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Brief communication "Fast-track earthquake risk assessment for selected urban areas in Turkey"

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Abstract. This study is presented as a contribution to earthquake disaster mitigation studies for selected cities in Turkey. The risk evaluations must be based on earthquake hazard analysis and city information. To estimate the ground motion level, data for earthquakes with a magnitude greater than 4.5 and an epicenter location within a 100-km radius of each city were used for the period from 1900 to 2006, as recorded at the Kandilli Observatory and Earthquake Research Institute. Probabilistic seismic hazard analysis for each city was carried out using Poisson probabilistic approaches. Ground motion level was estimated as the probability of a given degree of acceleration with a 10% exceedence rate during a 50-year time period for each city. The risk level of each city was evaluated using the number of houses, the per-capita income of city residents, population, and ground motion levels. The maximum risk level obtained for the cities was taken as a reference value for relative risk assessment, and other risk values were estimated relative to the maximum risk level. When the selected cities were classified according to their relative risk levels, the five most risky cities were found to be, in descending order of risk, Istanbul, Izmir, Ankara, Bursa, and Kocaeli.

1 Introduction

Communities have developed over time, and nature has always existed. More often than not, when communities have decided on a strategic location, environmental safety and health considerations were of secondary importance in the decision-making process (Tobriner, 2006).

Global earthquake risk has more than quadrupled in the past century as a result of global urbanization (Bilham, 1988, 1998). Supercities (with populations exceeding 2 million) developed in the late 19th century, and by 1950 there were two megacities (London and New York) with populations exceeding 8 million. By 2000, there were more than 140 supercities and 27 megacities. The total urban population by 2050 may exceed 5 billion people (roughly half the 2050 world total and equal to the entire world population in 1997) (Bilham, 1988, 1998).

Almost 8 million earthquake-related deaths have occurred in the past thousand years. Most of these earthquake events have occurred where large cities coincide with the Alpine/Himalayan, Andean, and East Asian seismic belts. More than half the world's supercities are located in places where future damage from $M > 7.5$ earthquakes is inevitable. On average, earthquakes kill 5000–8000 people per year in moderate events ($<$30 000 deaths/event). This rate has doubled twice in the past 250 years. However, the true annual fatality rate becomes much higher if catastrophic earthquakes (earthquakes where more than 30 000 are killed) are included. Although less than 4% of the world's population lives in megacities with 8 million or more inhabitants, half of these are located in earthquake-vulnerable locations (Bilham, 1988, 1998).

A seismic risk mitigation strategy has two main technical aspects: to construct high-performance buildings and other structures using earthquake-resistant designs, and to prepare emergency plans using realistic seismic scenarios. Both of these technical actions require a precise definition of the seismic action of potentially damaging earthquakes (Goula and Susagna, 2005).

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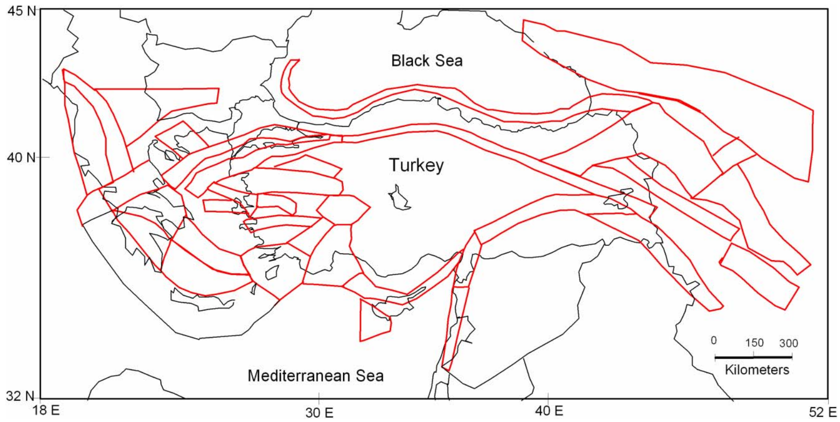

Fig. 1. Seismogenetic zones of Turkey (redrawn from Erdik et al., 1999).

Seismic hazard analyses aim to assess the probability that the ground motion parameter at a site due to earthquakes from potential seismic sources will exceed a certain value in a given time period (Erdik et al., 1999).

On a local or regional scale, several studies of earthquake hazards have been performed in Turkey (Alsan, 1972; Gencoglu and Tabban, 1973; Bath, 1979; Yarar et al., 1980; Erdik and Oner, 1982; Erdik et al., 1982, 1985, 1999, and Gulkan et al., 1993).

Turkey is located within the Alpine-Himalayan geodynamic system, which has been identified as one of the continental regions of the world with a long and well-documented history of earthquakes and ongoing earthquake activity. The objective of this study is to contribute to fast-track earthquake-hazard estimations for certain urban areas in Turkey.

2 Seismotectonic features and earthquake damage of Turkey

Turkey is characterized by a very complex geology, of which the main features have led to widely differing views of the geological evolution of Turkey (Okay, 2008). The westward motion of Turkey relative to Eurasia is related to the collision between Arabia and Eurasia in the Caucasus and Eastern Turkey (Ketin, 1948; McKenzie, 1972, 1978; Sengör, 1979a, b; Oral et al., 1995; Taymaz et al., 1991). The neotectonic-related geodynamic evolution of the Mediterranean started during and after the collision of Africa with Arabia. In this escape regime, the North and East Anatolian strike-slip fault systems play important roles. The N-S shortening deformation regime was replaced by an N-S extensional system in the western part of the Anatolian plate as a result of escape tectonic activity. In this period, the crust developed excessive degrees of thickening which was generated from the upper mantle (Taymaz et al., 1991).

The most frequent and destructive earthquakes in this region have occurred in Turkey. Historical records show that the Anatolian peninsula has experienced many major shocks that have damaged and destroyed urban centers. The Marmara Sea earthquake on 10 September 1509, destroyed Istanbul and was one of the largest earthquakes in the previous five centuries. In the 20th century, the most devastating earthquakes were the magnitude 8 Erzican-Refahiye earthquake of 26 December 1939; the magnitude 7.1 earthquake on 13 March 1992, near Erzincan which ruptured the same segment of the North Anatolian fault that broke in 1939 (500 dead, 2000 injured, 60 000 homeless); the Golcuk earthquake of 17 August 1999, with a magnitude $M =$ 7.6 that caused more than 15 000 dead and 40 000 injured people and economic losses of approximately 16 billion US$ (7% of GDP). The combined toll of these earthquakes concentrated on the North Anatolian fault zone was for the century 58 000 deaths, 116 000 injuries, and tremendous building damage and monetary losses (Taymaz et al., 1991; Gündogdu et al., 2002; Sayin et al., 2002). Figure 1 shows the seismogenetic source zones of Turkey.

Figure 2a shows population distribution in Turkey. Population in urban areas has been higher than rural areas since 1985. Figure 2b shows the destructive earthquakes in Turkey between 1900 and 2003 (Özmen, 2003). There were 148 earthquake disasters that killed 100 000 people, injured 71 790, and damaged 611 157 buildings. These have accounted for the %78 of the total number of buildings damaged by natural disasters in the 20th century alone. The amount of losses caused by earthquake disasters has therefore totalled to approximately 19 billion US$. Actually an earthquake of magnitude class 7 occurred there almost every 3 or 4 years and has caused a great amount of damage (Özmen, 2003).

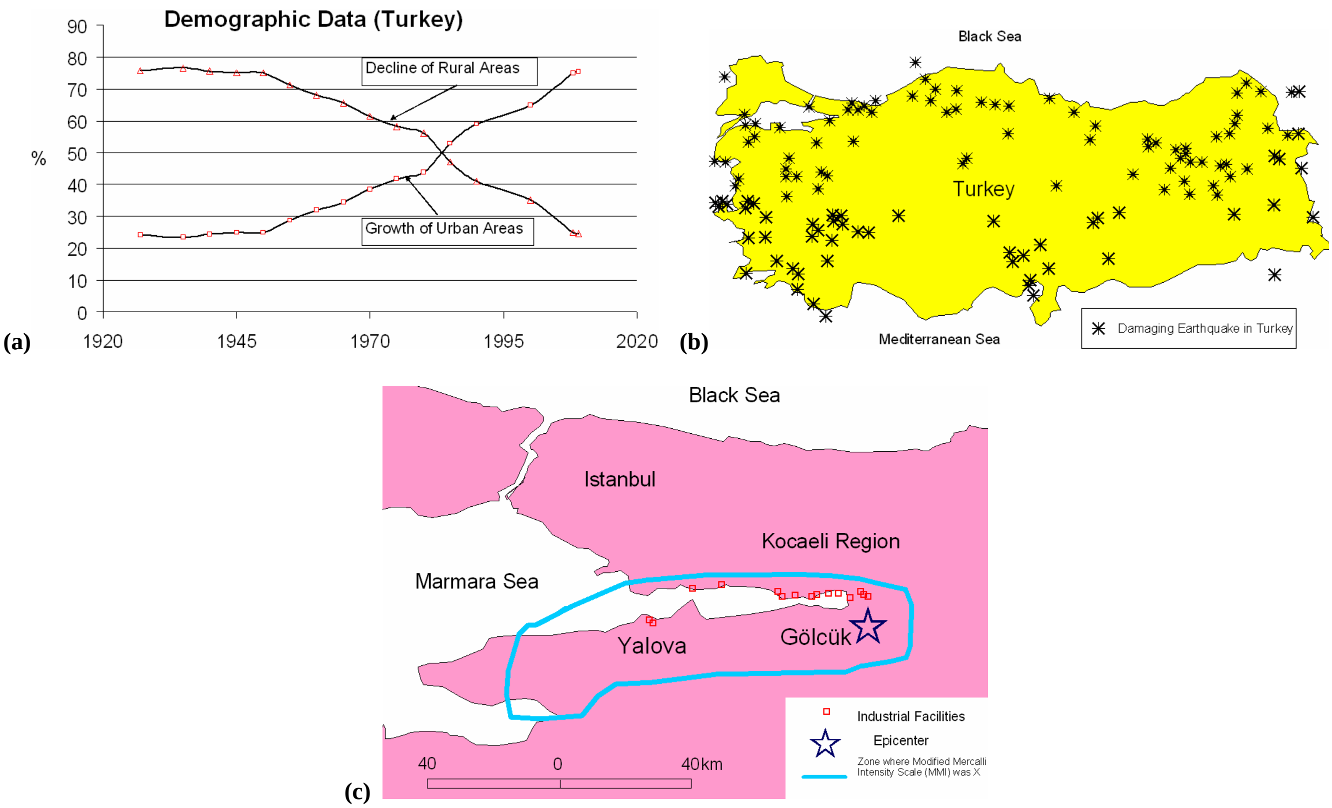

Fig. 2. **(a)** Population Distrubution in Turkey. **(b)** Epicentral location for damaging earthquakes occurring from 1900–2003 obtained from "General Management of Disaster Affairs of Turkey" (redrawn from Özmen, 2003). **(c)** Map showing the epicentre of the Kocaeli earthquake of 17 August 1999 and the location of industrial facilities (redrawn from Cruz, 2003).

The Turkish government has taken steps to protect its infrastructure from the impact of earthquakes through the adoption of seismic building codes; the most recent codes were updated in 1997 (Cruz and Steinberg, 2005). Due to the 7.4 earthquake in Kocaeli (Turkey) in 1999, thousands of residential and business units were damaged, and more than 350 industrial facilities in Kocaeli reported damage to their plants. In addition, the earthquake triggered large fires, toxic air releases of dangerous substances and oil spills at several industrial facilities. Figure 2c shows the epicentre of the Kocaeli earthquake, along with the location of industrial facilities. The earthquake was one of the first earthquakes in modern times to strike a highly urbanized and industrialized region. Kocaeli is one of the most densely populated regions, and accounts for 30% of industrial production in Turkey (Cruz, 2003).

3 Method and analysis of earthquake risk estimates

Seismic hazard analyses aim to assess the probability that the ground motion value at a site due to earthquakes from potential seismic sources will exceed a certain value during a given time period (Erdik et al., 1999). These analyses are often summarized by a seismic hazard curve showing annual probability of exceedence versus ground motion amplitude. Probabilistic seismic hazard analysis was used in this research to evaluate the seismic hazard level of the cities under study.

3.1 Probabilistic seismic hazard analysis for the cities under study

A probabilistic seismic hazard analysis has been carried out in this study. The coefficients of a Poisson distribution were calculated, and return periods for several magnitudes were found. From these coefficients, peak ground acceleration and earthquake hazard for a set of return periods and epicentral distances have been estimated, and substantial variations in the probability of occurrence have been noted. The range of earthquakes for analysis was taken to be from magnitude 4.5 to 7.5 within approximately a 100-km radius (Table 1). Minimum focal depth was selected as 10 km. However, this value is not fixed, but varies from one city to another according to local seismological characteristics.

Table 1. Earthquake magnitude ranges for each city within a 100-km radius.

Magnitude Ranges	$4.5 \le M < 5.0$	$5.0 \le M < 5.5$	$5.5 \le M < 6.0$	$6.0 \le M < 6.5$	$7.0 \le M < 7.5$

M (magnitude)	7.6
Δ, Epicentral Distance (km)	10
H, Focal depth (km)	10

Table 2. Examples of estimated acceleration values for design magnitude, epicentral distance (Δ, km), and focal depth (H, km).

Esteva (1970)	Donovan (1973)	Donavan (1973)	McGuier (1984)	Shah et al. (1974)	Oliviera (1974)	Joyner and Boore (1981)	Campbell (1997)	Campbell (1997)	Newmark and Roseblueth (1971)	Esteva and Roseblueth (1964)	Fukishima et al. (1988)	Abrahamson and Litehiser (1989)	Campbel (1981)	Average Acceleration Value (g)
0.36	0.61	0.39	0.53	0.76	0.36	0.56	0.33	0.3	0.73	0.77	0.43	0.44	0.77	0.52

Table 3a. Earthquake occurrence probability (%) for D (Year) for Adana city.

Magnitude Intervals	$4.5 \le M < 5.0$	$5.0 \le M < 5.5$	$5.5 \le M < 6.0$	$6.0 \le M < 6.5$	
Ni (Occurrence Numbers)	35	9	10		2
City: Adana	Probability (%) for D (Year)				Average Return Period
Magnitude (M)	10	50	75	100	(Year)
5	95.8	100.0	100.0	100.0	3
5.5	66.7	99.6	100.0	100.0	9
6	31.8	85.3	94.3	97.8	26
6.5	12.5	48.6	63.2	73.6	75
7	4.5	20.7	29.4	37.1	216
7.6	1.3	6.3	9.3	12.2	766

Table 3b. Earthquake occurrence probability (%) for D (Year) for. Ankara city.

Magnitude Intervals	$4.5 \le M < 5.0$	$5.0 \le M < 5.5$	$5.5 \le M < 6.0$		$6.0 \le M < 6.5$
Ni (Occurrence Numbers)	21	8	1		2
City: Ankara	Probability (%) for D (Year)				Average Return Period
Magnitude (M)	10	50	75	100	(Year)
5	95.8	100.0	100.0	100.0	3
5.5	66.7	99.6	100.0	100.0	9
6	31.8	85.3	94.3	97.8	26
6.5	12.5	48.6	63.2	73.6	75
7	4.5	20.7	29.4	37.1	216
7.6	1.3	6.3	9.3	12.2	766

Table 3c. Earthquake occurrence probability (%) for D (Year) for Antalya city.

Magnitude Intervals	$4.5 \leq M < 5.0$	$5.0 \leq M < 5.5$	$5.5 \leq M < 6.0$		$6.0 \leq M < 6.5$
Ni (Occurrence Numbers)	21	8	1		2
City: Antalya	Probability (%) for D (Year)				Average Return Period
Magnitude (M)	10	50	75	100	(Year)
5	95.8	100.0	100.0	100.0	3
5.5	66.7	99.6	100.0	100.0	9
6	31.8	85.3	94.3	97.8	26
6.5	12.5	48.6	63.2	73.6	75
7	4.5	20.7	29.4	37.1	216
7.6	1.3	6.3	9.3	12.2	766

Table 3d. Earthquake occurrence probability (%) for D (Year) for Balıkesir city.

Magnitude Intervals	$4.5 \leq M < 5.$	$5.0 \leq M < 5.5$	$5.5 \leq M < 6.0$	$6.0 \leq M < 6.5$	$6.5 \leq M < 7.0$
Ni (Occurrence Numbers)	68	26	16	6	1
City: Balıkesir	Probability (%) for D (Year)				Average Return Period
Magnitude (M)	10	50	75	100	(Year)
5	99.9	100.0	100.0	100.0	1
5.5	90.3	100.0	100.0	100.0	4
6	52.3	97.5	99.6	99.9	14
6.5	20.9	69.1	82.8	90.4	43
7	7.2	31.1	42.8	52.6	134
7.6	99.9	100.0	100.0	100.0	526

Table 3e. Earthquake occurrence probability (%) for D (Year) for Bursa city.

Magnitude Intervals	$4.5 \leq M < 5.0$	$5.0 \leq M < 5.5$	$5.5 \leq M < 6.0$	$6.0 \leq M < 6.5$	$7.0 \leq M < 7.5$
Ni (Occurrence Numbers)	54	24	12	4	1
City: Bursa	Probability (%) for D (Year)				Average Return Period
Magnitude (M)	10	50	75	100	(Year)
5	99.5	100.0	100.0	100.0	2
5.5	87.7	100.0	100.0	100.0	5
6	56.2	98.4	99.8	100.0	12
6.5	27.8	80.4	91.3	96.2	31
7	12.1	47.5	62.0	72.4	78
7.6	4.1	19.0	27.2	34.5	237

Table 3f. Earthquake occurrence probability (%) for D (Year) for Denizli city.

Magnitude Intervals	$4.5 \leq M < 5.0$	$5.0 \leq M < 5.5$	$5.5 \leq M < 6.0$	$6.0 \leq M < 6.5$	
Ni (Occurrence Numbers)	146	53	97	2	
City: Denizli	Probability (%) for D (Year)				Average Return Period
Magnitude (M)	10	50	75	100	(Year)
5	100.0	100.0	100.0	100.0	0.5
5.5	98.8	100.0	100.0	100.0	2
6	61.1	99.1	99.9	100.0	11
6.5	18.3	63.5	78.0	86.7	50
7	4.2	19.4	27.6	35.0	232
7.6	0.7	3.3	4.9	6.5	1481

Table 3g. Earthquake occurrence probability (%) for D (Year) for Diyarbakır city.

Magnitude Intervals	$4.5 \leq M < 5.0$	$5.0 \leq M < 5.5$	$5.5 \leq M < 6.0$	$6.0 \leq M < 6.5$	
Ni (Occurrence Numbers)	24	19	2	2	
City: Diyarbakır	Probability (%) for D (Year)				Average Return Period
Magnitude (M)	10	50	75	100	(Year)
5	91.8	100.0	100.0	100.0	4
5.5	55.7	98.3	99.8	100.0	12
6	23.3	73.4	86.3	92.9	38
6.5	8.3	35.0	47.6	57.8	116
7	2.8	13.1	19.0	24.5	356
7.6	0.7	3.6	5.3	7.0	1369

Table 3h. Earthquake occurrence probability (%) for D (Year) for Edirne city.

Magnitude Intervals	$4.5 \leq M < 5.0$	$5.0 \leq M < 5.5$	$5.5 \leq M < 6.0$		
Ni (Occurrence Numbers)	11	5	4		
City: Edirne	Probability (%) for D (Year)				Average Return Period
Magnitude (M)	10	50	75	100	(Year)
5	68.9	99.7	100.0	100.0	9
5.5	40.7	92.6	98.0	99.5	19
6	20.8	68.9	82.6	90.3	43
6.5	9.9	40.7	54.3	64.8	96
7	4.6	20.8	29.5	37.3	214
7.6	1.8	8.5	12.5	16.3	563

Table 3i. Earthquake occurrence probability (%) for D (Year) for Erzurum city.

Magnitude Intervals	$4.5 \le M < 5.0$	$5.0 \le M < 5.5$	$5.5 \le M < 6.0$	$6.0 \le M < 6.5$	$6.5 \le M < 7.0$
Ni (Occurrence Numbers)	80	35	19	4	2
City: Erzurum	Probability (%) for D (Year)				Average Return Period
Magnitude (M)	10	50	75	100	(Year)
5	100.0	100.0	100.0	100.0	1
5.5	93.7	100.0	100.0	100.0	4
6	61.0	99.1	99.9	100.0	11
6.5	27.4	79.8	90.9	95.9	31
7	10.3	41.9	55.7	66.2	92
7.6	2.9	13.8	20.0	25.7	337

Table 3j. Earthquake occurrence probability (%) for D (Year) for Gaziantep city.

Magnitude Intervals	$4.5 \le M < 5.0$	$5.0 \le M < 5.5$	$5.5 \le M < 6.0$		
Ni (Occurrence Numbers)	16	8	2		
City: Gaziantep	Probability (%) for D (Year)				Average Return Period
Magnitude (M)	10	(Year)	75	100	(Year)
5	71.8	99.8	100.0	100.0	8
5.5	29.6	82.7	92.8	97.0	28
6	9.3	38.6	51.9	62.3	103
6.5	2.7	12.6	18.4	23.7	370
7	0.7	3.7	5.5	7.2	1334
7.6	0.2	0.8	1.2	1.6	6215

Table 3k. Earthquake occurrence probability (%) for D (Year) for Hatay city.

Magnitude Intervals	$4.5 \le M < 5.0$	$5.0 \le M < 5.5$	$5.5 \le M < 6.0$	$6.0 \le M < 6.5$	
Ni (Occurrence Numbers)	26	7	5	1	
City: Hatay	Probability (%) for D (Year)				Average Return Period
Magnitude (M)	10	(Year)	75	100	(Year)
5	86.7	100.0	100.0	100.0	5
5.5	46.4	95.6	99.1	99.8	16
6	17.5	61.7	76.3	85.4	52
6.5	5.8	25.6	35.9	44.7	169
7	1.8	8.7	12.8	16.7	547
7.6	0.4	2.2	3.3	4.4	2246

Table 3l. Earthquake occurrence probability (%) for D (Year) for Istanbul city.

Magnitude Intervals	$4.5 \le M < 5.0$	$5.0 \le M < 5.5$	$5.5 \le M < 6.0$	$6.0 \le M < 6.5$	$6.5 \le M < 7.0$
Ni (Occurrence Numbers)	31	12	7	1	1
City: Istanbul	Probability (%) for D (Year)				Average Return Period
Magnitude (M)	10	50	75	100	(Year)
5	92.2	100.0	100.0	100.0	4
5.5	67.3	99.6	100.0	100.0	9
6	38.7	91.4	97.5	99.3	20
6.5	19.3	65.7	79.9	88.3	47
7	8.9	37.4	50.5	60.8	107
7.6	3.4	16.0	23.0	29.4	288

Table 3m. Earthquake occurrence probability (%) for D (Year) for zmir city.

Magnitude Intervals	$4.5 \le M < 5.0$	$5.0 \le M < 5.5$	$5.5 \le M < 6.0$	$6.0 \le M < 6.5$	$6.5 \le M < 7.0$
Ni (Occurrence Numbers)	74	26	21	10	1
City: Izmir	Probability (%) for D (Year)				Average Return Period
Magnitude (M)	10	50	75	100	(Year)
5	100.0	100.0	100.0	100.0	1
5.5	94.4	100.0	100.0	100.0	3
6	60.1	99.0	99.9	100.0	11
6.5	25.4	76.9	88.9	94.7	34
7	8.9	37.3	50.4	60.7	107
7.6	2.3	11.2	16.3	21.1	422

Table 3n. Earthquake occurrence probability (%) for D (Year) for Kars city.

Magnitude Intervals	$4.5 \le M < 5.0$	$5.0 \le M < 5.5$	$5.5 \le M < 6.0$	$6.0 \le M < 6.5$	
Ni (Occurrence Numbers)	64	21	7	7	
City: Kars	Probability (%) for D (Year)				Average Return Period
Magnitude (M)	10	50	75	100	(Year)
5	99.4	100.0	100.0	100.0	2
5.5	87.6	100.0	100.0	100.0	5
6	57.6	98.6	99.8	100.0	12
6.5	29.8	83.0	93.0	97.1	28
7	13.6	51.8	66.5	76.8	69
7.6	4.9	22.3	31.5	39.6	199

Table 3o. Earthquake occurrence probability (%) for D (Year) for Kayseri city.

Magnitude Intervals	$4.5 \leq M < 5.0$	$5.0 \leq M < 5.5$			
Ni (Occurrence Numbers)	5	1			
City: Kayseri	Probability (%) for D (Year)				Average Return Period
Magnitude (M)	10	50	75	100	(Year)
5	99.9	100.0	100.0	100.0	1
5.5	92.2	100.0	100.0	100.0	4
6	60.7	99.1	99.9	100.0	11
6.5	29.0	81.9	92.3	96.7	29
7	11.8	46.5	60.9	71.4	80
7.6	3.7	17.1	24.5	31.3	266

Table 3p. Earthquake occurrence probability (%) for D (Year) for Kocaeli city.

Magnitude Intervals	$4.5 \leq M < 5.0$	$5.0 \leq M < 5.5$	$5.5 \leq M < 6.0$
Ni (Occurrence Numbers)	87	21	18
City: Kocaeli	Probability (%) for D (Year)		
Magnitude (M)	10	50	75
5	99.9	100.0	100.0
5.5	92.2	100.0	100.0
6	60.7	99.1	99.9
6.5	29.0	81.9	92.3
7	11.8	46.5	60.9
7.6	3.7	17.1	24.5

Table 3q. Earthquake occurrence probability (%) for D (Year) for Konya city.

Magnitude Intervals	$4.5 \leq M < 5.0$	$5.0 \leq M < 5.5$	$5.5 \leq M < 6.0$
Ni (Occurrence Numbers)	10	5	3
City: Konya	Probability (%) for D (Year)		
Magnitude (M)	10	50	75
5	64.0	99.4	100.0
5.5	34.1	87.5	95.6
6	15.6	57.3	72.1
6.5	6.7	29.3	40.6
7	2.8	13.2	19.2
7.6	1.0	4.7	7.0

Table 3r. Earthquake occurrence probability (%) for D (Year) for Malatya city.

Magnitude Intervals	$4.5 \leq M < 5.0$	$5.0 \leq M < 5.5$	$5.5 \leq M < 6.0$
Ni (Occurrence Numbers)	50	14	6
City: Malatya	Probability (%) for D (Year)		
Magnitude (M)	10	50	75
5	97.2	100.0	100.0
5.5	70.8	99.8	100.0
6	34.7	88.1	95.9
6.5	13.7	52.1	66.9
7	5.0	22.5	31.8
7.6	1.4	6.9	10.1

Table 3s. Earthquake occurrence probability (%) for D (Year) for Samsun city.

Magnitude Intervals	$4.5 \leq M < 5.0$	$5.0 \leq M < 5.5$			
Ni (Occurrence Numbers)	13	4			
City: Samsun	Probability (%) for D (Year)				Average Return Period
Magnitude (M)	10	50	75	100	(Year)
5	49.0	96.5	99.4	99.9	15
5.5	14.6	54.7	69.5	79.5	63
6	3.7	17.0	24.4	31.1	268
6.5	0.9	4.3	6.4	8.4	1140
7	0.2	1.0	1.5	2.0	4847

Table 3t. Earthquake occurrence probability (%) for D (Year) for Siirt city.

Magnitude Intervals	$4.5 \leq M < 5.0$	$5.0 \leq M < 5.5$	$5.5 \leq M < 6.0$
Ni (Occurrence Numbers)	22	13	3
City: Siirt	Probability (%) for D (Year)		
Magnitude (M)	10	50	75
5	85.3	100.0	100.0
5.5	41.6	93.2	98.2
6	14.0	53.0	67.8
6.5	4.2	19.1	27.3
7	1.2	5.8	8.6
7.6	0.3	1.3	1.9

Table 3u. Earthquake occurrence probability (%) for D (Year) for Trabzon city.

Magnitude Intervals	$4.5 \le M < 5.0$	$5.0 \le M < 5.5$	$5.5 \le M < 6.0$
Ni (Occurrence Numbers)	2	1	1
City: Trabzon	Probability (%) for D (Year)		
Magnitude (M)	10	50	75
5	22.0	71.2	84.5
5.5	11.7	46.3	60.7
6	6.0	26.7	37.3
6.5	3.1	14.4	20.8
7	1.5	7.5	11.0
7.6	0.7	3.3	5.0

Table 3v. Earthquake occurrence probability (%) for D (Year) for Van city.

Magnitude Intervals	$4.5 \le M < 5.0$	$5.0 \le M < 5.5$	$5.5 \le M < 6.0$
Ni (Occurrence Numbers)	46	16	2
City: Van	Probability (%) for D (Year)		
Magnitude (M)	10	50	75
5	97.3	100.0	100.0
5.5	80.4	100.0	100.0
6	52.0	97.4	99.6
6.5	28.1	80.8	91.6
7	13.8	52.4	67.2
7.6	5.5	24.8	34.8

Table 3w. Earthquake occurrence probability (%) for D (Year) for Zonguldak city.

Magnitude Intervals	$4.5 \le M < 5.0$	$5.0 \le M < 5.5$	$5.5 \le M < 6.0$
Ni (Occurrence Numbers)	32	13	5
City: Zonguldak	Probability (%) for D (Year)		
Magnitude (M)	10	50	75
5	93.0	100.0	100.0
5.5	69.8	99.7	100.0
6	41.7	93.3	98.3
6.5	21.6	70.4	83.9
7	10.4	42.2	56.1
7.6	4.1	19.0	27.1

The Gutenberg-Richter recurrence relationships were determined using the following relation:

$$\log(N) = a - bM, \quad (1)$$

where a and b are regression coefficients. The earthquake occurrence probability was determined as:

$$\mathrm{Rm} = 1 - e^{-(N(M)\cdot D)},$$

where Rm = risk value (%), D is duration (year), and $N(M)$ is the frequency of occurrence of an earthquake of magnitude M as estimated by Eq. (1).

The attenuation relationship can be defined by several attenuation models (Table 2). The average acceleration values for the cities were then calculated with an exceedence probability of 10% in 50 years using these attenuation models. Finally, the acceleration values (g) from the attenuation relationships were used to obtain average values. An example of the estimated acceleration values depending on design magnitude, epicentral distance (Δ, km), and focal depth (H, km) is given in Table 2.

The probabilistic seismic hazard of each city is given in Table 3a–w, where each subtable contains magnitude intervals, occurrence numbers, average return periods, and probability (%) for D (year).

3.2 Risk model for the cities under study

The aim of this study is to determine earthquake risk levels. Twenty-three cities in Turkey were selected for this purpose. Earthquakes of a magnitude greater than 4.5, within 100 km of a city, and that has potential to cause severe damage were selected for analysis. A probabilistic seismic hazard analysis was carried out for each city using these data. Average acceleration values for each city, called "ground motion level" in this study, were calculated with an exceedence probability of 10% in 50 years using several attenuation models. Maximum and minimum acceleration values were obtained using attenuation relationships involving magnitude M, distance from the epicenter Δ (km), and focal depth H (km). The maximum acceleration value was obtained at the maximum epicentral distance (km) from the active fault zone of the region to the selected area. Similarly, the minimum acceleration value was obtained at the minimum epicentral distance (km) from the active fault zone of the region to the selected area.

Although ground motion level is an important component of hazard, risk level or risk values also depend on other factors, such as vulnerability and value at risk and can be formulated as described in the Seismic Microzoning for Municipalities Manual (Studer and Ansal, 2004):

Earthquake Risk =

Earthquake Hazard × Vulnerability × Value at Risk.

Table 4. Risk factors.

– Number of Houses.
– Population.
– National Incomes of Cities.
– Ground Motion Level.

In the present study, this risk formulation was redefined (as shown in Table 4) as:

Earthquake Risk =

Ground Motion Level × Number of Houses × Population

× Per Capita Income of City Residents.

Values for risk factors such as number of houses, population, and per capita incomes of city residents were obtained from the Turkish Statistical Institute.

The cities and their obtained relative risk levels are given in Table 5.

4 Results and discussion

A hazard analysis for each city was carried out using a Poisson probabilistic approach. After ground motion level was estimated for each city as a probability of a given level of acceleration with a 10% exceedence rate in 50 years, the risk level of each city was evaluated using number of houses, per capita income of city residents, population, and ground motion levels. The maximum risk level obtained for all the cities was taken as a reference value for relative risk assessment, and other risk values were estimated relative to the maximum risk level.

All structural inventories were evaluated equally as risk factors for want of a structural vulnerability classification for the selected cities. In fact, an earthquake-resistant structural behavior works toward minimizing earthquake risk, but other behaviors do not. In this study, soil and site conditions were not considered as risk factors because adequate soil information was not available to the same extent for all the cities. However, soil and site conditions are also among the most important risk factors. Despite these weaknesses, this study has been able to present a general view of the earthquake risk in certain cities in Turkey.

Studies on disaster management in Turkey date back to 1950's. These studies were designed to address all kind of natural disasters (mainly earthquakes). Their major weakness is that they do not include the technological accidents triggered by natural hazards. Even today, there is no regulation of technological accidents triggered by natural hazards. In Fig. 3, distribution of the surface area (km^2) as related to the earthquake zoning map of Turkey is

Table 5. Cities and their relative risk levels.

City Name	Number of Houses	Population	National Incomes of Cities (USD) for 2001	Ground Motion Level (with exceeding probability of 10 % in 50 years)		Risk = Acceleration x Population x House Number x National Incomes of Cities x 10^{-12}	Relative Risk Levels of Cities
				Max Acceleration (g)	Min Acceleration (g)		
Ankara	1 235 718	4 466 756	2752	0.43	0.08	6533.1	3
Adana	477 917	2 006 650	2146	0.48	0.09	984.4	6
Antalya	464 665	1 789 295	2193	0.24	0.08	436.1	8
Balıkesir	344 453	1 118 313	2005	0.54	0.11	418.3	9
Bursa	647 500	2 439 876	2507	0.73	0.16	2872.2	4
Denizli	239 846	907 325	2133	0.43	0.08	200.7	11
Diyarbakır	200 392	1 460 714	1313	0.29	0.07	111.6	14
Edirne	98 762	396 462	2403	0.45	0.10	42.0	21
Erzurum	122 284	784 941	1061	0.63	0.13	63.7	17
Gaziantep	286 278	1 560 023	1593	0.19	0.05	135.1	13
Hatay	274 285	1 386 224	1757	0.35	0.06	233.7	10
Istanbul	3 414 094	12 573 836	3063	0.69	0.15	90836.5	1
Izmir	1 175 123	3 739 353	3215	0.58	0.12	8205.0	2
Kars	30 203	312 205	886	0.59	0.17	5.0	22
Kayseri	287 535	1 165 088	1806	0.08	0.02	50.6	20
Kocaeli	359 801	1 437 926	6165	0.68	0.15	2179.9	5
Konya	491 220	1 959 082	1554	0.41	0.08	616.8	7
Malatya	158 089	72 2065	1417	0.49	0.10	79.7	16
Samsun	257 244	1 228 959	1680	0.20	0.03	105.5	15
Siirt	31 060	291 528	1111	0.22	0.05	2.2	23
Trabzon	198 862	740 569	1506	0.26	0.05	58.0	19
Van	80 859	979 671	859	0.86	0.19	58.5	18
Zonguldak	143 385	615 890	2969	0.76	0.17	198.2	12

Table 6. Distribution of technological and social risk elements in Turkey obtained from the "General Management of Disaster Affairs of Turkey".

Earthquake Zones in Turkey	Population (%)	Industry (%)	Hydrolic Dams (%)
Zone 1 (First Degree Hazard Zone)	45.0	51.0	46.0
Zone 2 (Second Degree Hazard Zone)	26.0	25.0	23.0
Zone 3 (Third Degree Hazard Zone)	14.0	11.0	14.0
Zone 4 (Forth Degree Hazard Zone)	13.0	11.0	11.0
Zone 5 (No Hazard Zone)	2.0	2.0	6.0

presented. In Table 6, the distribution of technological and social risk elements in Turkey is also presented.

When the selected cities were classified according to their relative risks, the five most risky cities, in descending order of risk, were found to be Istanbul, Izmir, Ankara, Bursa, and Kocaeli (Table 5).

To estimate earthquake risk, vulnerability information for each city must be elaborated in detail for earthquake-prone countries like Turkey. Other factors affecting earthquake risk, such as site and soil information, must also be determined by detailed seismic microzoning studies. Some studies for soil effects have been carried out by Ozcep and Zarif (2009), Korkmaz and Ozcep (2010); Ozcep et al. (2010a, b). Yet, these studies have only been done for

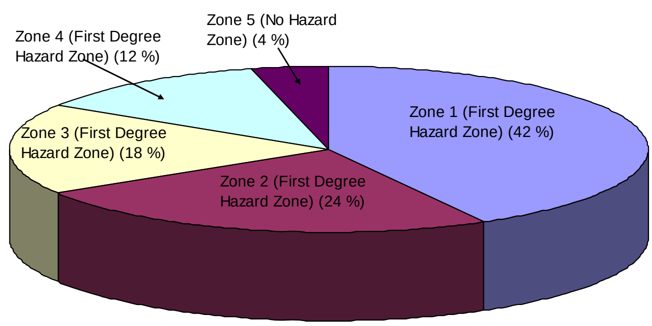

Fig. 3. Distribution of surface area (km^2) as related to the earthquake zoning map of Turkey obtained from the "General Management of Disaster Affairs of Turkey".

Istanbul and Yalova City. Later, we are going to carry out this type of studies for other cities. These studies will be integrated into the total risk factors in the future.

Fast-track earthquake risk determinations, such as those presented in this study, may be useful and valuable for prioritizing the most risky cities. The data and evaluations in this type of preparatory urban planning study are valuable in the mitigation phase of disaster management, because one of the most important functions of urban and regional planning must be to provide a safe environment for human beings.

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