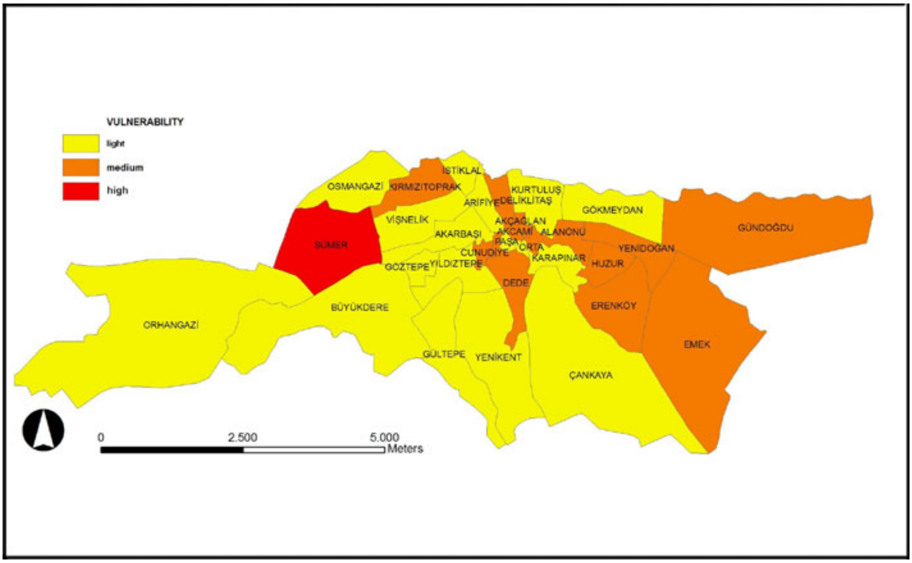

Fig. 9 Spatial distribution of overall vulnerability in the Odunpazari municipality

variations depending on the decision-makers' interest and type of the disaster phase to be considered.

3.7 Visualization of overall vulnerability in 3D

Visualization of the evaluated vulnerabilities provides input for decision-making and increases disaster awareness among decision-makers (US HHS 2002). In the literature, it has been shown that the presentation of hazards, vulnerability, coping capacity, and risk in the form of digital maps has a higher impact than traditional analog information representations (Martin and Higgs 1997). Digital maps are being progressively more used by disaster managers. In addition to the digital maps, 3D visualizations have the potential to be an even more effective communication tool (Kolbe et al. 2005, Marincioni 2007, Raper 1989, Zlatanova et al. 2002). Three-dimensional representations significantly reduce the amount of cognition exertion and improve the efficiency of the decision-making process (Kolbe et al. 2005, Zlatanova 2008). However, to achieve an appropriate 3D visualization, two aspects must be ensured: appropriate presentation and tools for interaction.

In such a visualization case, users are the key element which include municipality staff, such as urban planners, cartographers, and sociologists in the considered case study. They require clear view of the distribution of vulnerable regions throughout the city. The Eskisehir municipality has an urban information system infrastructure, so they have quite reliable data and sophisticated software (planning, cartographic, and GIS software). A 3D urban model environment is used to visualize the previously calculated social, physical, and accessibility vulnerability indexes of each building object. The pilot area is a part of the city centre and has various kinds of city development textures, including low-rise, historic buildings and high-rise apartments. There are nearly 400 buildings in the case study area.

Used data for visualization are as follows: vector layers from the Eskisehir Municipality Digital City Information System, street and building footprint layers, and 1/25,000 digital contour maps. To construct building objects, façade images and building height data are needed, which are collected by a field survey. The following steps are used to develop an urban model:

1. 2.5D DEM generation from digital contour maps.
2. Generation of façade textured boundary representation (B-rep) buildings by using building height information and ground images.
3. Draping of city furniture, tree points, road data, and building models with a terrain model.
4. Relating vulnerability indexes that are in the tabular form to the building objects.

The detail of the 3D virtual city model generation is given by Kemec and Duzgun (2006a, b). Figures 10 and 11 illustrate typical 3D visualization realizations. The main expected benefit of this pilot visualization application is to demonstrate the positive effects of well-balanced 3D models on the decision-makers as a communication tool.

4 Conclusions

The proposed integrated vulnerability assessment framework is flexible and can easily be applied to urban environments at various geographical scales with different mapping units. As the vulnerability maps prepared for the neighborhoods of the considered case study

Fig. 10 General view from the 3D urban visualization

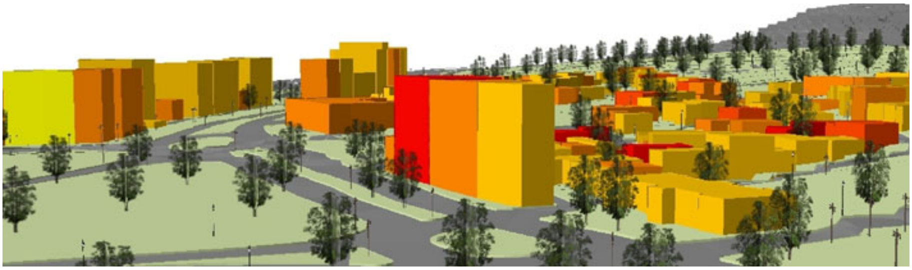

Fig. 11 Visualization of various vulnerabilities in the 3D city model

indicate the relative vulnerability of the neighborhoods in each vulnerability class (structural, socio-economical, and accessibility), it provides a guideline for the decision-makers to prioritize scarce resources. For example, the highly vulnerable neighborhoods due to their accessibility to critical services can be improved by providing more service locations or rearranging the service locations. In this sense, the overall vulnerability maps for the urban area have potential for decision-makers in designing vulnerability reduction strategies and hence risk reduction strategies. Moreover, as several aspects of elements at risk for an urban area are considered through vulnerability analyses, effect of changes in vulnerability conditions on the overall vulnerability maps can easily be determined. Although not all aspects of the proposed framework have been implemented in the case study, it is believed that if sufficient data become available, total vulnerability for the urban environment can be assessed in more detail. In addition, the developed framework enables decision-makers to monitor temporal and spatial changes in the urban environment due to implementation of risk reduction strategies.

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