AN INTEGRATED SEISMIC LOSS ESTIMATION METHODOLOGY: A CASE STUDY IN NORTHWESTERN TURKEY

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

ELİF MÜGE ÜN

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
CIVIL ENGINEERING

JULY 2011

Approval of the thesis:

AN INTEGRATED SEISMIC LOSS ESTIMATION METHODOLOGY: A CASE STUDY IN NORTHWESTERN TURKEY

submitted by **ELİF MÜGE ÜN** in partial fulfillment of the requirements for the degree of **Master of Science in Civil Engineering Department, Middle East Technical University** by,

Prof. Dr. Canan Özgen ______________
Dean, Graduate School of **Natural and Applied Sciences**

Prof. Dr. Güney Özcebe ______________
Head of Department, **Civil Engineering**

Assoc. Prof. Dr. Ayşegül Askan Gündoğan ______________
Supervisor, **Civil Engineering Dept., METU**

Assoc. Prof. Dr. Murat Altuğ Erberik ______________
Co-Supervisor, **Civil Engineering Dept., METU**

Examining Committee Members

Prof. Dr. Polat Gülkan ______________
Civil Engineering Dept., METU

Assoc. Prof. Dr. Ayşegül Askan Gündoğan ______________
Civil Engineering Dept., METU

Assoc. Prof. Dr. Murat Altuğ Erberik ______________
Civil Engineering Dept., METU

Asst. Prof. Dr. Alp Caner ______________
Civil Engineering Dept., METU

Volkan Aydoğan, M.Sc. ______________
Project Manager, PROMER CONS. ENG. LTD. CO.

Date: ______________

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last name: Elif Müge, Ün

Signature :

ABSTRACT

AN INTEGRATED SEISMIC LOSS ESTIMATION METHODOLOGY: A CASE STUDY IN NORTHWESTERN TURKEY

Ün, Elif Müge
M. Sc., Department of Civil Engineering
Supervisors: Assoc. Prof. Dr. Ayşegül Askan Gündoğan
Assoc. Prof Dr. Murat Altuğ Erberik

July 2011, 129 pages

Future seismic losses including the physical, economic and social ones as well as casualties concern a wide range of authorities varying from geophysical and earthquake engineers, physical and economic planners to insurance companies. As its many components involve inherent uncertainties, a probabilistic approach is required to estimate seismic losses.

This study aims to propose a probabilistic method for estimating seismic losses, and to predict the potential seismic loss for the residential buildings for a selected district in Bursa, which is a highly industrialized city in Northwestern Turkey. To verify the methodology against a past large event, loss estimations are initially performed for a district in Düzce, and the method is calibrated with loss data from the 12 November 1999 Düzce Earthquake.

The main components of the proposed loss model are seismic hazard, building vulnerability functions and loss as a function of damage states of buildings. To quantify the regional hazard, a probabilistic seismic hazard assessment approach is adopted. For different types of building structures, probability of exceeding predefined damage states for a given hazard level is determined using appropriate fragility curve sets. The casualty model for a given damage level considers the occupancy type, population of the building, occupancy at the time of earthquake occurrence, number of trapped occupants in the collapse, injury distribution at collapse and mortality post collapse. Economic loss is calculated by multiplying mean damage ratio with the total cost of initial construction. The proposed loss model combines these input components within a conditional probability approach. The results are expressed in terms of expected loss and losses caused by events with different return periods.

Key words: Earthquake, Seismic loss, Seismic hazard, Fragility, Vulnerability, Risk, Casualty, Economic loss

ÖZ

BÜTÜNLEŞİK SİSMİK KAYIP TAHMİNİ YÖNTEMİ: KUZEYBATI TÜRKİYE İÇİN ÖRNEK OLAY ÇALIŞMALARI

Ün, Elif Müge
Yüksek Lisans, İnşaat Mühendisliği Bölümü
Tez Yöneticileri: Doç. Dr. Ayşegül Askan Gündoğan
Doç. Dr. Murat Altuğ Erberik

Temmuz 2011, 129 sayfa

Depremlerin yol açtığı fiziksel, ekonomik, sosyal kayıplar ve can kayıplarının ileriye yönelik tahminleri, jeofizik ve deprem mühendislerinden, ekonomik planlamacılara ve sigorta şirketlerine kadar pek çok makamı yakından ilgilendirmektedir. İçerisindeki çoğu bileşenin yapısında varolan belirsizliklerden dolayı, sismik kayıpların tahmininde olasılıksal yöntemlere ihtiyaç duyulmaktadır.

Bu çalışma, olasılıksal yöntemler kullanarak sismik kayıpları tahmin eden bir model önermeyi ve Türkiye'nin kuzeybatısında bulunan ve oldukça sanayileşmiş bir şehir olmasından dolayı seçilen Bursa ilinde konut tipi binalarda, olası sismik kayıpları hesaplamayı amaçlamaktadır. Doğrulamak amacıyla, bu çalışmada önerilen yöntem yine Türkiye'nin kuzeybatısında bulunan ve 12 Kasım 1999 Depremini yaşamış olan Düzce ilinin seçilen bir bölgesinde uygulanmıştır. Elde edilen sonuçlar söz konusu depreme ait hasar verileriyle karşılaştırılmış, ve önerilen yöntem bu karşılaştırma sonucunda düzenlenmiştir.

Önerilen kayıp modelinin ana bileşenleri, sismik tehlike, binaların hasar görebilirlik fonksiyonları ve binaların hasar durumlarına bağlı olarak çıkarılan kayıp parametreleridir. Bölgesel sismik tehlikeyi hesaplamak için, olasılıksal sismik tehlike analizi kullanılmıştır. Değişik bina tipleri için, verilen sismik tehlike altında, bina hasarının önceden tanımlanmış hasar seviyelerini aşma olasılıkları ise kırılganlık eğrileri ile hesaplanmıştır. Verilen hasar durumundaki ölü sayısı; konut tipini, binanın içinde yaşayan nüfusu, deprem anındaki doluluk oranını, enkaz altında kalan

bina sakinlerinin oranını, çökme anında enkaz altında kalan kişilerin sağlık durumunu ve bu kişilerin ölüm oranlarını göz önüne alan bir model kullanılarak hesaplanmaktadır. Ekonomik kayıplar, ortalama hasar oranlarının, toplam yeniden yapım masraflarıyla çarpılmasıyla belirlenmiştir. Önerilen çalışmada, model bileşenleri, koşullu olasılık yaklaşımıyla birleştirilmektedir. Sonuçlar, ortalama kayıp, ve değişik tekekkür süreleri olan depremlerin yol açması beklenen kayıplar cinsinden sunulmaktadır.

Anahtar Kelimeler : Deprem, Sismik kayıp, Sismik tehlike, Kırılganlık, Hasar görebilirlik, Risk, Can kaybı, Ekonomik kayıp

To my family

To my supervisors,

Dr. Ayşegül Askan Gündoğan and

Dr. Murat Altuğ Erberik

ACKNOWLEDGEMENTS

First and foremost, I would like to thank my supervisors and my academic parents Assoc. Prof. Dr. Ayşegül Askan and Assoc. Prof. Dr. Murat Altuğ Erberik. This thesis would not have been possible without their patience, infinite attention, motivation and guidance. They have always encouraged and supported me throughout this study. I would like to offer my gratitude one more time for their priceless support.

It is a pleasure for me to acknowledge Prof. Dr. Semih Yücemen and Dr. Nazan Yılmaz for their support. I am honored to take a part in a study with them. I owe my deep gratitude to Dr. Engin Karaesmen and Dr. Erhan Karaesmen for their endless support and care throughout both of my undergraduate and graduate life. Many thanks go to Prof. Dr. Mehmet Utku for his sincere support on hard times. I also would like to thank Prof. Dr. Ahmet Yakut and Prof. Dr. Kemal Önder Çetin whose graduate courses helped me a lot in the preparation of this thesis.

I wish to express my gratitude to Muharrem Gürleyen Gök and Turkish Statistical Institute (Turkstat) for providing census of population and building data for the study regions. I am also grateful to Ministry of Public Works and Settlement for providing unit costs of initial construction.

I am indebted so much to my dearest friends Beliz Uğurhan, Dilek Okuyucu, Duygu Güleyen, Fatma Nurten Şişman and Gökhan Önder. With their endless love, support, patience and amenity, I felt more motivated to finish my thesis work. Thank you, you all mean a lot to me.

I also would like to thank my officemates, Ahmet Kuşyılmaz, Alper Özge Gür, Fırat Soner Alıcı, Güçlü Koray Çiftci, Kaan Kaatsız, Mehmet Başar Mutlu, Mustafa Can Yücel, Poureng Ezzatfer, Sadun Tanışer and Yasemin Didem Aktaş. You all added a lot to my graduate memories.

I have been partially supported by the Scientific and Technological Research Council of Turkey (TUBITAK) throughout this study period and I would like to express my sincere acknowledgments to TUBITAK for this support.

Finally, my deepest thanks and love belongs to my family, who were always there by my side… My dear mother deserves the greatest gratitude at all. She is the one who made me who I am. Whatever success I have achieved to date, my mother's part can never be paid.

TABLE OF CONTENTS

LIST OF TABLES

TABLES

LIST OF FIGURES

FIGURES

CHAPTER 1

INTRODUCTION

1.1 General

Earthquakes have been of considerable threat to the socioeconomic life of societies for centuries. Although they yield significant economic losses and physical damage, the most tragic impacts of earthquakes are the ones on the human life and health. In the last century, 1248 major earthquakes occurred worldwide, which caused more than 1 trillion USD (adjusted to the value of money in year 2000) and 1,685,000 officially-recorded fatalities (Coburn and Spence, 2002). Turkey is located in a seismically active region and more than 5% of this global total has occurred in Turkey between the years 1900-1999. It is therefore essential to model potential seismic losses for mitigation purposes.

Seismic loss estimation has fundamental importance for earthquake and geophysical engineers, economical and physical planners and insurance companies, as well as the society. Seismic losses are estimated for purposes of seismic design, rehabilitation of the buildings, disaster mitigation and emergency management. Seismic loss estimation procedures in general have three major components: quantification of seismic hazard, building fragility, and socioeconomic vulnerability. In the literature, majority of seismic loss estimation studies use deterministic approaches to estimate the seismic hazard at the region of interest. However, since the components of hazard involve inherent uncertainties, a probabilistic approach for the seismic hazard is conducted in this study. Building fragility can be estimated with detailed structural analysis of a single typical building. For a group of buildings in larger areas, damage probability matrices or fragility curves generated for a particular building stock can also be used. This study adopts the latter approach. Since each component is computed in a stochastic manner, the integration of these components is performed in a probabilistic framework from which physical, economic and human life losses are derived.

The scale of a seismic loss estimation study depends on its purpose. The study can be conducted for a single building, a small district, a city or a country. The resolution of such a study is a function of the size of the studied region, amount and reliability of the available data as well as the selected methodologies for each component. In this study, seismic losses are estimated for residential buildings in Düzce city center (study region 1) and Osmangazi subprovince of Bursa (study region 2) determined with corresponding resolutions by the available input data.

1.2 Literature Survey

Seismic loss estimation has gained the attention of many researchers for several decades. Initial attempts to develop seismic loss estimation studies were performed by Freeman (1932) for insurance companies. But the interest on seismic loss estimation studies increased after early 1970s. Since then, considerable number of methodologies has been proposed on seismic loss estimation. However, most of the researchers halted their studies at the physical vulnerability level.

Seismic loss estimation procedures in general have three major components: quantification of seismic hazard, building fragility, and socioeconomic vulnerability. Therefore these components can be divided into different subclasses in terms of the aforementioned components. Ground motion demand can be predicted with two approaches, namely; deterministic (Küçükçoban, 2004, Bal et al., 2008, Demircioğlu et al., 2010, Ugurhan et al., 2011) and probabilistic seismic hazard analyses (Smyth, 2004, Crowley and Bommer, 2006). The second component of loss estimation, building fragility, can be obtained by detailed structural analysis of a single building (Aslani, 2005). For a group of buildings in larger areas, damage probability matrices or fragility curves generated for a building stock can also be used (Akkar et al., 2005, Ay and Erberik, 2008, Erberik, 2008a, Erberik, 2008b, Askan and Yücemen, 2010). Casualty and economic loss estimation equations can be derived by empirical (Wald et al., 2008), analytical (FEMA, 2003) or hybrid (Wald et al., 2008, Wyss et al., 2009) approaches.

In the literature, majority of seismic loss estimation studies use the deterministic approach in order to estimate the seismic hazard at a region of interest. These deterministic studies generally employ regional past events or simulate potential ground motions. Ugurhan et al. (2011) presented a seismic damage estimation methodology combining simulated regional ground motions with the building vulnerability information, which are derived from fragility analyses. In another study, Küçükçoban (2004) has presented detailed damage distributions in Istanbul for deterministic scenario events suggested by Japanese International Cooperation Agency (JICA) to develop a computer software to carry out seismic damage assessment. Bal et al. (2008) determined damage distributions and social losses in Istanbul for a potential deterministic M_w=7.5 scenario earthquake scenario using a displacement-based earthquake loss assessment (DBELA) methodology for the Turkish building stock. The building inventory is generated randomly using Monte Carlo simulations. Loss assessment of the generated building stock is provided for the selected deterministic M_w=7.5 event.

Crowley and Bommer (2006) used a displacement-based earthquake loss assessment methodology for seismic loss estimation in Northern Marmara Sea Region. In that study, ground motions are calculated from probabilistic seismic hazard analysis which is derived by using stochastically-generated earthquake catalogs as well as multiple earthquake scenarios. A sensitivity analysis, is also carried out. The building vulnerability is predicted by DBELA methodology. Seismic losses are estimated for deterministic and probabilistic seismic hazard levels. It is concluded that, alternate approaches for determining seismic hazard yielded in considerably different loss estimates while PSHA approach is viewed as the most compromising one. The significance of accurate modeling of seismic hazard in loss estimation studies has been emphasized.

With the growing interest in seismic loss and risk assessment, development of computer programs on these topics has also advanced. One of the most distinguished ones is HAZUS, which is developed by Federal Emergency Management Agency of

United States (FEMA, 2003). HAZUS methodology estimates potential losses from due to various hazards like earthquakes, flood, and wind. United States Geological Survey developed a global loss estimation model called Prompt Assessment of Global Earthquake for Response (PAGER) to estimate the impact of earthquakes immediately after the events (Wald et al., 2008). Another example is QLARM, proposed by Wyss et al. (2009) which estimates global seismic damage and casualties. Further details on these computer programs are presented in Chapter 4. Karaman et al. (2010) has developed a computer program for Turkey, HAZTURK, based on MAEVIZ, Mid-America Earthquake Center platform. HAZTURK includes interdisciplinary algorithms and analyses considering deterministic earthquake scenarios. Building damage is estimated by fragility functions and economic loss is evaluated by proposed loss functions. Demircioğlu et al. (2010) have coded an earthquake loss estimation routine (ELER) for Euro-Mediterranean Region. In that study, casualty and economic loss estimations are based on HAZUS methodologies.

Recently, several loss and casualty estimation models have been proposed for the Marmara Sea Region considering ground motion scenarios along with appropriate building vulnerability functions. Bommer et al. (2002) developed an event-based probabilistic earthquake loss model for Turkish Catastrophe Insurance Pool (TCIP). In that study, the events are obtained from a synthetic earthquake catalog. Building vulnerability is derived as suggested by Kircher et al. (1997) and incorporated into HAZUS (FEMA,1999) methodology (Bommer et al. 2002). The scenarios are created based on a set of potential events and the results are presented in terms of annual average losses and loss exceedance probabilities.

Smyth et al. (2004) proposed a benefit-cost analysis for risk mitigation assessment of Turkey. In that study, different alternatives in the nature of problem as well as the direct costs in mitigation are considered. The proposed methodology chooses the best alternative by maximizing the net benefit of the client. For this purpose, loss systems with and without a mitigation system as well as the attractiveness of the selected mitigation system are taken into account. The ground motion demand is derived from hazard curves in terms of PGA levels. The structural analyses are performed on a representative building in Istanbul with different conditions namely; original unretrofitted and retrofitted with braced, partial shear wall, and full shear wall systems. Analytical fragility curves are generated using the results of 400 nonlinear dynamic structural analyses.

Aslani (2005) has also proposed a conceptual probabilistic loss estimation model for a single building. The components of the seismic loss are integrated using the theorem of total probability.

Recently, Ansal et al. (2009) proposed a loss estimation model in terms of building damage and casualty for the Marmara Sea Region. Deterministic ground motion scenarios based on finite-fault rupture models are integrated with time-dependent probabilistic seismic hazard assessment. Appropriate building vulnerability functions are derived using capacity spectrum method based on ATC-40 (1996) suggestions. Casualties are estimated using HAZUS (FEMA, 1999) procedures. It is once again confirmed that different ground motion characteristics affect the overall damage estimates significantly.

This thesis study adopts a probabilistic seismic hazard assessment methodology which takes into account the uncertainties related to the ground motions in the region of interest. Fragility curves generated by Erberik (2008a), Erberik (2008b) and Gencturk (2008) are utilized for RC, URM and woodframe structures, respectively. Casualties and economic losses are estimated using analytical expressions for Düzce City Center and Osmangazi subprovince of Bursa. Additional literature related to this work will be cited throughout the text whenever necessary.

1.3 Proposed Methodology

This study has two main objectives: One is to estimate the losses for residential buildings in Düzce city center (study region 1) after the 1999 Düzce earthquake for verification purposes. The other one is to predict the potential losses in Osmangazi subprovince of Bursa (study region 2) in a probabilistic manner. The components of the seismic loss model, which are seismic hazard, building fragility, casualty and economic loss, are integrated within a conditional probability approach (Figure 1.1). Seismic hazard in each study region is computed by probabilistic seismic hazard analyses (PSHA) while the building fragility is calculated by adopting appropriate fragility functions for the corresponding types of buildings. Seismic risk is defined by the level of loss or damage that is equaled or exceeded in a certain period of time (McGuire, 2004). The occurrence probability of a certain damage level for a given hazard level is multiplied by the probability of occurrence of that hazard level (Equation 1.1).

$$P(R > R_k) = P(DM > DL_i|GM_j) \times P(GM > GM_j) \tag{1.1}$$

where, R is the risk; DM is the observed damage of the structures; DL is the damage limit state and GM is the ground motion level. In Equation 1.1, *j* denotes the seismic event, *i* is the damage level and *k* corresponds to the level of risk, or in other words, level of damage for a given seismic event, *j*

In order to estimate the seismic risk, cumulative hazard curves are converted into probability density functions of seismic hazard while the cumulative fragility functions are converted into discrete damage probability matrices. Figure 1.2 summarizes the derivation of the seismic risk curves in this study

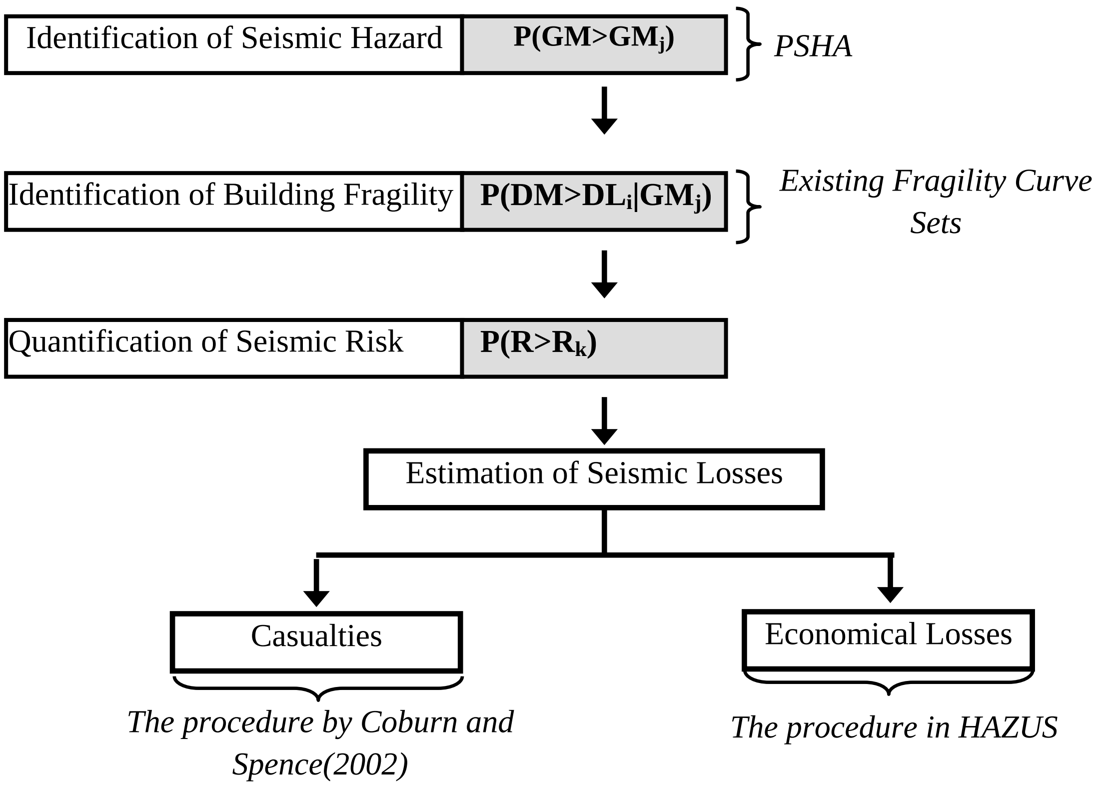

Figure 1.1: Main components of the proposed seismic loss estimation methodology

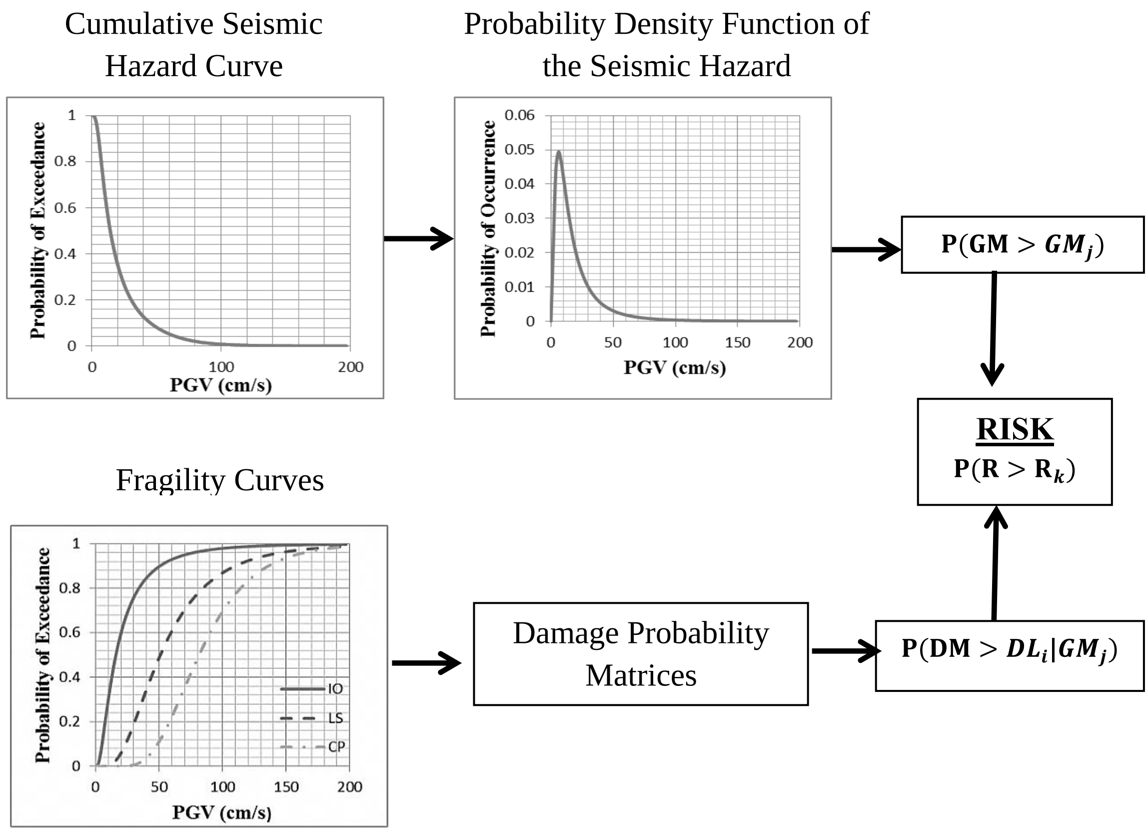

Figure 1.2: The schematic flowchart to estimate seismic risk

Once the risk curves for each building class are generated, they are multiplied by the number of buildings at that class, so damage distribution and number of collapsed buildings are obtained. Number of collapsed buildings is then related to the number of casualties in study regions 1 and 2 considering the occupancy type, population of the building, occupancy at the time of earthquake occurrence, number of trapped occupants in the collapse, injury distribution at collapse and mortality post collapse. The expected economic loss is estimated by multiplying the mean damage ratio (MDR) by the total cost of initial construction. Finally, the expected seismic losses for an arbitrary 50 year time window are estimated. In this study, the time period is selected to be 50 years which is the assumed average lifetime of residential buildings in Turkey. Seismic losses as a result of events with return periods of 10, 50, 100, 250, 475, 1000 and 2475 years are also computed.

1.4 Objectives and the Scope of the Study

This study aims to propose a versatile methodology for estimating potential physical and economic losses as well as casualties in future earthquakes. The outcome of this study can be used in insurance, disaster mitigation and retrofitting practices. The results are expressed in terms of both expected loss and events with different return periods. The proposed methodology is applied to the residential buildings in Osmangazi sub-province of Bursa (study region 2), which is located in one of the most critical earthquake zones in Northwestern Turkey. Bursa is expected to experience a major earthquake according to previous regional seismicity and existence of the active faults in the region. Since it is a highly populated and industrialized city, it is crucial to estimate the potential seismic losses in Bursa. Validation of the suggested methodology is performed in Düzce city center (study region 1), which experienced a M_w=7.1 magnitude earthquake in 1999. Estimated loss in Düzce is compared with the observed loss after the 1999 earthquake to validate the model.

In Chapter 2, fundamentals of the first component of seismic loss estimation, which is seismic hazard analysis, are introduced. Deterministic and probabilistic seismic hazard principles are presented along with several past studies. Specific emphasis is given to the analysis approach adopted in this thesis.

In Chapter 3, the second component of seismic loss estimation, fragility assessment, is presented. First, the definition and derivation of DPMs and fragility functions are discussed. New fragility curves are not generated in this study, therefore several past studies are briefly summarized and selected fragility curve sets are presented in detail.

Chapter 4 includes the casualty assessment studies. First, global casualty estimation studies are presented. In this study, the model suggested by Coburn and Spence (2002) is adopted to Turkey with several modifications. An analytical relationship between the number of collapsed buildings and number of casualties is proposed considering the occupancy type, population of the building, occupancy at the time of earthquake occurrence, number of trapped occupants in the collapse, injury distribution at collapse and mortality post collapse.

In Chapter 5, estimation of economic loss is explained. The components of economic loss are briefly discussed and previous studies on seismic economic loss are mentioned. In this study, economic losses caused only by the damage of structural members are taken into account.

Chapter 6 involves results of the aforementioned components of seismic loss estimation procedure. First, results of probabilistic seismic hazard analyses are shown. Then, the fragility curves for study regions 1 and 2 are presented. Following the risk analysis, results of casualty and economic loss assessments are presented in terms of expected losses and losses caused by events with different return periods. Finally, a validation study is conducted using the physical and human life loss data of 1999 Düzce Earthquake.

Chapter 7 summarizes the proposed study, discusses the results, presents the concluding remarks and suggests several directions for future studies.

CHAPTER 2

SEISMIC HAZARD ANALYSIS

2.1 General

Seismic Hazard Analysis (SHA) is the foundation of seismic loss estimation studies. From structural point of view, SHA provides the ground motion demand on the structures for which seismic loss in a certain period of time is to be estimated. In general, SHA is conducted in two alternative ways; namely deterministic seismic hazard analysis (DSHA) and probabilistic seismic hazard analysis (PSHA).

In this chapter, first, the principles of DSHA are discussed. Afterwards, PSHA is introduced and different approaches for preforming PSHA are presented. Several previous studies that utilized different approaches for both DSHA and PSHA are also mentioned throughout the chapter.

2.2 Deterministic Seismic Hazard Analysis

SHA is named as deterministic seismic hazard analysis if the analysis is conducted for a deterministic scenario. The scenario can either be a single event or a finite number of events where magnitudes and source-to-site distances are well known. The events can be selected among the historical ones or they can be based on most critical scenarios as well as simulated potential ground motions. Since this analysis is conducted for deterministic events, it neglects the inherent randomness of the ground motion process.

2.2.1 Deterministic Seismic Hazard Analysis Based on Past Events

In this approach, characteristics of the past events are used as input ground motion parameters to a seismic risk or loss study. The approach for selecting former events varies with respect to the study conducted. For instance, in estimating the future seismic loss of a certain region, ground motion records from historically significant events which are close to the site of interest are preferred (for example: 1992 Erzincan (M_w=6.8), 1998 Ceyhan (M_w=5.9), 1999 Kocaeli (M_w=7.4), and 1999 Düzce (M_w=7.1) earthquakes in Turkey). If seismic losses immediately after an earthquake are to be estimated, then the corresponding earthquake is considered as the deterministic scenario. United States Geological Survey (USGS) and World Agency of Planetary Monitoring and Earthquake Risk Reduction (WAPMERR) are two associations conducting loss estimation studies for particular earthquakes. Past events are also used for validation purposes. In this study, 1999 Düzce (M_w=7.1) earthquake is used to validate the proposed seismic loss estimation model.

2.2.2 Deterministic Seismic Hazard Analysis Based on Most Critical Events

When DSHA is based on the most critical or maximum credible events, maximum possible earthquake magnitudes in the region of interest along with the minimum source-to-site distances are considered. Among the events, the one producing the largest ground motion at a particular site is selected (Yılmaz, 2008). In other words, most critical events are the worst case scenarios with largest magnitudes and smallest source-to-site distances; which create the greatest possible ground motions. Thus, the most critical events have considerably low probability of exceedance. Today, maximum credible events are utilized for the seismic hazard analysis of critical structures such as nuclear power plants. Since these events tend to overestimate the potential hazard, they are not considered as practical engineering decisions (Gupta, 2002).

2.2.3 Deterministic Seismic Hazard Analysis Based on Simulation of Scenario Events

Ground motion simulations are essential for regions of sparse or no ground motion records. In seismic loss estimation process, ground motion simulations can be used to estimate ground motion intensity parameters and frequency content of potential ground motions. The frequency content of ground motions is in general treated in two different ways. Low frequency ground motions (f<1 Hz) are deterministic in nature; whereas high frequency ground motions have stochastic character. A variety of studies have been conducted to simulate both low and high frequency ground motions. For recent Turkish earthquakes, Uğurhan (2010) applied the stochastic finite-fault methodology with a dynamic corner frequency approach to simulate the shear wave portion of high frequency ground motions of 1992 Erzincan (Mw=6.8) and 1999 Düzce (Mw=7.1) earthquakes.

2.3 Probabilistic Seismic Hazard Analysis

Probabilistic seismic hazard analysis (PSHA) for a specific site consists of determining the frequency with which an earthquake characteristic takes on a defined range of values during some fixed time *t* in the future. The earthquake characteristic may be peak ground acceleration (PGA), peak ground velocity (PGV), Modified Mercalli Intensity (MMI), duration of seismic shaking, or displacement caused by a fault beneath a facility's foundation (McGuire, 2004). In other words, PSHA considers all seismic sources within a certain distance range, all rupture lengths (or areas) at every possible location on the source and it suggests the probability of exceedance or the probability of occurrence of ground motion parameters within a certain period of time. In the seismic loss estimation method proposed in this study, ground motion demand on the structures in the region of interest is determined using PSHA. In this manner, seismic loss of the structures in a certain period of time is estimated.

Probabilistic seismic hazard analysis was originally proposed by Cornell (1968). Since then, many studies have been carried out on this topic. Using PSHA, seismic hazard for specific sites, as well as hazard maps of many regions, cities and countries have been generated. In order to facilitate PSHA calculations, numerous computer programs have been developed. Most common and widely-used computer programs in a chronological order are given as: EQRisk (McGuire, 1976), FRISK (McGuire, 1978), SEISRISK II (Bender and Perkins, 1982), STASHA (Chiang et al., 1984), SEISRISK III (Bender and Perkins, 1987), Crisis (Ordaz, 2001), EZ-FRISK (Risk Engineering Inc., 2004), EXPEL (Benito et al., 2004). The main differences between the aforementioned programs come from seismic source characterization and integration methods utilized (Benito et al. 2004). In Turkey, first probabilistic seismic hazard studies were conducted by Gülkan and Yücemen (1975; 1976) and Gülkan and Gürpinar (1977). Following these studies, numerous researchers utilized PSHA for determining the seismic hazard level in Turkey. Erdik et al. (1985; 1999; 2004) performed regional probabilistic seismic hazard analyses for Turkey. Gülkan et al. (1993) and Özmen et al. (1997) generated seismic zoning maps for Turkey. Çetin (2000; 2004; 2007; 2009) studied seismic hazard and soil liquefaction hazard for dams. Yılmaz (2008) carried out a sensitivity study of probabilistic seismic hazard analysis with respect to different models.

Seismic hazard at a site is defined in terms of the frequency of exceeding a certain seismic hazard level, γ, as (McGuire, 1995):

$$\gamma(y) = \sum_i v_i \iiint f_M(m) \times f_R(r) \times f_e(\varepsilon) \times P[Y > y(m,r,\varepsilon)]\, dm\, dr\, d\varepsilon \tag{2.1}$$

where, v_i is the activity rate for source i, m is the magnitude, r is the site to source distance, ε is the randomness in the ground motion and y is the ground motion parameter. Figure 2.1 presents a flowchart summarizing the steps of PSHA by Federal Emergency Management Agency (FEMA).

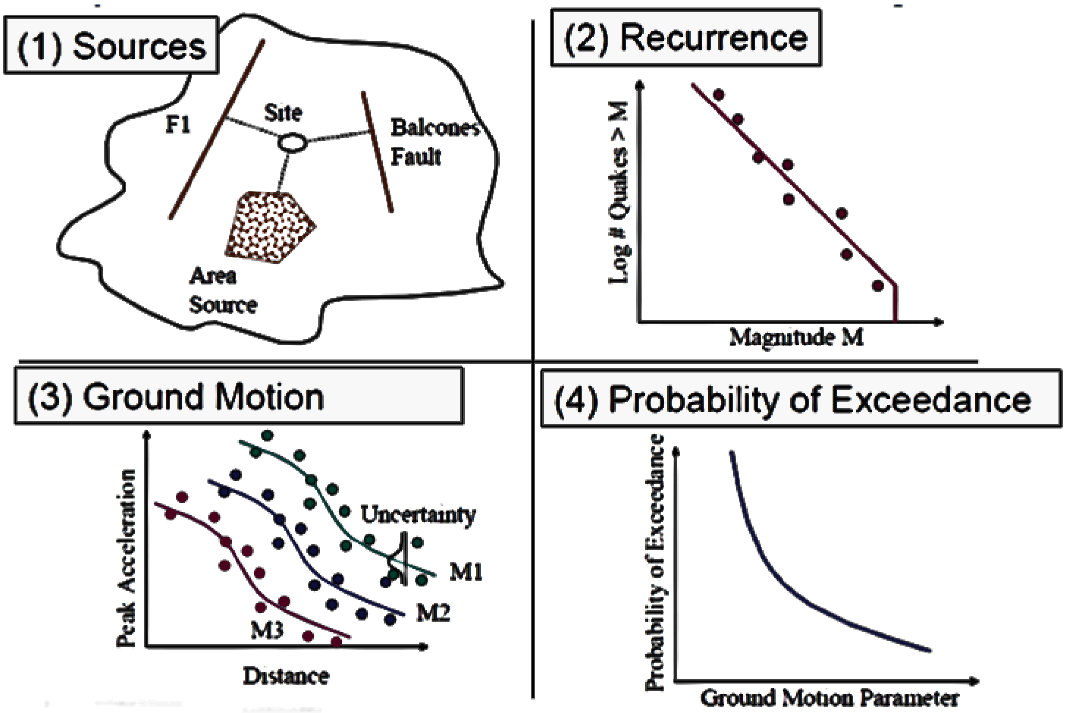

Figure 2.1: Steps in Probabilistic Seismic Hazard Analysis (FEMA, 2002)

Probabilistic seismic hazard analysis consists of six basic steps which are the identification of the earthquake catalog, definition of the seismic sources, computation of the activities of the seismic sources, selection of the ground motion prediction equations, construction of the computational algorithm and definition of the temporal occurrence relationships. These steps are discussed in detail in the following sections with specific emphasis on the selected approach for each step.

It should be noted that the resolution of a seismic hazard analysis study is a function of the size of the region studied, amount and reliability of the available data and the selected methodologies for each PSHA step.

2.3.1 Definition of the Earthquake Catalog

Determination of the activities of the seismic sources is a crucial step in seismic hazard analysis. Past events, which are obtained from global or local earthquake catalogs, can be used for this purpose. In this study, the earthquake catalog suggested by Kandilli Observatory and Earthquake Research Institute

(KOERI) (http://www.koeri.boun.edu.tr) is adopted from years 1900 to 2004 with a lower bound of moment magnitude M_w= 4.5.

The earthquake catalogs are statistically biased, thus they should not be used in their original forms in probabilistic seismic hazard analysis. (Yücemen, 2008) Yücemen (2008) has suggested several modifications to improve past event data (earthquake catalog) to be used in probabilistic seismic hazard analysis. The modifications can be summarized as follows: First of all, earthquake databases should be based on a single magnitude scale for seismic analysis purposes. Yücemen (2008) suggests M_w (moment magnitude) to be an appropriate magnitude scale. Furthermore, M_w is a common parameter in ground motion prediction equations. Empirical relationships relating magnitude to rupture length, rupture width, rupture area and surface displacement also considers M_w as the fundamental magnitude scale (Wells and Coppersmith, 1994). Therefore, it is reasonable to present all of the magnitudes in the earthquake catalog in M_w scale.

Next, Poisson model, for the temporal occurrence, is memory-independent and requires independency between events as a rule. On the other hand, many of the events in earthquake catalogs are certainly dependent on each other. Foreshocks and aftershocks depend on the main shocks in both time and space domains. Thus, foreshocks and aftershocks should be removed from the catalog. In order to eliminate the foreshocks and aftershocks from the earthquake catalog, many different methodologies have been proposed. Among those studies, the one which is developed by Deniz (2006) is selected which defines time (in days) and distance (in km) ranges to decide whether an event can be considered as a main shock or not (Table 2.1). Poisson model can be used in probabilistic seismic hazard analysis after the removal of foreshock and aftershocks from the earthquake catalog using the methodology by Deniz (2006). Following the methodology by Deniz (2006), 1999 Düzce Earthquake can be found as an aftershock of 1999 Kocaeli Earthquake. However, in literature, 1999 Düzce Earthquake is debated and finally stated to be a main shock. Therefore in this study, 1999 Düzce Earthquake is considered to be a main shock.

Table 2.1: Time and distance ranges that are required to define the foreshocks and aftershocks. (Deniz, 2006)

Magnitude	**Distance (km)**	**Time (days)**
4.5	35.5	42
5.0	44.5	83
5.5	52.5	155
6.0	63.0	290
6.5	79.4	510
7.0	100.0	790
7.5	125.9	1326
8.0	151.4	2471

Finally, the earthquake catalogs are never complete. In other words, addition of new data (especially with larger magnitudes) changes the proposed model. In addition, older records of the past events only include large magnitude earthquakes that occurred near the city centers. Therefore, earthquake catalogs are considered to be biased (Yücemen, 2008). In order to eliminate this bias, Yücemen (2008) recommends either using the complete and saturated part of the catalog or artificially completing the missing parts by a methodology proposed by Stepp (1973). Neglecting the effects of such a bias, this modification is not performed in this study. Seismicity of Düzce (study region 1) and Bursa (study region 2) are presented in Figures 6.1 and 6.2 in Chapter 6.

2.3.2 Determination of the Seismic Sources

The second step in seismic hazard analysis is the definition of the source or sources of earthquakes that could affect particular location at which the hazard is being evaluated. These sources are often called as seismotectonic sources or earthquake sources activated by tectonic forces (Reiter, 1990). In order to determine the seismic sources, location of the active faults and seismicity of the region of interest should be known. As a definition, a fault is a fracture or zone of fractures in rock along which the two sides have been displaced relative to each other parallel to the fracture (Bolt, 2000). Faults should be specified by geometry, sense of slip segmentation and a function of describing rupture length or area as a function of magnitude. (McGuire, 1993). On the other hand, it is not possible to identify every earthquake-generating fault in seismic hazard analysis. In addition, it is not feasible to use the pristine sources in active fault maps. The seismic sources are either unknown or need further simplifications.

In seismic hazard analysis, different earthquake-generating source geometries can be defined according to the amount of information available on the active fault mechanism at the region of interest. Figure 2.2 shows a flowchart for the selection of different geometries of seismic sources. Accordingly, there are three common different geometries for seismic sources: point, line and area. Properties of each are explained in the following paragraphs.

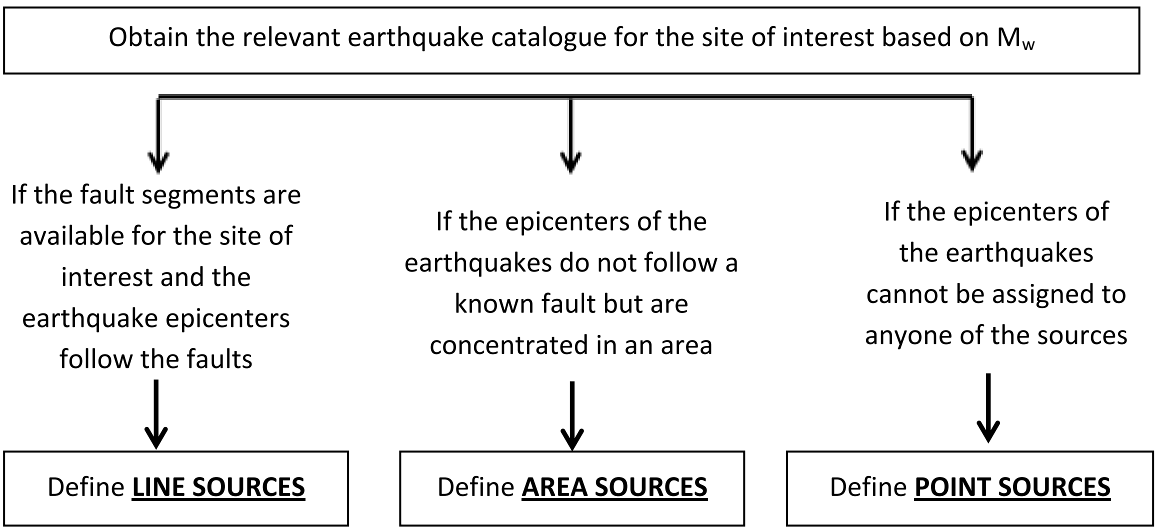

Figure 2.2: Flowchart for the definition of the seismic sources

- *Point Sources:* They were frequently used in the earlier seismic hazard analyses. Today, point sources are employed when neither the faults can be identified (line sources cannot be defined) nor the past events are concentrated in an area (area sources cannot be defined). Short faults with large distances to the site of interest can also be defined as point sources.

Point sources assume that the distance from the fault to the site is constant. The depth of the point source can be treated as either a constant or a random variable. If the depth is assumed to be constant, then the only random variable is the magnitude. In the latter case, both the magnitude and the depth can be the random variables. Uncertainty in the location of the point sources can also be taken into account by considering the standard deviations of the exact locations of the point sources. These source models are called spatially-smoothed background seismicity models.

- *Line Sources:* Line sources are defined when the locations of the active faults are known and the epicenters of the past events are concentrated around these faults. It is assumed that the earthquakes occur with equal probability at anywhere along the length of a line source. Line sources are simplified representations of active faults. The random variables in these sources are the magnitude and the source to site distance of events. Identification of the line sources requires a well-established geological structure and the correlation of the sources with the seismicity in the region of interest. Empirical relationships among rupture dimensions and moment magnitudes are used to define the random variables of magnitude and source-to-site distances in seismic hazard analysis. In order to define further characteristics of line sources, sense of slip, dip angle, maximum depth, total length, maximum rupture length, average displacement per event, slip rate and magnitude distributions can be defined. (McGuire, 1993). Characteristics of a line source are assumed to remain uniform throughout the source.

- *Area Sources:* When the locations of the active faults are not known or cannot be identified, but the epicenters of the past events are concentrated in a region, then area sources can be defined. On an area source, future seismicity is assumed to be a function of source properties and locations of energy release which do not vary in time and space (McGuire, 2004).

For an area source, the random variables are magnitude and source-to-site distance on a plain domain. Area sources can also be defined to take into account the uncertainties in the locations of the future events due to the faults whose locations are considered to be unreliable. Similar to the line sources, characteristics of area sources are assumed to be uniform throughout the source.

In this study, the active fault map of Turkey is obtained from strong ground motion database of Turkey (http://daphne.deprem.gov.tr). The active faults are represented as line sources. Unidentified faults at the regions where epicenters of the past events are concentrated in a region are represented as area sources. The past events which could be assigned to neither of these sources can be represented as point sources. However for this study, since their effects on the overall hazard is observed to be small, point sources are neglected. Seismic source geometries of Düzce and Bursa are presented in Figures 6.3 and 6.4 in Chapter 6.

2.3.3 Magnitude Recurrence Model

In seismic hazard analysis, earthquake probability distribution or magnitude recurrence relationship should be determined for every seismic source considered. A recurrence relationship indicates the chance of an earthquake of a given size occurring anywhere inside the source during a specified period of time (Reiter, 1990). In other words, magnitude-recurrence relationship for a seismic source represents the probability density function of the magnitudes of earthquakes, which belong to that source.

Recurrence relationships can be developed by relating the seismicity to the predefined seismic sources at the region of interest. There are several models for the development of magnitude recurrence relationships: exponential, truncated exponential, characteristic and truncated characteristic models.

- *Exponential Model (Gutenberg-Richter, 1956):* It is generally agreed that regional catalogs of seismicity are well described by Gutenberg-Richter relation. (Wesnousky, 1994). Gutenberg-Richter model assumes that the earthquake magnitudes are distributed exponentially for a given source. In other words, the exponential model assumes a linear relationship between the natural logarithm of the number of exceedance and magnitudes in a certain period of time. The equation of the line is derived using a linear regression analysis. Equations 2.2 and 2.3 represents the Gutenberg-Richter exponential model:

$$\ln(\lambda_n) = \alpha + \beta \times M_w \tag{2.2}$$

$$f_m(M) = \beta \times e^{-\beta(M-M_o)} \tag{2.3}$$

where λ_n is the number of events with magnitudes over M_w. Parameter β represents the slope of the line in Equation 2.2 and it describes the ratio of exceedance of the events with respect to each other. Thus, this parameter can be calculated with short term data. The constant term α in Equation 2.2 describes the seismic activity of the source. Precise calculation of this parameter requires long term data. It can be improved by balancing the energy between the annual potential energy stored according to slip rate of the fault and the energy expected to be released in an earthquake. Figures 2.3 and 2.4 present the exponential model according to Equations 2.2 and 2.3 respectively.

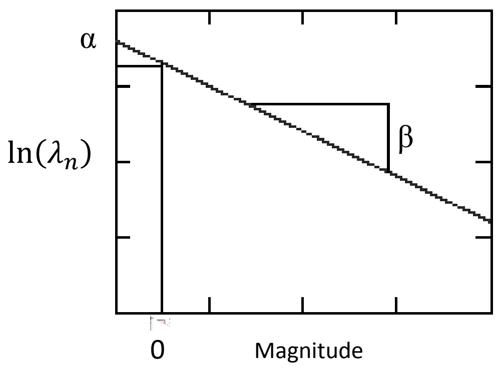

Figure 2.3 : The linear relationship between the natural logarithm of number of exceedance and the corresponding magnitudes of a particular source

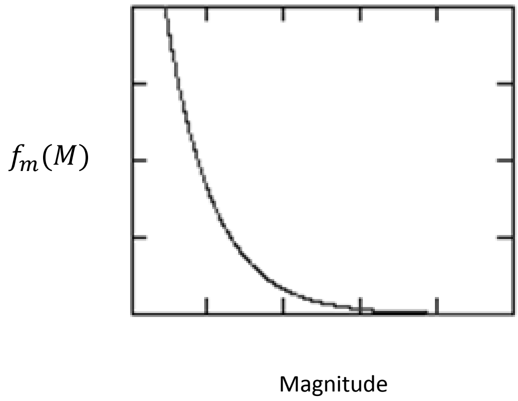

Figure 2.4 : The exponential distribution of the magnitudes for a particular fault

- *Truncated Exponential Model:* Truncated exponential model is similar to Gutenberg and Richter model. Equation 2.2 is also valid for the truncated exponential model. Parameters α and β in Equation 2.2 can be obtained in a similar manner. The only difference is, the magnitude range is Gutenberg and Richter model is from zero to infinity, whereas, truncated exponential model sets lower and upper bound magnitudes equating the area under the probability density function of magnitudes to unity. The lower bound magnitude can be taken as 4.0 or 4.5 according to Yücemen (2008). Following the recommendations of Yücemen (2008), in this study, lower bound moment magnitude is selected to be 4.5. Upper bound magnitude can be determined according to the maximum historical event or maximum rupture length, width, area or displacement. In this study, upper bound magnitude is estimated using the latter approach as suggested by Wells and Coppersmith (1994). Equation 2.4 shows the probability distribution function of magnitudes according to the truncated exponential model. Figure 2.5 presents the truncated exponential model given in Equation 2.4.

$$f_m(M) = \frac{\beta \times e^{-\beta(M-M_{min})}}{1-e^{-\beta(M_{max}-M_{min})}} \tag{2.4}$$

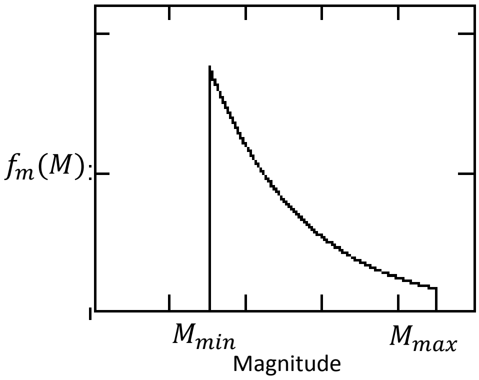

Figure 2.5: The truncated exponential distribution of the magnitudes for a particular fault

- *Characteristic Model (Characteristic Size Recurrence Model by Youngs and Coppersmith, 1985):* "Although the distribution of earthquake magnitudes on a seismic source is usually assumed to follow an exponential distribution, there is an increasing evidence that a characteristic earthquake model may be appropriate for individual faults." Youngs and Coppersmith (1985). Characteristic earthquake model is derived using both geological and seismicity data. Equation 2.6 represents the probability density function of magnitudes according to characteristic distribution model:

$$c = \frac{\beta \times e^{[-\beta \times (M_{max} - \Delta M_1 - \Delta M_2 - M_{min})]} \times \Delta M_2}{1 - e^{-\beta (M_{max} - \Delta M_1 - M_{min})}} \tag{2.5}$$

$$f_m(M) = \begin{cases} \frac{\beta \times e^{-\beta(M - M_{min})}}{1 - e^{-\beta(M_{max} - \Delta M_2 - M_{min})}} \times \frac{1}{1+c} & \text{if} \quad M_{min} \leq M \leq M_{max} - \frac{1}{2} \times \Delta M_2 \\ \frac{\beta \times e^{[-\beta \times (M_{max} - \Delta M_1 - \Delta M_2 - M_{min})]}}{1 - e^{-\beta(M_{max} - \Delta M_2 - M_{min})}} \times \frac{1}{1+c} & \text{if} \quad M_{max} - \frac{1}{2} \times \Delta M_2 \leq M \leq M_{max} + \frac{1}{2} \times \Delta M_2 \\ 0 & \text{otherwise} \end{cases} \tag{2.6}$$

In Equation 2.5, M_{min} and M_{max} are the lower and upper bound earthquake magnitudes, respectively. ΔM_1 and ΔM_2 are 1.0 and 0.5 respectively. Characteristic model assumes the magnitudes to have an exponential distribution up to maximum magnitude minus half of ΔM_2 value and a uniform distribution between $M_{max} \pm 1/2 \times \Delta M_2$. Characteristic model assigns higher recurrence rates to larger events when compared to the exponential model. Youngs and Coppersmith (1985) implies that exponential distribution model overestimates the rate of smaller events; while characteristic distribution model underestimates these rates. Figure 2.6 illustrates the probability distribution function of magnitudes according to the characteristic distribution model by Youngs and Coppersmith (1985).

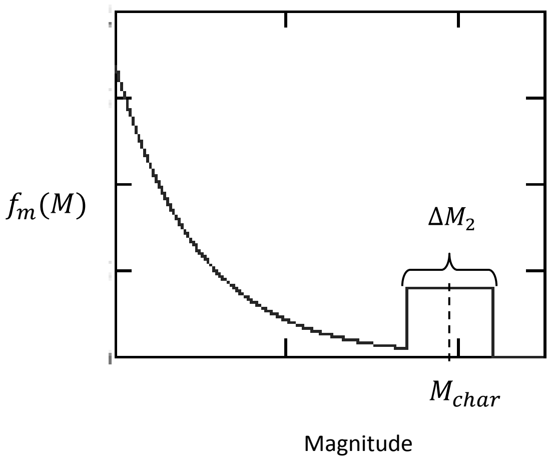

Figure 2.6: The characteristic distribution of the magnitudes for a particular fault

- *Truncated Normal Distribution Model:* Truncated normal distribution is similar to the characteristic distribution model. In truncated normal distribution model, the uniformly distributed portion of the magnitudes in the characteristic distribution model is assumed to be normally distributed. The mean of the normal distribution function is the characteristic magnitude and the area under the piecewise probability density function is unity. Figure 2.7 illustrates the probability distribution function of magnitudes according to truncated normal distribution model.

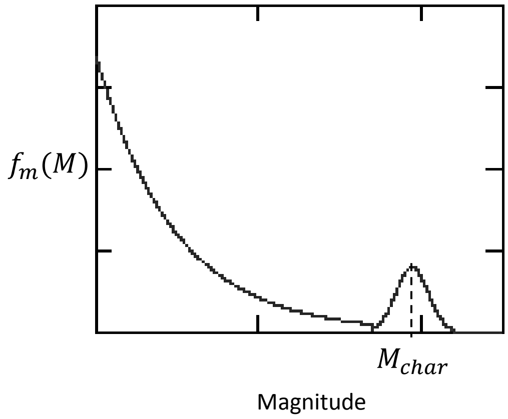

Figure 2.7 : The truncated normal distribution of the magnitudes for a particular fault

In this study, the exponential magnitude-recurrence model suggested by Gutenberg and Richter (1956) is used; which is embedded to SEISRISK III. As mentioned previously, the lower bound for moment magnitude is assumed to be 4.5 and the upper bound magnitude of the sources are defined according to the source geometry by using the methods suggested by Wells and Coppersmith (1994).

2.3.4 Ground Motion Prediction Equations:

Ground motion prediction equations (GMPEs) represent the change in the ground motion measures with respect to the distance from the epicenter for a predefined earthquake magnitude. These relationships are derived using regression analyses on past event datasets, and are subject to change with addition of recent data. Applied to ground motion the regression problem is more complex because of the large size of data base, the increased number of variables required and possible nonlinear relationships between these variables (Reiter, 1990). Ground motion prediction equations aim to estimate a dependent ground motion intensity parameter such as peak ground acceleration (PGA), peak ground velocity (PGV), peak ground displacement (PGD), spectral acceleration (S_a), spectral displacement (S_d). In ground motion regression analyses, the independent variables are generally the magnitude, source-to-site distance, local site conditions, fault mechanism and etc. Several GMPEs including Next Generation Attenuation (NGA) models and regional ground motion prediction studies conducted for Turkey are listed below. Details and derivations of these regression analyses are out of scope of this study and will not be presented here.

- *NGA Models:*
  - Abrahamson and Silva (2008) NGA Model
  - Boore & Atkinson (2008) NGA Model
  - Campbell & Bozorgnia (2008) NGA Model
  - Chiou & Youngs (2008) NGA Model
  - Idriss (2008) NGA Model

- *Attenuation Relationships Developed for Turkey:*
  - Inan et al. (1996)
  - Aydan et al. (2001)
  - Kalkan and Gülkan (2004)
  - Ulusay et al (2004)
  - Akkar and Bommer (2010)

In this study, the models generated by Boore and Atkinson (2008) and Akkar and Bommer (2010) are used to predict ground motions for different epicentral distances and magnitudes. These GMPEs are selected because the dataset of Boore and Atkinson (2008) contains the highest number of stations in Turkey compared to other NGA models. (Abrahamson et al., 2008). While Akkar and Bommer (2010) is the most recent local GMPE developed for Turkey. In this study, each one of the GMPEs is subjectively given 50% weight. Soil properties, site conditions and V_{s30} values for both Düzce and Bursa city centers are obtained from Strong Ground Motion Database of Turkey webpage (http://daphne.deprem.gov.tr). Both sites are assumed to be stiff soil with V_{s30} values of 400 m/s and 490 m/s for study region 1 and study region 2, respectively.

2.3.5 Temporal Occurrence Model

The probabilistic seismic hazard at a site is obtained by summing all possible earthquake scenarios at a region of interest to calculate total annual rate of exceedance of a certain ground motion parameter. (PGA, PGV, PGD, S_a, S_d, etc). For this purpose, temporal-occurrence models are utilized which compute the probability of exceedance of ground motion parameters in a certain period of time (t) from the annual rates of exceedance or occurrence. There are three major temporal occurrence models: Poisson Model, Renewal Model and Hybrid Model. Within the scope of this study, only Poisson Model is explained.

- *Poisson Model:* Poisson distribution calculates the probability of the number of earthquakes in a certain period of time. Poisson distribution model assumes that the earthquakes are independent, seismicity is stationary and the events do not occur simultaneously. Poisson model is commonly used because of its simplicity in capturing the basic elements of the problem. Besides its simplicity, the outcomes have been observed to be successful, it is physically reasonable and the sum of non-Poissonian processes can be approximated to be Poisson process (Cornell 1988). As mentioned previously, since the events in the dataset should be independent in a Poisson model, foreshocks and aftershocks are removed from the catalog. Equation 2.7 shows the probability of exceedance of a certain ground motion parameter at least once according to the Poisson model:

$$P(N \geq 1) = 1 - e^{-\nu . t} \tag{2.7}$$

In Equation 2.7, **N** is the number of exceedance of a certain ground motion parameter, $\boldsymbol{\nu}$ is the annual rate of exceedance of this ground motion parameter and is assumed to be constant within the time domain where **t** is the selected time period. The Poisson model is assumed to be suitable for modeling the occurrences of earthquakes within time domain (Yücemen, 2008).

In this study, the time period is selected as 50 years which is the average lifetime of residential buildings in Turkey. Poisson model is adopted here assuming the events are independent from each other in time and space domain. The Poisson model is assumed to be practical for modeling the occurrences of the earthquakes within time domain when a single fault is not dominating the hazard and when the time since occurrence of the last event exceeds mean recurrence interval which is rare according to McGuire (2004).

The annual rates of exceedance and occurrence of the events for both PGA and PGV for Düzce and Bursa city centers are calculated using the computer program SEISRISK III which is developed by Bender and Perkins (1987). SEISRISK III was used to generate the probabilistic seismic hazard maps of USA from 1972 to 1992 by US Geological Survey (USGS). Today, SEISRISK III is still being used for educational purposes and in development of seismic hazard maps for several regions of interest. It should be noted that this study calculates the hazard at the centers of the study regions and assumes that it is constant throughout the selected districts.

CHAPTER 3

FRAGILITY ASSESSMENT OF BUILDING STRUCTURES

3.1 General

Second major component of seismic loss estimation is the computation of the building response for a given ground motion demand. Seismic damage states of building structures can be obtained by fragility analysis. Fragility is defined as the degree of loss to a given element or sets of elements at risk resulting from a given level of hazard (Coburn and Spence, 2002). In other words, fragility of a building is the probability of that building being in each predefined damage state.

Fragility analysis can be performed based on observations, experiments, expert opinions and analytical computations. In general, observation based fragility analysis deals with the existing damage while the latter ones concentrate on estimated performances of structures. In order to estimate seismic loss, fragility functions are integrated with seismic hazard.

Fragility of structures can be defined by Damage Probability Matrices (DPM) or fragility functions. In this chapter, first the definition and derivation of DPMs are discussed along with the past studies on this subject. Then, definition and derivation of the fragility functions are presented. In this study, new fragility curves are not derived. Rather the existing ones are adopted for reinforced concrete (RC), unreinforced masonry (URM) and woodframe structures. In the last part of this chapter, the selected fragility curve sets, which are used in this study, are presented together with the reasons of this preference.

3.2 Damage Probability Matrices

3.2.1 Definition and Derivation of DPMs

A damage probability matrix (DPM) quantifies the level of damage for a particular type of structure at a given hazard level. In other words, damage probability matrices represent the probability of occurrence of a certain damage state for a given ground motion demand. In general, level of damage in DPMs is represented by Damage States (DS) and ground motion demand is represented by Modified Mercalli Intensity (MMI). The sum of probabilities of being in a specific damage state should add up to unity for a given MMI level.

DPMs can be derived using empirical, theoretical and subjective methods. Empirical methods use the past damage observations in order to estimate future damage state distributions. Empirical methods are reliable if the datasets avoid certain deficiencies such as limited amount of data; bias towards damaged, noteworthy or several selected buildings; data which are not collected in a proper manner (King et al., 2005). Theoretical methods are the analytical methods, in which the building damage is computed by dynamic analyses of the modeled structures. Finally, subjective methods are based on expert opinion on the damage distributions of structures under consideration.

3.2.2 Past Studies on DPMs

Damage probability matrices are initially derived by Whitman. In 1973, Whitman constructed DPMs for multistory buildings in Boston using empirical, theoretical and subjective methods. In ATC 13 (1985) DPMs based on empirical data were developed while in HAZUS (FEMA, 2003) empirical results were combined with analytical ones.

In Turkey, initial attempts to generate DPMs were made by Gürpınar et al. (1978) and Gürpınar and Yücemen (1980). In these studies, DPMs were developed for the structures designed and constructed both in accordance with the code and not in accordance with the code using subjective and empirical methods. Later, Gülkan et al. (1992) constructed subjective and empirical damage distributions for buildings in Turkey. Afterwards, Yücemen and Bulak (1997) and Bulak (1997) developed DPMs in order to estimate earthquake insurance premiums in Turkey for seismic zones I, II, III and IV.

Recently, Askan (2002) has generated DPMs considering three different approaches. The first one is the best estimate DPM weighted average of the expert opinion and observed data whose weights are 0.25 and 0.75, respectively. The latter approach is a reliability-based model where simple strength-related damage indices are defined without performing response analysis of the structures (Askan and Yücemen, 2010). The damage rates are computed by comparing the resistance and force indices, based on the classical first order reliability theory. The final approach is the estimation of the damage ratios by discriminant analysis. In that approach, building damage states are discriminated with respect to the damage indicating structural parameters. Finally, the DPMs from these alternative methods are compared with each other and against the observed data. A more concise and improved presentation of this study is given in Askan (2002) and Askan and Yücemen (2010).

In this study, fragility functions are used to define building damage distributions. However, DPMs can be used for the same purpose as well. These two terms can be converted to each other. In other words, DPMs can be derived from the fragility functions by discretizing the continuous damage distributions or vice versa (King et al., 2005). In Table 3.1, an example DPM is presented with the conditional probability of discrete damage states (None, Light, Moderate, Heavy and Collapse in this case) as a function of ground motion demand parameter (MMI in this case). For each damage state, a corresponding central damage ratio is defined. Central damage ratio is an average damage ratio for each damage state. In Table 3.1, P(DS,I) represents the probability of experiencing certain damage state, DS for a given ground motion intensity, I.

Table 3.1: An example form of a damage probability matrix (Askan and Yücemen, 2010)

Damage State (DS)	Damage Ratio (%)	Central Damage Ratio (%)	MMI=V	MMI=VI	MMI=VII	MMI=VIII	MMI=IX
None	0-1	0	Damage State Probabilities P(DS,I)				
Light	1-10	5					
Moderate	10-50	30					
Heavy	50-90	70					
Collapse	90-100	100					

3.3 Fragility Assessment of Building Structures

3.3.1 Definition and Derivation of Fragility Curves:

Fragility curves are functions which represent the probability that a given structure's response to various levels of seismic loading exceeds performance limit states (Shinozuka et al., 2000). These curves represent the probability of exceedance of a certain damage state for a given ground motion demand. Fragility curves can be generated for an individual building or a population of buildings in a region. The ones generated for an individual building require detailed structural analyses and considerable computational effort. Fragility curves generated for a group of buildings include sampling of the building stock, probabilistic description of response and focus on global response parameters rather than local ones. This is a trade-off between computational cost and accuracy of results.

Once the building inventory is defined, it is divided into smaller subclasses. In this study, the fragility curves represent the building populations of certain structural types, namely; RC frame buildings, URM buildings and woodframe buildings, which are located in regions of interest.

There exists no consensus on a standard procedure to generate fragility curves for building structures since different researchers have adopted different approaches in the literature. In the presence of adequate amount of field data, observation-based fragility curves can be generated. For example, Rosetto and Elnashai (2003) derived vulnerability functions using 99 seismic damage distributions as a result of 19 earthquakes concerning about 340,000 European-type RC structures. The fragility curves can also be generated from experimental data. Chong and Soong (2000) combined experimental and analytical methodologies in order to derive fragility functions of free standing rigid equipment. In that study, parameters of the fragility curves are obtained by applying a range of ground motion excitations to the experimental setup on the shake table.

The most common way of generating fragility curves is through analytical simulations. There are different analytical methods depending on the needs and facilities of the researcher. In most general sense, linear static, nonlinear static, linear dynamic and nonlinear dynamic approaches can be used in the generation of fragility curves for building structures. The buildings can be modeled as Single-Degree-of-Freedom (SDOF) or Multi-Degree-of-Freedom (MDOF) systems. In the absence of field, experimental and analytical data, fragility curves can be generated based on expert opinion. This technique has been widely used for earthquake damage and loss assessment in the context of well-known methodologies such as ATC-13 and HAZUS. Among the aforementioned techniques, analytical approach is used in this study for the generation of the fragility curves. Generic buildings are simulated analytically by employing simplified structural models and the seismic response parameters are monitored for different levels of seismic demand.

In order to derive the fragility curves, ground motion demand on the structures of interest should be determined. This demand can be defined using past (historical) event records or synthetically generated site specific ground motions. The number of the past events, number of the records and the locations of the records vary among different studies. On the other hand, in most of the studies, near source effects, extreme site amplifications and rupture directivity effects are neglected. Different ground motion parameters can be used in the generation of fragility curves for building structures. Among these, the most common ones are MMI, PGA, PGV, spectral acceleration (S_a) and spectral displacement (S_d). In this study, PGA is employed to define the seismic fragility of URM and woodframe building structures whereas PGV is used for RC frame building structures.

Different limit states can be specified either based on the literature, analytically or experimentally derived values. Limit state values specified based on the previous research consider the equivalent ductility capacities of the models. The ones determined considering analytically-derived values are generally a function of yielding of the elements. Limit state values defined using experimentally-derived values are based on the equivalent ductility capacities of the models, yielding of the elements and some predefined damage indices. Figure 3.1 summarizes the steps of fragility curve generation.

3.3.2 Past Studies on Fragility Curves

This study focuses on the seismic fragility of the aforementioned three major structural types that exist in the building stocks of the study regions 1 and 2. There are past studies to generate fragility curves for Turkish RC frame and URM buildings. However, there is no previous study on fragility functions related to woodframe structures in Turkey. Several studies on generation of the fragility functions are presented in the following sections.

3.3.2.1 Reinforced Concrete Buildings

Recently there have been several attempts to generate fragility curves for Turkish RC frame buildings. The most common ones are listed below:

- Erberik (2008a)
- Kırçıl and Polat (2006)
- Akkar et al. (2005)
- Ay and Erberik (2008)

The purpose of each study is to derive fragility functions for RC buildings in Turkey. However different approaches to the problem of interest resulted in different fragility curves. All of the aforementioned studies are briefly summarized in this section. Further details of this comparison can be found elsewhere.

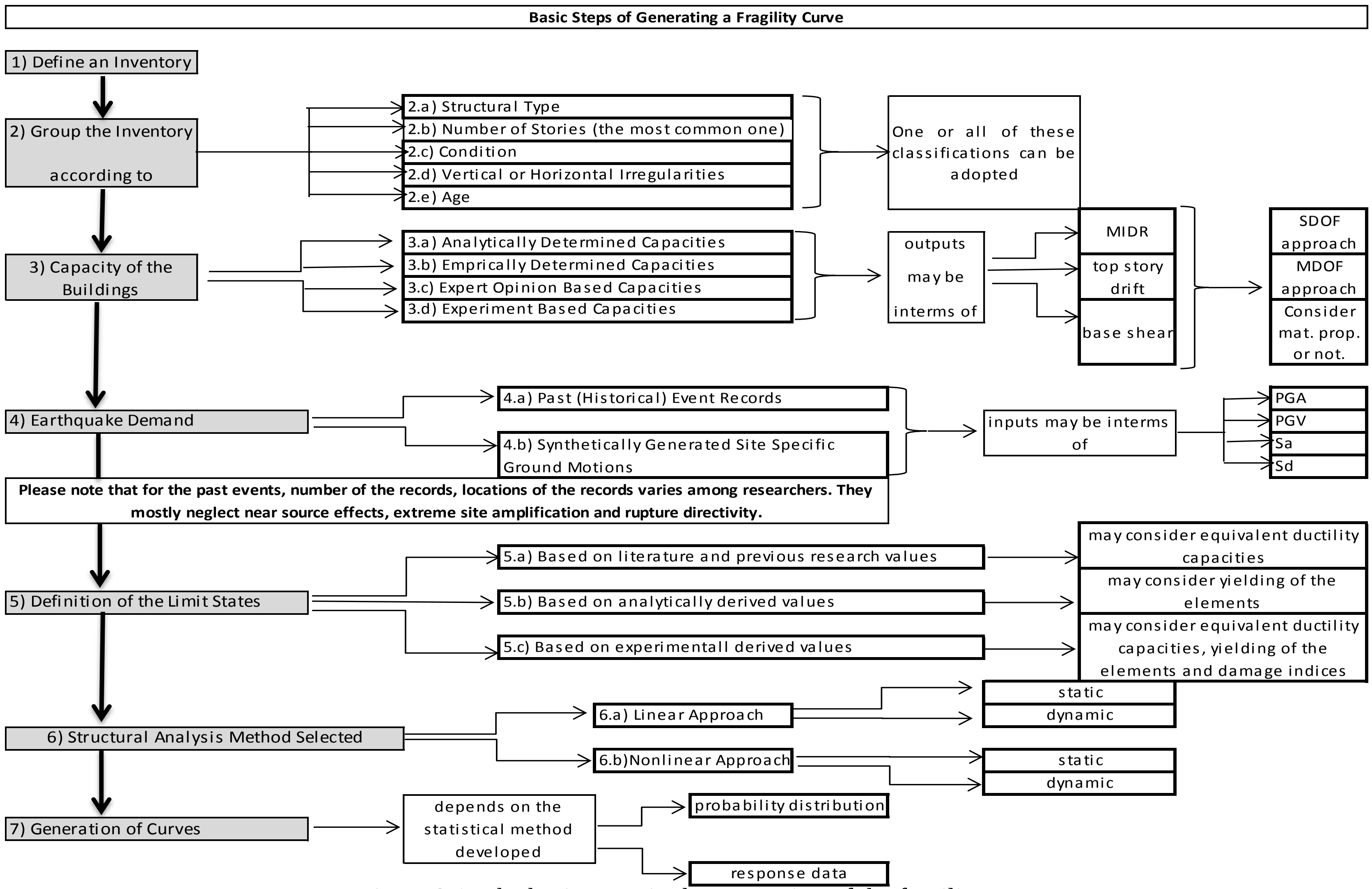

Figure 3.1: The basic steps in the generation of the fragility curves

- *Erberik (2008a):*

In this study, 28 buildings out of 500 buildings which experienced both the 1999 Kocaeli and 1999 Duzce earthquakes are selected as the building database. The buildings in the inventory were divided into 4 subgroups according to the number of stories and the existence of the infill walls, namely low-rise bare frame (LRBF), low-rise infill walls (LRINF), mid-rise bare frame (MRBF), mid-rise infill walls (LRINF). The RC frame structures with masonry infill walls are further classified as “high”, “moderate” and “low” according to their current status in terms of structural performance and the level that they conform to the basic principles of earthquake-resistant design. The sub-class named as “high” corresponds to new RC frame building structures that are expected to perform well during earthquakes as they have been designed and constructed according to the earthquake-resistant codes and regulations. The “moderate” sub-class represents an important percentage of the building stock concerning the RC residential buildings in Turkey. They are generally engineered structures but they may violate some fundamental requirements of earthquake resistant design which in turn means that they have several structural deficiencies. The last sub-class, “low”, stands for buildings, which have not been designed to resist earthquake loads and have major structural deficiencies that endanger their seismic safety. It has been observed that the buildings in this sub-class generally experienced heavy damage or collapsed during the recent major earthquakes in Turkey. The damage states are defined as: none, light, moderate and severe damage or collapse. Characterization of the ground motions is achieved by a selection of 100 ground motions from worldwide events. The ground motion parameter is taken to be PGV since this parameter is deemed to have a good correlation with inelastic response and damage. The ground motion set is divided into twenty groups with equal PGV intervals, where each one of the groups has five records. Three limit states are defined in the study, namely serviceability, damage control and collapse prevention. In Serviceability limit state (LS1), stiffness of the structure governs the behavior. Damage control limit state (LS2) is governed by strength whereas deformation and deformation governs collapse prevention limit state (LS3). Time history analyses are conducted on the equivalent SDOF models of the selected RC buildings and the analyses results are plotted as probability of exceeding each limit state versus PGV. Then a cumulative lognormal fit is performed using the method of least squares. Figure 3.2 presents the fragility curves derived by Erberik (2008a) for RC frame structures with infill walls in Turkey.

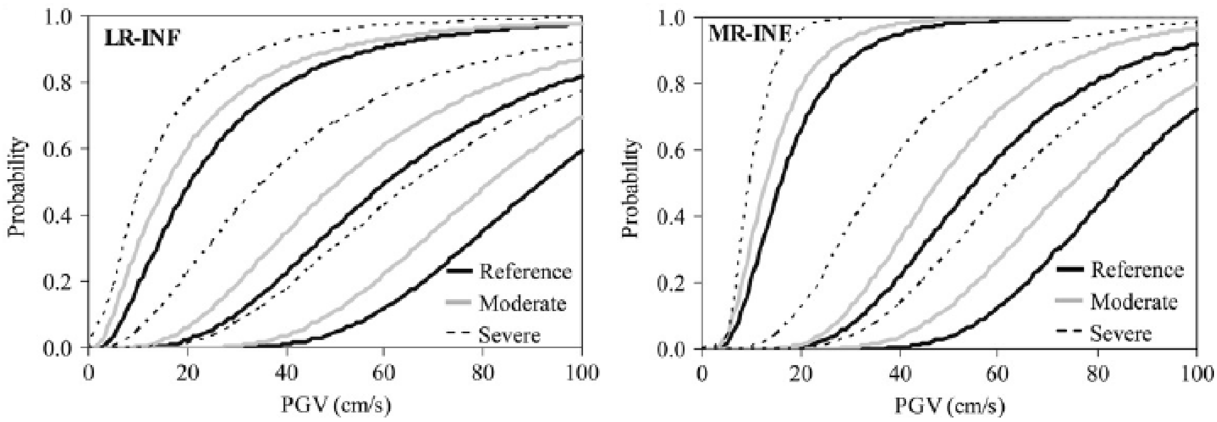

Figure 3.2: The Fragility curves developed by Erberik (2008a) for RC structures for reference, medium quality and severe quality structures.

- *Kircil and Polat (2006):*

Kircil and Polat (2006) developed fragility curves for midrise reinforced concrete frame buildings in Turkey. In order to form the inventory, 12 reinforced concrete buildings with three, five and seven stories (four structures for each group) which had been designed according to 1975 code, are selected. This study considers two main performance levels, namely; immediate occupancy (yielding) and collapse prevention (collapse), whose definitions are obtained from ATC 40 and FEMA 356. The damage measure parameter is the maximum interstory drift ratio. 12 artificial ground motions are considered to represent the seismic demand on this fragility curve generation methodology. Fragility curves are generated for spectral acceleration (in g), spectral displacement (in cm) and peak ground acceleration (in g) in this study. For the generation of the fragility curves for four and six story buildings, a linear regression analysis is conducted. The fragility curves developed by Kircil and Polat (2006) for midrise reinforced concrete buildings in Turkey as a function of PGA (g) are presented in Figure 3.3.

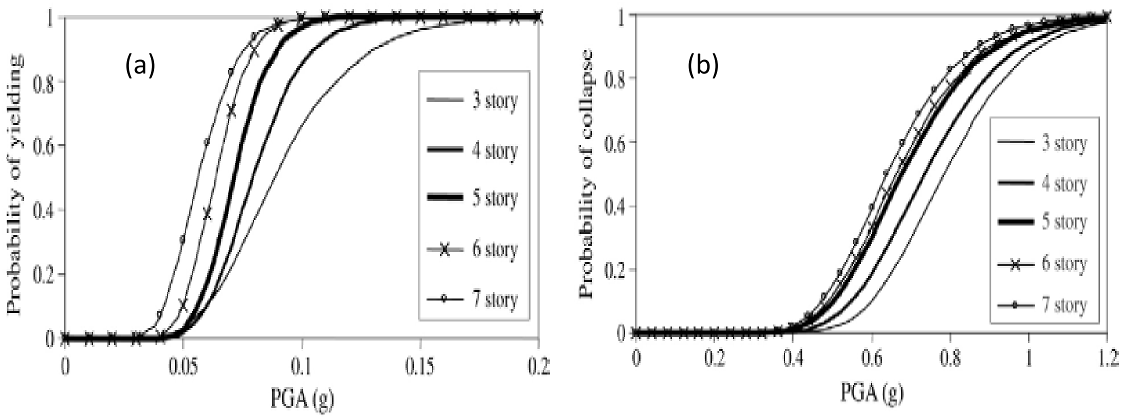

Figure 3.3 The fragility curves for (a) yielding and (b) collapse probabilities versus PGA (g).

- *Akkar et al. (2005):*

Akkar et al. (2005) developed a methodology to generate fragility curves for low and midrise ordinary reinforced concrete buildings in Turkey. The inventory in this study is formed by extracting 32 reinforced concrete sample buildings from a building database of approximately 500 buildings. The authors defined three limit states which are immediate occupancy (light damage), life safety (moderate damage) and collapse prevention (severe damage). The definitions of these performance limits were adopted from international guidelines. A set of 82 historical ground motion records were used to define the earthquake demand on the building inventory. The capacity curve, which is the base shear versus roof displacement curve, is determined using a nonlinear static analysis (displacement controlled nonlinear static procedure). Once the capacity curve is generated, it is idealized by a bilinear plot considering the procedures suggested in FEMA-356 (ASCE, 2000). The selected ground motion parameter in the study of Akkar et al. (2005) is PGV. The exceedance probabilities of the predefined limit states are computed from the scatter data of PGV versus maximum global drift for each building class. Figure 3.4 presents the fragility curves generated by Akkar et al. (2005) for 2, 3, 4 and 5 story RC buildings in Turkey.

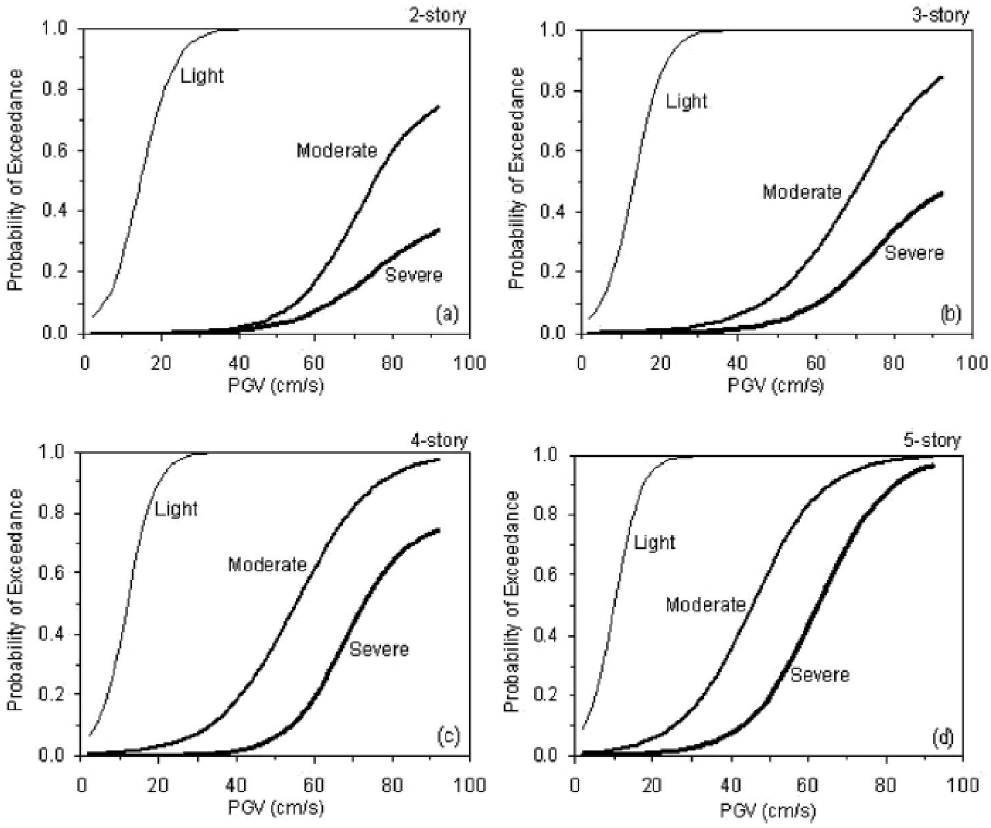

Figure 3.4: The fragility curves generated by Akkar et al (2005) for RC structures.

- *Ay and Erberik. (2008):*

In this study, the structural parameters of the analytical building inventory are simulated by Latin Hypercube Sampling (LHS) method. 20 planar frame models are generated with 3, 5, 7 and 9 number of stories. The buildings in the inventory are further classified according to their structural qualities and named as poor, typical and superior building classes. The authors defined four different damage states, namely; DS1 (no damage), DS2 (significant damage), DS3 (severe damage) and DS4 (collapse). In this study, the buildings are modeled with two dimensional multi degree of freedom systems. In order to obtain the ground motion demand parameters, nonlinear time history analyses are performed on the structural models and the results are presented in terms of maximum inter story drift ratios. This study considers three ground motion sets. The ground motion parameter is selected to be PGV. These three sets are in the PGV range of 0-20 cm/s 20-40cm/s and 40-60cm/s, with 20 ground motion record in each one. The results are obtained in terms of maximum interstory drift ratio (MIDR). PGV and MIDR values are assumed to have normal distribution. The fragility curves are generated for the aforementioned building classes by fitting a cumulative lognormal distribution function. The authors also performed an application of the methodology to Fatih, Istanbul and concluded that the generated fragility curves can be used in the loss estimation studies. Figure 3.5 shows example fragility curves derived by Ay and Erberik (2008) for typical reinforced concrete buildings.

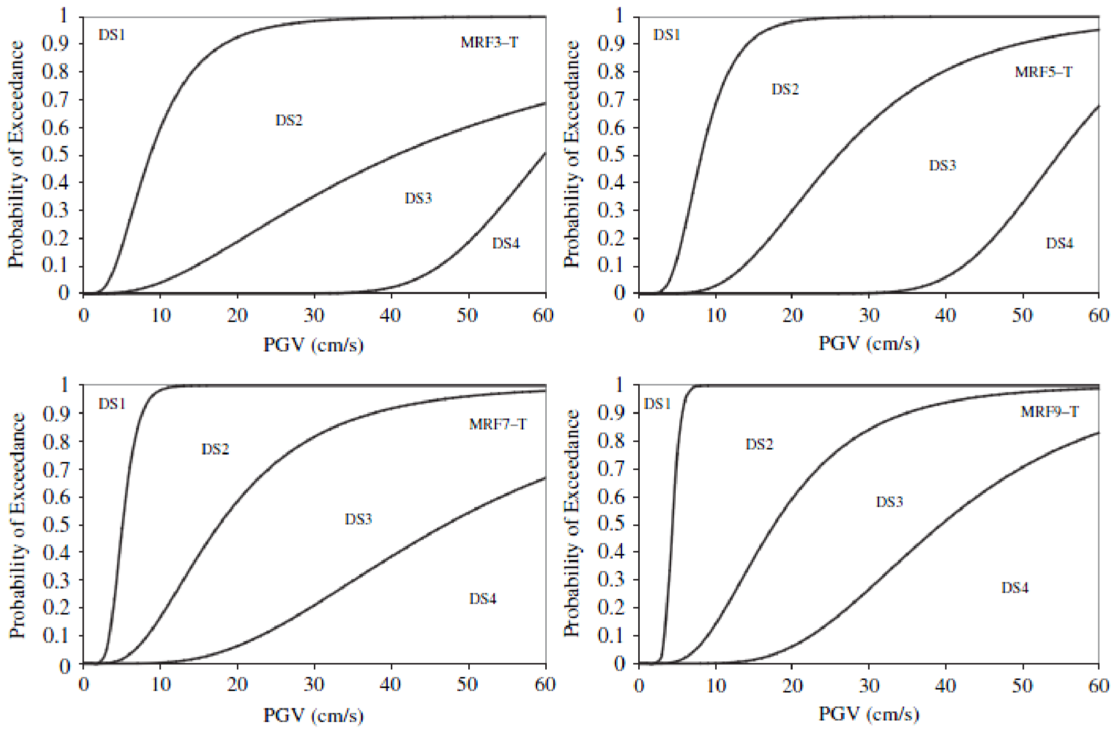

Figure 3.5: Example fragility curves for typical subclass generated by Ay and Erberik (2008)

3.3.2.2 Unreinforced Masonry Buildings

The only study for fragility curves for unreinforced masonry structures in Turkey is performed by Erberik (2008b), and the details of this study are summarized in this section.

- *Erberik (2008b)*

In the study, 120 sub-classes of masonry buildings were considered in terms of number of stories, material type and quality, plan geometry and the distribution of the load-bearing walls and openings in plan. In order to form the inventory, two different building datasets are used. The first one is obtained after the 1995 Dinar Earthquake for seismic damage assessment of 140 masonry buildings in the region, while the second one is obtained from the Zeytinburnu subprovince of Istanbul, as a part of Istanbul MasterPlan study and it consists of 69 buildings. In this study, two different limit states are defined as LS1 and LS2 noting that masonry structures have limited deformation capacities. LS1 corresponds to the threshold point of elastic behavior and LS2 corresponds to the ultimate capacity. The ground motion parameter in this study is selected to be PGA due to its good correlation with the seismic behavior of rigid masonry structures. Fifty ground motion records at stiff soil site are selected between 0.01g to 0.8 g. Time-history analyses are performed to quantify the seismic demand on the buildings and the variability in the base shear capacity is obtained by performing pushover analyses. In order to define the base shear demand as a function of the PGA values, a simple scatter is plotted and a linear fit is done. Finally, in order to investigate the validity of the methodology, the generated fragility curves are compared with the observed damage by a group of masonry buildings after the 1995 Dinar Earthquake. Figure 3.6 shows several fragility curves for masonry buildings developed by Erberik (2008b).

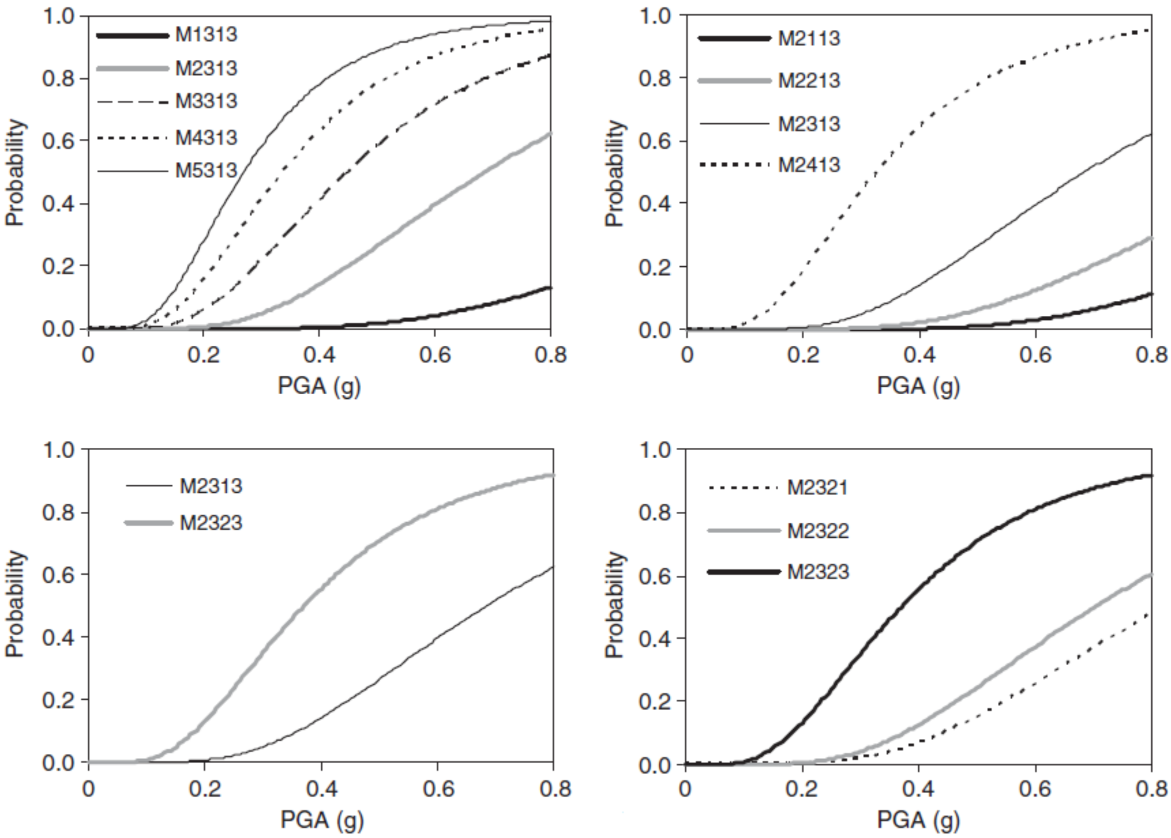

Figure 3.6: Example fragility curves for masonry buildings developed by Erberik (2008b) with respect to number of stories, material strength, regularity in plan and the criterion about wall length and the openings.

3.3.2.3 Woodframe Buildings

There is no analytically derived fragility information related to woodframe structures in Turkey although empirically determined curves have been derived (Gülkan et al., 1992). This is not surprising since this construction type is not very popular in most parts of Turkey. However, woodframe structures constitute a significant portion of the residential building stock in Northern and Northwestern Anatolia regions due to availability of material, especially in Düzce (study region 1). Hence it is appropriate to include woodframe structures for the estimation of seismic losses in study region 1. In this section, among several global fragility studies for woodframe structures, two of them are briefly discussed:

- Porter et al. (2002)
- Gencturk et al. (2008)

- *Porter et al. (2002)*

Porter et al. (2002) have developed fragility functions for woodframe structures in order to estimate seismic fragility of woodframe buildings under the CUREE-Caltech Woodframe Project. In their study, an assembly-based vulnerability methodology is developed. This methodology considers principles of structural modeling, non-linear time history analysis, laboratory tests and construction-cost estimation principles. The building inventory consists of 19 woodframe buildings with different ages, sizes, configuration, quality of construction, retrofit and redesign conditions. The buildings in the inventory are further classified as small house, large house, town house and apartment buildings. The buildings are uniquely modeled and the analyses are performed based on Monte Carlo simulations. Ground motion recordings are taken from a previous study of Somerville et al. (1997), which have been developed for the Los Angeles region. The fragility curves are developed based on peak interstory drift ratios as a function of spectral acceleration (S_a). Further information and details about this study is available on Porter et al. (2002).

- *Gencturk et al. (2008)*

Gencturk et al. (2008) developed fragility relationships for woodframe structures to be used in loss assessment studies. The building inventory of 16 woodframe structures with different seismic design levels were obtained from three different database, namely; CUREE – Caltech Woodframe Project (Fischer et al., 2001 and Isoda et al., 2002), ATC-63 Project and Texas A&M Woodframe Project (Rosowsky and WeiChiang, 2007). The building inventory is further classified as W1 (woodframe structures with floor areas smaller than 5000 feet square) and W2 (woodframe structures with floor areas greater than 5000 feet square). Four seismic design levels are defined namely; pre (P), low (L), moderate (M) and high (H) code.

Gencturk et al. (2008) assigned four damage states which are slight, moderate, extensive and complete. Ground motion demand is simulated using a set of synthetically generated acceleration time histories with 5% exceedance in 50 years considering New Madrid Seismic Zone (NMSZ). This set includes 10 accelerograms. In order to develop the fragility curves, structural assessment is performed using pushover analysis and results are converted into acceleration displacement response spectra (ADRS) to be used in Capacity Spectrum Method (CSM). Finally, fragility functions as a function of both peak ground acceleration (PGA) (conventional fragility relationships) and spectral displacement (S_d) (HAZUS compatible fragility relationships) are generated. Figure 3.7 shows example conventional fragility curves developed by Gencturk et al. (2008).

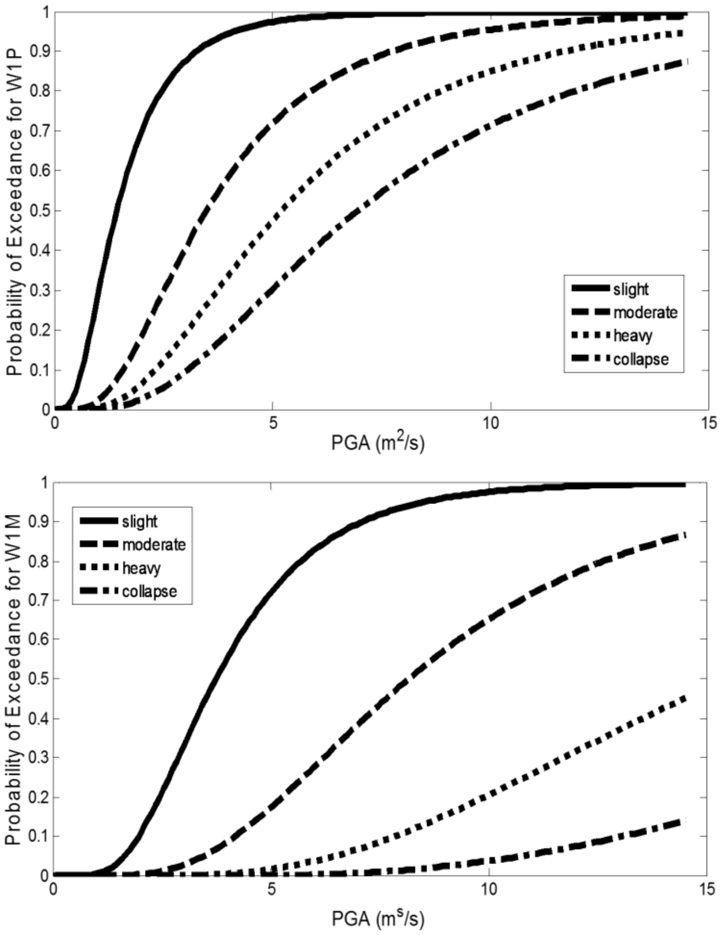

Figure 3.7: Example fragility curves for woodframe buildings developed by Gencturk et al (2008)

3.3.3 Selected Studies:

In this study, in order to estimate future casualties and economic losses, new fragility curves are not generated, but instead, appropriate past studies are adopted for reinforced concrete (RC), unreinforced masonry (URM) and woodframe structures. Among the fragility curve sets developed for reinforced concrete structures, the most appropriate ones for this study belong to Erberik (2008a). On the other hand, fragility curves for unreinforced masonry structures in Turkey are only generated by Erberik (2008b). Therefore, this study of Erberik is adopted in this study. There is no fragility information related to woodframe structures in Turkey. In this study, the fragility curve sets generated by Gencturk *et al*. (2008) are adopted which are originally derived for US buildings.

There are several reasons for the selection of the fragility curves for RC buildings generated by Erberik (2008a). First, the analytical models developed in this study are based on existing RC frame buildings in study region 1, for which detailed site investigations were carried out. In addition, since these buildings experienced the 1999 earthquakes, it was possible to compare the estimated damage obtained from the fragility information with the observed damage after the earthquakes. Since, the field observations are collected after 1999 Kocaeli and Düzce earthquakes, influence of these earthquakes on the building structures are required to be reflected. Therefore, in this validation, conditional probability of damage is considered and total probability theorem is adopted. The comparison results were satisfactory, hence it can be concluded that the set of fragility curves proposed by Erberik (2008) reflect the inherent characteristics of the RC frame buildings in Turkey, and can be used in the proposed seismic loss estimation methodology. A validation study for URM structures is also carried by Erberik (2008b). In this fashion, estimated damage is compared with the visually-inspected damage observed for 140 masonry buildings in Dinar after 1995 Dinar event. The fragility curves for woodframe structures developed by Gencturk *et al*. (2008) are adopted since the woodframe building sub-classes conducted in that study have similarities with the local woodframe residential buildings in Turkey.

CHAPTER 4

CASUALTY ESTIMATION

4.1 General

Casualty estimation in seismic loss studies is of extreme importance. One of the most important earthquake impacts, and the one which is most widely quoted as a measure of an earthquake's severity, is the number of people killed and injured. (Spence and So, 2011). Turkey has suffered from catastrophic earthquakes recently which had resulted in more than 15,000 fatalities. This fact brings the need for systematic seismic casualty estimation studies for Turkey.

In this chapter, first, several global seismic casualty estimation methodologies are presented. Then, the casualty model suggested by Coburn and Spence (2002) is discussed and adopted for Turkey.

4.2 Global Seismic Casualty Estimation Models

Seismic casualties can be estimated using two different models: empirical and analytical. These models are generally represented as a function of ground motion parameters (e.g. PGA, PGV). Distinction among different casualty models mostly arises at the input level. Empirical models consider fatality data of past events as an input to estimate casualty rates in an earthquake as a function of ground motion intensity. Analytical models calculate the building collapse rates analytically and estimate fatalities considering daily population dynamics at the region of interest. There are also semi-empirical models that compute building damage distributions from an empirical approach and estimate casualties. (Spence and So, 2011).

HAZUS (FEMA, 2003) adopts analytical models to estimate casualties and injuries caused only by building and bridge damage, in particular for developed countries where building inventory and population properties and distributions are available. HAZUS considers population distribution according to census tract, building stock inventory, damage state probabilities, time of day during the event (2 AM, 2 PM, 5 PM), casualty and collapse rates (FEMA, 2003). Casualties are given as a function of casualty rates and exposed population. Casualty rates are represented as a function of collapse rates. HAZUS (FEMA, 2003) methodology assumes a strong correlation between building damage (both structural and non-structural) and number of casualties. Output is obtained using a forward logic tree approach.

United States Geological Survey (USGS) developed a global model to estimate the impact of earthquakes on humans immediately after the earthquakes. The system developed by USGS called Prompt Assessment of Global Earthquakes for Response (PAGER) collects building information, building distribution and population data in order to estimate rapid earthquake casualties and injuries. Despite the scarcity of resources on hand and limited publicly available datasets, USGS attempted to develop the first open, peer-reviewed, publicly available global building inventory database (Jaiswal and Wald, 2010). The datasets are available online at USGS PAGER website (http://earthquake.usgs.gov/earthquakes/pager/). USGS PAGER system initially adopted an empirical methodology to estimate earthquake casualties. However, a semi-empirical methodology has also been developed where grid-base fatality functions considering building inventory and its distribution, vulnerability functions, fatality and injury rates are taken into account. Although USGS's primary efforts are on improving global building and population data, the final goal is to introduce a simple and consistent loss model as a function of dominating construction types.

Wyss et al. (2009) have developed a computer tool namely QLARM to estimate global seismic damage and casualties as a function of time of earthquake, coordinates of the epicenter, depth and magnitude of the event (http://www.wapmerr.org/qlarm.asp). Wyss et al. (2009) are also developing building and population data but contrary to USGS PAGER system, these data are not publically accessible. Similar to USGS PAGER approach, QLARM also adopts a semi-empirical model. Building vulnerability classes have been estimated based on World Housing Encyclopedia (WHE). For casualty and injury rates, HAZUS (FEMA, 2003) datasets have been referred (Spence and So, 2011). The input parameters are calibrated according to past event data, which consists of more than 1000 earthquakes. The purpose of scenario loss estimation studies is basically risk mitigation while the purpose of real-time loss estimates is to alert international rescue agencies.

Coburn and Spence (2002) proposed a global seismic casualty estimation model considering the building type, population of the building, occupancy at the time of earthquake occurrence, number of trapped occupants in the collapse, injury distribution at collapse and mortality post collapse. In this thesis, this model is adopted to Turkey with some modifications. Coburn and Spence (2002) presented an analytical relationship between the number of collapsed buildings and the number of people killed. The relationship between number of collapsed buildings to number of people killed in past events is presented in Figure 4.1. A “lethality ratio”, which is the ratio of fatalities to the number of occupants present in the collapsed buildings at the time of earthquake is defined to estimate number of casualties. In that study, casualties are assumed to be a function of number of collapsed buildings and the lethality ratio. Lethality ratio is expressed in terms of several predefined M parameters which are derived from or compared with the published casualty data.

Using these parameters, lethality ratio and the number of people killed in an earthquake can be defined by equations 4.1 and 4.2:

$$LR = M_1 \times M_2 \times M_3 \times (M_4 + (1 - M_4) \times M_5) \times M_6 \tag{4.1}$$

$$C = D \times LR \tag{4.2}$$

In Equations 4.1 and 4.2, LR is the lethality ratio, M_1 is the population per building, M_2 is the occupancy at the time of the earthquake, M_3 is the trapped occupants by collapse, M_4 is the injury distribution at collapse, M_5 is the mortality post collapse and M_6 represents the collapsed buildings in the most severe damage state (Heavy Damage/Collapse). C is the number of fatalities and D is the number of collapsed buildings.

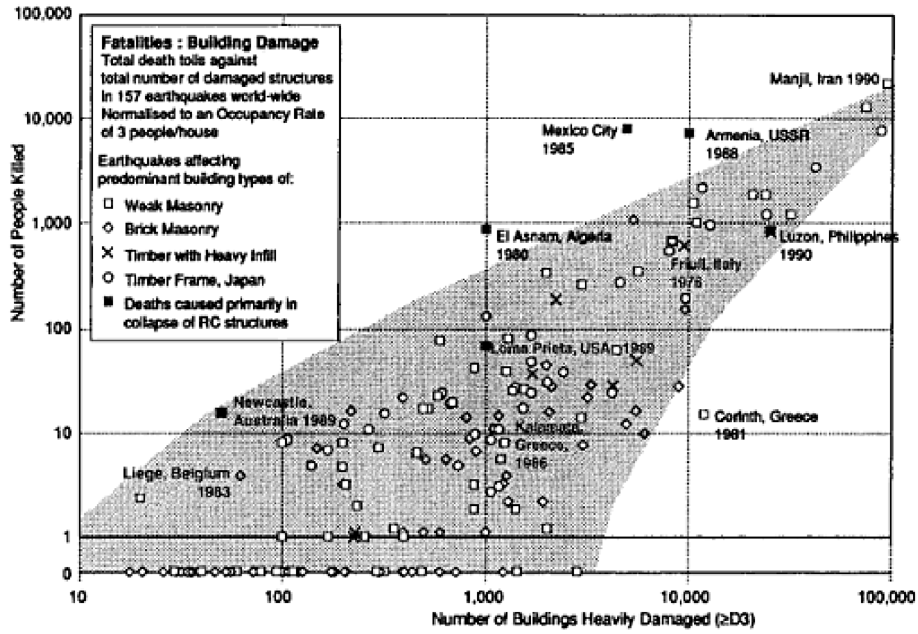

Figure 4.1: Relationship between number of collapsed buildings to number of people killed in earthquakes (Coburn and Spence, 2002)

In the following section, definition of M parameters is presented in detail and modifications of these parameters for Turkey are discussed.

4.3 Proposed Seismic Casualty Model

In this study, the casualty estimation model proposed by Coburn and Spence (2002) is adopted to Turkey with several modifications. Two basic assumptions are made. The first one is, number of fatalities is considered only if the building collapses. In other words, fatalities at none, slight and moderate damage states are ignored. The second assumption is; although Furukawa et al. (2010) mentioned that there is a strong correlation between casualties and interior space damage, casualties only due to structural damage is taken into account. In other words, casualties caused by secondary disasters such as fires, landslides or tsunamis, overturning objects, accidents, heart attacks are neglected. According to Coburn and Spence (2002), 75% of the casualties are caused by building damage. If fatalities in secondary disasters are ignored, this ratio increases to 90%.

In the proposed model, casualties are estimated according to Equation 4.2. The building damage states are analytically computed from appropriate fragility functions described in the previous chapter. Number of collapsed buildings is calculated by multiplying the risk of collapse of buildings, with the number of the buildings in the inventory.

There is a complex relationship between the number of collapsed buildings and number of casualties according to building characteristics, occupant behavior and search and rescue (SAR) capability at the location of the event. This complexity is simplified and represented with several M parameters. Definition and modification of these M parameters is defined in detail in the following paragraphs.

4.3.1 Parameter M_1:

Parameter M_1 in Equation 4.1 represents the original population per building. In order to estimate casualties, the population in the area at the time of the earthquake and the distribution of this population into buildings of different types must be estimated. (Spence and So, 2011).

The population in the area at the time of earthquake is a function of population per building and daily population dynamics. Daily population dynamics is represented by parameter M_2 which is presented in the next section. Exact value of population per building can be obtained from local authorities. But in general, this information is estimated approximately by the use of national or global census data.

In order to estimate the approximate population per building, both number of housing units in that building and average number of households (population per housing unit) must be determined. Population per housing unit in Turkey has been previously estimated by both WHE-PAGER and Census of Population (2000) data. Figure 4.2 shows distribution of this data for entire Turkey according to Census of population (2000). Table 4.1 presents the population per housing unit values obtained from both WHE-PAGER (1994) for Turkey and Census of Population (2000) for Düzce (study region 1) and Bursa (study region 2) district centers.

Table 4.1: The average size of households for urban areas according to several sources

Location	Source	Date	Average size of housholds for urban areas
Turkey	WHE-PAGER	1994	4.2
Turkey	Census of Population	2000	4.18
Duzce	Census of Population	2000	4.32
Bursa	Census of Population	2000	3.82

Census of population data is more up to date and is prepared in a smaller scale than WHE-PAGER population data. Thus, in this study, average size of households is assumed to be 4.32 for study region 1 and 3.82 for study region 2.

Figure 4.2 The size of household population distribution for Turkey. (Census of Population (2000))

Next, population per building (M_1) is defined as a function of number of stories of each building. Number of stories of each building in both study regions has been gathered from Turkish Statistics Authority (Census of buildings, 2000). Japan International Cooperation Agency (JICA) (2002) suggests a relationship between number of stories and the number of housing units in that building (Figure 4.3). Equation 4.3 is a polynomial fit to the plot suggested by JICA (2002) relating number of stories (a) to the number of housing units in that building (N).

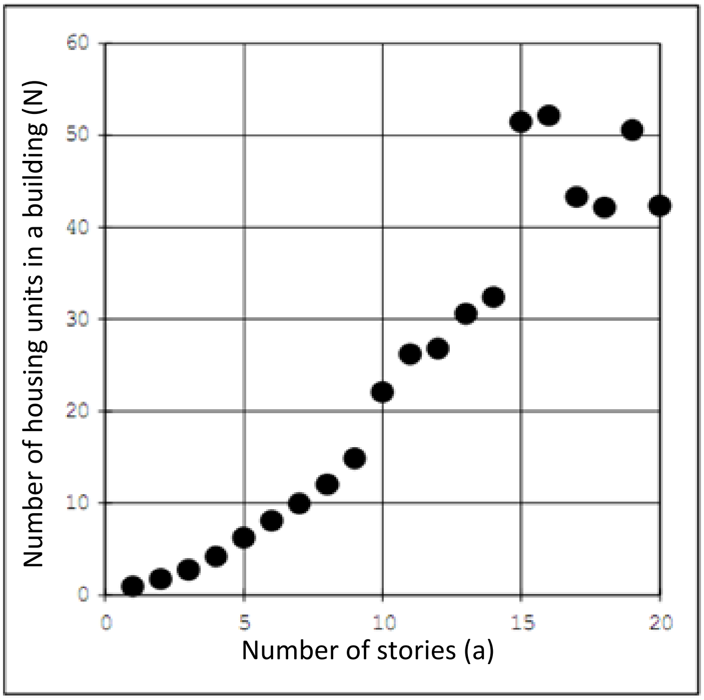

Figure 4.3: The number of the houses in a building versus number of the stories.

$$N(a) = 0.1301 \times a^2 + 0.6701 \times a - 0.27 \tag{4.3}$$

In this study, population per building (parameter M_1) is defined by Equations 4.4 and 4.5 for study regions 1 and 2 respectively.

$$M_{1SR1} = N(a) \times 4.32 \tag{4.4}$$

$$M_{1SR2} = N(a) \times 3.82 \tag{4.5}$$

4.3.2 Parameter M_2:

Parameter M_2 in Equation 4.1 represents the occupancy at the time of earthquake, which is computed from daily population dynamics. M_2 is a percentage of M_1 to estimate the population in the area at the moment of earthquake. The time of earthquake is strongly correlated to the amount of population exposed to the earthquake (Jaiswal and Wald, 2010). For example, during daytime, some of the population is assumed to be at school, at work or travelling, whereas during early daytime and night hours, most of the population is expected to be at home. (Spence and So, 2011). Thus, larger number of fatalities is expected in residential buildings at night than during the daytime. Coburn and Spence (2002) proposed an occupancy model at the time of earthquake as a function of time for urban and rural residential buildings and non-residential buildings (Figure 4.4).

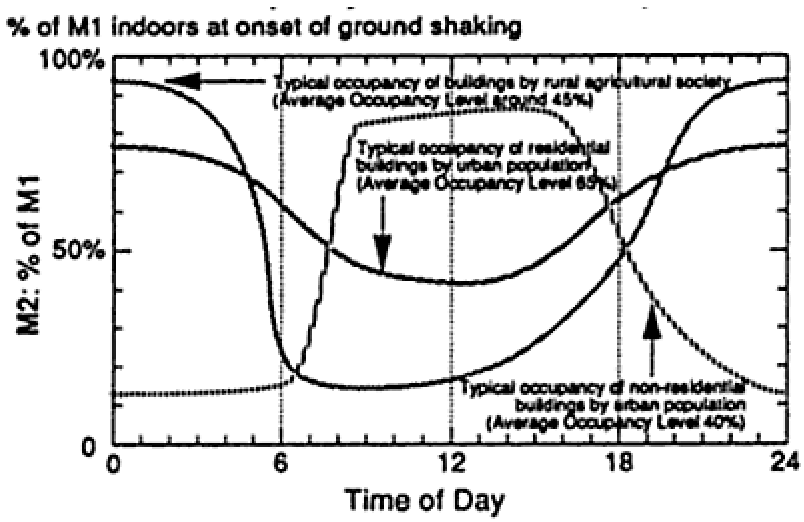

Figure 4.4: Parameter M_2: Occupancy at the time of earthquake (Coburn and Spence, 1992).

In this study, a similar model is derived for urban residential buildings in Turkey, considering the demographic characteristics, population profile and employment status based on Census of Population (2000) data. This model is computed referring to the equations suggested by Jaiswal and Wald (2010). Table 4.2 illustrates the employment status and distribution of the population in the urban regions (at the province centers). In this table, non-working population includes the age group 0-6, unemployed population, homemakers, retired people and welfare recipients. For the student population, this study assumes all of the children between the ages 6-12 attend to school. Above the age 12, number of students who attend to school is explicitly represented in the census of population (2000) data.

Table 4.2: Employment status distribution of the population at the province centers in Turkey (based on Census of Population 2000)

Type of the employment	Population belonging to that group at the province centers
Non-working*	13,771,212
Students	6,225,696
Scientific, technical, professional and related workers	1,208,769
Administration and managerial workers	245,012
Clerical and related workers	1,063,872
Commercial and sales workers	1,078,889
Agriculture, hunting, forestry and fishing	112,639
Mining and quarrying	21,052
Manufactring Industry	2,140,998
Electricy, gas and water	55,556
Service workers	1,086,961
Agricultral, animal, husbandry, forestry workers, fishermen and hunters	123,618
Nonagricultral production and related workers, transport equipment operators and laborers	3,465,505
Unknown	8,596
Total	**30,608,375**

* See definition in text.

In this study, three occupancy categories as a function of time of a day are defined: night, day and transit times. 22:00 to 05:00 is assumed to be the night time where indoor occupancy of the residential buildings is relatively high. 10:00 to 17:00 is assumed to be the day time during which people are mostly at school, at work or outside. Rest of the day people are assumed to be travelling. Thus, the occupancy category at which most of the population is assumed to be travelling is named as the transit time of the day.

Occupancy at the time of earthquake is computed from employment status and distribution data. Hourly probable location of the population at each employment group is estimated according to Jaiswal and Wald (2010). Equations 4.6, 4.7 and 4.8 represent the distribution of the urban indoor residential population for day, night and transit times, respectively as a function of the employment classes.

$$M_{2\,Night} = 0.999 \times F_{nwf} + 0.84 \times F_{ind} + 0.89 \times F_{ser} + 0.998 \times F_{agr} \qquad (4.6)$$

$$M_{2\,Day} = 0.4 \times F_{nwf} + 0.01 \times F_{ind} + 0.01 \times F_{ser} + 0.01 \times F_{agr} \qquad (4.7)$$

$$M_{2\,Transit} = 0.75 \times F_{nwf} + 0.20 \times F_{ind} + 0.25 \times F_{ser} + 0.45 \times F_{agr} \qquad (4.8)$$

In Equations 4.6, 4.7 and 4.8, F_{nwf} is the fraction of the non-working population to the total population which includes the unemployed population and population with unknown employment status in Table 4.2. F_{ind} is the fraction of the population employed in the industrial sector to the total population. Administrative, and managerial workers, clerical and related workers, commercial and sales workers, manufacturing industry and people who work at the electricity, gas and water sector in Table 4.2 are merged under industrial sector. F_{ser} is the fraction of the population employed in the service sector to the total population. In this study, students; scientific, technical, professional and related workers as well as the service workers in Table 4.2 are considered to be included in the service sector. F_{agr} is the fraction of the population employed in the agricultural sector to the total population which includes the agriculture, hunting, forestry, fishing, mining, quarrying population as well as the related workers in Table 4.2. In this manner, M_2 parameter is defined with a piecewise function (Equation 4.9).

$$M_2(t) = \begin{cases} 94\ \% & for\ 22{:}00 < t \leq 05{:}00 \\ 49\% & for\ 06{:}00 < t \leq 10{:}00 \\ 19\% & for\ 10{:}00 < t \leq 17{:}00 \\ 49\% & for\ 17{:}00 < t \leq 22{:}00 \end{cases} \quad (4.9)$$

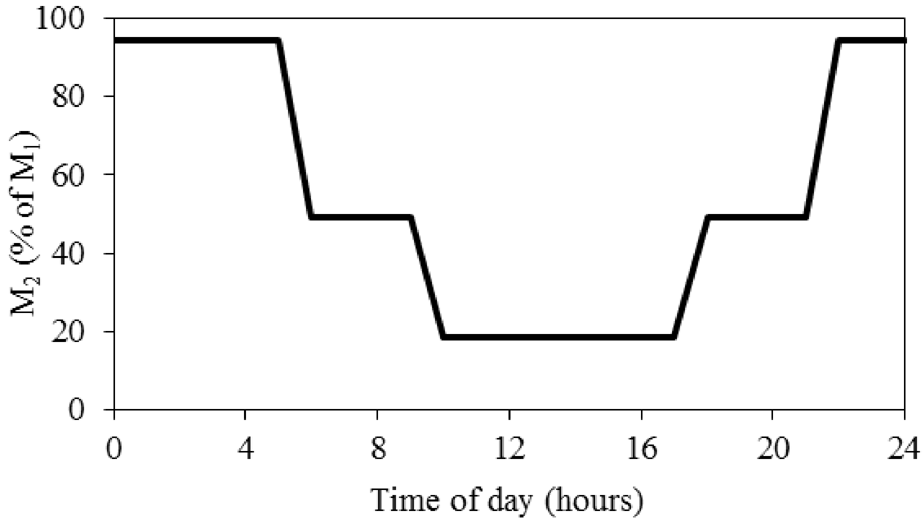

Figure 4.5: The occupancy at the time of earthquake as a percentage of the urban building population suggested by Equation 4.9.

For future seismic loss estimation studies, time of the earthquake is not predictable, so an average M_2 parameter is required for probabilistic seismic loss estimation purposes. In this study, the weighted average of the M_2 parameter is calculated as 54%. Coburn and Spence (2002) estimates this value around 65%.

4.3.3 Parameter M_3:

Parameter $\boldsymbol{M_3}$ in Equation 4.1 represents the percentage of occupants trapped by the earthquake. Number of fatalities in an earthquake depends on the type of the structural system, number of stories, time of the event, occupancy at the time of event as well as the occupant behavior and response (Jaiswal and Wald, 2010). However, it is difficult to predict human response and reflex at the time of earthquake. Moreover, there is a lack of statistical data on the number of occupants who are able to evacuate the buildings before or immediately after the collapse (FEMA, 2003). Thus, prediction of the percentage of the trapped occupants is a challenging effort and contains the highest uncertainty among the other M parameters.

Recent survivor questionnaire studies (e.g. So, 2011) have aimed to improve the perception of human response at the time of earthquake and collapse. Coburn and Spence (1992) have computed parameter M_3 as a function of ground motion intensity for masonry buildings and frequency content of ground motion for reinforced concrete buildings. In that study, both a building collapse range (from one wall collapse to entire building collapse) and occupant's self-evacuation efforts are considered. In this manner, occupants trapped by collapse as a percentage of M_2 (i.e. percentage of occupants who are unable to escape) are computed (Figure 4.6).

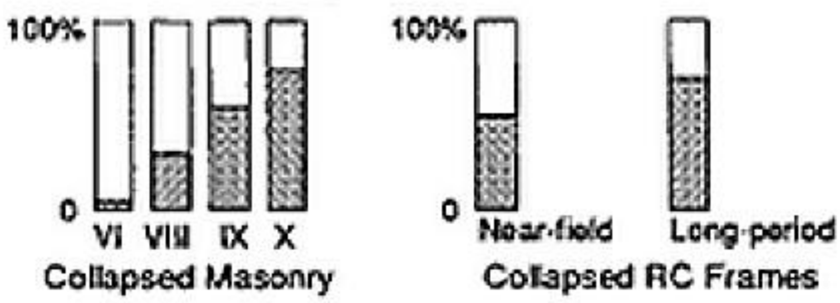

Figure 4.6: The estimation of the M_3 parameter based on ground motion effects and building type. (Coburn and Spence, 2002)

In this study, building damage is computed from appropriate fragility functions. Fragility curves do not separate total collapse from partial collapse and does not give any information about the level of the collapse. Determination of an exact M_3 parameter on the other hand requires a detailed structural analysis which is out of the scope of this study. In this study, all of the collapsed buildings are assumed to be totally damaged. Since destructive earthquakes in general last between 30 to 60 seconds, it is common practice to assume that 50% of the occupants at the first story can escape until the building collapses and rest of the occupants remains inside. (e.g.: FEMA, 2003, Coburn et al., 1992). Briefly, in order to compute parameter M_3, half of the first story population ratio is subtracted from unity:

$$M_3 = (1 - \frac{1}{num.of\ stories} \times 0.5) \tag{4.10}$$

In reality, parameter M_3 could be smaller than the recommended value due to presence of partial collapse of the structures. However, improvement of this parameter is not possible in the absence of a detailed structural analysis, more data and survivor questionnaires.

4.3.4 Parameter M_4:

Parameter $\boldsymbol{M_4}$ in Equation 4.1 represents the injury distribution of the trapped occupants at the time of collapse. Coburn and Spenc (1992) states that injuries and fatalities are in general caused from getting trapped under heavy weight or suffocation from dust of collapsed walls or other structural elements. In their study, a four stage injury distribution (ranging from light injuries to fatalities) chart is proposed for reinforced and masonry buildings (Table 4.3). This distribution was gathered from injury and mortality statistics of past events.

Table 4.3: The injury distribution at collapse of the occupants trapped (% of M_3) suggested by Coburn and Spence (2002)

Triage Injury Category	**Masonry**	**RC**
1) Dead or unsaveable	20	40
2) Life threatening cases needing immediate medical attention	30	10
3) Injury requiring hospital treatment	30	40
4) Light Injury not necessitating hospitalization	20	10

In this study, injury distribution at collapse is assumed to show none or slight differences among different countries worldwide. Thus, Table 4.3 suggested by Coburn and Spence (2002) is directly adopted. Equations 4.11, 4.12 and 4.13 show the ratio of dead or unsaveable occupants who are trapped under reinforced concrete or masonry building debris at the instant of collapse, respectively. Although woodframe structures are not mentioned in that study, here parameter M_4 of woodframe structures is assumed to be equal to the that of the URM structures.

$$M_{4RC} = 0.40 \tag{4.11}$$

$$M_{4URM} = 0.20 \tag{4.12}$$

$$M_{4Woodframe} = 0.20 \tag{4.13}$$

4.3.5 Parameter M_5:

Parameter $\boldsymbol{M_5}$ in Equation 4.1 represents mortality post collapse, which is very difficult to obtain due to lack of data. Trapped occupants will eventually lose lives if they are not evacuated from the collapsed buildings. Mortality post collapse is a function of time, injury level of trapped occupants as well as search and rescue effectiveness of the region of interest. Coburn and Spence (2002) proposed a global fade-away function considering Turkey in their statistical calculations. Assuming that the mortality post collapse function does not change considerably from country to country, or region to region, global distributions suggested by Coburn and Spence (2002) is adopted in this study. Figure 4.7 illustrates the fade-away function of trapped survivors with respect to time and Table 4.4 shows percentage of these people in collapsed buildings that eventually lose lives.

Table 4.4: Percentage of trapped survivors in collapsed buildings that subsequently die (Coburn and Spence, 2002)

Situation	**Masonry**	**RC**
Community incapacitated by high casualty rate	95	-
Community capable of organising rescue activities	60	90
Community + emergnecy squads after 12 hours	50	80
Community + emergency squads + SAR experts after 36 hours	45	70

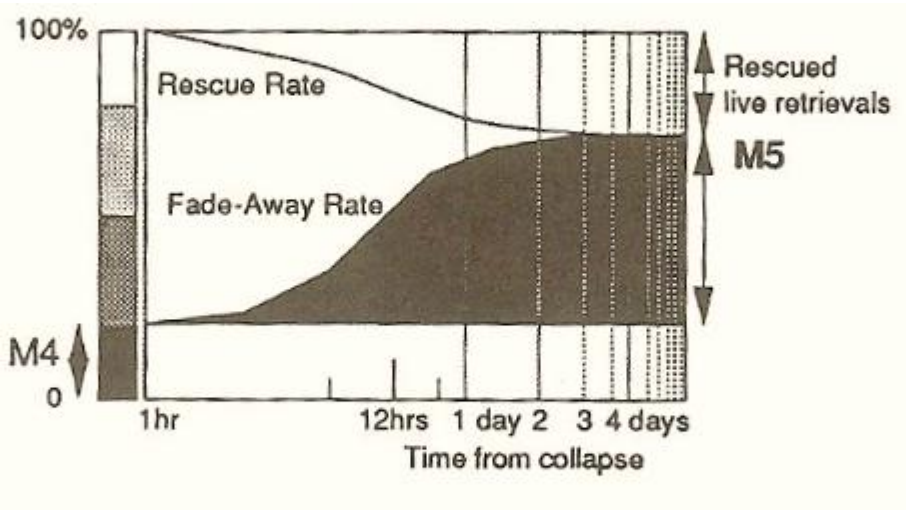

Figure 4.7: Percentage of trapped survivors before they are rescued (Coburn and Spence 2002)

Equations 4.14, 4.15 and 4.16 show the ratio of mortalities post collapse who eventually lose their lives under reinforced concrete or masonry buildings debris as a function of time. Again, parameter M_5 of woodframe structures is assumed to be equal to that of URM structures.

$$M_{5RC} = 0.70 \tag{4.14}$$

$$M_{5URM} = 0.45 \tag{4.15}$$

$$M_{5Woodframe} = 0.45 \tag{4.16}$$

4.3.6 Parameter M_6:

Parameter $\boldsymbol{M_6}$ in Equation 4.1 represents the ratio of collapsed buildings in the most severe damage state in this study, which includes heavy damage and collapse cases. However, in this thesis number of fatalities is considered if and only if the building collapses. Therefore, these two cases should be separated and the rate of collapsed buildings should be identified. Askan and Yücemen (2010) presented the damage distributions of the buildings after recent earthquakes in Turkey stating that the number of heavily damaged buildings is almost equal to the number of collapsed buildings (Table 4.5). Accordingly, parameter M_6 is assumed to be 0.5.

Table 4.5: Empirical DPM constructed by Askan and Yücemen (2010)

	1995 Dinar (MMI=VIII)		1999 Adapazarı (MMI=IX)	1999 Düzce (MMI=IX)
Damage State (DS)	AC	NAC		
None	0.23	0.24	0.04	0.17
Light	0.31	0.24	0.34	0.16
Moderate	0.38	0.41	0.27	0.28
Heavy	0.04	0.05	0.175	0.19
Collapse	0.04	0.06	0.175	0.20

4.3.7 Combination of Casualty Parameters:

After combining all M parameters the lethality ratio for this study as a function of only the number of stories are given as:

$$LR_{SR1RC} = ((N(a) \times 4.32) \times (0.54) \times (1 - \frac{1}{a} \times 0.5) \times (0.40 + (1 - 0.40) \times (0.7))) \times 0.50 \quad (4.17)$$

$$LR_{SR1URM} = ((N(a) \times 4.32) \times (0.54) \times (1 - \frac{1}{a} \times 0.5) \times (0.20 + (1 - 0.40) \times (0.45))) \times 0.50 \quad (4.18)$$

$$LR_{SR1WF} = ((N(a) \times 4.32) \times (0.54) \times (1 - \frac{1}{a} \times 0.5) \times (0.20 + (1 - 0.40) \times (0.45))) \times 0.50 \quad (4.19)$$

$$LR_{SR2RC} = ((N(a) \times 3.82) \times (0.54) \times (1 - \frac{1}{a} \times 0.5) \times (0.40 + (1 - 0.40) \times (0.7))) \times 0.50 \quad (4.20)$$

$$LR_{SR2URM} = ((N(a) \times 3.82) \times (0.54) \times (1 - \frac{1}{a} \times 0.5) \times (0.20 + (1 - 0.40) \times (0.45))) \times 0.5 \quad (4.21)$$

$$LR_{SR2WF} = ((N(a) \times 3.82) \times (0.54) \times (1 - \frac{1}{a} \times 0.5) \times (0.20 + (1 - 0.40) \times (0.45))) \times 0.5 \quad (4.22)$$

In Equations 4.17 to 4.23, N is the number of the housing units in the building (equation 4.3) and a is the number of the stories in the building. The number of collapsed buildings obtained previously and M parameters are substituted in Equation 4.2 to yield the number of casualties. The expected numbers of casualties for study regions 1 and 2 are presented in Chapter 6.

CHAPTER 5

ECONOMIC LOSS ASSESSMENT

5.1 General

Once a destructive earthquake occurs, the surrounding area suffers from serious financial loss not only due to the repair and replacement costs of the damaged structures, but also due to the reduction in production and manufacturing opportunities. Thus, economic loss is one of the major impacts of an earthquake. Formerly, funding the costs of repair and reconstruction of the damaged and collapsed buildings was legal liability of the Turkish Government. Hence, the Turkish Government had faced up with an enormous economic crisis after the 1999 Kocaeli and Düzce earthquakes. (Bommer et al., 2002). Today, although all the citizens must insure their houses by private insurance companies, economic loss assessment is still significant in seismic loss estimation studies.

In this chapter, first, the components of seismically induced economic loss are discussed. Next, several previous economic loss estimation studies and effects of past events on Turkish economy are presented. In this study, economic losses only due to structural damage is considered by referring to

methodology. Definition of economic losses due to non-structural damage and operation costs are presented as well but their computation is out of the scope of this study.

5.2 Components of Economic Loss Estimation

Seismic economic losses can be classified as direct and indirect losses following the HAZUS methodology (FEMA, 2003) as well as the losses caused by secondary events. Components of total seismic economic losses are presented in Figure 5.1.

Direct economic losses are further classified as losses due to structural and non-structural damage. Economic losses resulting from structural damage is a function of building vulnerability. In Chapter 3, three damage states were defined for building structures namely, “none-light”, “moderate-extensive” and “heavy-collapse”. Repair costs of the buildings at the first and second damage states and replacement costs of the buildings at the third damage state are considered as direct economic losses caused by structural damage. For a given occupancy and damage state, building repair and replacement costs are estimated as the product of the floor area of each building type within the given occupancy, the probability of the building type being in the given damage state, and repair costs of the building type per square meter for the given damage state, summed over all building types within the occupancy (FEMA, 2003). This study considers only the urban residential buildings in study regions 1 and 2.

Repair and replacement costs of damaged and demolished non-structural members, respectively as well as the building contents losses can be considered as economic losses resulting from non-structural damage. HAZUS further classifies the non-structural damage as “acceleration-sensitive damage” and “drift-sensitive damage” but it detaches the building contents losses from this category. In HAZUS methodology, repair and replacement costs of non-structural members (pipes, windows, exterior and interior walls, ceilings, elevators, electrical and mechanical equipment, lightings, etc.) and costs of building contents (furniture, computers and other supplies) are computed separately. These losses are assumed to be certain percentages of building replacement costs and are considered to be a function of occupancy and damage states of the buildings. Computation of economic losses due to non-structural damage requires structural and architectural plans of the buildings as well as detailed structural analyses which is out of the scope of this study.

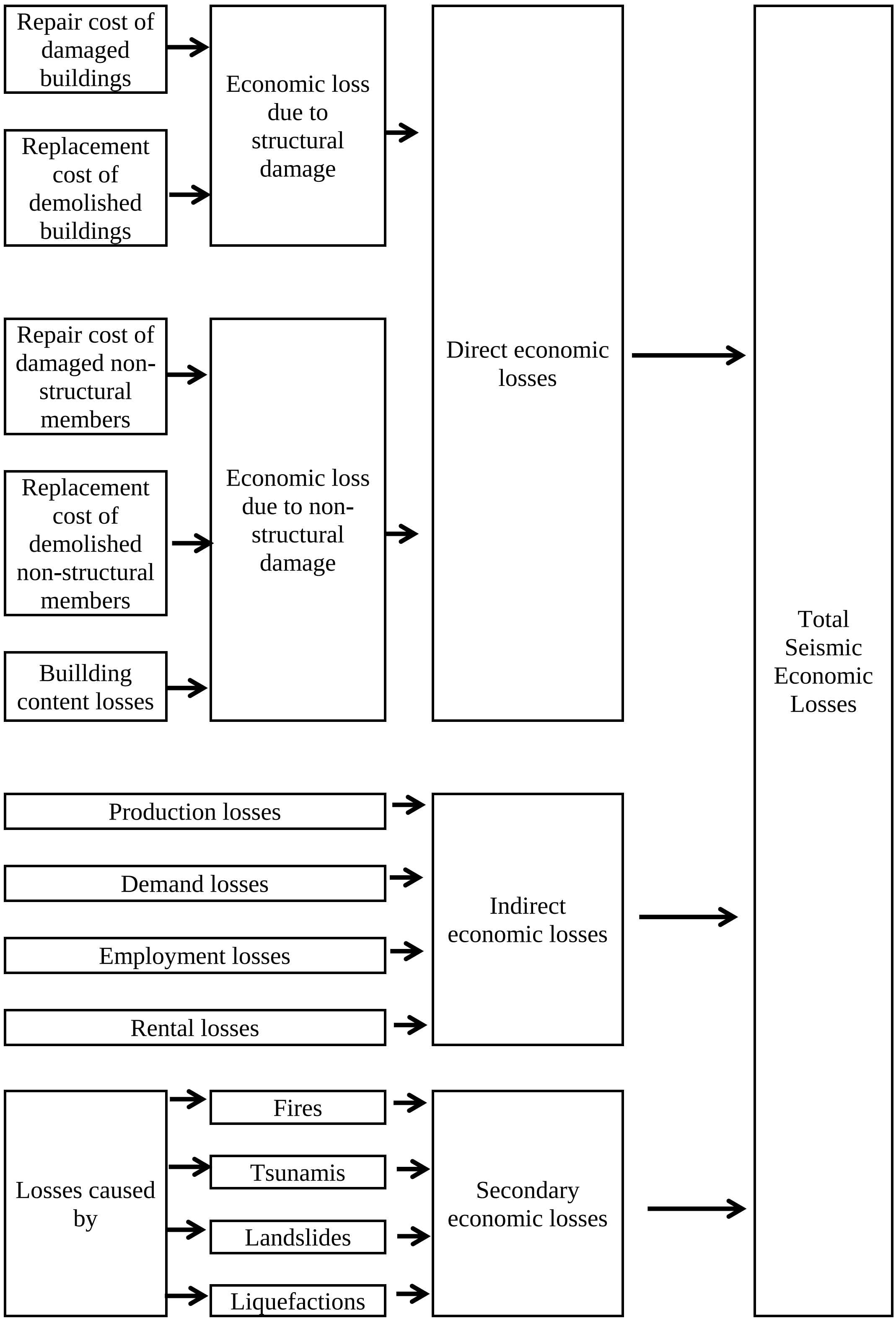

Figure 5.1 :Components of total seismic economic losses (HAZUS)

Earthquakes cause not only economic losses due to direct damage but they also cause interruptions on production, demand and employments. HAZUS classifies these interruptions as indirect losses. In some cases, indirect losses can be more critical than direct economic losses, especially if the earthquake occurs in a highly industrialized region. Earthquakes reduce the production and manufacturing power of the region. At the same time, earthquakes change the demand rates on the productions from other regions as well. In such a case, national economy is seriously affected. When the industrial sector suffers from an earthquake, the commercial sector is also influenced.

Earthquakes can also have negative impacts on the agricultural sector hence the irrigation systems, pipelines, dams, water supplies are damaged (Coburn and Spence 2002). Tourism, treatment and relocation of the earthquake victims, emergency shelters and temporary housings can be considered as the other sources of indirect economic losses. In HAZUS methodology, there exist forward-linked (considers the region as a customer to sell the outputs), backward-linked (considers the region as supplier to provide inputs) and inter-industry models to simulate regional and national economy in order to compute indirect economic losses. In this study, only the urban residential buildings are taken into account, therefore the industrial, commercial and governmental losses are neglected. Rental losses can be considered as residential indirect economic losses, but their contribution to the gross economic loss is neglected in this study.

Secondary hazards such as fires, tsunamis, liquefactions, landslides and floods are generally experienced after the earthquakes. These collateral hazards also lead to economic losses. Computation of these losses require building inventories and details of the secondary hazard. Thus they are difficult to estimate since there is a scarcity of available data. In HAZUS, economic losses caused by secondary hazards are not explicitly calculated because these losses are regarded as very broad estimates and double counting of damage is also possible (FEMA, 2003). Although damage due to collateral hazards may exceed the ones due to the earthquakes (e.g.: the 2011 Japan earthquake), detailed studies are required, which is out of the scope of this study.

5.3 Past Seismic Economic Loss Estimation Models

Turkish economy has suffered considerably after the recent earthquakes. Prime Ministry of the Government of Turkey has divulged the monetary losses due to physical damage and interruption at the production, only for the industrial sector as 675.1 million USD and 810,8 million USD respectively (considering the approximate exchange rates of 1999) (Prime Ministry Crisis Management Center, 2000). Reduction of the gross domestic product (GDP) is reported to be 1.3 billion U.S dollars in the disaster area (Prime Ministry Crisis Management Center, 2000). This fact brings the need for economic loss estimation models as a part of seismic risk mitigation. Thus, within the last decade, several economic loss estimation models have been proposed.

Bommer et al. (2002) proposed an earthquake loss model for Turkish catastrophe insurance. That study is conducted for Turkish Emergency Flood and Earthquake Recovery Program (TEFER) after the 1999 Kocaeli (M_w=7.4) and Duzce (M_w=7.1) earthquakes. Seismic hazard is modeled by individual earthquakes in order to consider secondary hazards and physical details of the event (magnitude, duration, shape of the response spectrum). Building vulnerability is represented by both fragility curves and capacity curves. Conditional structural damage is integrated among all predefined building classes. Economic losses are represented as a function of average reconstruction cost per building and damage distribution of the buildings. Computation of the monetary losses is similar to the one in HAZUS methodology. These losses are presented in terms of average annual expected loss and loss exceedance probabilities for the entire country in the province level.

Ergönül (2005) proposed a probabilistic seismic economic loss estimation approach targeting the decision makers. In that study, repair and reconstruction costs, casualties, indirect costs are related to the physical damage using Monte Carlo simulations. Discount rates (%), initial cost (USDmillion), annual expenditures (USDmillion), economic value (USDmillion/year), supply and recovery costs (USDmillion), economic loss (USDmillion/year) and earthquake occurrence time (year) are considered as random variables with different probability distributions. Economic losses are computed by subtracting future value of the inventory when the earthquake occurs from the future value of the inventory when the earthquake does not occur. The output of the study is presented in terms of probability distributions with different recovery periods.

An alternative approach to seismic economic loss estimation is proposed by Bal et al. (2007). In that study, detailed structural characteristics of Turkish reinforced concrete buildings in Northern Marmara Region are presented. The economic loss is expressed as a function of damage states and costs of initial construction. Year 2006 values of construction costs per meter square are obtained from Ministry of Public Works and Settlement. In that study, certain percentages of total cost of initial construction at each damage stage (slight, moderate, severe and collapse) are defined by referring to governmental and private sources (Table 5.1). In this table, severe and heavy damage states include rubble removal.

Table 5.1: Percentages of total cost of initial construction for each damage stage (Bal et al., 2007)

Damage State	Damage Percentage (%)
Slight	16
Moderate	33
Severe	105
Heavy	104

That study finally computes the total economic loss by considering the initial construction costs per meter square, demolishing and transportation costs, building area and damage states of the structures obtained from the appropriate vulnerability functions.

5.4 Proposed Seismic Economic Loss Model

In this thesis, economic losses caused only by structural damage are considered. Direct losses due to non-structural damage require detailed structural analyses while the contribution of indirect losses of the residential buildings to the total economic losses is considerably low. Hence, non-structural and indirect losses are neglected. As economic losses resulted from secondary events are difficult to estimate due to scarcity of available data, these losses are out of the scope of this study.

In order to estimate direct economic losses due to direct structural damage, HAZUS definitions are employed. In HAZUS, the cost of structural damage of an occupancy class is defined as the multiplication of the building replacement cost of that class by the mean damage ratio (MDR). Total cost of structural damage is obtained by integrating the results for all occupancy classes. Although 33 occupancy classes are defined in HAZUS, in this study only three classes exist namely; reinforced concrete, unreinforced masonry and woodframe multi-family dwellings. The expected seismic economic loss in this study is computed by using Equation 5.1.

$$EEL = \sum_i A_i \times U_i \times (\sum_j (P(DS = DS_j) \times CDR_j)) \qquad (5.1)$$

In Equation 5.1, EEL is the total replacement cost. Parameter A_i is the total area of the buildings in the inventory for each occupancy class i. Parameter U_i is the unit costs of initial construction of the occupancy class i. The data related to the parameters A_i and U_i for study region 2 have been obtained from Turkstat and Ministry of Public Works and Settlement, respectively. Total area of the buildings is computed approximately considering the weighted average of the floor areas in study region 2. Table 5.2 shows the number of buildings corresponding to different ranges of floor areas for study region 2. Average floor area of the residential buildings in study region 2 is computed to be 119 m^2 according to census of buildings (2000) data. Ministry of Public Works and Settlement proposes cost of initial construction per meter square for buildings structures in Turkey every year. Accordingly, unit costs of initial construction of year 2010 are used. In this fashion, unit cost of initial construction of residential buildings up to 4 stories is taken to be 448 TL/m^2 (280 USD/m^2), while the same value of the residential buildings with more than 4 stories is considered to be 577 TL/m^2 (350 USD/m^2). Multiplication of the average floor area, number of stories in a building and the cost of initial construction per meter square gives the total cost of initial construction per one building.

Table 5.2: Number of buildings corresponding to different area ranges for study region 2 (Census of building, 2000, Turkstat)

Floor area (m^2)	Number of Buildings
0-49	4,103
50-74	12,770
75-99	40,106
100-149	24,498
150-199	3,532
200-299	3,515
300-399	1,047
400-499	561
500-749	594
750-999	218
1000-1999	262
2000+	177
Unknown	144
Total	91,527

The term $P(DS = DS_j)$ in Equation 5.1 represents the occurrence probability of the damage state j. The exceedance probabilities of the limit states are obtained from appropriate fragility functions defined in Chapter 3. CDR is the central damage ratio at the corresponding damage states. Askan and Yücemen (2010) have defined central damage ratios for none, light, moderate, heavy and collapse as 0%, 5%, 30%, 70% and 100%, respectively. In this study, there are three damage states; namely none/slight damage, moderate/extensive damage and heavy damage/collapse. Average central damage ratios for these damage states are modified from the values suggested by Askan and Yücemen (2010) (Table 5.3).

Table 5.3: Central damage ratios of each building classes

Damage State	Central Damage Ratio (CDR) (%)
None-Light	5
Moderate-Extensive	40
Heavy-Collapse	85

It is common practice to express the total replacement cost as a product of mean damage ratios and cost of initial construction (Bal et al., 2007). As mentioned before, economic loss caused by structural damage is only a percentage of the overall loss. However, there is scarcity of data on the deaggregated components of the total economic loss and most of the data from past events constitute the indirect economic losses only. Although the distribution is not presented, total economic loss caused by the earthquakes in 1999 in Turkey is estimated to be more than 20 billion USD (AHDER, 2011).

CHAPTER 6

INTEGRATION OF THE COMPONENTS AND RESULTS OF THE CASE STUDIES

6.1 General

This study has two major objectives: One is to estimate the losses in Düzce city center (study region 1) after the 1999 Düzce (M_w =7.1) earthquake for verification of the proposed model. The second objective is to predict the potential losses in Osmangazi subprovince of Bursa (study region 2) using the same model. Seismic loss estimation procedures in general have three major components: prediction of the ground motion, building fragility, and socioeconomic vulnerability. In this study, ground motion demand on the buildings is predicted using probabilistic seismic hazard analysis. Building vulnerability is computed by adopting appropriate fragility functions. Finally, casualties and economic losses are estimated for the computed damage distribution.

Section 6.2 and Section 6.3 presents the derivation of the probabilistic seismic hazard curves for both study regions and the selected fragility curves, respectively. In Section 6.4, seismic hazard and building fragility functions are integrated for the quantification of seismic risk for the study regions. Then, building damage distributions are obtained as a function of seismic risk and building inventory at the regions of interest. Section 6.5 utilizes the damage distributions in order to estimate casualties for both study regions. Section 6.6 presents economic losses for study region 2. Finally, the proposed methodology is compared and verified with the 1999 Düzce earthquake (M_w=7.1) in Section 6.7. Finally, estimated seismic losses along with the observed damage and loss distributions are presented along with a discussion of results.

6.2 Derivation and Presentation of the Seismic Hazard for Case Study Regions

Determination of the ground motion demand is the initial step of a seismic loss estimation methodology. In this study, ground motion demand is computed by using probabilistic seismic hazard analysis. PSHA considers all sources within a certain distance to the site; all rupture lengths (or areas) at every possible location on the source and suggests the probability of exceedance of ground motion parameters within a certain period of time.

In order to calculate the seismic hazard for a region, first, the seismicity of the region and then the location and characteristics of the seismic sources in that region are defined. Subsequently, activities of the seismic sources are determined. Finally, seismic hazard of the region of interest is computed by means of source activity, GMPEs and temporal-recurrence relationships. In this study, probabilistic seismic hazard curves for study regions 1 and 2 are generated using the computer program SEISRISK III, developed by Bender and Perkins (1987). Although the steps of the probabilistic seismic hazard analysis are presented in Chapter 2 with specific emphasis on the selected approaches, here a brief summary is presented along with the attained results.

Earthquake catalogues of Düzce and Bursa were obtained from Kandilli Observatory and Earthquake Research Institute (http://www.koeri.boun.edu.tr). The events with epicenters that are at most 200 km away from the selected district with $M_w > 4.5$, occurred between years 1900 and 2004 are considered. Fore and aftershocks are naturally not independent of the main shocks. On the other hand, Poisson model (see Equation 2.7 in Chapter 2), which has no memory and assumes independency between the events, is used in the temporal occurrence model in this study. Therefore, for consistency, fore and aftershocks are eliminated using the methodology suggested by Deniz (2006) (Table 2.1). Figures 6.1 and 6.2 present the seismicity of study regions 1 and 2, respectively.

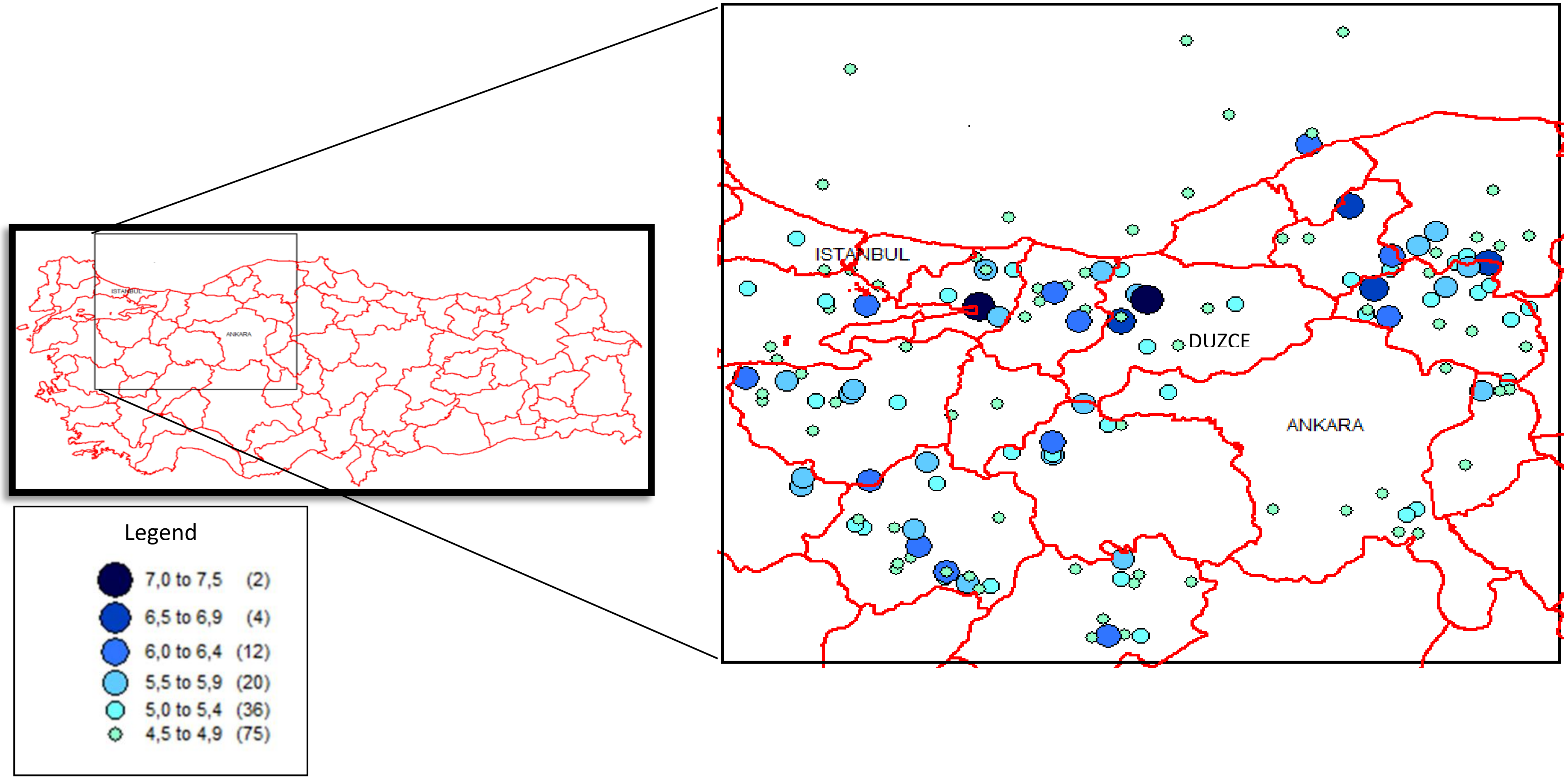

Figure 6.1: The distribution of the mainshocks 200 km around Duzce City Center

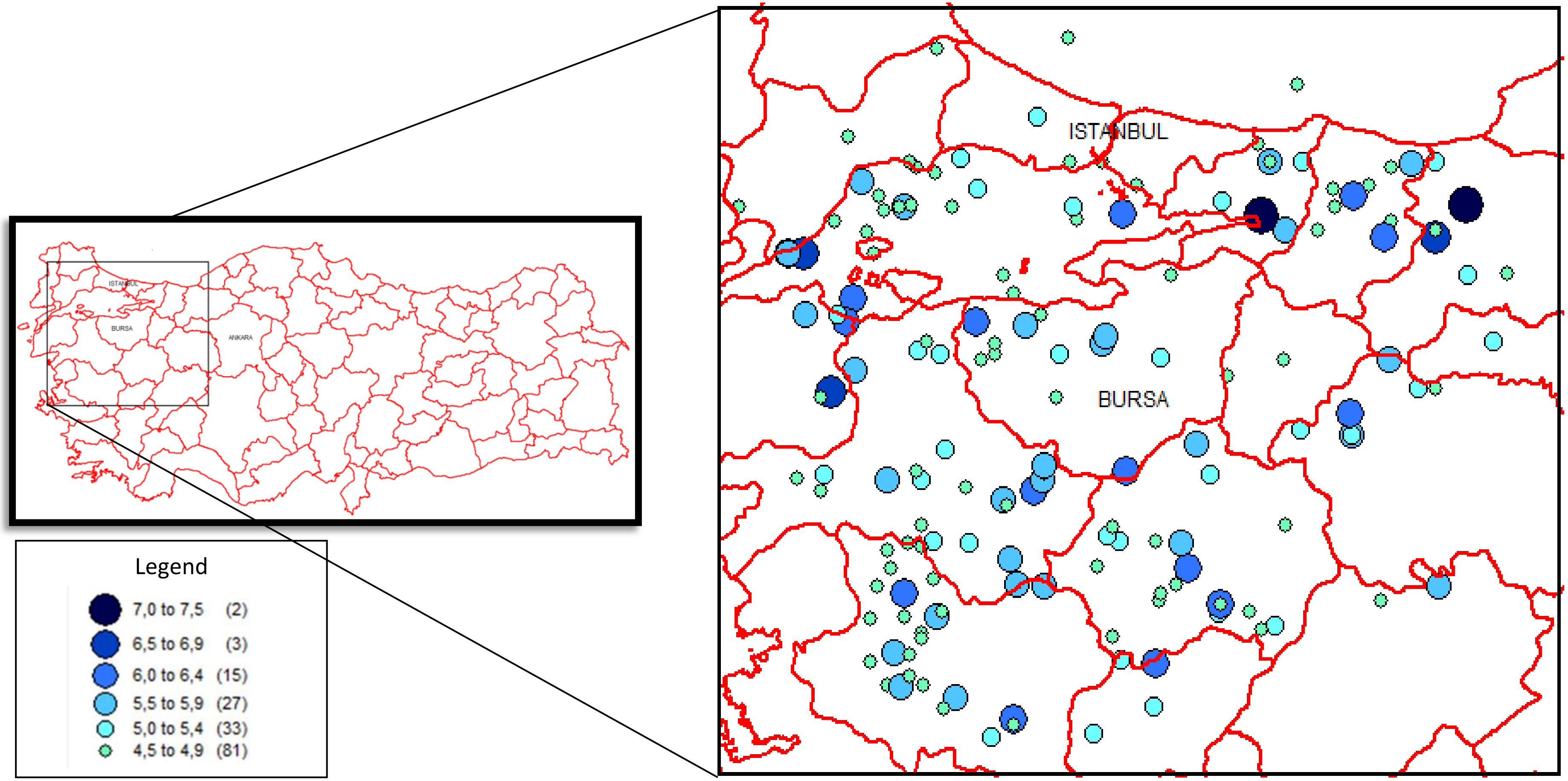

Figure 6.2: The distribution of the mainshocks 200 km around Bursa City Center.

The active fault map of Turkey is obtained from the webpage of Strong Ground Motion Database for Turkey (http://daphne.deprem.gov.tr). For practical reasons, if the epicenters of the past events cluster along the known active faults, line sources are defined. If the epicenters of the past events are concentrated within an area but not around any known active fault systems, then area sources are defined. In a more detailed seismic hazard analysis, seismic sources can be modeled more elaborately. However, Yücemen (2008) states that the results are less sensitive to the uncertainty in the location of the faults than to the other uncertainties such as those in the attenuation relationships. Figures 6.3 and 6.4 present the locations and geometry of the seismic sources in study regions 1 and 2, respectively.

Once the seismic sources are determined; activities of these sources are calculated for the study regions (Figures 6.5 and 6.6). Magnitude-recurrence models of a seismic source represent the probability distribution of the magnitudes of earthquakes generated by that source. This study uses the exponential magnitude-recurrence model suggested by Gutenberg and Richter (1956), which is embedded to SEISRISK III (Equations 2.2, 2.3 and Figure 2.3 presented in Chapter 2). In this study, lower bound for moment magnitude is assumed to be 4.5 and the upper bound magnitudes are defined according to the source dimensions based on the suggestion of Wells and Coppersmith (1994).

In this study, ground motion prediction equations generated by Boore and Atkinson (2008) and Akkar and Bommer (2010) are used to predict ground motions for different epicentral distances and magnitudes. The relationships by Boore and Atkinson (2008) considered higher number of stations in Turkey than other NGA models whereas Akkar and Bommer (2010) is the most recent local attenuation relationship. In this study, each one of the attenuation relationships is given 50 percent weight. Soil properties, site conditions and V_{s30}values for both study regions are obtained from the webpage of Turkish Strong Ground Motion Database (http://daphne.deprem.gov.tr). Both sites are assumed to be stiff soil with V_{s30} values 400 cm/s and 490 cm/s for study regions 1 and 2, respectively. In this study, SEISRISK III is used to calculate rates of exceedance of both PGA and PGV for study regions 1 and 2.

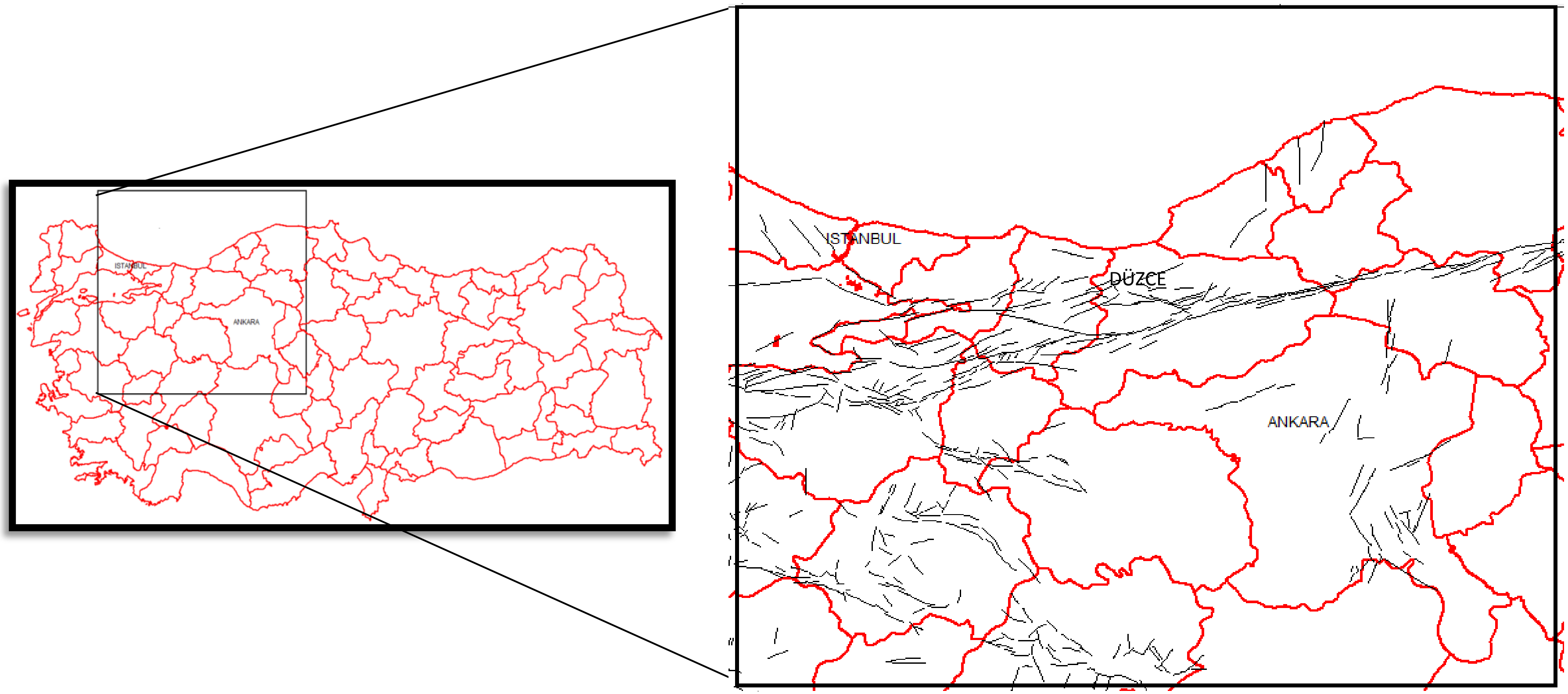

Figure 6.3: The sources 200 km around Duzce City Center

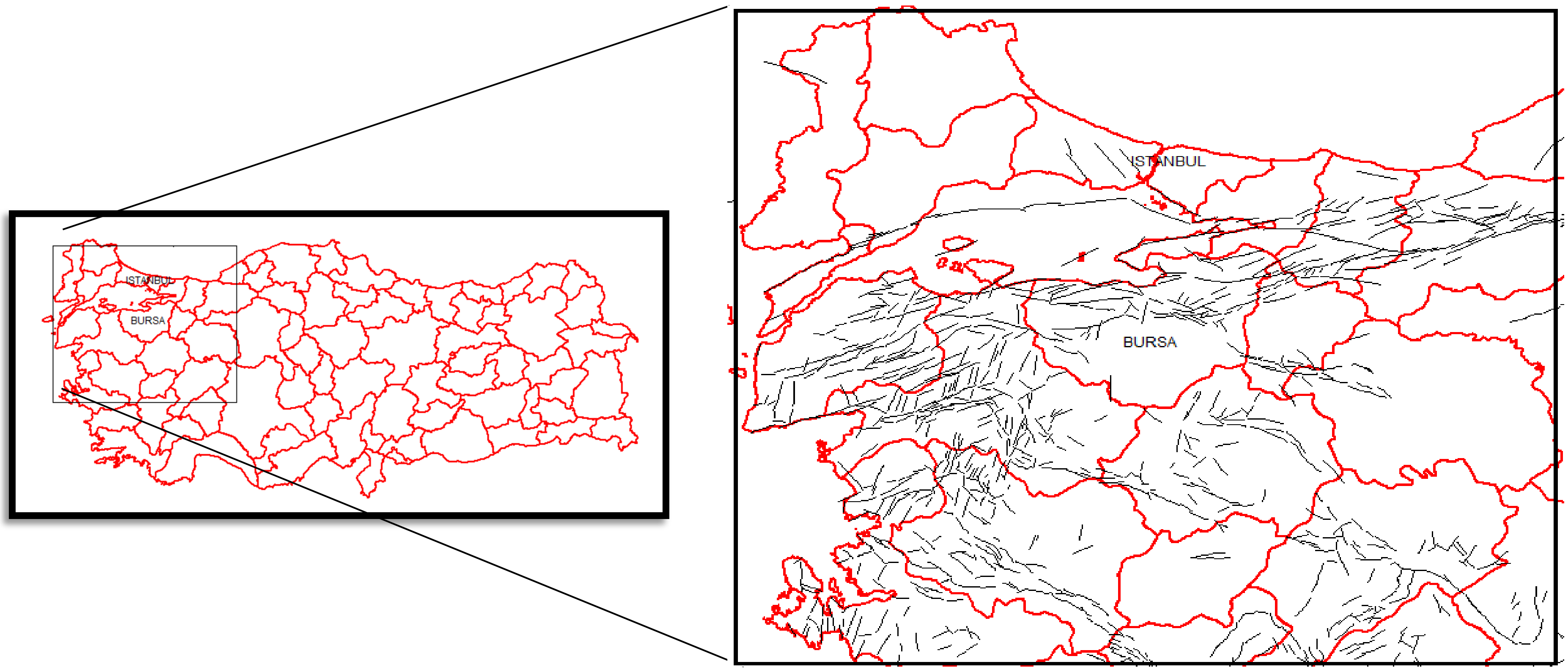

Figure 6.4: The sources 200 km around Bursa City Center.

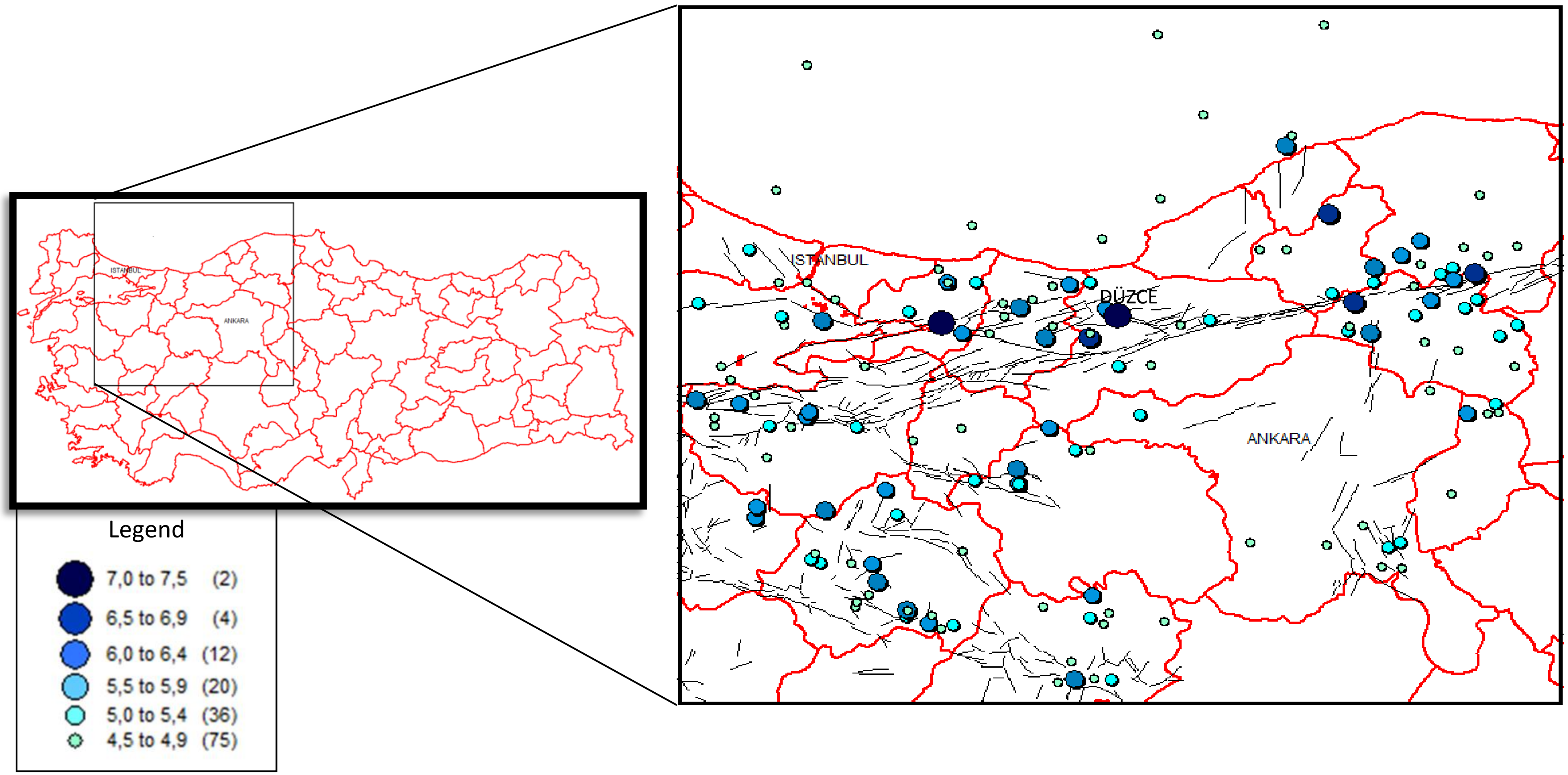

Figure 6.5: The distribution of the mainshocks 200 km around Duzce City Center along with the sources.

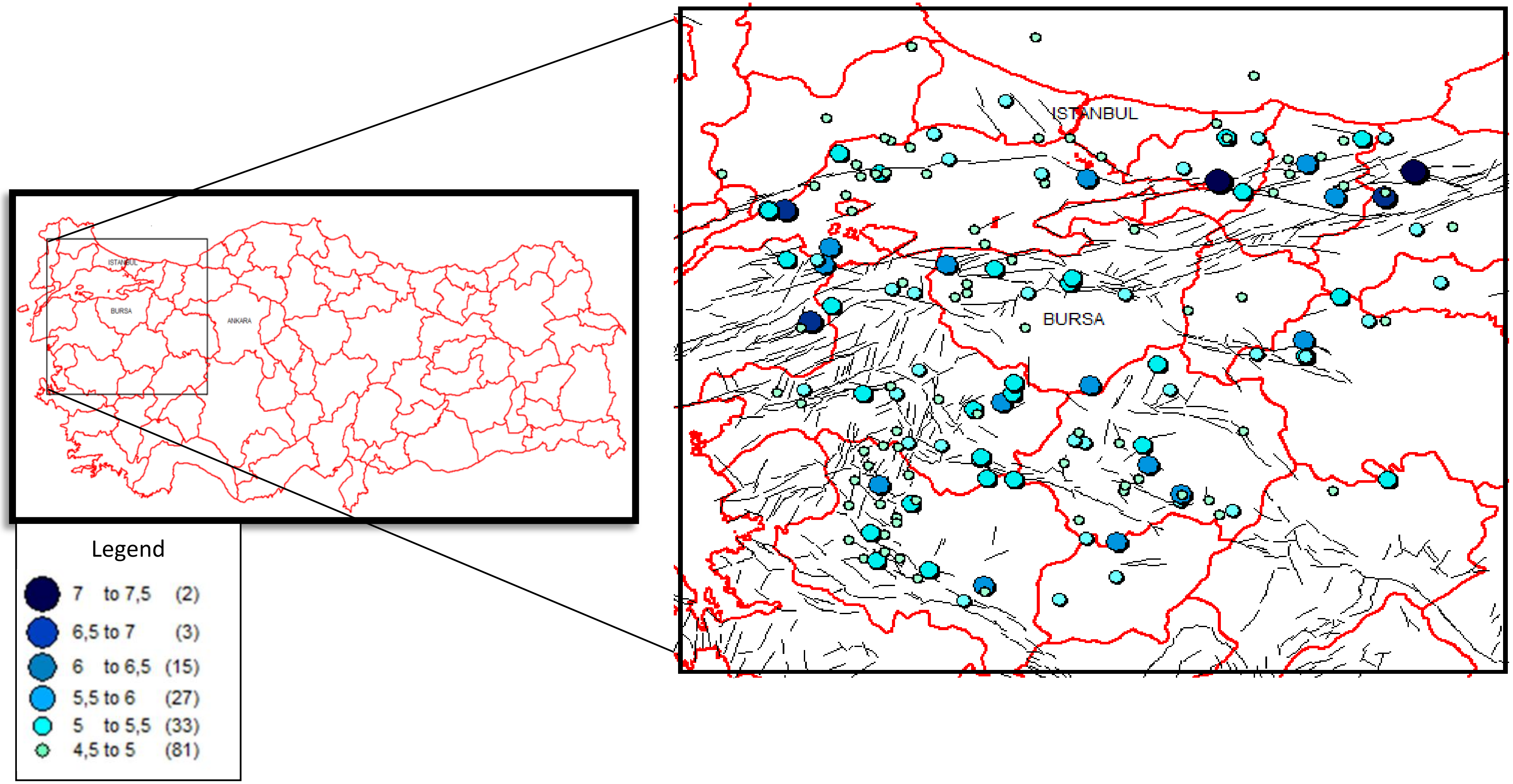

Figure 6.6: The distribution of the mainshocks 200 km around Bursa City Center along with the sources.

In this study, seismic hazard is computed for a time period of 50 years. Alternative time periods can also be selected depending on the significance of the buildings and user needs. Figures 6.7.a, 6.7.b, 6.7.c and 6.7.d present 50 year hazard curves in terms of PGA and PGV for the district centers of both study regions. This study assumes a constant seismic hazard throughout the selected district. These probabilistic seismic hazard curves are derived using GMPEs suggested by both Akkar and Bommer (2010) and Boore et al. (2008). As observed from the figures, probability curves of the alternative attenuation relationships, in particular the ones derived for PGA, almost coincide with each other.

In order to determine the resulting probabilistic seismic hazard for both study regions, a 50% weight is assigned to each hazard curve obtained using the selected attenuation relationships. These hazard curves of both study regions are observed to be close to each other in Figures 6.7.a, 6.7.b, 6.7.c and 6.7.d due to similar site conditions, seismicities and source activities. Therefore, using the same fragility functions as well as casualty and economic loss functions will result in similar damage and loss distributions, as long as characteristics of the building inventory in both study regions are similar.

The cumulative seismic hazard curves presented in Figures 6.7.a, 6.7.b, 6.7.c and 6.7.d are then converted into probability density functions so that the area under the hazard curve equals unity. Once the cumulative hazard is converted into probability density functions, a lognormal probability density function is fitted to the resulting hazard curve. Table 6.1 presents the main descriptors of lognormal distribution of seismic hazard.

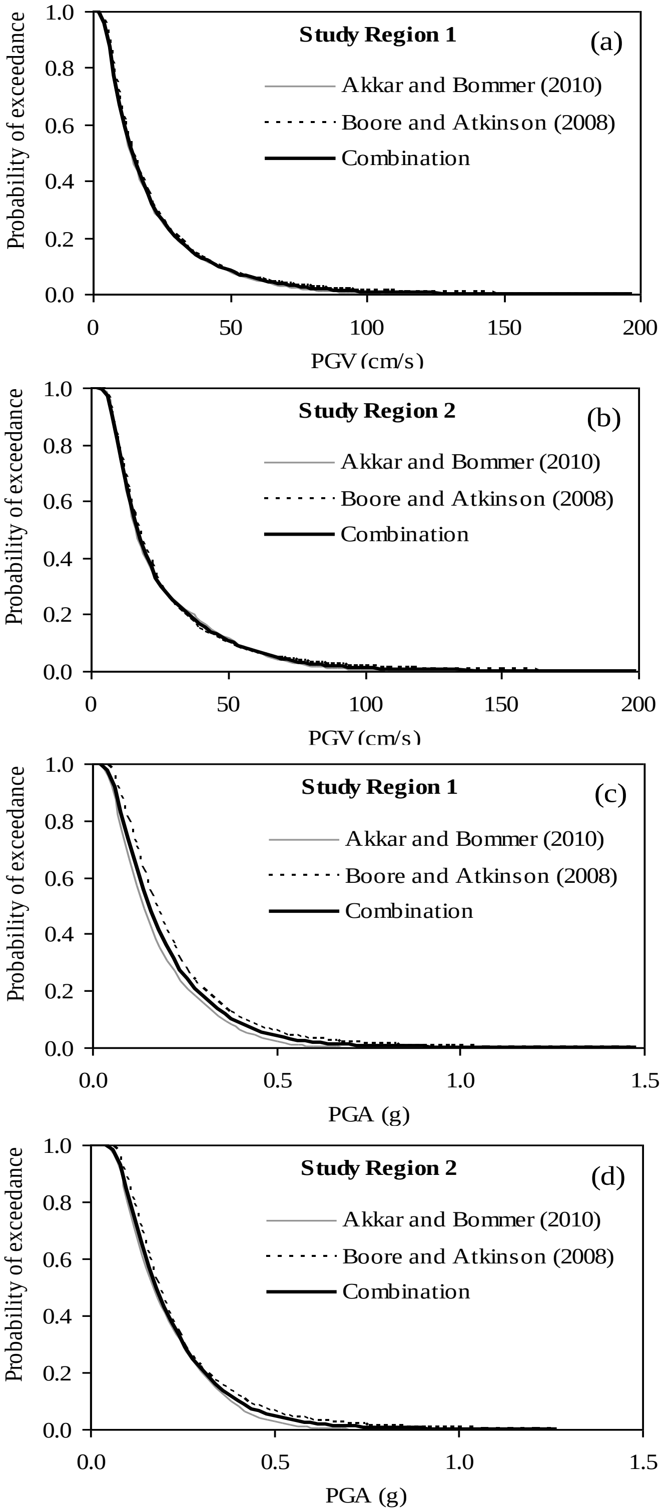

Figure 6.7. Hazard Curves for **a)** study region 1 in PGV, **b)** study region 1 in PGV, **c)** study region 1 in PGA, **d)** study region 2 in PGA

Table 6.1: Main descriptors of the lognormal probability density functions of seismic hazard for PGV (cm/s) and PGA (m/s^2) for both study regions.

	λ (lognormal mean)	ζ (lognormal standard deviation)
PGV (cm/s) for study region 1	2.6	0.9
PGV (cm/s) for study region 2	2.76	0.625
PGA (m/s^2) for study region 1	0.49	0.7
PGA (m/s^2) for study region 2	0.535	0.58

In this study, seismic loss is calculated for different return periods as well. Table 6.2 presents ground motion levels with different return periods which are computed using probabilistic seismic analyses for study regions 1 and 2. These PGA and PGV values are also obtained using a combination of GMPEs suggested by Akkar and Bommer (2010) and Boore et al. (2008) each with a 50 % weight.

Table 6.2: PGA (g) and PGV (cm/s) values with different return periods for study regions 1 and 2

Return Period (years)	**Study Region 1**		**Study Region 2**	
	PGA (g)	**PGV (cm/s)**	**PGA (g)**	**PGV (cm/s)**
10	0.03	2.65	0.05	4.60
50	0.12	10.90	0.15	13.75
100	0.19	18.30	0.21	20.70
250	0.30	32.65	0.32	37.80
475	0.38	45.50	0.40	51.50
1000	0.48	61.65	0.50	67.45
2475	0.59	81.35	0.61	87.35

6.3 Fragility Assessment

This study focuses on the seismic fragility of the reinforced concrete (RC), unreinforced masonry (URM) and woodframe structures within the building stocks of the study regions 1 and 2. Several past attempts to generate fragility curves for these aforementioned building classes have been mentioned in Chapter 3. In this section, a brief summary of the adopted studies for each building class is presented.

For reinforced concrete structures, fragility curve sets developed by Erberik (2008a) are adopted to this study. In this proposed study, labels of the subclasses defined by Erberik (2008a) are modified for simplicity. The labels for the reinforced concrete building sub-classes in the proposed methodology are LR-A, LR-B, LR-C, MR-A, MR-B and MR-C, where LR and MR denote low-rise and mid-rise, A, B and C denote sub-classes high, moderate and low, respectively.

Fragility curves for unreinforced masonry structures in Turkey generated by Erberik (2008b) are used in this study. However, the fragility curve sets are re-arranged to be used in the loss estimation methodology in this study. According to this new classification, masonry structures are considered as “urban engineered”, “urban non-engineered” and “rural non-engineered”. The first sub-class refers to masonry buildings in urban regions, which have been constructed according to the basic principles of the earthquake resistant design. They are generally up to 5 stories, have rectangular plans, constructed with good quality of load-bearing wall material (either solid or perforated clay brick with high compressive strength) and globally the structures in this sub-class exhibit box-like behavior, in which the structural walls keep their integrity. The variants in this sub-class are labeled as UE1, UE2, UE3, UE4 and UE5 according to their number of stories. The second sub-class stands for masonry buildings up to five stories in urban regions, which violate many of the code principles and therefore possess numerous structural deficiencies. The structures in this sub-class generally have irregular plan geometries with many projections and they are constructed by using perforated clay brick or concrete masonry units with low compressive strength. The variants in the second sub-class are named as UN1, UN2, UN3, UN4 and UN5, considering the number of stories. The last sub-class of masonry buildings represents rural type of masonry structures, which have been built in a traditional manner without any engineering intervention. They are generally constructed from rubble stone or adobe units up to three stories and possess poor wall-to-wall and wall-to-floor connections. The masonry structures in this sub-class are highly vulnerable to seismic action of even moderate intensity. The variants in the second sub-class are named as RN1, RN2 and RN3, considering the number of stories.

Although no fragility functions have been derived for woodframe structures in Turkey, in this study, instead of generating new fragility curves for Turkish woodframe structures, the fragility curve sets generated by Gencturk *et al*. (2008) are adopted. Here, only two sub-classes from Gencturk's study are selected to represent the existing wood-frame buildings in the study region. These are one or two story residential buildings with sub-standard (pre-code) or standard (moderate-code) construction. Woodframe fragility sub-classes are labeled as WF1 and WF2. Details about the fragility curve generation methodology of RC, URM and woodframe frame buildings are summarized in Table 6.3.

Table 6.3. Summary of the fragility curve generation methodologies developed for RC frame, URM and woodframe structures

Properties of the Methodologies	RC Frame Structures	URM Structures	Woodframe Structures
Identification of Hazard	100 actual ground motion records with wide range of characteristics	50 actual ground motion records from firm soil sites	10 synthetic acceleration time histories for each of soft soil, competent soil and rock
Hazard Parameter	PGV	PGA	PGA
Demand Analysis	Nonlinear Dynamic	Linear Dynamic	Nonlinear Dynamic
Capacity Analysis	Nonlinear Static	Nonlinear Static	Nonlinear Static
Analytical Model	SDOF	MDOF	SDOF
Response Parameter	Global Drift	Shear Force	Roof Drift Value
No. of Limit States	3	2	4
Treatment of Uncertainty	Record-to-record variability, period, strength ratio, post-yield to initial stiffness ratio	Capacity, demand and modeling uncertainty in terms of β parameters	Variation of capacity diagrams under each building category
Verification	Yes	Yes	No

As it can be observed from Table 6.3, the fragility curve sets for RC frame, URM and woodframe buildings have different number of limit states (LS). Hence these limit states should be harmonized in order to obtain a unified definition of damage and loss for different structural types. In order to achieve this task, the definitions of limit states are compared with each other and it is decided to consider two limit states (yield and ultimate) common for all structural types. This means there are three damage states (DS); for “None/Slight Damage”, “Moderate/Extensive Damage”, “Heavy Damage/Collapse”. Considering these definitions, it can be stated that there is no change for URM structures since they already have two limit states. For RC frame structures, existing three limit states are reduced to two, by considering LS1 as yield and LS3 as ultimate. In the case of woodframe structures, LS1 is taken as the yield limit state and LS3 is considered as the ultimate limit state. The harmonized fragility curve sets for all structural types are presented in Figure 6.8.a-f. For URM buildings, the curves only up to 3 stories for urban engineered (UE1-UE3) and non-engineered (UN1-UN3) sub-classes are presented in the figure. These cumulative fragility curves are further converted into DPMs in order to derive seismic risk curves.

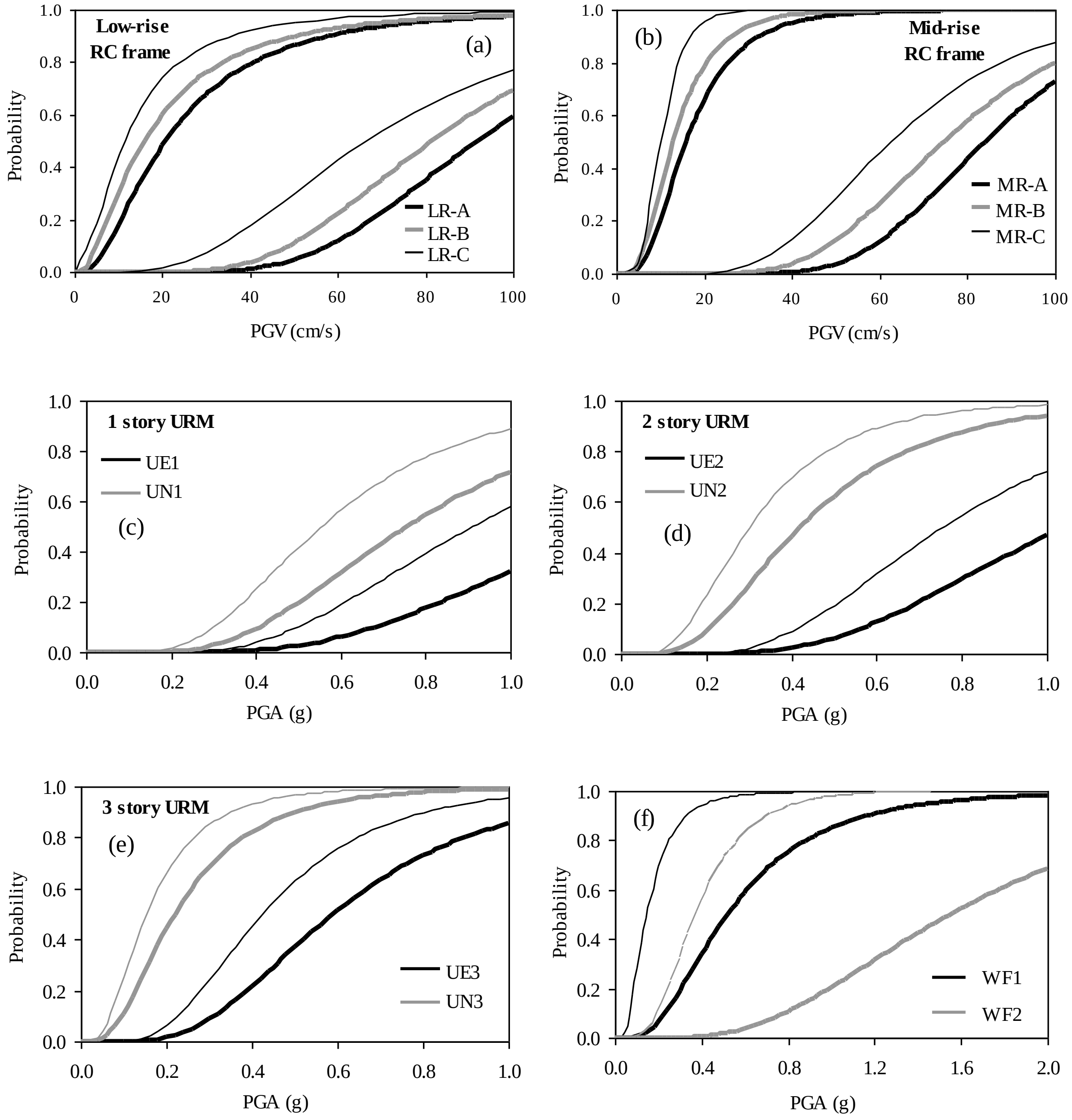

Figure 6.8. Harmonized fragility curves for a) low-rise RC frame buildings, b) mid-rise RC frame buildings, c) 1 story URM, d) 2 story URM, e) 3 story URM, f) woodframe

6.4 Risk and Physical Loss Assessment

6.4.1 Risk Curves

Seismic risk is defined as the level of loss or damage that is equaled or exceeded in a certain period of time (McGuire, 2004). In most general terms, seismic risk is the probability of exceeding of a certain building damage state for a given seismic hazard level multiplied by the probability of occurrence of that hazard level (Equation 1.1 in Chapter 1).

In order to quantify the seismic risk for the study regions, seismic hazard and building fragility are integrated. Then seismic risk is utilized for the estimation of physical and economic losses as the final product of the proposed methodology. Among these tasks, the most important one is the quantification of seismic risk. Seismic risk curves are probability density functions of ground motion parameters. The area under the risk curve for a certain building class gives the expected risk in a certain period of time for a certain damage level. The sum of the areas under the risk curves for all damage states of the same building class is equal to unity. Risk curves are derived for all building classes and an example risk curve for building subclass MR-B is demonstrated in Figure 6.9.

A low hazard level has a high probability of occurrence but causes small damage, while a high level hazard causes considerable damage but have a low probability of occurrence. Hence, a risk curve has a bell shape. Figure 6.9 shows that as the level of damage increases, area under the risk curves considerably decreases. For a given hazard, area under the risk curves depends on the building vulnerability, where more severe damage level has a lower probability of exceedance. Besides, the peak of the risk curves shifts to higher ground motion levels with increasing damage levels. This is because smaller damage levels are more probable to be exceeded at lower ground motion levels while higher ground motion levels reduce the probability of occurrence of slighter damage states and increase that of heavier damage states. The summation of areas of different damage states for a building class is unity as expected.

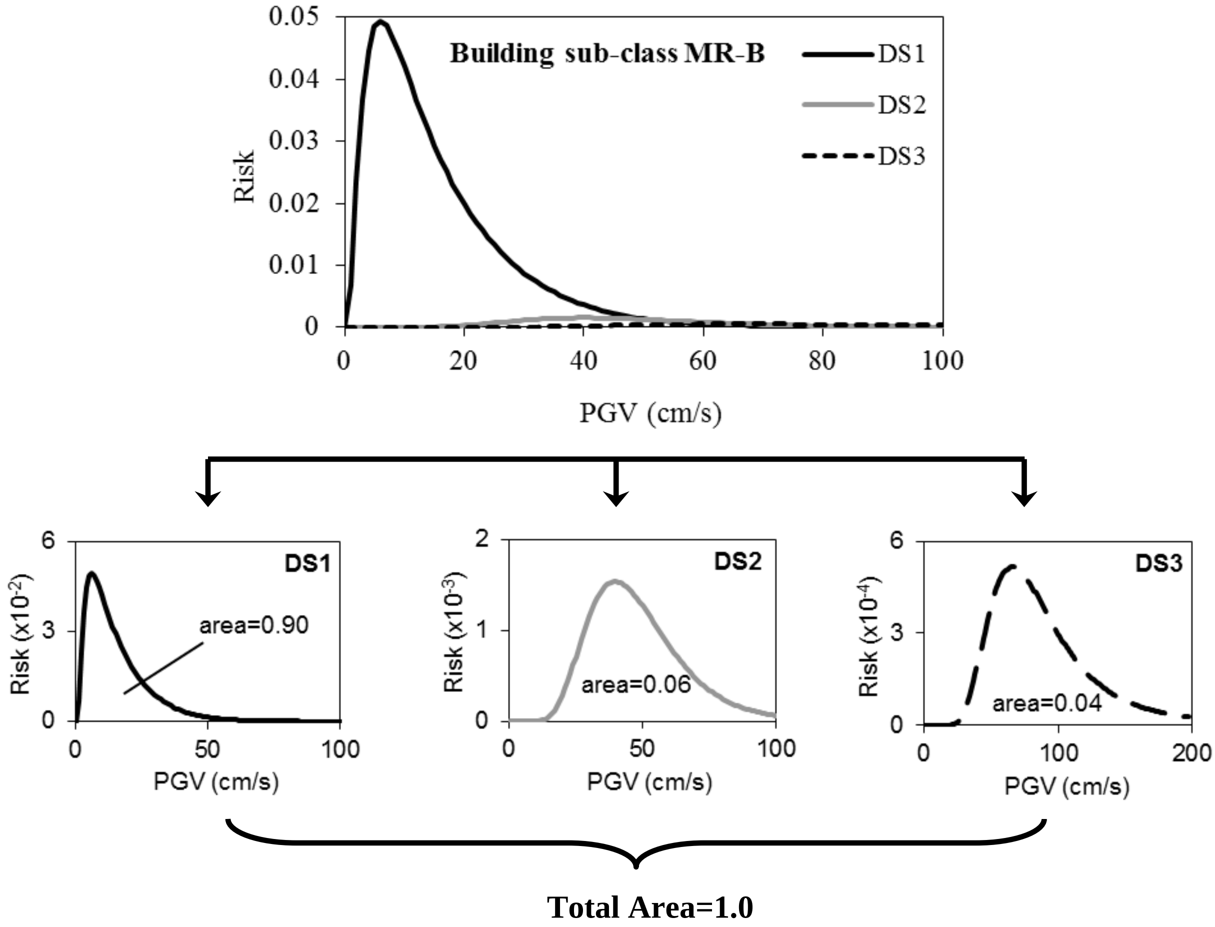

Figure 6.9. Risk curves for building sub-class MR-B for DS1, DS2, and DS3 in study region 1.

6.4.2 Building Stock

Once the risk curves for each building class are generated, they are multiplied by the number of buildings for each class in order to obtain the damage distribution and the number of collapsed buildings. Building information in the study region based on structural type versus number of stories is gathered from Turkish Statistics Authority (Turkstat) census of buildings 2000 data (Table 6.4). The data is classified in three categories: RC frame, URM and woodframe buildings. Only residential buildings of the aforementioned types up to 10 stories are used in this study. Table 6.4 shows that the distribution of the structural types in the inventory of both study regions are similar. In both of the study regions, RC buildings constitute the majority of the structures. Percentage of woodframe structures in study region 1 are greater than the ones in study region 2 while for URM buildings, it is the opposite.

Table 6.4: Building inventory data obtained from Turksat for study regions 1 and 2

Building Type	Study Region 1	Study Region 2
REINFORCED CONCRETE BUILDINGS		
Low-Rise Frames	5,543 (65.2%)	48,029 (47.11%)
Mid-Rise Frames	1,100 (12.9%)	18,002 (19.71%)
UNREINFORCED MASONRY BUILDINGS		
1-Story	792 (9.3%)	10,472 (11.46 %)
2-Stories	514 (6%)	11,170 (12.23 %)
3-Stories	33 (0.44%)	5,125 (5.61%)
> 3-Stories	11 (0.1%)	2,075 (2.27%)
STEEL FRAME BUILDINGS		
Steel Frame Buildings	39 (0.5%)	157 (0.17 %)
WOOD FRAME BUILDINGS		
Wood Frame Buildings	468 (5.5%)	1,316 (1.44 %)
Total Number of Buildings	8,500	91,346

The next step is to match the buildings in the inventory to the predefined fragility subclasses in order to compute seismic damages of both study regions. For future seismic loss estimation purposes, it is intended to obtain a one-to-one correspondence between these two terms. However it is not possible to know the current state of each existing building in the inventory. Therefore a simplified approach should be used in order to determine the seismic vulnerability of the building stock under consideration. This is achieved by simulating the building population using sampling methods. In order to prevent an unconstrained sampling which can lead to misleading results, the buildings in the inventory are classified according to the existing detailed building database obtained during Istanbul Master Plan Project from Fatih sub-province of Istanbul. This extensive database includes more than 25,000 buildings of different types and provides detailed information about each building in terms of major structural parameters. In this fashion, distributions of the existing buildings in each fragility subclass for both study regions are assigned. In some cases, multiple assignments are done for a building in the database due to lack of sufficient data. Hence, the percentages of fragility sub-class assignments are obtained within some intervals. For instance, for mid-rise RC frame buildings, 5%-15% can be assigned to the MR-A sub-class, 25%-50% can be assigned to the MR-B sub-class and 45%-60% can be assigned to the MR-C sub-class. Similar numbers have been obtained also for mid-rise RC frame buildings, urban engineered and non-engineered URM buildings and woodframe buildings where analytical simulations are carried out by constrained sampling. The simulated number of buildings according to each fragility sub-class for study regions 1 and 2 are listed in Tables 6.5 and 6.6, respectively.

In order to verify the proposed methodology, estimated damage is compared with the observed damage after the 1999 Düzce (M_w=7.1) event. For this purpose, damage distributions in study region 1 are computed for this deterministic scenario. In this case, different from the future loss estimation part, only the fragility sub-classes LR-C, MR-C, UN1-UN5 and WF2 are assigned to the existing buildings in order to simulate their actual state just before the earthquake. The reason for assigning the worst fragility sub-classes to the buildings is that most of these buildings had already been damaged during the 1999 Kocaeli earthquake M_w=7.4, which happened 3 months before the Düzce earthquake. This is a very extraordinary case since the considered buildings had been subjected to two major earthquakes in a very short period of time. Hence it is decided to represent their vulnerable and damaged status before the second earthquake by assigning the aforementioned fragility sub-classes.

Table 6.5. Inventory simulation for the existing buildings in study region 1 (for the future seismic loss estimation part) that are assigned to the available fragility sub-classes

<table>
<tr><td>Type of construction</td><td colspan="30">Corresponding fragility sub-classes and number of assigned buildings</td></tr>
<tr><td colspan="31">RC Frame</td></tr>
<tr><td>Low-rise</td><td colspan="10">LR-A</td><td colspan="10">LR-B</td><td colspan="10">LR-C</td></tr>
<tr><td>Number of buildings</td><td colspan="10">328</td><td colspan="10">1,762</td><td colspan="10">3,453</td></tr>
<tr><td>Mid-rise</td><td colspan="10">MR-A</td><td colspan="10">MR-B</td><td colspan="10">MR-C</td></tr>
<tr><td>Number of buildings</td><td colspan="10">94</td><td colspan="10">332</td><td colspan="10">674</td></tr>
<tr><td colspan="31">URM</td></tr>
<tr><td>Urban engineered</td><td colspan="6">UE1</td><td colspan="6">UE2</td><td colspan="6">UE3</td><td colspan="6">UE4</td><td colspan="6">UE5</td></tr>
<tr><td>Number of buildings</td><td colspan="6">461</td><td colspan="6">336</td><td colspan="6">21</td><td colspan="6">4</td><td colspan="6">2</td></tr>
<tr><td>Urban non-engineered</td><td colspan="6">UN1</td><td colspan="6">UN2</td><td colspan="6">UN3</td><td colspan="6">UN4</td><td colspan="6">UN5</td></tr>
<tr><td>Number of buildings</td><td colspan="6">331</td><td colspan="6">178</td><td colspan="6">12</td><td colspan="6">3</td><td colspan="6">2</td></tr>
<tr><td colspan="31">Woodframe</td></tr>
<tr><td>Existing buildings</td><td colspan="15">WF1</td><td colspan="15">WF2</td></tr>
<tr><td>Number of buildings</td><td colspan="15">313</td><td colspan="15">155</td></tr>
</table>

Table 6.6. Inventory simulation for the existing buildings in study region 2 that are assigned to the available fragility sub-classes

<table>
<tr><td>Type of construction</td><td colspan="30">Corresponding fragility sub-classes and number of assigned buildings</td></tr>
<tr><td colspan="31">RC Frame</td></tr>
<tr><td>Low-rise</td><td colspan="10">LR-A</td><td colspan="10">LR-B</td><td colspan="10">LR-C</td></tr>
<tr><td>Number of buildings</td><td colspan="10">4,601</td><td colspan="10">21,754</td><td colspan="10">16,674</td></tr>
<tr><td>Mid-rise</td><td colspan="10">MR-A</td><td colspan="10">MR-B</td><td colspan="10">MR-C</td></tr>
<tr><td>Number of buildings</td><td colspan="10">2,246</td><td colspan="10">9,667</td><td colspan="10">6,089</td></tr>
<tr><td colspan="31">URM</td></tr>
<tr><td>Urban engineered</td><td colspan="6">UE1</td><td colspan="6">UE2</td><td colspan="6">UE3</td><td colspan="6">UE4</td><td colspan="6">UE5</td></tr>
<tr><td>Number of buildings</td><td colspan="6">7,068</td><td colspan="6">7,542</td><td colspan="6">3,690</td><td colspan="6">1,147</td><td colspan="6">269</td></tr>
<tr><td>Urban non-engineered</td><td colspan="6">UN1</td><td colspan="6">UN2</td><td colspan="6">UN3</td><td colspan="6">UN4</td><td colspan="6">UN5</td></tr>
<tr><td>Number of buildings</td><td colspan="6">3,404</td><td colspan="6">3,628</td><td colspan="6">1,435</td><td colspan="6">519</td><td colspan="6">140</td></tr>
<tr><td colspan="31">Woodframe</td></tr>
<tr><td>Existing buildings</td><td colspan="15">WF1</td><td colspan="15">WF2</td></tr>
<tr><td>Number of buildings</td><td colspan="15">908</td><td colspan="15">408</td></tr>
</table>

6.4.3 Estimated Building Damage Distributions for Study Regions 1 and 2

In order to calculate the expected seismic damage distributions in the study regions of interest in 50 years, first 50-year risk curves are integrated and then they are multiplied by the number of buildings in the corresponding fragility subclasses. The damage that the buildings experience in an earthquake is also named as physical loss. Total physical loss is another common indicator of an earthquake severity along with the casualties and economic losses. Building damage distributions are useful for comparison purposes versus a scenario event as well as computation of other socio-economic loss components. In literature, most of the seismic loss estimation studies are ceased at the physical loss level. This study carries this tradition one step forward and building damage distributions are utilized in order to estimate seismic fatalities and economic losses. Figure 6.10 presents the estimated expected damage distribution for study regions 1 and 2 for RC, URM, wood-frame buildings separately along with the estimated overall damage distributions for both regions.

As it can be seen from Figure 6.10, about 85% percent of the buildings are expected to experience none-to-light damage, about 10 % percent of the buildings are expected to experience moderate-to-extensive damage and 5 % percent of the buildings are expected to experience either a heavy damage or collapse. The resulting damage distributions are observed to be in the same order of magnitude for both study regions. Damage distributions are represented as a function of ground motion level, building vulnerability and characteristics of the buildings in the inventory. Since the same fragility functions have been adopted for these two regions, similarity in the 50 year hazard levels of study regions 1 and 2 as well as the building characteristics resulted in this resemblance. However, Figure 6.10 shows that study region 2 involves slightly less seismic risk then study region 1 does, in 50 years. Table 6.7 presents the damage distributions for different return periods for both study regions. In this case, ground motions with corresponding return periods are treated as deterministic events while performing the fragility analyses. Damage distributions in both study regions are observed to be similar due to the reasons which have been discussed previously.

These damage state probabilities are the mean values of wide range of damage distributions including the ones caused by lower ground motion levels with high probability of occurrences (higher weights) and the ones caused by higher ground motion levels with low probability of occurrences (lower weights). That is why 50-year expected damage levels in both study regions are estimated to be considerably low.

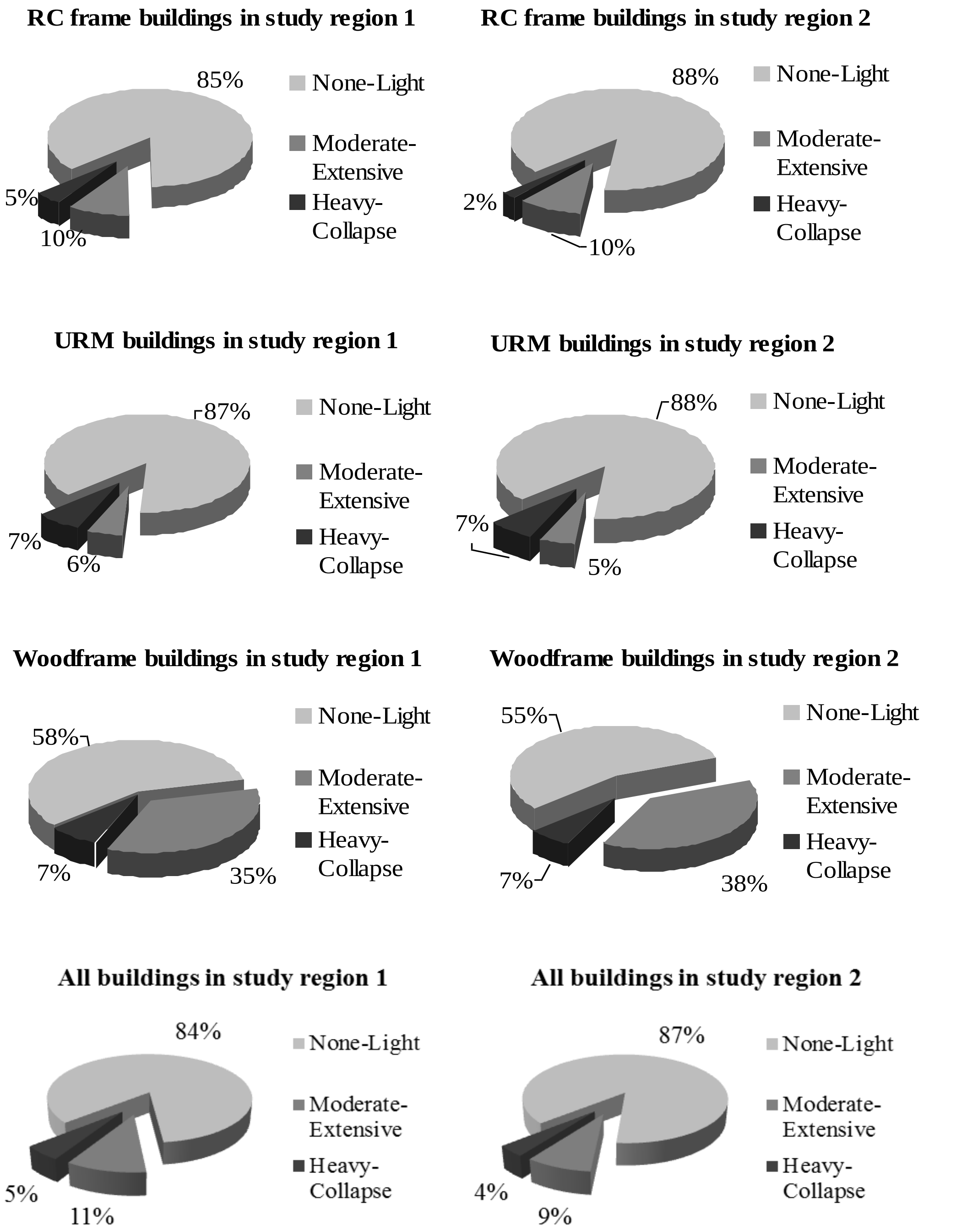

Figure 6.10. The estimated damage distributions in study regions 1 and 2 for 50 years

Table 6.7: Damage distributions for different return periods for study regions 1 and 2

Return Period (years)	Study Region 1											
	RC			URM			WOODFRAME			TOTAL		
	DS1 (%)	DS2 (%)	DS3 (%)	DS1 (%)	DS2 (%)	DS3 (%)	DS1 (%)	DS2 (%)	DS3 (%)	DS1 (%)	DS2 (%)	DS3 (%)
10	99.98	0.02	0.00	100.00	0.00	0.00	99.57	0.43	0.00	99.96	0.04	0.00
50	97.70	2.29	0.02	98.74	0.81	0.44	74.36	25.00	0.64	96.57	3.31	0.12
100	90.71	8.93	0.36	95.85	2.44	1.70	53.21	43.38	3.42	89.46	9.80	0.74
250	68.96	26.58	4.44	88.15	6.30	5.63	31.41	56.41	12.18	69.94	25.00	5.06
475	49.10	36.72	14.18	80.67	9.63	9.70	21.15	58.76	20.09	52.59	33.61	13.79
1000	30.51	36.50	33.00	70.07	13.78	16.07	12.82	57.48	29.70	35.85	34.04	30.11
2475	17.00	26.10	56.92	58.07	17.70	24.22	7.26	53.63	38.89	23.01	26.29	50.70
Return Period (years)	**Study Region 2**											
	RC			URM			WOODFRAME			TOTAL		
	DS1 (%)	DS2 (%)	DS3 (%)	DS1 (%)	DS2 (%)	DS3 (%)	DS1 (%)	DS2 (%)	DS3 (%)	DS1 (%)	DS2 (%)	DS3 (%)
10	99.91	0.09	0.00	99.49	0.35	0.15	96.73	3.27	0.00	99.73	0.22	0.05
50	96.34	3.60	0.06	93.91	3.06	3.03	63.45	35.03	1.52	95.10	3.89	1.02
100	89.26	10.21	0.52	88.76	5.30	5.94	47.04	48.02	4.86	88.50	9.21	2.30
250	62.39	30.84	6.77	77.41	9.62	12.96	27.36	58.05	14.59	66.63	24.53	8.84
475	41.83	38.70	19.46	68.61	12.45	18.94	18.31	58.97	22.72	49.96	30.69	19.34
1000	25.22	35.08	39.70	57.78	15.32	26.89	11.02	56.61	32.37	35.31	29.14	35.54
2475	13.54	23.08	63.38	46.77	17.49	35.74	6.31	52.05	41.64	23.94	21.73	54.32

6.5 Casualty Assessment

Seismic causalty estimation is a complex effort due to lack of data in addition to the complicated relationship between the building damage and number of fatalities. Therefore, it is essential to collect adequate amount of data and perform a multidisciplinary study on this problem. However, when this is not possible, several simplifications should be considered. In this study, the casualty estimation model proposed by Coburn and Spence (2002) is adopted to Turkey with some modifications. In Chapter 4, it is mentioned that several M parameters are utilized in order to relate number of collapsed buildings to the number of casualties (Equations 4.1 and 4.2 in Chapter 4).

Number of the collapsed buildings in a building class is obtained by multiplying the risk of collapse by the number of the buildings in the inventory of that class. Parameters M_1, M_2, M_3, M_4, M_5 and M_6 in Equation 4.1 denoted for population of the building, occupancy at the time of earthquake occurrence, number of trapped occupants in the collapse, injury distribution at collapse, mortality post collapse and ratio of collapsed buildings to the heavily damaged ones, respectively. Table 6.8 summarizes the M parameters utilized for study regions 1 and 2 as presented in Chapter 4. In Table 6.8 parameter “a” represents the number of stories of a building.

Table 6.8 : Summary of the M parameters defined in Chapter 4 for the study regions

		Study Region 1	Study Region 2
M_1		$4.32(0.13a^2+0.67a - 0.27)$	$3.82(0.13a^2+0.67a - 0.27)$
M_2		0.54	0.54
M_3		(1 - 0.5 /a)	(1 - 0.5 /a)
M_4	RC	0.40	0.40
	URM	0.20	0.20
	Woodframe	0.20	0.20
M_5	RC	0.70	0.70
	URM	0.45	0.45
	Woodframe	0.45	0.45
M_6		0.50	0.50

Once the casualty parameters are substituted into Equation 4.2, casualty curves of both study regions for each building class are obtained. Area under each curve denotes the expected number of casualties in 50 years for that building class. Sum of the individual expected casualties for every building class results yields the total-expected casualty in each study region. Example casualty curves for study region 1 are presented in Figure 6.11 Expected number of casualties in 50 years in study regions 1 and 2 are presented in Table 6.9, while Table 6.10 illustrates the number of casualties expected as a result of the events with different return periods.

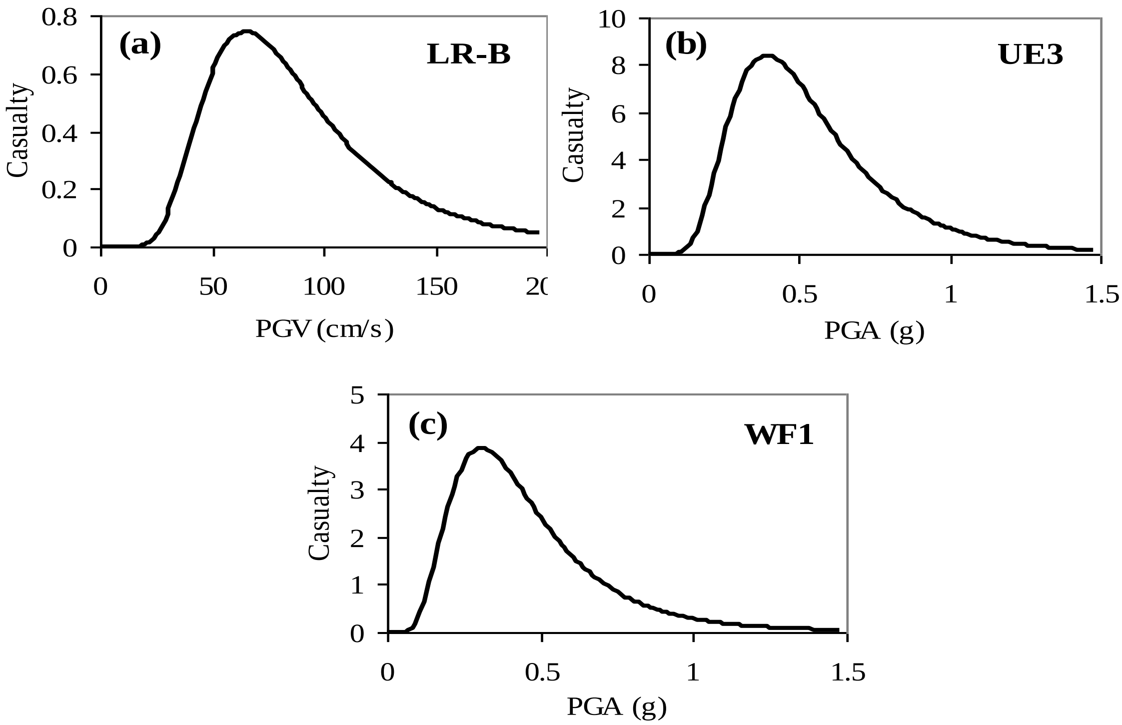

Figure 6.11: Example casualty curves in study region 1 for 50 years for building sub-classes **(a)** LR-B, **(b)** UE3, **(c)** WF1

Table 6.9: Expected number of casualties in 50 years for study regions 1 and 2

	Expected number of casualties for study region 1	Expected number of casualties for study region 2
Reinforced Concrete	147	850
Masonry	55	1639
Woodframe	9	31
Total	211	2520
Casualty Ratios (%)	0.30	0.27

Table 6.10: Number of casualties expected with different return periods for study regions 1 and 2

Return Period (years)	**Study Region 1**			
	RC	**URM**	**Woodframe**	**Total**
10	0	0	0	0
50	0	5	0	5
100	8	14	2	24
250	122	36	7	165
475	447	56	12	515
1000	1111	78	18	1,207
2475	1952	101	24	2,077
Return Period (years)	**Study Region 2**			
	RC	**URM**	**Woodframe**	**Total**
10	0	42	0	42
50	14	624	7	645
100	132	1098	22	1,252
250	2347	2063	66	4,476
475	7570	2757	103	10,430
1000	16197	3529	146	19,872
2475	26101	4224	189	30,514

In summary, 211 people are expected to lose lives in study region 1 in 50 years which is 0.30% of the population while 2520 people are expected to lose lives in study region 2 in 50 years which is 0.27% of the population. Study region 2 is populated about more than 10 times when compared to the study region 1. Therefore, expected number of casualties for study regions show considerable differences while the casualty ratios for both study regions are quite similar. Since the damage distributions in both study regions are at the same order of magnitude, similar casualty ratios are also expected. The number of casualties considerably increases with increasing return periods.

6.6 Economic Loss Assessment

Seismic events result in considerable amount of monetary losses. These losses are caused by structural damage, non-structural damage, interruptions on production, demand and employments as well as the secondary events. As in the case of seismic casualty estimation methodology, a multidisciplinary study should be performed in order to estimate total seismic economic loss within a certain range of accuracy.

. In this study, only the urban residential buildings in the study regions are taken into account, therefore the industrial, commercial and governmental losses are neglected. Rental losses can be considered as residential indirect economic losses, but their contribution to the economic loss is also neglected in this study. Computation of economic losses due to non-structural damage requires structural and architectural plans of the buildings as well as detailed structural analyses. Economic losses resulted from secondary events are difficult to estimate since there is scarcity of available data. These losses are out of the scope of this study. In other words, this study considers the economic loss caused only by direct structural damage.

Economic losses resulting from structural damage is a function of building vulnerability distributions. As discussed before, three damage states exist in the quantification of seismic fragility for all building types in this study. Repair costs of the buildings in DS1 and DS2 and replacement costs of the buildings in DS3 are considered as direct economic losses caused by structural damage.

As mentioned in Chapter 5, in order to estimate direct economic losses due to direct structural damage, HAZUS definitions are employed. In HAZUS, cost of structural damage of an occupancy class is defined as the multiplication of the building replacement cost of that class by the mean damage ratio. Total cost of structural damage is obtained by integrating the results for all occupancy classes. The expected seismic economic loss is computed using Equation 5.1 in Chapter 5.

In general terms, economic loss in this study is computed by multiplying total cost of initial construction by the mean damage ratio of corresponding building classes. Table 6.11 illustrates the MDRs of RC, URM and woodframe structures. In Table 6.11, CDRs are modified from the values suggested by Askan and Yücemen (2010).

Table 6.11: MDRs of RC, URM and woodframe structures in study region 2

		P(DS>LS$_i$)			**CDR x P(DS>LS$_i$)**		
	CDR (%)	RC	URM	Woodframe	RC	URM	Woodframe
DS1	5	0.88	0.88	0.55	0.044	0.044	0.0275
DS2	40	0.1	0.05	0.38	0.04	0.02	0.152
DS3	85	0.02	0.07	0.07	0.017	0.0595	0.0595
MDR (%)					**10.1**	**12.35**	**23.9**

In order to calculate average total cost of initial construction, total building area is multiplied by the unit cost of initial construction. These unit costs are obtained from Ministry of Public Works and Settlement, 2010 data. In this fashion, initial cost of construction of urban residential buildings are taken as 448 TL/m^2 (280 USD/m^2) and 577 TL/m^2 (350 USD/m^2) for the ones up to 4 stories and more than 4 stories, respectively. Average building floor area in study region 2 is calculated as 119 m^2 in Chapter 5. Average building floor area multiplied by the number of stories in a building results in average total building area.

Finally, the expected economic loss caused by RC, URM and woodframe residential buildings is presented in Table 6.12. Expected economic loss for the time period of 50 years in study region 2 is calculated as approximately 1.457 billion TL (911 million USD).

Table 6.12: 50 year expected economic loss for study region 2

Structural Type	50 year Expected economic loss (million TL)	50 year Expected economic loss (million USD)
RC Frame Building	1,049	655
URM Building	378	237
Woodframe	30	19
Total	1,457	911

The expected economic loss is the mean value considering all possible ground motions in the region of interest. In addition, this value does not include economic losses caused by other factors than the structural damage in the buildings. Therefore, the actual expected economic loss is definitely expected to be larger than 1.457 billion TL (911 million USD).

The seismic economic losses caused by structural damage for different return periods are presented in Table 6.13. As the return period of an event increases, the economic impact of this event also increases dramatically.

Table 6.13**:** Economic losses caused by structural damage of the residential buildings in study region 2 with different return periods.

Return Period (years)	Economic Loss in Study Region 2 (million TL)			
	RC	URM	Woodframe	Total
10	522	161	8	691
50	655	260	23	938
100	933	356	32	1,321
250	2,202	574	46	2,822
475	3,542	751	55	4,348
1000	5,092	977	63	6,132
2475	6,623	1,217	71	7,911

6.7 Seismic Loss Estimation of the 1999 Düzce Earthquake: A Validation Study

Formerly in this chapter, future seismic losses in study regions 1 and 2 are estimated probabilistically for 50 years. Since future events involve inherent uncertainties, a probabilistic approach is utilized. Consequently, the results of the study are presented in terms of expected damage distributions, casualties and economic losses within a certain period of time.

In order to check the validation of the proposed methodology, the estimated results should be compared with the observed data after a previous event. Study region 1 has experienced a major earthquake in 1999. Therefore, the results of the methodology proposed in this study are validated against the 1999 Düzce Earthquake (M_w=7.1).

For this deterministic case, probability of hazard is assumed to be unity and ground motion demand on the buildings is obtained from attenuation relationships used in this study (Akkar and Bommer, 2010 and Boore et al., 2008). Again, each one of the attenuation relationships has 50 percent weight. Similarly, ground motion levels are assumed to be constant throughout the selected district. The same fragility, casualty and economic loss functions of the probabilistic approach are adopted. One difference is as mentioned before, fragility sub-classes for deficient buildings are assigned to the buildings because, most of these buildings had already been damaged during the 1999 Kocaeli earthquake (M_w=7.4). Another difference is that, since this earthquake occurred at 18:58 p.m. with local time, instead of a mean occupancy at the time of earthquake (M_2) value, a constant value of M_2 is used. In this deterministic case, parameter M_2 is taken as 0.491.

The observed building damage after the 1999 Düzce Earthquake (Özmen, 2000) and estimated damage are presented in Figure 6.12. Düzce earthquake is a very special case, that only three months earlier, the region had experienced another catastrophic earthquake, the 1999 Kocaeli Earthquake (M_w=7.4). Thus, the buildings had already suffered from damage and were weaker than their expected performances, while most of the inhabitants had left their apartments.

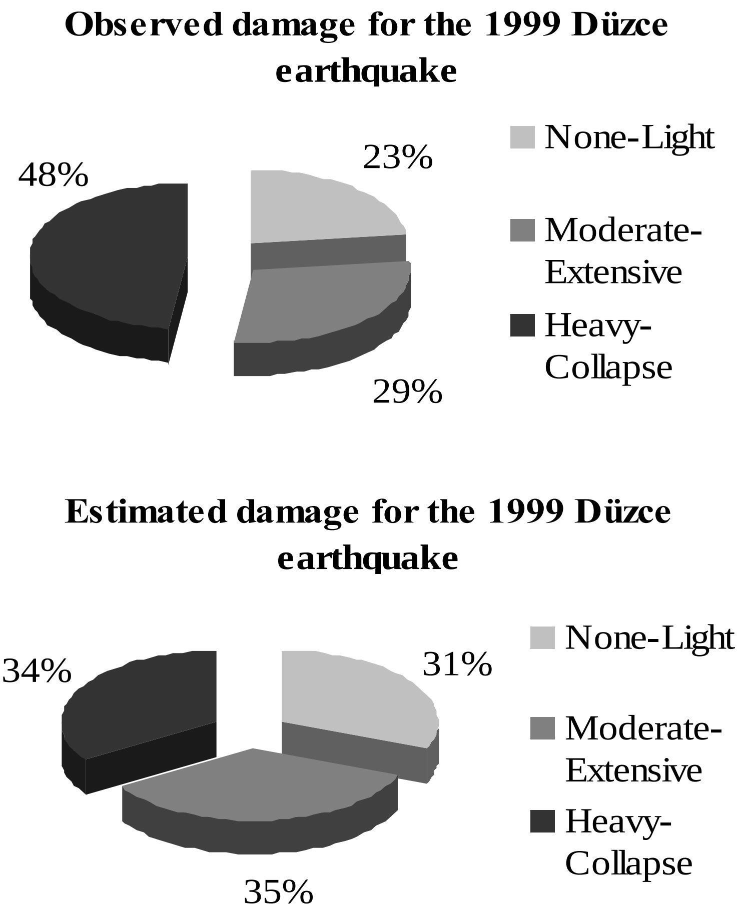

Figure 6.12. Observed and estimated damage distributions for the 1999 Düzce earthquake in study region 1 (Düzce city center)

The estimated inhabitants of the buildings were more than the actual population on the day of earthquake. Another important point is that the official number of casualties is between the number of casualties calculated by the probabilistic and deterministic approaches. This result is expected since the deterministic model tends to overestimate the hazard for a single event whereas the probabilistic model takes into account the entire magnitude range along with their probability of occurrences to estimate the expected hazard level in 50 years.

CHAPTER 7

SUMMARY AND CONCLUSIONS

7.1 Summary

The main objective of this study is to propose a seismic loss estimation model that will eventually be implemented for entire Turkey, for use in seismic design or rehabilitation of the buildings, disaster mitigation and emergency management. In order to take into account the inherent uncertainties of the components of seismic loss, a fully probabilistic approach is adopted. Proposed method considers every possible ground motion demand on the building stock in the study regions. This model is verified for Düzce city center (Study Region 1) and Osmangazi subprovince of Bursa (Study Region 2).

Ground motion parameters, peak ground velocity (PGV) and peak ground acceleration (PGA), are estimated from probabilistic seismic hazard analysis. PSHA is conducted using the computer program SEISRISK III (Bender and Perkins, 1987). Seismicity as well as the geometry and location of the seismic sources are defined from Kandilli Observatory and Earthquake Research Institute and Strong Ground Motion Database for Turkey respectively. In order to compute the activities of the seismic sources, exponential model suggested by Gutenberg and Richter (1958) is used. The ground motion prediction equations (GMPEs) derived by Boore et. al (2008) and Akkar and Bommer (2010) are adopted. Finally, in order to obtain the cumulative seismic hazard rates, Poisson model is utilized. In this study, hazard curves are derived for 50 years, where 50 years is the assumed mean economic lifetime of residential structures in Turkey. Cumulative seismic hazard functions for the study regions are then converted into probability density functions of seismic hazard for integration in the seismic risk assessment. Next, events with different return periods are extracted from the cumulative hazard curves. For the validation study, ground motion parameters of the deterministic scenario, 1999 Düzce Earthquake (M_w=7.1), is calculated using the aforementioned GMPEs.

Building damage is determined from appropriate fragility functions. In this study, new fragility curves are not derived, instead, previously derived functions for reinforced concrete (RC), unreinforced masonry (URM) and woodframe structures are adopted. For RC buildings, fragility curves generated by Erberik (2008a) are utilized, since these curves are based on the building stock in Study Region 1 and validation of the methodology after 1999 earthquakes is provided. Fragility curves for URM buildings in Turkey are only developed by Erberik (2008a) therefore, this study of Erberik (2008b) is adopted which was validated previously. No fragility curves have been generated for woodframe structures in Turkey, therefore the global fragility functions developed by Gencturk et al. (2008) are adopted. All of the aforementioned studies are slightly modified and the fragility curves are harmonized to provide consistency among each other in this study.

Fragility functions are integrated with the seismic hazard curves and probable distributions of damage caused by every possible seismic demand are computed. In other words, seismic risk, which is defined as probability of experiencing damage for a certain ground motion demand is calculated. Once the seismic risk curves are combined with the building inventory in the study regions, expected physical damage distributions are obtained.

In order to estimate the seismic casualties, an analytical relationship between the number of collapsed structures and number of fatalities suggested by Coburn and Spence (2002) is adopted and modified for Turkey. This analytical relationship consists of six parameters and considers the occupancy type, population of the building, occupancy at the time of earthquake occurrence, number of trapped occupants in the collapse, injury distribution at collapse, mortality post collapse.

Economic loss is calculated based on HAZUS methodology where mean damage ratios multiplied by total cost of initial construction of the buildings. This study only considers the direct economic losses caused by structural damage. Central damage ratios are modified from the values suggested by Askan and Yücemen (2010). Eventually, mean damage ratios are computed. Unit cost of initial construction is obtained from Ministry of Public Works and Settlement and average building area is computed from Census of Buildings 2000 data.

Finally, the building damage is combined with the derived casualty and economic loss functions and expected future seismic losses are estimated. The proposed methodology is validated against the observed damage and fatalities of 1999 Düzce Earthquake (M_w=7.1). Similarities and differences between observed and estimated values are discussed in detail.

7.2 Conclusions

Past experiences have proved that earthquakes have significant impacts one the socioeconomic life. Future seismic loss estimation is required especially for risk and loss mitigation purposes. Most of the earlier studies have terminated their research at the physical loss level. However, a study considering all of the components of seismic loss from the source of the event to the final socioeconomic impact is essential and beneficial. This study is an initial attempt for an end-to-end computation of seismic losses from seismic hazard to casualties and economic losses.

In this study, during the validation process for Study Region 1, it is observed that the building damage is underestimated whereas the number of casualties is overestimated. This is mainly due to the fact that study region 1, Düzce city center, is an exceptional case, where most of the buildings had already been damaged by another major earthquake that happened only three months ago and most of the people were not residing in their damaged houses when the earthquake happened. Therefore, it is not possible to know the actual state of the buildings and the number of habitants in these buildings at the time of the earthquake. These can only be approximated with a certain level of accuracy as done in this study. Moreover, the fragility curves used in this study do not distinguish heavy damage, partial collapse and total collapse states and consider these as one single damage state (i.e. DS3). This over simplification, which is vital since the fragility of a large population of buildings is under concern, eventually causes an overestimation in the number of casualties. In other words, the number of buildings, in which the occupants are trapped are assumed to be more than the actual number. Finally, it should also be pointed out that seismic hazard is considered to be constant throughout the region; this is an assumption that also increases the number of estimated casualties in the 1999 Düzce Earthquake.

This study suggests a methodology that estimates seismic casualty and economical losses within a conditional probability framework. The results are introduced to the benefits of economic and physical loss planners and insurance companies. On the basis of the methodology suggested herein and without disregarding the assumptions and simplifications made at different stages of the study, following conclusions are drawn:

- The results reveal that 5.1 % of the residential buildings in study region 1 and 3.8 % of the residential buildings in study region 2 are expected to suffer from at least heavy damage in 50 years. Expected numbers of casualties for study regions 1 and 2 in 50 years are 211 and 2520, respectively. The expected economic loss for study region 2 is 911 million USD in 50 years. Considering the 1999 Düzce earthquake, this study estimates a collapse rate of 34% for the residential buildings and 720 fatalities, while the observations state that 48% of the residential buildings have collapsed or suffered heavy damage with 469 fatalities in Düzce city center.

- For the 1999 Düzce earthquake, the official number of casualties (469) is between the expected number of casualties in 50 years (211) and the estimated number (722) by using a deterministic approach. This result is expected since the deterministic model tends to overestimate the hazard for a single event whereas the probabilistic model takes into account the entire magnitude range along with their probability of occurrences to estimate the expected hazard level in 50 years.

- For the events with lower return periods, relatively less damage and less seismic losses are expected. However, for an event with 2475 year return period, almost 30% of the population are expected to lose their lives while the economic loss caused only by structural damage will be about 8 billion TL (5 billion USD) for study region 2 only. It is observed that the increase in the loss levels decreases with increasing return periods.

- Considering all these results, improvements in the construction quality in highly populated and industrialized regions of Turkey (such as the study regions considered in this thesis) is crucial for risk mitigation.

- This is one of the most versatile studies performed for Turkey that combines seismic hazard with building fragilities in order to estimate the number of casualties and economic losses. The estimated results in terms of physical damage and casualties are observed to be in the same order of magnitude with the actual observations. It is always possible to improve the physical and economic loss estimations if the data concerning the loss parameters are improved.

7.3 Future Recommendations

- The proposed methodology is generated for Düzce city center and Osmangazi subprovince of Bursa. This methodology can be further developed and applied to entire Turkey. As a result, seismic loss maps can be developed for Turkey in terms of expected loss for various time periods, based on events with different return periods or based on alternative deterministic scenarios.

- A modular and practical seismic loss estimation methodology is proposed in this study. Different techniques can be used for the identification of seismic hazard and building fragility. The components, which may be obtained from any suitable method, could be easily integrated in the proposed algorithm to estimate seismic losses without altering the backbone of the methodology.

- An interdisciplinary study should be carried out in order to improve the parameters in the analytical equations of casualty and economic loss. Parameter M_1 and information on building stocks can be further improved if more detailed population and building data is available. An interdisciplinary cooperation with the social scientists would yield a better estimate of parameter M_2. In order to improve parameters M_3 and M_6, detailed structural analyses of typical building types should be performed. For better estimates of parameters M_4 and M_5, again more data is required from the health institutions. In this study, economic loss caused only by structural damage is taken into account. Other components of economic loss can be considered within an interdisciplinary study with researchers from the field of construction management.

- More comprehensive seismic loss studies can be performed by taking one step further and considering injury distribution of the victims, sheltering requirements, social impacts as well as the indirect and secondary economic losses.

- The resolutions in this study are relatively low due to the size of the study regions and lack of input data to be used during the analyses. This and similar studies point out the necessity of data collection and standardization. If the observed damage and loss data are recorded better, this will significantly improve future seismic loss studies. The collected data should be as unbiased as possible. In addition, the collected datasets should be continuously updated.

- An uncertainty analysis on the model parameters should be carried out and confidence intervals should be defined.

- The proposed methodology should be verified against future events, whenever data is available and if necessary, essential modifications should be considered.

REFERENCES

Abrahamson N., G.A. Atkinson, D. Boore, Y. Bozorhnia, K. Campbell, B. Chiou, I.M. Idriss, W. Silva, R. Youngs (2008). Comparison of the NGA Ground-Motion Records, *Earthquake Spectra* **24**; 45-66.

Abrahamson N.A., W.J. Silva (2008). Summary of the Abrahamson & Silva NGA Ground-Motion Relations, *Earthquake Spectra* **24**; 67-97.

Afete Hazırlık ve Deprem Eğitimi Derneği. http://www.ahder.org [12.06.2011].

Akkar S, J.J Bommer (2010). Empirical Equations for the Prediction of PGA, PGV, and Spectral Accelerations in Europe, the Mediterranean Region, and the Middle East, *Seismological Research Letters* **81-2**; 195-206.

Akkar S., H. Sucuoğlu, A. Yakut (2005). Displacement-Based Fragility Functions for Low- and Mid-Rise Ordinary Concrete Buildings, *Earthquake Spectra* **21-4**; 901-927

American Society of Civil Engineers (ASCE) (2000). Prestandard and Commentary for the Seismic Rehabilitation of Buildings, prepared for the SAC joint Venture, *Federal Emergency Management Agency*, Report No. **FEMA-356**, Washington, DC.

Ansal A., A. Akinci, G. Cultera, M. Erdik, V. Pessina, G. Tönük, G. Ameri (2009). Loss estimation in Istanbul based on deterministic earthquake scenarios of the Marmara Sea region (Turkey), *Soil Dynamics and Earthquake Engineering* **29-4**; 699-709.

Applied Technology Council (1985). Earthquake Damage Evaluation Data for California. ATC-13, Redwood City, California.

Applied Technology Council (1996). Seismic Evaluation and Retrofit of Concrete Building, ATC-40, Redwood City, California.

Applied Technology Council (2007). Recommending Methodology for Quantification of Building System Performace and Response Parameters, ATC-63, Redwood City, California.

Askan A. (2002). Stochastic Methods for the Estimation of Potential Seismic Damage, *MS Thesis, Civil Engineering Department, Middle East Technical University, Ankara Turkey.*

Askan A., M.S. Yücemen (2010). Probabilistic methods for the estimation of potential seismic damage: Application to reinforced concrete buildings in Turkey, *Structural Safety* **32-4**; 262-271.

Aslani H., E. Miranda (2005). Probabilistic Earthquake Loss Estimation and Loss Disaggregation in Buildings, *The John A. Blume Earthquake Engineering Center, Report No. 157*, Department Civil and Environmental Engineering, Stanford University, Stanford, CA, USA.

Ay B.O., M.A. Erberik (2008). Vulnerability of Turkish Low-Rise and Mid-Rise Reinforced Concrete Frame Structures, *Journal of Earthquake Engineering* **12-1**; 2-11.

Aydan Ö., H. Kumsar, R. Ulusay (2001). How to Infer the Possible Mechanism and Characteristics of Earthquakes from the Striations and Ground Surface Traces of Existing Faults, *Seismic Fault Induced Failures*; 161-170.

Bal E.İ., H. Crowley, R. Pinho (2008). Displacement-based earthquake loss assessment for an earthquake scenario in Istanbul, *Journal of Earthquake Engineering* **12-2**; 12-22.

Bal İ.E., H. Crowley, R. Pinho, F.G. Gülay (2007). Structural Characteristics of Turkish RC Building Stock in Northern Marmara Region for Loss Assessment Applications, *Istituto Universitario di Studi Superiori (IUSS) Press*, Pavia

Bender B., D. Perkins (1982). SEISRISK II: A Computer Program for Seismic Hazard Estimation, *U.S. Geological Survey, Open-File Report* **No. 82-293**.

Bender B., D. Perkins (1987). SEISRISK III: A Computer Program for Seismic Hazard Estimation, *U.S. Geological Survey Bulletin* **1772**.

Benito B., J.M. Gaspar-Escribano, J.M. Tevar, M.J. Garcia, E. Jimenez (2004). The Expel Code for Probabilistic Seismic Hazard Analysis and Uncertainties Evaluation, *13th World Conference on Earthquake Engineering, Vancouver, B.C., Canada*, 15pp

Bolt B.A. (2000). Earthquakes, *4th Ed., W.H. Freeman and Company*, New York.

Bommer J., R. Spence, M. Erdik, S. Tabuchi, N. Aydinoglu, E. Booth, D. del Re, O. Peterkan (2002). Development of an Earthquake Loss Model for Turkish Catastrophe Insurance, *Journal of Seismology* **6-3**; 431-446

Boore D.M., G.M. Atkinson (2008). Ground-Motion Prediction Equations for the Average Horizontal Component of PGA, PGV and 5%-Damped PSA at spectral periods between 0.01 s and 10.0 s, *Earthquake Spectra* **24**; 99-138.

Bulak B.S. (1997). A Sthocastic Methodology for the Estimation of Earthquake Insurance Premiums, *MS Thesis, Civil Engineering Department, Middle East Technical University, Ankara Turkey*.

Campbell K.W., Y. Bozorgnia (2008). NGA Ground Motion Model for the Geometric Mean Horizontal Component of PGA, PGV and 5%-Damped Linear Elastic Response Spectra for periods between 0.01 s and 10.0 s, *Earthquake Spectra* **24**; 139-171.

Çetin K.Ö., A.A. Yunatıcı, S. Çağlı, T. Gülkokar, R. Aktaş, F. Altınışık, S. Çelik, H.M. Arabacı, M. Çekmeceli (2004). GIS-Based Probabilistic Seismic Hazard and Liquefaction Initiation Assessment for the City of Bursa. *10th National Conference of Soil Mechanics and Foundation Engineering, Istanbul Technical University*, Istanbul, 2004. (In Turkish).

Çetin K.Ö., R.B. Seed, A. der Kiureghian (2000). Probabilistic Assessment of *Liquefaction Initiation Hazard, 12th World Conference in Earthquake Engineering*, Auckland, New Zeland, January 2000.

Çetin K.Ö., S. Ünsal, A.A. Yunatıcı (2009). An Integrated Seismi Hazard Framework for Assessing the Liquefaction Triggering of Dam Foundation Soils, *2nd Interational Dam Safety Symposium and Exhibition*, Eskişehir, 2009.

Chiang W-L., G.A. Guidi, C.P. Mortgat, C.C. Schoof, H.C. Shah (1984). Computer Program for Seismic Hazard Analysis. A User Manual (Stanfors Seismic Hazard Analysis-STASHA), *The John A. Blume Earthquake Engineering Center, Report No. 62*, Department Civil and Environmental Engineering, Stanford University, Stanford, CA, USA.

Chiou B.S., R.R. Youngs (2008). An NGA Model for the Average Horizontal Component of Peak Ground Moion and Response Spectra, *Earthquake Spectra* **24**; 173-215.

Chong W.H., T.T. Soong (2000). Sliding Fragility of Unrestrained Equipment in Critical Facilities, Technical Report MCEER-00-0005, *Multidisciplinary Center for Earthquake Engineering Research*, Buffalo, NY.

Coburn A., R. Spence (2002). Earthquake Protection, *2nd Ed., John Wiley and Sons*, London.

Coburn A.W., R.J.S. Spence, A. Pomonis (1992). Factors Determining Human Casualty Levels in Earthquakes: Mortaility Prediction in Building Collapse, *Proceedings of the Tenth World Conference on Earthquake Engineering*, Madrid, Spain.

Cornell C.A. (1968). Engineering Seismic Risk Analysis, *Bulletin of the Seismological Society of America* **58-5**; 1583-1606

Cornell C.A., S.R. Winterstein (1988). Temporal and Magnitude Dependence in Earthquakes in Earthquake Recurrence Models, *Bulletin of the Seismological Society of America* **78-4**; 1522-1537.

Crowley H., J.J. Bommer (2006). Modeling Seismic Hazard in Earthquake Loss Models with Spatially Distributed Exposure, *Bulletin of the Seismological Society of America* **4-3**; 249-273.

Demircioğlu M.B., M. Erdik, U. Hancilar, E. Harmandar, Y. Kamer, K. Sesetyan, C. Tuzun, C. Yenidogan, A.C. Zulfikar (2010). Earthquake Loss Estimation Routine ELER v3.0 Technical Manual, *Network of Research Infrastructures for European Seismology*.

Deniz A. (2006). Estimation of Earthquake Insurance Premium Rates Based on Stochastic Methods, *MS Thesis, Civil Engineering Department, Middle East Technical University, Ankara, Turkey*.

Erberik M.A. (2008a). Fragility-Based Assessment of Typical MidRrise and Low-Rise RC Buildings in Turkey, *Engineering Structures* **37-3**; 1360-1374.

Erberik M.A. (2008b). Generation of Fragility Curves for Turkish Masonry Buildings Considering In-Plane Failure Modes, *Earthquake Eng. and Structural Dynamics* **37-3**; 387-405.

Erdik M., M. Demircioğlu, K. Sesetyan, E. Durukal, B. Siyahi (2004). Earthquake Hazard in Marmara Region, Turkey, *Soil Dynamics and Earthquake Engineering* **24-8**; 605-631.

Erdik M., V. Doyuran, N. Akkaş, P. Gülkan (1985). A Probabilistic Assessment of Seismic Hazard in Turkey, *Tectonopyhsics* **117-3-4**; 295-344.

Erdik M., Y. Biro, T. Onur, K. Sesetyan, G. Birgoren (1999) Assessment of Earthquake Hazard in Turkey and Neighboring Regions, *Annali Di Geofisica* **42-6**; 1125-1138.

Ergönül S. (2005). A Probabilistic Approach for Earthquake Loss Estimation, *Structural Safety* **27-4**; 309-321.

FEMA (Federal Emergency Management Agency) (2003). HAZUS, Earthquake Loss Estimation Methodology: Technical Manual MR4. Federal Emergency Management Agency, Washington, DC.

FEMA (Federal Emergency Management Agency) (1999). HAZUS, Earthquake Loss Estimation Methodology: Technical Manual. Federal Emergency Management Agency, Washington, DC.

FEMA (Federal Emergency Management Agency) (2002). Seismic Hazard Analysis. Federal Emergency Management Agency, Washington, DC.

Fischer D., A. Filiatrault, B. Foltz, C.-M. Uang, F. Seible (2001). Shake Table Tests of a Two Story Woodframe House, CUREE Consortiun of Universities for Research in Earthquake Engineering **Publication No. W-06**, Richmond, CA.

Freeman J.R. (1932). Earthquake Damage and Earthquake Insurance: Studies of a Rational Basis for Earthquake Insurance, also Studies of Engineering Data for Earhquake-Resisting Construction, *1st Ed.*, *McGraw-Hill*, New York.

Furukawa A., R. Spence, Y. Ohta, E. So, (2010). Analytical Study on Vulnerability Functions for Casualty Estimation in the Collapse of Adobe Buildings Induced by Earthquake, *Bulletin of the Seismological Society of America* **8-2**; 451-479

Gencturk B., A.S. Elnashai, J. Song (2008). Fragility Relationships for Populations of Woodframe Structures Based on Inelastic Response, *Journal of Earthquake Engineering* **12-S2**; 119-128.

Gülkan P., A. Gürpınar (1977). Northwestern Anatolian Earthquake Risk, *Earthquake Engineering Research Center*, METU, Ankara **Report No.** 77-05. (in Turkish).

Gülkan P., A. Kocyigit, M.S. Yücemen, V. Doyuran, N. Başöz (1993). A Seismic Zone Map of Turkey Derived From Recent Data, *Earthquake Engineering Research Center, METU*, **Report No. 93-01** (in Turkish).

Gülkan P., M.S. Yücemen (1975). A Seismic Risk Study of İzmir, *Proceedings of 5th European Confererence on Earthquake Engineering* **2**, *İstanbul.*

Gülkan P., M.S. Yücemen (1976). Assessment of Seismic Risk for Akkuyu, *Applied Research Report* **No. 76-04-03-37**, METU, Ankara.

Gülkan P., O. Ergunay, H. Sucuoglu (1992) Earthquake Vulnerability, Loss and Risk Assessment in Turkey, *Proceedings of the Tenth World Conference on Earthquake Engineering*, Madrid, Spain.

Gupta I.D. (2002). The State of the Art in Seismic Hazard Analysis, *ISET Journal of Earhquake Technology* **39-4**; 311-346

Gürpınar A., M. Abalı, M.S. Yücemen, Y. Yeşilçay (1978). Zorunlu Deprem Sigortası Uygunluğu, Deprem Mühendisliği Araştırma Enstitüsü, **Rapor No. 78-08**, *Orta Doğu Teknik Üniversitesi, Ankara, Türkiye.*

Gürpınar A., M.S. Yücemen (1980). An Obligatory Earthquake Insurance Model for Turkey, Proceedings of International Conference on Engineering for Protection from Natural Disasters, *Asian Institute of Technology*, Bangkok, Thailand, 895-906.

Gutenberg B, C.F. Richter (1956). Magnitude and energy of earthquakes, *Annali fi Geofisica*; **9(1)**.

Idriss I.M. (2008). Am NGA Empirical Model for Estimating the Horizontal Spectral Values Generated by Shallow Crustal Earthquakes, *Earthquake Spectra* **24**; 217-242.

Inan E., Z. Çolakoğlu, N. Koç, N. Bayülke, E. Çoruh (1996). Earthquake Catalogs with Acceleration Records from 1976 to 1996, *General Directorate of Disaster Affairs, Earthquake Research Department*, Ankara, Turkey, 98pp. (In Turkish).

Isoda H., B. Foltz, A. Filiatrault (2002). Seismic Modeling of Index Woodframe Buildings, CUREE Consortiun of Universities for Research in Earthquake Engineering **Publication No. W-12**, Richmond, CA.

Jaiswal K.S., D.J. Wald (2010). Development of Semi-Empirical Loss Model Within the USGS Prompt Assessment of Global Earthquakes for Response (PAGER) System, *Proceedings of 9th US and 10th Canadian Conference on Earthquake Engineering: Reaching Beyond Borders*, Toronto, Canada.

Japan International Cooperation Agency (JICA), Istanbul Metropolitan Municipality (IMM) (2002). A Disaster Prevention/Mitigation Basic Plan In Istanbul Including Microzonation in the Republic of Turkey, Technical Report.

Kalkan E., P. Gülkan (2004). Site-Dependent Spectra Derived from Ground Motion Records in Turkey, *Earthquake Spectra* **20-4**; 1111-1138.

Kandilli Observatory and Earthquake Research Institute. http://www.koeri.boun.edu.tr [18 November 2010]

Karaman H., M. Sahin, A.S. Elnashai (2008) Earthquake Loss Assessment Features of MAEviz-ISTANBUL(HAZTURK), *Journal of Earthquake Engineering* **12-S2**;175-186

King S.A., A.S. Kiremidjian, P. Sarabandi, D. Pachakis (2005) Correletion of Observed Building Performance with Measured Ground Motion, *The John A. Blume Earthquake Engineering Center, Report No. 148*, Department Civil and Environmental Engineering, Stanford University, Stanford, CA, USA.

Kircher C.A., A.A. Nassar, O. Kustu, W.T. Holmes (1997). Development of Building Damage Functions for Earthquake Loss Estimation, *Earthquake Spectra* **13-4**; 663-682.

Kırçıl M.S., Z. Polat (2006). Fragility Analysis of Mid-Rise R/C Frame Buildings, *Engineering Structures* **28-9**; 1335-1345.

Küçükçoban S. (2004). Development of a Software for Seismic Damage Estimation: Case Studies, *MS Thesis, Civil Engineering Department, Middle East Technical University, Ankara Turkey*

McGuire R.K. (1976). Fortran Computer Program for Seismic Risk Analysis, *U.S. Geological Survey, Open-File Report* **No. 76-67**, Denver, Colorado.

McGuire R.K. (1978). *FRISK:* Computer Program for Seismic Risk Analysis Using Faults as Earthquake Sources, *U.S. Geological Survey, Open-File Report* **No. 78-1007**.

McGuire R.K. (1993). Computation of Seismic Hazard, *Annali Di Geofisica* **36-3-4**; 181-200.

McGuire R.K. (1995). Probabilistic Seismic Hazard Analysis and Design Earthquakes: Closing the Loop, *Bulletin of the Seismological Society of America* **85-5**; 1275-1284.

McGuire R.K. (2004). Seismic Hazard and Risk Analysis. *Earthquake Engineering Research Institute*, MNO-10

Ministry of Public Works and Settlement http://www.bayindirlik.gov.tr [22.04.2011].

Ordaz M., Aguilar A., J. Arboleda (2001). CRISIS 2001. Program for Computing Seismic Hazard, Instituto de Ingenieria UNAM.

Özmen B., G. Bagci (2000). 12 November 1999 Düzce Earthquake Report, Ministry of Public Works and Settlement, General Directorate of Disaster Affairs, Ankara (in Turkish).

Özmen B., M. Nurlu, H. Güler (1997). Examination of Earthquake Zones by Geographic Information System, *The Ministry of Public Works and Settlement*, Ankara. (In Turkish).

Porter K.A., .J.L Beck, H.A. Seligson, C.R. Scawthorn, L.T. Tobin, R. Young, T. Boyd (2002). Improving Loss Estimation for Woodframe Buildings: Volume 1: Report, Final Report of Tasks 4.1 and 4.5 of the CUREE-Caltech Woodframe Project, *Consortium of Universities for Research in Earthquake Engineering*, Richmond, CA.

Reiter L. (1990). Earthquake Hazard Analysis Issues and Insights, *Columbia University Press*, New York.

Risk Engineering Inc. (2004). EZ-FRISK Version 6.12, Risk Engineering Inc., Boulder, Colorado.

Rosowsky, D. and P. WeiChiang (2007). Pushover Curves for Woodframe Buildings.

Rossetto T., A.S. Elnashai (2003). Derivation of Vulnerability Functions for European Type RC Structures Based on Observational Data, *Engineering Structures* **25-10**; 1241-1263.

Shinozuka M., M. Grigorlu, A.R. Ingrffea, S.L. Billington, P. Feenstra, T.T. Soong, A.M. Reinhorn, E. Maragakis (2000). Development of Fragility Information for Structures and Nonstructural Components, Technical Report MCEER2000, *Multidisciplinary Center for Earthquake Engineering Research*, Buffalo, NY

Smyth A.W., G. Altay, G. Deodatis, M. Erdik, G. Franco, P. Gulkan, H. Kunreuther, H. Luş, E. Mete, N. Seeber, Ö. Yüzügüllü (2004). Probabilistic Benefit-Cost Analysis for Earthquake Damage Mitigation: Evaluating Measures for Apartment Houses in Turkey, *Earthquake Spectra* **20-1**; 171-203.

So E.K.M. (2011). Challenges in Collating Earthquake Casualty Field Data, *Advances in Natural and Technological Hazard Research* **29-4**; 231-254.

Somerville P., N. Smith, S. Punyamurthula, S. Sun (1997). Development of Ground Motion Time Histories for Phase 2 of the FEMA/SAC Steel Project, *SAC Joint Venture, Background Document Report* **No. SAC/BD-97/04**.

Spence R.J.S., E.K.M. So (2011). Human Casualties in Earthquakes: Modelling and Mitigation, *Proceedings of the Ninth Pacific Conference on Earthquake Engineering Building an Earthquake-Resilient Society*, Auckland, New Zealand.

Stepp J.C. (1973). Analysis of Completeness of the Earthquake Sample in the Puget Sound Area, in Contributions to Seismic Zoning, *NOAA Tech. Report,* Washington D.C.

Strong Ground Motion Database for Turkey. http://daphne.deprem.gov.tr [03 December 2010].

T.C. Başbakanlık Kriz Yönetim Merkezi (2000). Depremler 1999, 17 Ağustos ve 12 Kasım Depremlerinden Sonra Bakanlıklar ve Kamu Kuruluşlarınca Yapılan Çalışmalar, T.*C. Başbakanlık Kriz Yönetim Merkezi*

Turkish Statistics Authority (http://www.tuik.gov.tr) [18.04.2011].

Uğurhan B. (2010). Stochastic Strong Ground Motion Simulations on North Anatolian Fault Zone and Central Italy: Validation, Limitation and Sensitivity Analyses, *MS Thesis, Civil Engineering Department, Middle East Technical University, Ankara Turkey*

Ugurhan B., A. Askan, M.A. Erberik (2011). A Methodology Loss Estimation in Urban Regions Based on Ground Motion Simulations, *Bulletin of the Seismological Society of America* **101-2**; 710-725.

Ulusay R., E. Tuncay, H. Sönmez, C. Gökçeoğlu (2004). An Attenuation Relationship Based on Turkish Strong Motion Data and Iso-Acceleration Map of Turkey, *Engineering Geology* **74-3-4**; 265-291.

Wald D.J., P.S. Earle, T.I. Allen, K. Jaiswal, K. Porter, and M. Hearne (2008). Development of the U.S. Geological Survey's PAGER system (Promt Assessment of Global Earhtquakes for Response). Proc. 14th World Conf. Earthq. Eng., Beijing, China, 8pp.

Wells D.L., K.J. Coppersmith (1994). New Empirical Relationships among Magnitude, Rupture Length, Rupture Width, Rupture Area and Surface Displacement, *Bulletin of the Seismological Society of America* **84**-4; 974-1002.

Wesnousky, S.G. (1994). Gutenberg-Richter or Characteristic Earthquake Distribution, Which Is It?, *Bulletin of the Seismological Society of America* **84-6**; 1940-1959.

WHE-PAGER, World Housing Encyclopedia (http://www.world-housing.net) [12.02.2011].

Whitman R.V. (1973). Damage Probability Matrices for Prototype Buildings, *Structural Publicaton* **380**, Massachuttes Institute of Technology, Boston, MA, USA.

World Agency of Planetary Monitoring and Earthquake Risk Reduction, (http://www.wapmerr.org/qlarm.asp) [20.05.2010].

Wyss M., G. Trendafiloski, Ph. Rosset (2009). Rapid Earthquake Casualty Estimates for Developing Countries, *Second International Workshop on Disaster Casualties*, Cambridge, June 2009.

Yılmaz N. (2008). Probabilistic Seismic Hazard Analysis: A Sensitivity Study with Respect to Different Models, *PhD Thesis, Civil Engineering Department, Middle East Technical University, Ankara Turkey*

Youngs R.R., K.J. Coppersmith (1985). Implications of Fault Slip Rates and Earthquake Recurrence Models to Probabilistic Seismic Hazard Estimates, *Bulletin of the Seismological Society of America* **75-4**; 939-964.

Yücemen M.S. (2008). Probabilistic Methods in Seismic Hazard Estimation in Basic Principles of Earthquake Engineering for Building Structures. Editors: Canbay E, Ersoy E, Özcebe G, Sucuoğlu H, Wasti TS. Ankara. (In Turkish).

Yücemen, M.S., B.S. Bulak (1997). Deprem Sigorta Primlerinin İstatistiksel Yöntemlerle Belirlenmesi, Dördüncü Ulusal Deprem Mühendisliği Konferansı, *Orta Doğu Teknik Üniversitesi, Ankara, Türkiye*, 699-707.

Yunatıcı A.A., K.Ö. Çetin (2007). Probabistic Seismic Hazard Analysis for Büyük Karaçay Dam and HEPP, *1st National Dam Safety Symposium and Exhibition*, Ankara, 2007. (In Turkish).

APPENDIX A

EARTHQUAKE CATALOG OF THE MAINSHOCKS WITHIN 200 KM AROUND STUDY REGION 1

Table A.1: Earthquake Catalog of the Mainshocks within 200 km around study region 1

	Year	Month	Day	Latitude	Longitude	Depth	Mw
1	1901	**5**	12	**39.8**	**30.5**	**15**	**5.3**
2	1905	4	15	**40.2**	**29**	**6**	**5.7**
3	1905	4	30	**39.8**	**30.5**	**22**	**5.5**
4	1905	10	22	**41**	**31**	**27**	**5.4**
5	1907	1	22	**41**	**29**	**12**	**4.7**
6	1907	8	21	**40.7**	**30.1**	**15**	**5.6**
7	1918	8	9	**40.89**	**33.41**	**10**	**5.8**
8	1919	5	27	**39.13**	**31.02**	**10**	**5.5**
9	1919	6	9	**41.16**	**33.2**	**10**	**5.8**
10	1919	6	9	**40.68**	**33.89**	**10**	**5.3**
11	1923	5	29	**41**	**30**	**25**	**5.6**
12	1923	10	26	**41.2**	**28.6**	**24**	**5.3**
13	1924	9	1	**40.9**	**29.2**	**15**	**4.6**
14	1925	6	10	**41**	**29**	**8**	**4.6**
15	1925	6	24	**40.88**	**30.39**	**10**	**4.8**
16	1925	9	14	**39**	**31**	**30**	**5.2**
17	1926	12	16	**40.13**	**30.72**	**10**	**5.8**
18	1927	2	7	**39**	**31**	**15**	**5.4**
19	1928	1	24	**40.99**	**30.86**	**10**	**5.5**
20	1928	5	2	**39.64**	**29.14**	**10**	**6**
21	1928	5	6	**39.8**	**30.5**	**12**	**5.3**
22	1928	10	4	**40.22**	**33.67**	**10**	**5.8**
23	1929	4	5	**41.5**	**31.5**	**33**	**4.9**
24	1929	4	8	**41.2**	**32.2**	**30**	**4.8**
25	1929	4	27	**40.51**	**31.43**	**70**	**4.9**
26	1932	10	15	**40.9**	**30.6**	**15**	**4.7**

Table A.1 (continued): Earthquake Catalog of the Mainshocks within 200 km around study region 1

	Year	Month	Day	Latitude	Longitude	Depth	Mw
27	1933	2	5	**41.5**	**31.5**	**10**	**4.6**
28	1933	5	15	**41.26**	**31.09**	**60**	**4.9**
29	1933	6	28	**39.3**	**33.2**	**30**	**4.9**
30	1933	7	12	**41.22**	**34.02**	**50**	**4.8**
31	1933	12	21	**41.21**	**33.64**	**60**	**4.9**
32	1935	7	12	**40.6**	**33.6**	**30**	**4.9**
33	1936	2	7	**42.3**	**29**	**15**	**4.7**
34	1936	11	18	**41.25**	**33.33**	**10**	**5.5**
35	1938	5	14	**39.74**	**33.55**	**10**	**4.9**
36	1938	5	31	**40.9**	**33.73**	**10**	**5.3**
37	1939	9	15	**39.76**	**29.56**	**20**	**5.8**
38	1940	2	1	**41**	**33**	**30**	**5.2**
39	1940	6	13	**41.34**	**30.17**	**30**	**4.8**
40	1940	8	19	**40.13**	**30.09**	**40**	**4.7**
41	1940	10	11	**40.81**	**33.3**	**10**	**5.2**
42	1943	4	14	**39.62**	**29.64**	**40**	**5.3**
43	1943	6	20	**40.85**	**30.51**	**10**	**6.4**
44	1943	9	6	**40.21**	**31.35**	**10**	**5.2**
45	1943	11	26	**41.05**	**33.72**	**10**	**6.8**
46	1944	2	1	**41.41**	**32.69**	**10**	**6.8**
47	1944	4	5	**40.84**	**31.12**	**10**	**5.6**
48	1944	6	25	**38.97**	**29.87**	**40**	**5.6**
49	1945	2	9	**40.5**	**31.2**	**30**	**5.2**
50	1946	1	21	**41.05**	**33.48**	**60**	**5.3**
51	1946	7	16	**38.63**	**31.15**	**40**	**5.3**
52	1946	8	25	**41.52**	**33.75**	**10**	**4.9**
53	1947	12	19	**40.71**	**32.82**	**10**	**5.2**
54	1948	11	13	**40.23**	**29.02**	**60**	**5.7**
55	1948	12	13	**41**	**30**	**15**	**4.5**
56	1949	5	13	**40.94**	**32.71**	**20**	**5.3**
57	1949	11	28	**40.98**	**30.74**	**10**	**4.9**
58	1951	3	12	**42**	**31.8**	**30**	**4.9**
59	1951	8	13	**40.88**	**32.87**	**10**	**6.6**
60	1952	1	22	**40.8**	**30.4**	**15**	**4.6**
61	1952	3	19	**39.6**	**28.64**	**40**	**5.5**
62	1953	6	3	**40.28**	**28.53**	**20**	**5.5**
63	1953	9	7	**41.09**	**33.01**	**40**	**6**

Table A.1 (continued): Earthquake Catalog of the Mainshocks within 200 km around study region 1

	Year	Month	Day	Latitude	Longitude	Depth	Mw
64	1953	12	13	**41.16**	**33.81**	**50**	**4.9**
65	1955	6	26	**41.11**	**33.33**	**10**	**4.8**
66	1956	1	6	**41**	**30.2**	**10**	**5.2**
67	1956	2	20	**39.89**	**30.49**	**40**	**6.2**
68	1956	8	28	**41.08**	**29.93**	**80**	**4.8**
69	1957	5	26	**40.67**	**31**	**10**	**6.7**
70	1957	9	21	**40.75**	**34.02**	**40**	**5.3**
71	1957	10	24	**40.06**	**29.75**	**10**	**4.9**
72	1957	12	26	**40.83**	**29.72**	**10**	**5.4**
73	1958	5	21	**40.65**	**33.36**	**10**	**4.8**
74	1959	4	2	**40.5**	**29.41**	**20**	**4.8**
75	1961	3	28	**39.82**	**30.19**	**10**	**5.3**
76	1962	4	19	**40.75**	**28.84**	**10**	**4.6**
77	1963	9	18	**40.77**	**29.12**	**40**	**6.2**
78	1964	6	19	**40.74**	**32.83**	**33**	**4.8**
79	1964	10	6	**40.3**	**28.23**	**34**	**6.2**
80	1964	12	13	**40.7**	**31**	**10**	**4.5**
81	1965	1	20	**40.5**	**34**	**33**	**4.7**
82	1965	4	3	**42.54**	**32.65**	**32**	**4.6**
83	1966	6	5	**39.07**	**29.34**	**36**	**4.5**
84	1966	11	3	**38.97**	**31.1**	**9**	**4.8**
85	1966	12	10	**41.09**	**33.56**	**13**	**5.1**
86	1966	12	30	**40.74**	**30.74**	**31**	**4.5**
87	1967	4	7	**40**	**31**	**10**	**4.5**
88	1967	6	13	**39.03**	**31.14**	**2**	**4.8**
89	1967	6	23	**40.85**	**33.65**	**20**	**5.4**
90	1967	7	22	**40.67**	**30.69**	**33**	**6.2**
91	1967	8	6	**41**	**28.8**	**10**	**4.5**
92	1968	5	6	**40.33**	**28.63**	**4**	**4.6**
93	1968	9	3	**41.81**	**32.39**	**5**	**6**
94	1968	11	9	**40.15**	**28.35**	**24**	**4.5**
95	1969	1	14	**39.4**	**30.1**	**10**	**4.5**
96	1969	2	12	**40.7**	**30.29**	**30**	**4.6**
97	1969	12	24	**40.5**	**28.4**	**10**	**4.7**
98	1970	3	28	**39.21**	**29.51**	**18**	**6.2**
99	1970	4	19	**40**	**30.9**	**10**	**5.3**
100	1970	4	24	**39.01**	**29.7**	**44**	**5.4**

Table A.1 (continued): Earthquake Catalog of the Mainshocks within 200 km around study region 1

	Year	Month	Day	Latitude	Longitude	Depth	Mw
101	1971	5	23	**39.96**	**28.72**	**3**	**4.6**
102	1971	5	25	**39.05**	**29.71**	**16**	**6**
103	1972	3	14	**39.32**	**29.47**	**38**	**5.6**
104	1972	5	28	**38.96**	**30.04**	**29**	**5.1**
105	1972	10	4	**39.14**	**29.44**	**34**	**4.8**
106	1973	2	19	**40.28**	**33.86**	**22**	**5**
107	1975	1	21	**39.07**	**30.67**	**23**	**4.8**
108	1975	7	30	**39.45**	**32.13**	**2**	**4.8**
109	1975	9	22	**40.36**	**33.4**	**3**	**4.5**
110	1976	2	18	**41.88**	**32.42**	**3**	**4.5**
111	1976	5	8	**39.33**	**29.1**	**33**	**5.1**
112	1976	8	22	**39.35**	**29.03**	**23**	**5.1**
113	1977	3	23	**39.63**	**28.65**	**23**	**4.5**
114	1977	9	25	**38.64**	**31.03**	**18**	**4.5**
115	1977	10	5	**41.02**	**33.57**	**10**	**5.6**
116	1978	6	10	**42.48**	**31.48**	**22**	**4.9**
117	1978	7	4	**39.45**	**33.19**	**23**	**5**
118	1979	6	28	**40.78**	**31.85**	**10**	**5**
119	1979	7	18	**39.66**	**28.65**	**7**	**5.5**
120	1980	2	14	**39.1**	**29.35**	**10**	**4.5**
121	1981	12	26	**40.15**	**28.74**	**7**	**5**
122	1981	12	28	**39.39**	**29.06**	**10**	**4.6**
123	1982	6	9	**40.14**	**28.89**	**10**	**4.5**
124	1983	4	21	**39.31**	**33.06**	**36**	**4.8**
125	1983	10	21	**40.14**	**29.35**	**12**	**5.3**
126	1983	11	6	**39.33**	**29.32**	**14**	**4.7**
127	1985	2	7	**39.02**	**29.88**	**36**	**4.7**
128	1985	4	6	**39.55**	**32.93**	**5**	**4.5**
129	1986	2	26	**38.98**	**31.52**	**10**	**4.5**
130	1986	10	17	**41.2**	**32.39**	**12**	**4.5**
131	1987	10	27	**40.42**	**28.46**	**18**	**4.5**
132	1988	4	24	**40.88**	**28.24**	**11**	**5.3**
133	1989	2	15	**39.05**	**29.71**	**23**	**4.5**
134	1990	8	5	**40.23**	**33.88**	**17**	**4.9**
135	1991	2	12	**40.8**	**28.82**	**10**	**5.1**
136	1992	3	22	**40.2**	**28.35**	**24**	**4.9**
137	1993	11	1	**38.94**	**29.95**	**7**	**4.8**

Table A.1 (continued): Earthquake Catalog of the Mainshocks within 200 km around study region 1

138	1993	12	12	**41.55**	**28.79**	**28**	**4.9**
139	1999	8	17	**40.76**	**29.95**	**17**	**7.5**
140	1999	8	24	**39.44**	**32.67**	**10**	**4.8**
141	1999	11	12	**40.81**	**31.19**	**10**	**7.2**
142	2000	6	6	**40.7**	**32.98**	**10**	**6**
143	2001	3	22	**38.74**	**30.87**	**10**	**4.9**
144	2001	8	12	**40.22**	**33.81**	**10**	**4.5**
145	2002	2	3	**38.63**	**30.9**	**10**	**6**
146	2004	4	13	**40.75**	**31.64**	**10**	**4.6**
147	2005	5	15	**38.62**	**30.78**	**10**	**4.5**
148	2005	7	30	**39.42**	**33.11**	**1**	**5.4**
149	2005	12	28	**40.98**	**33.29**	**6**	**4.5**

APPENDIX B

EARTHQUAKE CATALOG OF THE MAINSHOCKS WITHIN 200 KM AROUND STUDY REGION 2

Table B.1: Earthquake Catalog of the Mainshocks within 200 km around study region 2

	Year	Month	Day	Latitude	Longitude	Depth	Mw
1	1901	5	12	39.8	30.5	15	5.3
2	1903	4	4	39	28	20	5.6
3	1904	12	1	38.7	27.7	20	4.9
4	1905	1	11	39.6	27.9	15	5.3
5	1905	10	22	41	31	27	5.4
6	1905	4	30	39.8	30.5	22	5.5
7	1905	4	15	40.2	29	6	5.7
8	1907	1	22	41	29	12	4.7
9	1907	8	21	40.7	30.1	15	5.6
10	1912	8	10	40.6	27.1	15	6.2
11	1912	8	9	40.6	27.2	16	6.9
12	1917	4	10	40.6	27.1	15	5.5
13	1919	10	13	41.5	28	12	4.7
14	1919	5	27	39.13	31.02	10	5.5
15	1923	10	26	41.2	28.6	24	5.3
16	1923	5	29	41	30	25	5.6
17	1924	9	1	40.9	29.2	15	4.6
18	1924	4	14	39	27.8	15	4.9
19	1924	1	22	39.51	28.4	80	5.5
20	1924	12	22	39.6	27.7	15	5.5
21	1925	6	10	41	29	8	4.6
22	1925	6	24	40.88	30.39	10	4.8
23	1926	1	13	38.64	28.11	50	5.8
24	1926	12	16	40.13	30.72	10	5.8
25	1928	5	3	40.8	26.8	4	4.6
26	1928	5	6	39.8	30.5	12	5.3
27	1928	1	24	40.99	30.86	10	5.5
28	1928	5	2	39.64	29.14	10	6

Table B.1 (continued): Earthquake Catalog of the Mainshocks within 200 km around study region 2

29	**1929**	**10**	**10**	**41.11**	**27.46**	**15**	**4.7**
30	**1929**	**4**	**27**	**40.51**	**31.43**	**70**	**4.9**
31	**1932**	**10**	**15**	**40.9**	**30.6**	**15**	**4.7**
32	**1935**	**1**	**4**	**40.4**	**27.49**	**30**	**6.2**
33	**1935**	**1**	**4**	**40.3**	**27.45**	**20**	**6.2**
34	**1937**	**5**	**23**	**38.69**	**27.78**	**10**	**5.5**
35	**1938**	**7**	**2**	**40.17**	**27.88**	**10**	**5.3**
36	**1939**	**9**	**15**	**39.76**	**29.56**	**20**	**5.8**
37	**1940**	**8**	**19**	**40.13**	**30.09**	**40**	**4.7**
38	**1940**	**6**	**13**	**41.34**	**30.17**	**30**	**4.8**
39	**1941**	**2**	**9**	**40.13**	**28.27**	**30**	**4.8**
40	**1942**	**8**	**12**	**39.13**	**27.64**	**50**	**4.9**
41	**1942**	**2**	**5**	**38.84**	**27.74**	**10**	**5.5**
42	**1942**	**6**	**16**	**40.8**	**27.8**	**20**	**5.7**
43	**1942**	**10**	**28**	**39.1**	**27.8**	**50**	**6**
44	**1942**	**11**	**15**	**39.55**	**28.58**	**10**	**6**
45	**1943**	**9**	**6**	**40.21**	**31.35**	**10**	**5.2**
46	**1943**	**4**	**14**	**39.62**	**29.64**	**40**	**5.3**
47	**1943**	**6**	**20**	**40.85**	**30.51**	**10**	**6.4**
48	**1944**	**6**	**25**	**38.79**	**29.31**	**40**	**6**
49	**1945**	**2**	**9**	**40.5**	**31.2**	**30**	**5.2**
50	**1948**	**12**	**13**	**41**	**30**	**15**	**4.5**
51	**1948**	**8**	**10**	**38.48**	**28.94**	**80**	**5.2**
52	**1948**	**11**	**13**	**40.23**	**29.02**	**60**	**5.7**
53	**1949**	**1**	**4**	**38.9**	**27.9**	**14**	**4.7**
54	**1949**	**11**	**28**	**40.98**	**30.74**	**10**	**4.9**
55	**1950**	**11**	**28**	**39.73**	**28.05**	**40**	**5.3**
56	**1951**	**9**	**15**	**40.15**	**28.02**	**40**	**5.3**
57	**1952**	**1**	**22**	**40.8**	**30.4**	**15**	**4.6**
58	**1952**	**3**	**13**	**41.02**	**28.14**	**11**	**5.2**
59	**1952**	**3**	**19**	**39.6**	**28.64**	**40**	**5.5**
60	**1953**	**7**	**22**	**39.24**	**28.43**	**10**	**5.4**
61	**1953**	**6**	**3**	**40.28**	**28.53**	**20**	**5.5**
62	**1953**	**3**	**18**	**39.99**	**27.36**	**10**	**6.8**
63	**1956**	**7**	**18**	**39.96**	**27.3**	**60**	**4.7**
64	**1956**	**8**	**28**	**41.08**	**29.93**	**80**	**4.8**
65	**1956**	**1**	**6**	**41**	**30.2**	**10**	**5.2**

Table B.1 (continued): Earthquake Catalog of the Mainshocks within 200 km around study region 2

	Year	Month	Day	Latitude	Longitude	Depth	Mw
66	1956	2	20	39.89	30.49	40	6.2
67	1957	10	24	40.06	29.75	10	4.9
68	1957	10	11	39.32	28.19	10	5.2
69	1957	12	26	40.83	29.72	10	5.4
70	1957	5	26	40.67	31	10	6.7
71	1959	4	2	40.5	29.41	20	4.8
72	1959	7	26	40.91	27.54	10	5.5
73	1961	3	28	39.82	30.19	10	5.3
74	1962	4	19	40.75	28.84	10	4.6
75	1962	9	14	39.57	28.17	40	4.7
76	1963	4	28	39.32	27.82	30	4.9
77	1963	9	18	40.77	29.12	40	6.2
78	1964	12	13	40.7	31	10	4.5
79	1964	10	6	40.3	28.23	34	6.2
80	1965	10	18	38.83	27.83	36	4.7
81	1965	3	2	38.47	28.33	42	5.3
82	1966	6	5	39.07	29.34	36	4.5
83	1966	12	30	40.74	30.74	31	4.5
84	1966	5	22	38.7	27.92	23	4.9
85	1966	8	21	40.33	27.4	12	5.1
86	1967	4	7	40	31	10	4.5
87	1967	7	31	40.6	27.62	4	4.5
88	1967	8	6	41	28.8	10	4.5
89	1967	1	29	38.99	27.6	33	4.7
90	1967	5	9	39.61	27.15	37	4.7
91	1967	7	22	40.67	30.69	33	6.2
92	1968	3	21	38.8	27.6	52	4.5
93	1968	11	9	40.15	28.35	24	4.5
94	1968	5	6	40.33	28.63	4	4.6
95	1968	11	3	38.81	29.11	23	5.1
96	1969	1	14	39.4	30.1	10	4.5
97	1969	2	12	40.7	30.29	30	4.6
98	1969	12	24	40.5	28.4	10	4.7
99	1969	3	3	40.08	27.5	6	5.8
100	1969	3	25	39.25	28.44	37	5.8
101	1969	3	23	39.14	28.48	9	5.9
102	1969	3	28	38.55	28.46	4	6.1

Table B.1 (continued): Earthquake Catalog of the Mainshocks within 200 km around study region 2

	Year	Month	Day	Latitude	Longitude	Depth	Mw
103	1970	3	29	38.74	27.83	56	4.8
104	1970	4	9	39.4	27.9	15	4.8
105	1970	4	19	40	30.9	10	5.3
106	1970	5	12	38.6	29.3	33	5.3
107	1970	4	24	39.01	29.7	44	5.4
108	1970	4	23	39.13	28.65	28	5.5
109	1970	3	28	39.21	29.51	18	6.2
110	1971	5	23	39.96	28.72	3	4.6
111	1971	5	1	40.95	27.99	13	4.7
112	1971	4	27	38.91	29.06	14	4.9
113	1971	2	23	39.62	27.32	10	5.3
114	1971	5	25	39.05	29.71	16	6
115	1972	10	4	39.14	29.44	34	4.8
116	1972	9	3	39.16	27.98	30	4.9
117	1972	5	28	38.96	30.04	29	5.1
118	1972	3	14	39.32	29.47	38	5.6
119	1975	1	21	39.07	30.67	23	4.8
120	1976	5	8	39.33	29.1	33	5.1
121	1976	8	22	39.35	29.03	23	5.1
122	1977	3	23	39.63	28.65	23	4.5
123	1978	1	19	38.93	27.9	10	4.5
124	1978	6	15	40.79	27.68	28	4.9
125	1979	7	18	39.66	28.65	7	5.5
126	1980	2	14	39.1	29.35	10	4.5
127	1980	5	4	39.22	28.97	22	4.8
128	1981	12	28	39.39	29.06	10	4.6
129	1981	3	12	40.8	28.09	12	4.8
130	1981	12	26	40.15	28.74	7	5
131	1982	9	9	40.98	27.87	10	4.5
132	1982	7	12	41	27.83	25	4.7
133	1982	11	2	38.52	28.46	31	4.7
134	1983	11	6	39.33	29.32	14	4.7
135	1983	10	21	40.14	29.35	12	5.3
136	1983	7	5	40.33	27.21	7	5.8
137	1984	3	29	39.64	27.87	12	4.7
138	1985	4	27	40.74	27.38	9	4.5
139	1985	2	7	39.02	29.88	36	4.7

Table B.1 (continued): Earthquake Catalog of the Mainshocks within 200 km around study region 2

	Year	Month	Day	Latitude	Longitude	Depth	Mw
140	1985	12	1	39.29	27.7	10	4.7
141	1986	5	14	39.49	28.42	8	4.6
142	1987	10	27	40.42	28.46	18	4.5
143	1988	4	24	40.88	28.24	11	5.3
144	1989	2	15	39.05	29.71	23	4.5
145	1990	12	19	38.59	28.04	7	4.5
146	1991	2	12	40.8	28.82	10	5.1
147	1992	3	22	40.2	28.35	24	4.9
148	1993	11	1	38.94	29.95	7	4.8
149	1993	12	12	41.55	28.79	28	4.9
150	1995	2	8	40.8	27.77	10	4.6
151	1995	4	13	40.85	27.65	27	4.9
152	1998	3	5	39.55	27.3	23	4.6
153	1999	9	20	40.69	27.58	16	4.8
154	1999	7	25	39.33	27.98	15	5.2
155	1999	11	12	40.81	31.19	10	7.2
156	1999	8	17	40.76	29.95	17	7.5
157	2001	6	22	39.31	27.91	10	4.8
158	2002	3	23	40.81	27.84	12	4.5
159	2003	6	22	39.02	28.03	11	4.5
160	2003	6	9	40.21	27.94	17	4.8
161	2004	11	5	39.21	27.72	8	4.7