RELATIONSHIPS BETWEEN FELT INTENSITY AND RECORDED GROUND MOTION PARAMETERS FOR TURKEY

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

BY

MUSTAFA BİLAL

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

JANUARY 2013

Approval of the thesis:

RELATIONSHIPS BETWEEN FELT INTENSITY AND RECORDED GROUND MOTION PARAMETERS FOR TURKEY

submitted by **MUSTAFA BİLAL** 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, Gradute School of **Natural and Applied Sciences** ____________

Prof. Dr. Ahmet Cevdet Yalçıner
Head of Department, **Civil Engineering** ____________

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

Examining Committee Members:

Prof. Dr. M. Semih Yücemen
Civil Engineering Dept., METU ____________

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

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

Assist. Prof. Dr. Zeynep Gülerce
Civil Engineering Dept., METU ____________

Dr. Nazan Kılıç
Disaster and Emergency Management Presidency, AFAD ____________

Date: 29.01.2013

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 : Mustafa Bilal
Signature :

ABSTRACT

RELATIONSHIPS BETWEEN FELT INTENSITY AND INSTRUMENTAL GROUND MOTION PARAMETERS FOR TURKEY

Bilal, Mustafa
M.Sc., Department of Civil Engineering
Supervisor: Assoc. Prof. Dr. Ayşegül Askan Gündoğan
January 2013, 85 pages

Earthquakes are among natural disasters with significant damage potential; however it is possible to reduce the losses by taking several remedies. Reduction of seismic losses starts with identifying and estimating the expected damage to some accuracy. Since both the design styles and the construction defects exhibit mostly local properties all over the world, damage estimations should be performed at regional levels.

Another important issue in disaster mitigation is to determine a robust measure of ground motion intensity parameters. As of now, well-built correlations between shaking intensity and instrumental ground motion parameters are not yet studied in detail for Turkish data.

In the first part of this thesis, regional empirical Damage Probability Matrices (DPMs) are formed for Turkey. As the input data, the detailed damage database of the 17 August 1999 Kocaeli earthquake (Mw=7.4) is used. The damage probability matrices are derived for Sakarya, Bolu and Kocaeli, for both reinforced concrete and masonry buildings. Results are compared with previous similar studies and the differences are discussed. After validation with future data, these DPMs can be used in the calculation of earthquake insurance premiums.

In the second part of this thesis, two relationships between the felt-intensity and peak ground motion parameters are generated using linear least-squares regression technique. The first one correlates Modified Mercalli Intensity (MMI) to Peak Ground Acceleration (PGA) whereas the latter one does the same for Peak Ground Velocity (PGV). Old damage reports and isoseismal maps are employed for deriving 92 data pairs of MMI, PGA and PGV used in the regression analyses. These local relationships can be used in the future for ShakeMap applications in rapid response and disaster management activities.

Keywords: Damage probability matrix, reinforced concrete buildings, masonry buildings, felt-intensity, least-squares regression, Modified Mercalli Intensity (MMI).

ÖZ

TÜRKİYE İÇİN HİSSEDİLEN ŞİDDET İLE ÖLÇÜLEN YER HAREKETİ PARAMETRELERİ ARASINDAKİ İLİŞKİ

Bilal, Mustafa
Yüksek Lisans, İnşaat Mühendisliği Bölümü
Tez Yöneticisi: Doç. Dr. Ayşegül Askan Gündoğan
Ocak 2013, 85 sayfa

Depremler yüksek hasar potansiyeli taşıyan doğal afetlerdir. Ancak bu afetlerden doğacak kayıpları çeşitli önlemler ile azaltmak mümkündür. Sismik kayıpların azaltılması hasarın tanımlanması ve belli bir mertebe derecesinde belirlenmesi ile başlar. Tüm dünyada hem tasarım biçimleri hem yapım kusurları bölgesel özellikler gösterdiği için, hasar belirlemeleri bölgesel düzeyde gerçekleştirilmelidir.

Zarar azaltma konusunda bir diğer önemli husus, yer hareketi şiddeti için güvenilir bir ölçünün belirlenmesidir. An itibariyle, Türkiye verileri için hissedilen şiddet ile ölçülen yer hareketi parametreleri arasında iyi kurulmuş bağıntılar bulunmamaktadır.

Bu tezin birinci kısmında, Türkiye için bölgesel ampirik Hasar Olasılık Matrisleri (HOM) oluşturulmuştur. Girdi verisi olarak 17 Ağustos 1999 Kocaeli (Mw=7.4) depreminin detaylı veritabanı kullanılmıştır. Hasar olasılık matrisleri Sakarya, Bolu ve Kocaeli'ndeki betonarme ve yığma yapılar için çıkarılmıştır. Sonuçlar önceki çalışmalar ile karşılaştırılmış ve farklar açıklanmıştır. Gelecek veriler ile doğrulandıktan sonra bu HOMlar, deprem sigorta prim hesaplarında kullanılabilecektir.

Bu tezin ikinci kısmında, doğrusal en küçük-kareler regresyon yöntemi kullanılarak hissedilen şiddet ile maksimum yer hareketi parametreleri arasında iki bağıntı oluşturulmuştur. Bu bağıntılardan ilki Değiştirilmiş Mercalli Şiddeti (MMI) ile Maksimum Yer İvmesi (MYİ), ikincisi ise MMI ile Maksimum Yer Hızı (MYH) arasındadır. Regresyon analizinde kullanılan 92 adet MMI, MYİ ve MYH veri çifti oluşturmak için eski hasar raporları ve eşşiddet haritaları kullanılmıştır. Bu yerel bağıntılar, gelecekte acil müdahale ve afet yönetimi amaçlarıyla ShakeMap uygulamalarında kullanılabilecektir.

Anahtar Kelimeler: Hasar Olasılık Matrisleri, betonarme yapılar, yığma binalar, hissedilen şiddet, en küçük-kareler regresyonu, Değiştirilmiş Mercalli Şiddeti (MMI).

To My Family
And My Supervisor Assoc. Prof. Dr. Ayşegül Askan Gündoğan

ACKNOWLEDGMENTS

I would like to express my deepest gratitude to my supervisor, Assoc. Prof. Dr. Ayşegül Askan Gündoğan for her invaluable guidance, knowledge, endless support, encouragement and insight throughout the research. It was a pleasure for me to work with her.

I would like to thank Prof. Dr. M. Semih Yücemen, Assoc. Prof. Dr. M. Altuğ Erberik and Dr. Nazan Kılıç for sharing their knowledge without any hesitation.

I would like to acknowledge AFAD, for the damage and MMI database provided.

I would like also to thank my dear family members, Elif, Mehmet, Sevde Bilal for their love and support.

Finally, I would like to thank Mehmet As, Gözde Bilgin, Melih Bozkurt, Özge Mişe, Fatma Nurten Şişman, Shaghayegh Karimzadeh and Arash Maghsoudloo for their help and true friendship.

TABLE OF CONTENTS

LIST OF TABLES

TABLES

LIST OF FIGURES

FIGURES

CHAPTER 1

INTRODUCTION

1.1General

Earthquakes are among natural disasters with significant damage potential; however it is possible to reduce the losses by taking several remedies. Reduction of seismic losses starts with identifying and estimating the expected damage to some accuracy. Estimation of potential seismic damage must be performed in a probabilistic framework due to the inherent random nature of the variables involved. Probabilistic approach can be applied in more than one way but the most common approaches are the analytical and empirical ones. In the analytical approach, reliability theory is used to estimate the probabilities that a group of structures will experience certain damage states. Empirical approach fundamentally employs relative frequency analyses on different damage states among all structures of interest. As the data source, empirical method relies on damage databases built from site surveys performed after major earthquakes. For realistic and complete estimates of damage probabilities, alternative methods must be used complementarily.

Since both the design styles and the construction defects exhibit mostly local properties all over the world, damage estimations should be performed at regional levels. However, there is a trade-off between the resolution and accuracy of loss estimation studies. As a result, practical but realistic models should be developed and validated whenever possible with real data in the form of case studies.

Another important issue in disaster mitigation is to determine a robust measure of ground motion intensity parameters. This is an essential research problem since the quantification of ground motion is important for many studies ranging from damage models to isoseismal maps or hazard analyses. The instrumental ground motion parameters such as peak ground acceleration, velocity or spectral quantities are used as completely quantitative measure of input ground motions. However, in some cases qualitative shaking intensity measures such as felt intensity are required. A common application is the digital isoseismal maps (or as recently called ShakeMaps) used for rapid response purposes. In ShakeMaps, the affected area is determined from relationships between felt intensity and instrumental ground motion parameters. Similar to damage assessment, studies related to felt intensity must be investigated on a regional scale.

Both damage estimations and felt intensity measures require well-archived and robustly-collected regional datasets. As of now, in Turkey there is significant on-going effort for realistic seismic damage prediction and loss estimation. On the other hand, robust correlations between shaking intensity and instrumental ground motion parameters are not yet studied in detail for Turkish data. Both research fields require intense and validated efforts for effective disaster mitigation in the country.

1.2Objectives and Scope

There are two fundamental objectives of this thesis. First one is to update the existing empirical damage probability matrices for Turkey using a detailed regional damage database. The second objective of this thesis is to derive relationships between instrumental ground motion parameters and felt intensity for Turkey. For both objectives, regional damage reports, surveys and isoseismal maps are employed. In the long run, results of this study and similar studies can be used for regional disaster mitigation purposes.

In Chapter 2, regional DPMs for both reinforced concrete and masonry structures are constructed using the detailed damage database of the 17 August 1999 Kocaeli (Mw=7.4) earthquake. The obtained matrices are then compared with the previous studies. Finally, a best estimate damage probability matrix for reinforced concrete structures is obtained by combining the empirical DPM proposed in this thesis with the subjective DPM from relevant studies.

In Chapter 3, relationships are proposed between subjective and instrumental measures of ground motions. For this purpose, correlations between MMI and PGA as well as MMI and PGV are obtained from a country-level database. The dataset involves 92 MMI versus PGA/PGV pairs from 14 earthquakes with moment magnitudes between 5.7 and 7.4. Then, the proposed relationships are compared with previous studies.

In Chapter 4, a summary of the thesis along with the conclusions is presented. Then, limitations of the current work are discussed in addition to recommendations for future studies.

The related literature is discussed in detail within each chapter.

CHAPTER 2

REGIONAL DAMAGE PROBABILITY MATRICES BASED ON DAMAGE DATA FROM 17 AUGUST 1999 KOCAELİ EARTHQUAKE (M_W=7.4)

2.1General

Earthquakes are natural disasters with significant damage potential but the resulting losses can be reduced by taking several measures. To reduce potential seismic damage, an essential first step is the strict application of seismic codes. In Turkey, up to now, the seismic design regulations have been modified seven times. The first regulation, became effective in 1940, was an adaptation of the Italian Code. Later, each updated version of the code included significant improvements (Alyamaç and Erdoğan, 2005). The current code was released in 2007.

According to the current regulations, a building designed according to the code should satisfy the following criteria:

- It should remain in the elastic range and have no damage when subjected to an earthquake of light intensity.
- It should not be damaged beyond the repairable damage limits when subjected to an earthquake of medium intensity.
- It should not collapse when subjected to an earthquake of high intensity.

To assess the damage rates under different shaking levels, damage needs to be quantified and measured in a standard manner. One approach to quantify seismic damage rates is to perform fragility analyses. Fragility is defined as the probability of a system reaching a limit state as a function of seismic intensity levels (Kafalı and Grigouri, 2004). The analyses are generally carried out by using analytical, empirical or subjective method where the results can be expressed in terms of fragility curves or damage probability matrices.

In the analytical method, in order to estimate the limit states of the structure, the seismic performance under a given ground motion level is observed through detailed time history analysis or other simplified methods.

The empirical method is based on the fundamental idea that similar type of structures experience similar damage rates under earthquakes. It involves analysis of empirical data collected in post-earthquake surveys.

The subjective method includes expert opinions for the assessment of the damage probabilities under various levels of shaking intensities. The experts are requested to give their opinions on the level of the damage based on their relevant experience on seismic damage assessment.

For engineered structures where a reasonable estimate of earthquake resistance can be made, analytical method is used. For non-engineered structures that are mostly built from materials with low resistance, seismic capacity is more difficult to calculate. Still, for these kinds of structures, there is plenty of data available making the empirical method suitable (Coburn and Spence, 2002).

While damage probability matrices show discrete values, fragility curves provide continuous representations. Indeed, fragility curves are functions that represent the probability of a structure's response to exceed performance limit states under various levels of seismic shaking (Shinozuka et al., 2000). In other words, these curves give the probability of exceedance of a certain damage state under a given seismic loading.

There has been considerable effort for creating fragility curves of building types in Turkey. Akkar et al. (2005) developed a methodology to generate fragility curves for 2, 3, 4, and 5 storey reinforced concrete buildings using the procedures defined in FEMA-356 (ASCE, 2000). The selected ground motion parameter is PGV for that study. Later, Kırçıl and Polat (2006) developed fragility curves for midrise residential buildings. The study was conducted with 12 reinforced concrete buildings of 3, 5 and 7 storeys that are built according to the 1975 code. Using 12 artificial ground motions, fragility curves for spectral acceleration (SA), spectral displacement (SD), and peak ground acceleration (PGA) are generated.

Erberik (2008a) generated fragility curves using 28 buildings that have experienced both the 17 August 1999 Kocaeli and 12 November 1999 Düzce (Mw=7.2) earthquakes. These buildings are divided into four groups according to the height of the building and existence of infill walls: low-rise bare frame (LRBF), low-rise infill walls (LRINF), mid-rise bare frame (MRBF), and mid-rise infill walls (MRINF). The ones with infill walls are further divided into three groups named as high, moderate and low classes according to their structural performance. Sub-class high is used for the new buildings that are constructed according to the code and are expected to show satisfactory performance in an earthquake. Moderate class buildings are the ones that are built according to the code but have some structural defects. Sub-class low represents the ones, which are non-engineered and have structural defects. Three limit states: serviceability, damage control and collapse prevention are selected in that study. Serviceability limit state is controlled by the stiffness of the structure; damage control limit state is controlled by strength; and collapse prevention is controlled by deformation. PGV is selected to be the main ground motion intensity parameter in that study. The probability of exceeding each limit state for various levels of PGV is obtained for the selected building types in Turkey.

Erberik (2008b) generated fragility curves also for masonry structures using database of the 1 October 1995 (Mw=6.4) Dinar earthquake and masonry structure database in Zeytinburnu province as a part of Istanbul Master Plan study. The database consists of 140 buildings for Dinar earthquake and 69 buildings for Zeytinburnu province. 120 subclasses are generated by classifying the buildings according to their number of storeys; type and quality of the material; plan geometry; and distribution of the load carrying walls and openings. Taking into account that masonry structures have limited deformation capacities, two limit states are defined as L1 and L2 representing the limits for elastic behaviour and ultimate capacity, respectively. PGA is used as the ground motion intensity measure due to its good correlation with the seismic behaviour of the rigid masonry structures. The resulting fragility curves are then compared with the observed damage rates of a group of masonry structures in the database of the 1 October 1995 Dinar earthquake. Time history analysis is carried out to obtain the seismic demand of the structures whereas the variability in the base shear capacity is obtained by pushover analysis.

An alternative way to express the vulnerability is to use damage probability matrices. A damage probability matrix (DPM) expresses the discrete probabilities for certain damage states to be experienced by a given building type during shaking of various intensities.

In this thesis, a regional empirical DPM is constructed using the detailed damage database resulting from the 17 August 1999 Kocaeli earthquake. Such detailed DPMs are necessary for a regional evaluation of the correlation between damage ratios and hazard levels. In the following sections, first, DPMs are described in detail along with the previous studies, and then the DPMs derived in this work are presented.

2.2Damage Probability Matrices

DPMs were first introduced by Whitman (1973), for multi-storey buildings in the aftermath of the 1971 San Fernando earthquake. An element in this matrix, Pr(DS,I), gives the probability of occurrence of a damage state (DS) under an earthquake intensity, I. The sum of any column in this matrix is equal to unity. Table 2.1 shows an example of a damage probability matrix.

Table 2.1: A typical damage probability matrix with central damage ratios as given by Gürpınar et al. (1978)

<table>
<tr><th>Damage State (DS)</th><th>Central Damage Ratio (%)</th><th>MMI=V</th><th>MMI=VI</th><th>MMI=VII</th><th>MMI=VIII</th><th>MMI=IX</th></tr>
<tr><td>None</td><td>0</td><td colspan="5" rowspan="5">Damage State Probabilities, Pr(DS,I)</td></tr>
<tr><td>Light</td><td>5</td></tr>
<tr><td>Moderate</td><td>30</td></tr>
<tr><td>Heavy</td><td>70</td></tr>
<tr><td>Collapse</td><td>100</td></tr>
</table>

Damage state (DS) is the verbal or rational representation of the damage that would result in a structure under an earthquake of specific intensity. Verbal definitions are generally used in qualitative assessment of damage. Rational expression is used to quantify the damage if the original cost of the structure is known. The ratio of the cost of repair to the cost of replacement of the structure is defined as Damage Ratio (DR). As the name implies, this ratio takes values that range from 0% to 100%. However, representative damage ratios are required in order to set a relationship with the damage states and make the calculations easier. Therefore, the term Central Damage Ratio (CDR) is defined for a representative value of each damage ratio.

Use of a single damage ratio is preferred to summarize a full DPM. This ratio is called Mean Damage Ratio (MDR) and is obtained by the following equation:

$$MDR\ (I) = \sum_{DS} \mathrm{Pr}(DS, I) * CDR(DS) \qquad (2.1)$$

where

MDR(I): Mean damage ratio corresponding to the intensity level I,

Pr(DS,I): Damage state probability defined as the ratio of number of buildings that are in damage state DS at intensity I to the total number of buildings subjected to the earthquake of intensity I as given in Equation (2.2),

CDR(DS): Central damage ratio corresponding to damage state DS.

An element in this matrix Pr(DS,I) is obtained by the following equation (Whitman, 1973):

$$\mathrm{Pr(DS, I)} = \frac{\mathrm{N(DS, I)}}{\mathrm{N(I)}} \tag{2.2}$$

It should be kept in mind that, there may be variations in the damage resulting from particular intensity of earthquake due to different resistances introduced by the design or quality of construction; or due to the spatial differences in ground motion values although the felt intensity is mostly the same.

In general, Modified Mercalli Intensity (MMI) is used for defining shaking intensities. MMI is a qualitative and subjective assessment instrument that is based on the observed damage and human responses to the ground motion. However, most of the isoseismal maps of the earthquakes occurred in Turkey are prepared based on the Medvedev-Sponheuer-Karnik (MSK) scale. This scale was first proposed by Sergei Medvedev, Wilhelm Sponheuer and Vit Karnik in 1964. It has 12 levels similar to the Modified Mercalli Intensity scale. MSK became very popular in Europe and USSR in late 1970s and early 1980s. Then in 1990s European Seismological Commission formulated a new measure called “European Macroseismic Scale” based on the principles of the MSK scale. However today, MMI is still the most extensively used seismic scale for intensity measurement. Therefore, in order to be consistent with the current studies, in this study MSK values are converted to MMI values to be used in damage probability matrices. Similarly, in the next chapter, to derive a relationship between measured ground motion parameters and felt intensity, MMI values are employed. The conversion between different scales, including MMI and MSK, proposed by Musson et al. (2010) is presented in Table 2.2.

Table 2.2: Non prescriptive guidelines to conversion from five major scales to EMS-98 (after Musson et al., 2010)

MMI-56	**EMS-98**	**MSK**
1	1	1
2	2	2
3	3	3
4	4	4
5	5	5
6	6	6
7	7	7
8	8	8
9	9	9
10	10	10
11		11
12		12

Since the intensities in this thesis range between I and X, converting the MSK values directly to MMI values in this range is believed to contribute no significant error.

Studies show that as a result of alternative design strategies and damage distributions, different correlations between damage states and damage ratios arise. Table 2.3, which is a part of Whitman's study, presents the damage state definitions, damage ratios and corresponding central damage ratios. Later, the damage states are reduced as displayed in Table 2.4.

Table 2.3: Earthquake damage states (after Whitman, 1973)

	Description of Level of Damage	Damage Ratio	
		Central Value (%)	Range (%)
0	No Damage	0	0-0.05
1	Minor non-structural damage, a few walls and partitions cracked, incidental mechanical and electrical damage.	0.1	0.05-0.3
2	Localized non-structural damage, more extensive cracking (but still not widespread); possibly damage to elevators and/or other mechanical/electrical components.	0.5	0.3-1.25
3	Widespread non-structural damage, possibly a few beams and columns cracked, although not noticeable.	2	1.25-3.5
4	Minor structural damage, obvious cracking or yielding in a few structural members; substantial non-structural damage with widespread cracking.	5	3.5-7.5
5	Substantial structural damage requiring repair or replacement of some structural members; associated extensive non-structural damage.	10	7.5-20
6	Major structural damage requiring repair or replacement of any structural members; associated non-structural damage requiring repairs to major portion of interior; building vacated during repairs.	30	20-65
7	Building condemned.	100	20-65
8	Collapse	100	65-100

Table 2.4: Relationship between extended and shortened damage states

Extended (Original) Damage States	Shortened Damage States		
	Level of Damage	Symbol	CDR (%)
0	None	O	0
1 2	Light	L	0.3
3 4 5	Moderate	M	5
6	Heavy	H	30
7	Total	T	100
8	Collapse	C	100

In Turkey, originally five main damage states were used in damage assessment forms, which are No Damage (N), Light Damage (L), Moderate Damage (M), Heavy Damage (H) and Collapse (C). Later, heavy damage and collapse were combined to yield four different damage states.

Gürpınar et al. (1978) estimated the damage ranges and central damage ratios corresponding to five damage states mentioned above by using expert opinions and investigating previous studies. In this study, the CDR values of Gürpınar et al. (1978) as given in Table 2.5 are used in obtaining regional DPMs.

Table 2.5: Damage ratios and central damage ratios corresponding to each damage state (after Gürpınar et al., 1978)

Damage State	Damage Ratios (%)	Central Damage Ratio (%)
No Damage	0-1	0
Light Damage	1-10	5
Moderate Damage	10-50	30
Heavy Damage	50-90	70
Collapse	90-100	100

2.3 Previous Studies on Damage Probability Matrices

DPMs are a subject of interest in the literature worldwide. In this section some of them are discussed briefly.

2.3.1 Whitman (1973)

As previously mentioned, the first empirical DPM was developed by Whitman in 1973 based on the damage information from 1971 San Fernando earthquake. In that study, buildings are classified according to their age, type of building material and height. The buildings in the inventory are grouped as prior to 1933 and post 1947 according to their age. 1947 is the year that modern code requirements become effective in the United States. Between 1933 and 1947, not many buildings were constructed, therefore the buildings constructed between 1933 and 1947 were not taken into consideration in that study. According to the second classification criteria, the buildings are divided into two as steel or concrete based on their construction material. The buildings are further grouped according to their height using the number of stories. Table 2.6 gives the damage probability matrix prepared for 5-7 storey reinforced concrete buildings in the inventory.

Table 2.6: Empirical DPM constructed in Whitman's study (1973)

Damage State (DS)	**CDR (%)**	**MMI=VI**		**MMI=VII**		**MMI=VII-VIII**	
		Pre-1933	**Post-1947**	**Pre-1933**	**Post-1947**	**Pre-1933**	**Post-1947**
None	0	1.00	0.86	0.16	0.21	-	0
Light	0.3	0	0.14	0.42	0.42	-	0.25
Moderate	5	0	0	0.32	0.37	-	0.75
Heavy	30	0	0	0.10	0	-	0
Collapse	100	0	0	0	0	-	0
Total		1.00	1.00	1.00	1.00	-	1.00

2.3.2 Gürpınar et al. (1978)

As the first DPM for Turkey, Gürpınar et al. (1978) conducted a study on damage probability matrices to be used in relationship with the mandatory earthquake insurance program in Turkey. The study was carried out by preparing a questionnaire involving damage state probabilities of reinforced concrete structures under earthquakes of intensities MMI=V to MMI=IX. The questionnaire was sent to thirty experienced earthquake experts. Using their mean values of estimates, a subjective damage probability matrix is constructed. The matrices are prepared for earthquake zones 1 to 4. The conformity of the building to the code "Specifications for Structures to be Built in Disaster Areas" is classified as AC and NAC where AC stands for "in accordance with the code" and NAC stands for "not in accordance with the code". Table 2.7 to Table 2.10 present the subjective damage probability matrices obtained in that study.

Table 2.7: Subjective DPM, based on expert opinion, for seismic zone 1 in Turkey (after Gürpınar et al., 1978)

Damage State (DS)	CDR (%)	MMI=V		MMI=VI		MMI=VII		MMI=VIII		MMI=IX	
		AC	NAC	AC	NAC	AC	NAC	AC	NAC	AC	NAC
None	0	0.86	0.59	0.78	0.53	0.50	0.18	0.25	0.05	0.03	0
Light	5	0.11	0.20	0.15	0.21	0.32	0.24	0.39	0.20	0.18	0.07
Moderate	30	0.03	0.13	0.06	0.16	0.14	0.29	0.22	0.33	0.43	0.23
Heavy	70	0	0.05	0.01	0.06	0.02	0.19	0.11	0.24	0.28	0.40
Collapse	100	0	0.03	0	0.04	0.02	0.10	0.03	0.18	0.08	0.30
MDR(%)		1.45	11.4	6.25	14.05	9.2	33.2	19.25	45.7	41.4	65.3

Table 2.8: Subjective DPM, based on expert opinion, for seismic zone 2 in Turkey (after Gürpınar et al., 1978)

Damage State (DS)	CDR (%)	MMI=V		MMI=VI		MMI=VII		MMI=VIII		MMI=IX	
		AC	NAC	AC	NAC	AC	NAC	AC	NAC	AC	NAC
None	0	0.95	0.71	0.84	0.58	0.43	0.15	0.20	0.02	0.01	0
Light	5	0.05	0.15	0.13	0.18	0.39	0.30	0.19	0.17	0.12	0.06
Moderate	30	0	0.11	0.03	0.17	0.16	0.32	0.40	0.38	0.45	0.25
Heavy	70	0	0.03	0	0.05	0.02	0.19	0.18	0.28	0.35	0.38
Collapse	100	0	0	0	0.02	0	0.04	0.03	0.15	0.07	0.31
MDR(%)		0.25	6.15	1.55	11.5	8.15	28.4	28.6	46.9	45.6	65.4

Table 2.9: Subjective DPM, based on expert opinion, for seismic zone 3 in Turkey (after Gürpınar et al., 1978)

Damage State (DS)	**CDR (%)**	**MMI=V**		**MMI=VI**		**MMI=VII**		**MMI=VIII**		**MMI=IX**	
		AC	**NAC**	**AC**	**NAC**	**AC**	**NAC**	**AC**	**NAC**	**AC**	**NAC**
None	0	0.94	0.66	0.78	0.58	0.37	0.15	0.10	0.02	0	0
Light	5	0.06	0.20	0.19	0.15	0.37	0.22	0.26	0.16	0.09	0.02
Moderate	30	0	0.09	0.03	0.20	0.24	0.37	0.38	0.43	0.38	0.28
Heavy	70	0	0.05	0	0.05	0.02	0.19	0.22	0.23	0.32	0.38
Collapse	100	0	0	0	0.02	0	0.07	0.04	0.16	0.21	0.32
MDR(%)		0.3	7.2	1.85	12.3	10.5	32.5	32.1	45.8	55.3	67.1

Table 2.10: Subjective DPM, based on expert opinion, for seismic zone 4 in Turkey (after Gürpınar et al., 1978)

Damage State (DS)	**CDR (%)**	**MMI=V**		**MMI=VI**		**MMI=VII**		**MMI=VIII**		**MMI=IX**	
		AC	**NAC**	**AC**	**NAC**	**AC**	**NAC**	**AC**	**NAC**	**AC**	**NAC**
None	0	0.82	0.55	0.70	0.37	0.36	0.15	0.06	0.03	0	0
Light	5	0.10	0.20	0.24	0.17	0.35	0.22	0.25	0.08	0.06	0.03
Moderate	30	0.08	0.18	0.06	0.33	0.21	0.32	0.35	0.33	0.34	0.22
Heavy	70	0	0.07	0	0.07	0.05	0.20	0.21	0.32	0.39	0.37
Collapse	100	0	0	0	0.06	0.03	0.11	0.13	0.24	0.21	0.38
MDR(%)		2.9	11.3	3	21.7	14.6	35.7	39.5	56.7	58.8	70.7

In the same study, an empirical damage probability matrix is as well generated using damage assessment forms of the 22 May 1971 (Ms=6.8) Bingöl and 19 August 1976 (Mw=6.1) Denizli earthquakes prepared by the former General Directorate of Disaster Affairs. Data from these earthquakes helped to fill the columns for MMI=VI and MMI=VIII under NAC heading since these buildings were constructed before 1975 Code. Table 2.11 displays the corresponding DPM.

Table 2.11: Empirical DPM for seismic zone 1 in Turkey, based on earthquake damage reports (after Gürpınar et al., 1978)

Damage State (DS)	CDR (%)	MMI=V	MMI=VI	MMI=VII	MMI=VIII	MMI=IX
None	0	NA	0.40	NA	0.16	NA
Light	5	NA	0.38	NA	0.27	NA
Moderate	30	NA	0.17	NA	0.36	NA
Heavy	70	NA	0.05	NA	0.15	NA
Collapse	100	NA	0	NA	0.06	NA
MDR(%)		-	10.5	-	28.7	-

Later, the empirical and subjective DPMs are combined with subjective weights assigned to each component. The resulting hybrid DPMs are presented in Table 2.12 to Table 2.15.

Table 2.12: DPM proposed for seismic zone 1 in Turkey (after Gürpınar et al., 1978)

Damage State (DS)	CDR (%)	MMI=V		MMI=VI		MMI=VII		MMI=VIII		MMI=IX	
		AC	NAC	AC	NAC	AC	NAC	AC	NAC	AC	NAC
None	0	1	0.95	0.95	0.70	0.70	0.50	0.50	0.20	0.30	0.05
Light	5	0	0.05	0.05	0.15	0.20	0.20	0.20	0.20	0.30	0.20
Moderate	30	0	0	0	0.10	0.10	0.15	0.20	0.40	0.20	0.40
Heavy	70	0	0	0	0.05	0	0.10	0.10	0.10	0.20	0.20
Collapse	100	0	0	0	0	0	0.05	0	0.10	0	0.15
MDR(%)		0	0.25	0.25	7.25	4	17.5	14	30	21.5	42

Table 2.13: DPM proposed for seismic zone 2 in Turkey (after Gürpınar et al., 1978)

Damage State (DS)	CDR (%)	MMI=V		MMI=VI		MMI=VII		MMI=VIII		MMI=IX	
		AC	NAC	AC	NAC	AC	NAC	AC	NAC	AC	NAC
None	0	1	0.95	0.90	0.70	0.65	0.50	0.45	0.20	0.25	0.05
Light	5	0	0.05	0.10	0.15	0.20	0.20	0.25	0.20	0.30	0.20
Moderate	30	0	0	0	0.10	0.10	0.15	0.20	0.40	0.25	0.40
Heavy	70	0	0	0	0.05	0.05	0.10	0.10	0.10	0.20	0.20
Collapse	100	0	0	0	0	0	0.05	0	0.10	0	0.15
MDR(%)		0	0.25	0.50	7.25	7.5	17.5	14.3	30	23	42

Table 2.14: DPM proposed for seismic zone 3 in Turkey (after Gürpınar et al., 1978)

Damage State (DS)	CDR (%)	MMI=V		MMI=VI		MMI=VII		MMI=VIII		MMI=IX	
		AC	NAC	AC	NAC	AC	NAC	AC	NAC	AC	NAC
None	0	1	0.95	0.80	0.70	0.55	0.50	0.35	0.20	0.15	0.05
Light	5	0	0.05	0.10	0.15	0.20	0.20	0.25	0.20	0.30	0.20
Moderate	30	0	0	0.10	0.10	0.15	0.15	0.25	0.40	0.30	0.40
Heavy	70	0	0	0	0.05	0.10	0.10	0.15	0.10	0.25	0.20
Collapse	100	0	0	0	0	0	5	0	0.10	0	0.15
MDR(%)		0	0.25	3.5	7.25	12.5	17.5	19.3	30	28	42

Table 2.15: DPM proposed for seismic zone 4 in Turkey (after Gürpınar et al., 1978)

Damage State (DS)	**CDR (%)**	**MMI=V**		**MMI=VI**		**MMI=VII**		**MMI=VIII**		**MMI=IX**	
		AC	**NAC**	**AC**	**NAC**	**AC**	**NAC**	**AC**	**NAC**	**AC**	**NAC**
None	0	1	0.95	0.80	0.70	0.55	0.50	0.35	0.20	0.15	0.05
Light	5	0	0.05	0.10	0.15	0.20	0.20	0.25	0.20	0.30	0.20
Moderate	30	0	0	0.10	0.10	0.15	0.15	0.25	0.40	0.30	0.40
Heavy	70	0	0	0	0.05	0.10	0.10	0.15	0.10	0.25	0.20
Collapse	100	0	0	0	0	0	5	0	0.10	0	0.15
MDR(%)		0	0.25	3.5	7.25	12.5	17.5	19.3	30	28	42

2.3.3 Bulak (1997) and Yücemen and Bulak (1997)

Bulak (1997) and Yücemen and Bulak (1997) extended the previous studies on insurance premiums for Turkey. Empirical damage probability matrices for seismic zones 1 and 2 are obtained using damage assessment reports of the 22 May 1971 (Ms=6.8) Bingöl, 19 August 1976 (Mw=6.1) Denizli, 30 October 1983 (Mw=6.6) Erzincan, 05 May 1986 (Mw=6.0) Malatya and 13 March 1992 (Mw=6.6) Erzincan earthquakes. The empirical damage probability matrix obtained from those earthquakes is given in Table 2.16.

In that study, the buildings built not only before the code but also after the Code are classified as NAC. Since the information regarding the structures was insufficient, these structures are believed not to satisfy the requirements of the Code.

Bulak (1997) constructed damage probability matrices using weighted averages with respect to the number of buildings involved in each inventory. Combined empirical damage probability matrices with MMI=VI and MMI=VII for seismic zone 1 and damage probability matrices with MMI=VII and MMI=VIII for seismic zone 2 are presented in Table 2.17.

Table 2.16: Empirical damage data in the form of a DPM (after Bulak, 1997)

Damage State (DS)	CDR (%)	19.8.1976 Denizli MMI=VI	18.11.1983 Erzincan MMI=VI	6.6.1986 Malatya MMI=VII	22.05.1971 Bingöl MMI=VIII	13.3.1992 Erzincan MMI=VIII
None	0	0.49	0.74	0.45	0.04	0.31
Light	5	0.37	0.23	0.39	0.43	0.48
Moderate	30	0.13	0.03	0.12	0.26	0.09
Heavy	70	0.01	0.00	0.03	0.135	0.07
Collapse	100	0.00	0.00	0.00	0.135	0.05
Number of Buildings		378	112	89	46	415

Table 2.17: Empirical DPM for zones 1 and 2 with MMI values of VI, VII and VIII (after Bulak, 1997)

Damage State (DS)	CDR (%)	ZONE 1 MMI=VI	ZONE 2 MMI=VII	ZONE 2 MMI=VIII	ZONE 1 MMI=VIII
None	0	0.54	0.45	0.04	0.31
Light	5	0.34	0.39	0.43	0.48
Moderate	30	0.11	0.125	0.26	0.09
Heavy	70	0.01	0.035	0.135	0.07
Collapse	100	0.00	0.00	0.135	0.05
Number of Buildings		490	89	46	415

Bulak (1997) also developed a best estimate damage probability matrix that covers both AC and NAC buildings by combining subjective damage probability matrices of Gürpınar (1978) and empirical damage probability matrices using weighted averages of 0.25 and 0.75, respectively. These damage probability matrices are further revised by Yücemen and Bulak (2000). The final versions are given in Table 2.18 to Table 2.21.

Table 2.18: Best estimate DPM for zone 1 (after Yücemen and Bulak, 2000)

Damage State (DS)	**CDR (%)**	**MMI=V**		**MMI=VI**		**MMI=VII**		**MMI=VIII**		**MMI=IX**	
		AC	**NAC**	**AC**	**NAC**	**AC**	**NAC**	**AC**	**NAC**	**AC**	**NAC**
None	0	1	0.95	0.95	0.58	0.70	0.30	0.50	0.18	0.30	0.05
Light	5	0	0.05	0.05	0.29	0.20	0.42	0.20	0.41	0.30	0.20
Moderate	30	0	0	0	0.11	0.10	0.19	0.20	0.22	0.20	0.40
Heavy	70	0	0	0	0.02	0	0.08	0.10	0.10	0.20	0.20
Collapse	100	0	0	0	0	0	0.01	0	0.09	0	0.15
MDR(%)		0	0.25	0.25	6.1	4	14.9	14	25.2	21.5	42

Table 2.19: Best estimate DPM for zone 2 (after Yücemen and Bulak, 2000)

Damage State (DS)	**CDR (%)**	**MMI=V**		**MMI=VI**		**MMI=VII**		**MMI=VIII**		**MMI=IX**	
		AC	**NAC**	**AC**	**NAC**	**AC**	**NAC**	**AC**	**NAC**	**AC**	**NAC**
None	0	1	0.95	0.90	0.58	0.65	0.30	0.45	0.18	0.25	0.05
Light	5	0	0.05	0.10	0.29	0.20	0.42	0.25	0.41	0.30	0.20
Moderate	30	0	0	0	0.11	0.10	0.19	0.20	0.22	0.25	0.40
Heavy	70	0	0	0	0.02	0.05	0.08	0.10	0.10	0.20	0.20
Collapse	100	0	0	0	0	0	0.01	0	0.09	0	0.15
MDR(%)		0	0.25	0.50	6.1	7.5	14.9	14.3	25.2	23	42

Table 2.20: Best estimate DPM for zone 3 (after Yücemen and Bulak, 2000)

Damage State (DS)	**CDR (%)**	**MMI=V**		**MMI=VI**		**MMI=VII**		**MMI=VIII**		**MMI=IX**	
		AC	**NAC**	**AC**	**NAC**	**AC**	**NAC**	**AC**	**NAC**	**AC**	**NAC**
None	0	1	0.95	0.85	0.58	0.60	0.30	0.40	0.18	0.20	0.05
Light	5	0	0.05	0.10	0.29	0.20	0.42	0.25	0.41	0.30	0.20
Moderate	30	0	0	5	0.11	0.15	0.19	0.25	0.22	0.30	0.40
Heavy	70	0	0	0	0.02	0.05	0.08	0.10	0.10	0.20	0.20
Collapse	100	0	0	0	0	0	0.01	0	0.09	0	0.15
MDR(%)		0	0.25	2	6.1	9	14.9	15.8	25.2	24.5	42

Table 2.21: Best estimate DPM for zone 4 (after Yücemen and Bulak, 2000)

Damage State (DS)	**CDR (%)**	**MMI=V**		**MMI=VI**		**MMI=VII**		**MMI=VIII**		**MMI=IX**	
		AC	**NAC**	**AC**	**NAC**	**AC**	**NAC**	**AC**	**NAC**	**AC**	**NAC**
None	0	1	0.95	0.80	0.58	0.55	0.30	0.35	0.18	0.15	0.05
Light	5	0	0.05	0.10	0.29	0.20	0.42	0.25	0.41	0.30	0.20
Moderate	30	0	0	0.10	0.11	0.15	0.19	0.25	0.22	0.30	0.40
Heavy	70	0	0	0	0.02	0.10	0.08	0.15	0.10	0.25	0.20
Collapse	100	0	0	0	0	0	0.01	0	0.09	0	0.15
MDR(%)		0	0.25	3.5	6.1	12.5	14.9	19.3	25.2	28	42

2.3.4 Askan (2002) and Askan and Yücemen (2010)

Askan (2002) generated DPMs using three different stochastic approaches. The first approach involves derivation of DPMs using damage databases of major earthquakes occurred in Turkey (the 17 August 1999 Kocaeli and 12 November 1999 Düzce earthquakes). The second approach is based on classical reliability method in which the load and the capacity are taken as random variables. Finally, the third approach is computing damage rates with Discriminant Analysis. This method is a statistical technique which requires a number of parameters that are correlated with structural damage to identify the damage states with discriminant functions. The results from the alternative methods are compared among themselves. Herein, only the empirical and reliability-based DPMs from Askan (2002) are reviewed.

The damage assessment reports prepared by former General Directorate of Disaster Affairs and METU are used in Askan (2002) for the revision of the DPMs given by Yücemen and Bulak (1997). The data of 27 June 1998 (Mw=6.2) Ceyhan earthquake is not used because it is noticed that the damage states included a clear bias towards lower damage states. As observed in Table 2.22, it was possible to separate buildings as AC and NAC only in the inventory of 1 October 1995 Dinar earthquake. For other earthquake inventories, all of the buildings were considered as NAC.

Table 2.22: Empirical damage state probabilities compiled from different earthquakes (after Askan, 2002)

Damage State (DS)	CDR (%)	1976 Denizli MMI=VI	1983 Erzincan MMI=VI	1986 Malatya MMI=VII	1971 Bingöl MMI=VIII	1992 Erzincan MMI=VIII	1995 Dinar MMI=VIII		1999 Kocaeli MMI=IX	1999 Düzce MMI=IX
							AC	NAC		
None	0	0.49	0.74	0.45	0.12	0.31	0.23	0.24	0.04	0.17
Light	5	0.37	0.23	0.39	0.29	0.48	0.31	0.24	0.34	0.16
Moderate	30	0.13	0.03	0.12	0.31	0.09	0.38	0.41	0.27	0.28
Heavy	70	0.01	0	0.03	0.18	0.07	0.04	0.05	0.175	0.19
Collapse	100	0	0	0	0.10	0.05	0.04	0.06	0.175	0.20
Number of buildings and flats		378	112	89	46	415	39		79458 flats	31800 flats+119 buildings
Mean damage ratio (%)		6.45	2.05	7.65	33.35	15.00	19.75	23.00	39.55	42.50

The empirical damage probability matrices for MMI=VI, VIII and IX for seismic zone 1 and MMI=VII and VIII for seismic zone 2 obtained by Askan (2002) are given in Table 2.23.

Table 2.23: Empirical DPM for zones 1 and 2 (after Askan, 2002)

Damage State (DS)	CDR (%)	ZONE 1 MMI=VI	ZONE 2 MMI=VII	ZONE 2 MMI=VIII	ZONE 1 MMI=VIII	ZONE 1 MMI=IX
None	0	0.54	0.45	0.04	0.30	0.08
Light	5	0.34	0.39	0.43	0.45	0.29
Moderate	30	0.11	0.125	0.26	0.13	0.27
Heavy	70	0.01	0.035	0.135	0.07	0.18
Collapse	100	0.00	0.00	0.135	0.05	0.18
MDR(%)		5.7	8.15	32.9	16.1	40.15

In order to obtain a complete set of DPMs, Askan (2002) combined subjective DPMs of Gürpınar et al. (1978) and empirical DPMs obtained in that study with weights of 0.25 and 0.75, respectively. Best estimate DPMs of Askan (2002) are given in Table 2.24 to Table 2.27.

Table 2.24: Best estimate DPM proposed for zone 1 (after Askan, 2002)

Damage State (DS)	CDR (%)	MMI=V		MMI=VI		MMI=VII		MMI=VIII		MMI=IX	
		AC	NAC	AC	NAC	AC	NAC	AC	NAC	AC	NAC
None	0	1	0.95	0.95	0.58	0.70	0.46	0.50	0.28	0.30	0.07
Light	5	0	0.05	0.05	0.29	0.20	0.34	0.20	0.39	0.30	0.27
Moderate	30	0	0	0	0.11	0.10	0.14	0.20	0.20	0.20	0.30
Heavy	70	0	0	0	0.02	0	0.05	0.10	0.07	0.20	0.19
Collapse	100	0	0	0	0	0	0.01	0	0.06	0	0.17
MDR(%)		0	0.25	0.25	6.2	4	10.4	14	18.9	21.5	40.7

Table 2.25: Best estimate DPM proposed for zone 2 (after Askan, 2002)

Damage Damage State (DS)	CDR (%)	MMI=V		MMI=VI		MMI=VII		MMI=VIII		MMI=IX	
		AC	NAC	AC	NAC	AC	NAC	AC	NAC	AC	NAC
None	0	1	0.95	0.90	0.58	0.65	0.46	0.45	0.28	0.25	0.07
Light	5	0	0.05	0.10	0.29	0.20	0.34	0.25	0.39	0.30	0.27
Moderate	30	0	0	0	0.11	0.10	0.14	0.20	0.20	0.25	0.30
Heavy	70	0	0	0	0.02	0.05	0.05	0.10	0.07	0.20	0.19
Collapse	100	0	0	0	0	0	0.01	0	0.06	0	0.17
MDR(%)		0	0.25	0.50	6.2	7.5	10.4	14.3	18.9	23	40.7

Table 2.26: Best estimate DPM proposed for zone 3 (after Askan, 2002)

Damage State (DS)	CDR (%)	MMI=V		MMI=VI		MMI=VII		MMI=VIII		MMI=IX	
		AC	NAC	AC	NAC	AC	NAC	AC	NAC	AC	NAC
None	0	1	0.95	0.85	0.58	0.60	0.46	0.40	0.28	0.20	0.07
Light	5	0	0.05	0.10	0.29	0.20	0.34	0.25	0.39	0.30	0.27
Moderate	30	0	0	0.05	0.11	0.15	0.14	0.25	0.20	0.30	0.30
Heavy	70	0	0	0	0.02	0.05	0.05	0.10	0.07	0.20	0.19
Collapse	100	0	0	0	0	0	0.01	0	0.06	0	0.17
MDR(%)		0	0.25	2	6.2	9	10.4	15.8	18.9	24.5	40.7

Table 2.27: Best estimate DPM proposed for zone 4 (after Askan, 2002)

Damage State (DS)	**CDR (%)**	**MMI=V**		**MMI=VI**		**MMI=VII**		**MMI=VIII**		**MMI=IX**	
		AC	**NAC**	**AC**	**NAC**	**AC**	**NAC**	**AC**	**NAC**	**AC**	**NAC**
None	0	1	0.95	0.80	0.58	0.55	0.46	0.35	0.28	0.15	0.07
Light	5	0	0.05	0.10	0.29	0.20	0.34	0.25	0.39	0.30	0.27
Moderate	30	0	0	0.10	0.11	0.15	0.14	0.25	0.20	0.30	0.30
Heavy	70	0	0	0	0.02	0.10	0.05	0.15	0.07	0.25	0.19
Collapse	100	0	0	0	0	0	0.01	0	0.06	0	0.17
MDR(%)		0	0.25	3.5	6.2	9.5	10.4	16	18.9	28	40.7

As a second approach, Askan (2002) used the classical reliability model. Similar to the model proposed by Shiga (1977), that study considers force and resistance properties and definitions of an earthquake and seismic resistance index. The results obtained using classical reliability theory are given in Table 2.28 to Table 2.30.

Table 2.28: DPM for Erzincan damage database as generated by the reliability-based model (after Askan, 2002)

Damage State	**CDR(%)**	**VI**	**VII**	**VIII**	**IX**	**X**
None	0	0.97	0.87	0.61	0.30	0.08
Light	5	0.03	0.11	0.29	0.38	0.28
Moderate	30	-	0.01	0.08	0.21	0.30
Severe	85	-	0.01	0.02	0.11	0.34
MDR(%)		0.15	1.7	5.55	17.55	39.3

Table 2.29: DPM for Dinar damage database as generated by the reliability-based model (after Askan, 2002)

Damage State	**CDR(%)**	**VI**	**VII**	**VIII**	**IX**	**X**
None	0	0.97	0.81	0.41	0.10	0.01
Light	5	0.03	0.17	0.44	0.40	0.13
Moderate	30	-	0.01	0.13	0.35	0.33
Severe	85	-	0.01	0.02	0.15	0.53
MDR(%)		0.15	2	7.8	25.25	55.6

Table 2.30: DPM for Düzce damage database as generated by the reliability-based model (after Askan, 2002)

Damage State	**CDR(%)**	**VI**	**VII**	**VIII**	**IX**	**X**
None	0	0.99	0.88	0.60	0.23	0.05
Light	5	0.01	0.10	0.32	0.44	0.25
Moderate	30	-	0.01	0.06	0.24	0.35
Severe	85	-	0.01	0.02	0.09	0.35
MDR(%)		0.05	1.65	5.1	17.1	41.5

It is noticed that almost same degree of damage prediction for Erzincan and Düzce but higher estimates for Dinar earthquakes is obtained. Askan (2002) highlights that this is due to the lower amount of reinforced concrete wall areas in the buildings involved in Dinar inventory.

Further detailed information on this study could be found in Askan and Yücemen (2010).

That study was a first attempt to derive a regional DPM. However, in this thesis, a more detailed damage database is used.

2.3.5 Deniz (2006) and Deniz and Yücemen (2009)

Deniz (2006) obtained realistic estimates of the earthquake insurance premium rates for reinforced concrete and masonry structures in Turkey.

The study was carried out using conventional probabilistic seismic hazard analysis which involves comprehensive past earthquake data and local attenuation relationships based on recent strong motion records, in combination with modern and reliable statistical methods. Estimation of the damage was performed by both empirical and subjective damage probability matrices. Deniz (2006) obtained DPMs for 17 August 1999 Kocaeli, 12 November 1999 Düzce, 03 February 2002 Bolvadin-Çay-Sultandağı (Mw=6.5), 10 April 2003 İzmir-Urla-Seferhisar (Mw=5.7), 01 May 2003 Bingöl (Mw=6.3), 13 July 2003 Malatya-Pütürge-Doğanyol (Mw=5.5), 23-26 July 2003 Denizli-Buldan (Mw=5.3, Mw=4.9), 11 August 2004 Elazığ-Sivrice-Maden (Mw=5.6), 25 January 2005 Hakkari (Mw=5.8) and 12-14 March 2005 Çat-Karlıova (Mw=5.6, Mw=5.8) earthquakes from the archives of former General Directorate of Disaster Affairs.

Deniz (2006) combined the damage databases of 17 August 1999 Kocaeli and 12 November 1999 Düzce earthquakes to obtain a representative DPM using the damage assessment forms of Bolu, Düzce, Eskişehir, Sakarya, Yalova and Zonguldak.

Only two intensity maps prepared for 17 August 1999 Kocaeli (Özmen, 1999) and 03 February 2002 Bolvadin-Çay-Sultandağı earthquakes (Erdik et al., 2002) were available and used in analyses. The intensity values for remaining earthquakes were obtained by intensity attenuation relationship of Musson (2002). Finally, best estimate DPMs are generated in that study.

Further detailed information on that study could be found in Deniz and Yücemen (2009).

2.4 Derivation of Regional Empirical Damage Probability Matrices for Northwestern Turkey from the 17 August 1999 Kocaeli Earthquake

As discussed in the previous section, most of the past attempts in Turkey on DPMs are macro-scale studies which include damage ratios computed on a single intensity scale. In other words, every earthquake is assigned a single MMI value. Then, the damage ratios are calculated based on the damage databases collected mostly at the city centres that are closest to the epicenter of the earthquakes. However, as the spatial distribution of peak ground motion intensity parameters of major events show large variations, damage rate assessments need to be done at micro-scales whenever possible. This study provides a detailed and upgraded version of regional DPMs for Northwestern Turkey based on the isoseismal map of the 17 August 1999 Kocaeli earthquake prepared by the former General Directorate of Disaster Affairs. The spatial distributions of the MMI levels are different for the city centres studied in this thesis. Certainly the damage database also belongs to the 17 August 1999 Kocaeli event.

2.4.1 Data Collection and Regional DPMs

17 August 1999 Kocaeli earthquake (Mw=7.4) caused severe structural damage to the buildings in the Marmara region along with enormous social and economic losses.

Initially, to observe the spatial variation of the felt intensity during the 17 August 1999 Kocaeli earthquake, the isoseismal map given in Figure 2.1 is examined. It is observed that different city centres exhibit different MMI levels.

Next, in order to see the distribution of damage states in the region, city-wise DPMs are computed using damage assessment forms filled by experts of the former General Directorate of Disaster Affairs. The resulting DPMs are based on assessment of households instead of buildings, since the data is collected on household basis. Converting number of households to the number of buildings would further introduce error into the data. Also, in a previous study, Wu et al. (2004) state that household index is better than the building index for computing damage rates due to the detailed investigations involved. The regional DPMs in this thesis are formed by processing the database involving approximately 170,000 flats in the central districts of Sakarya, Kocaeli and Bolu. A typical form used in the assessment is given in Figure 2.2 and Figure 2.3. While filling the form, the experts gathered information not only about the damage state but also about the ownership and reconstruction phases.

The electronic damage database is formed from paper-based damage files (page by page) located at the Disaster and Emergency Management Presidency. Figure 2.4 shows the archive of Department of Recovery of AFAD.

In the forms the buildings are recorded in three different categories, namely Part A, B and C. Part A is used for masonry, part B is for framed and part C is for mixed type of structures. Masonry structures have six subtypes; rounded rubble masonry (A1), angular stone masonry (A2), ashlars stone masonry (A3), brick wall (A4), briquette (A5) and adobe (A6). Framed structures divide into three; half timbered (B1), timberwork (B2) and reinforced concrete (B3). The third type only has semi-framed (C1) as a subtype. It must be noted that some of this data is not recorded accurately. Some files do not involve number of storeys or other important information. However, rather than decreasing the database size, the DPMs are evaluated in coarser categories. In other words, in this study, number of storeys and detailed subtypes of buildings are not taken into consideration in the computation of DPMs.

In addition, in this study, the dataset is divided into two major groups, as reinforced concrete structures (B3) and others (O). Due to the very small number of B1, B2 and C1 buildings compared to the masonry buildings (A), those subgroups are neglected and group O indicates majorly the masonry buildings in the region. It must be noted that in this study, masonry subtypes are combined due to the lack of classification in most of the damage assessment forms.

In the damage reports, no information exists whether the buildings are designed according to the code or not. However, considering the common construction and design defects in the region, buildings used in the analyses are considered as NAC buildings. Given the field surveys after the 17 August 1999 Kocaeli earthquake, this assumption is believed to be valid for most buildings in the region.

First, the district level DPMs obtained in this study are presented in Table 2.31 to Table 2.33 along with the total number of households used for each district per building type. Then, comparisons with previous studies are made.

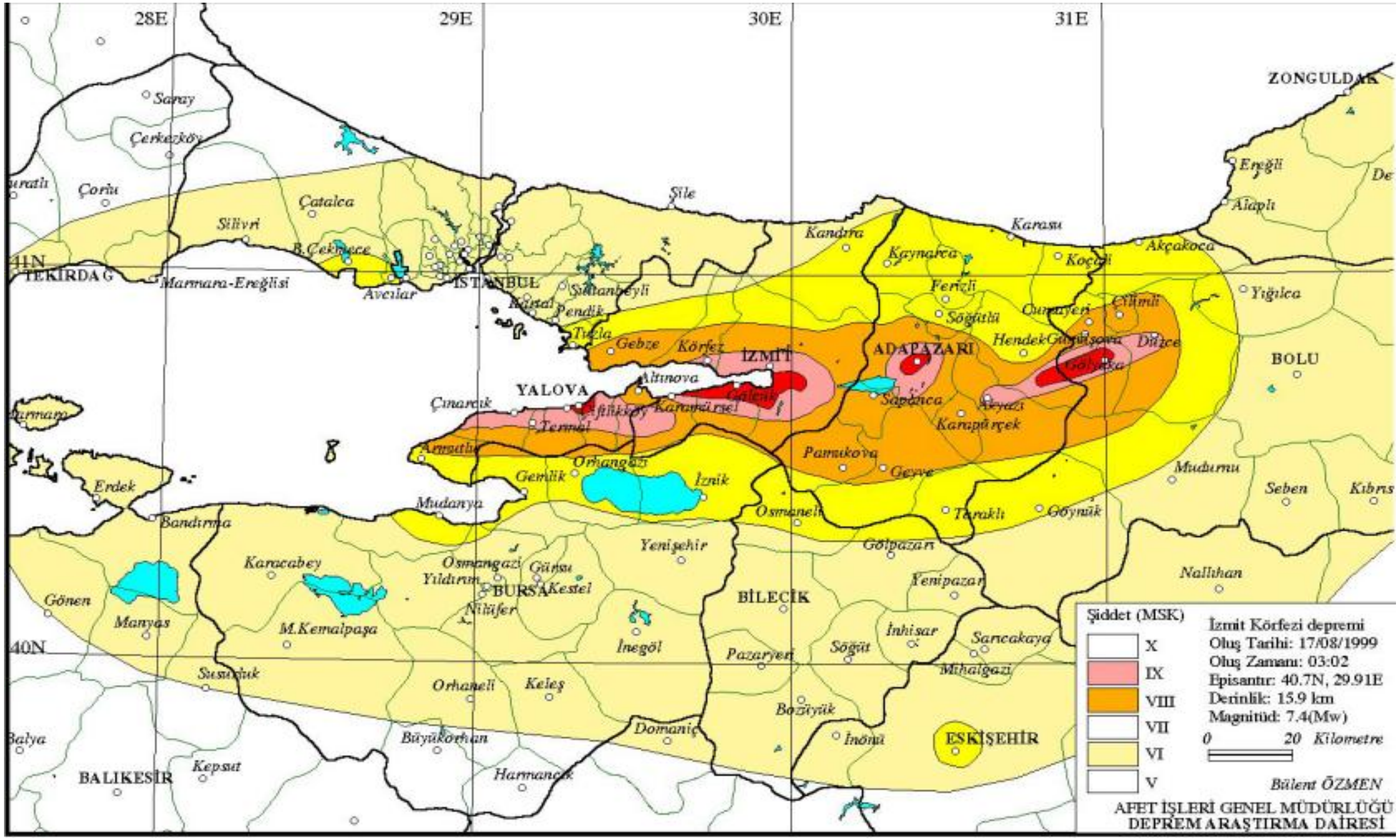
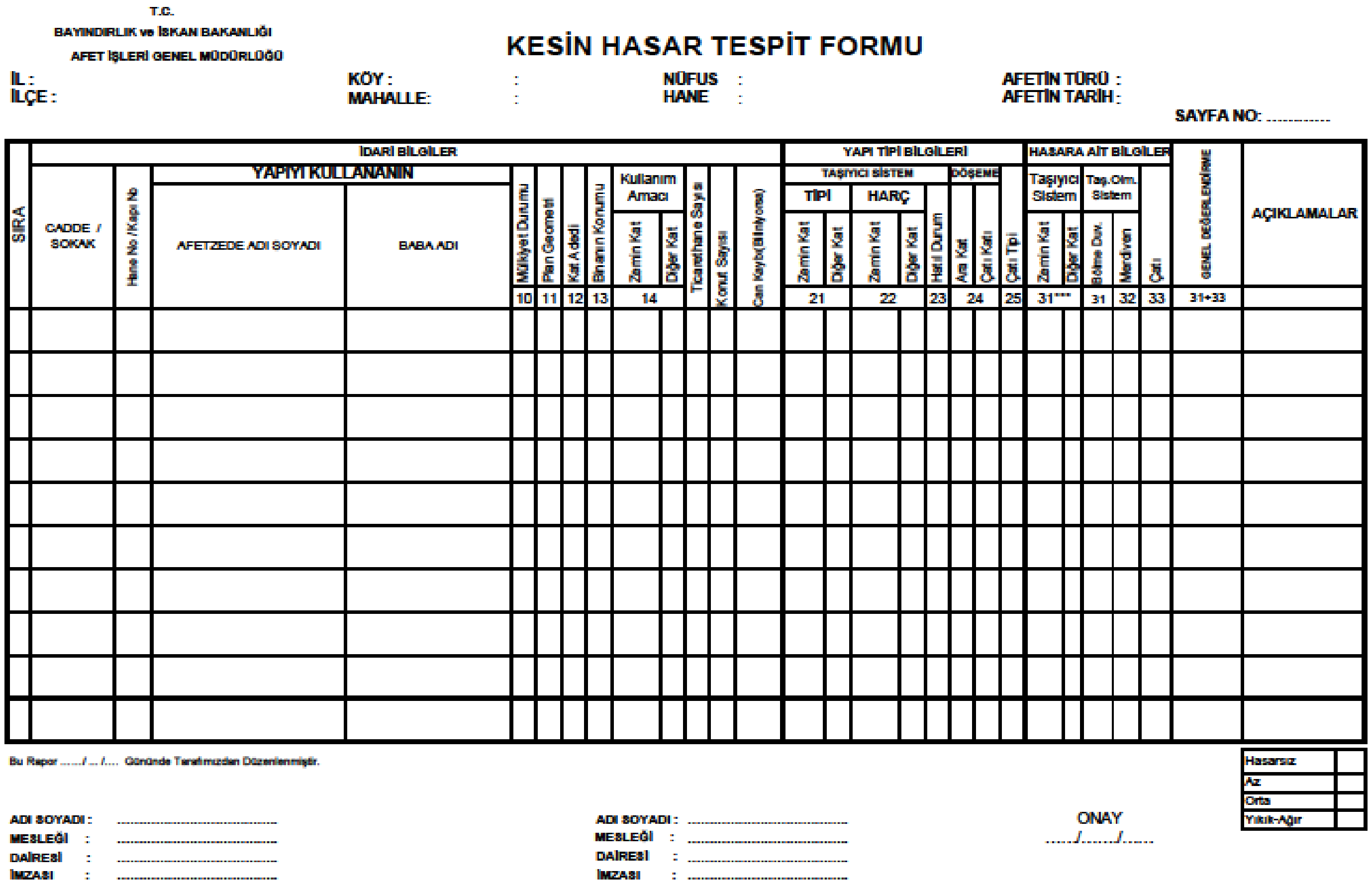


Figure 2.1: Intensity map of 17 August 1999 Kocaeli earthquake (Prepared by former General Directorate of Disaster Affairs)



T.C.
BAYINDIRLIK ve İSKAN BAKANLIĞI
AFET İŞLERİ GENEL MÜDÜRLÜĞÜ

KESİN HASAR TESPİT FORMU

İL :
İLÇE :
KÖY : :
MAHALLE: :
NÜFUS :
HANE :
AFETİN TÜRÜ :
AFETİN TARİH :
SAYFA NO: ....

SIRA	İDARİ BİLGİLER													YAPI TİPİ BİLGİLERİ								HASARA AİT BİLGİLER					GENEL DEĞERLENDİRME	AÇIKLAMALAR
	CADDE / SOKAK	Hane No / Kapı No	YAPIYI KULLANANIN						Kullanım Amacı					TAŞIYICI SİSTEM					DÖŞEME			Taşıyıcı Sistem		Taş.Olm. Sistem				
			AFETZEDE ADI SOYADI	BABA ADI	Mülkiyet Durumu	Plan Geometri	Kat Adedi	Binanın Konumu	Zemin Kat	Diğer Kat	Ticarethane Sayısı	Konut Sayısı	Can Kaybı(Bilinyorsa)	TİPİ Zemin Kat	TİPİ Diğer Kat	HARÇ Zemin Kat	HARÇ Diğer Kat	Hatıl Durum	Ara Kat	Çatı Katı	Çatı Tipi	Zemin Kat	Diğer Kat	Bölme Duv.	Merdiven	Çatı		
					10	11	12	13	14					21		22		23	24		25	31***		31	32	33	31+33	

Bu Rapor ....../ ... /.... Gününde Tarafımızdan Düzenlenmiştir.

Hasarsız	
Az	
Orta	
Yıkık-Ağır	

ADI SOYADI : ....
MESLEĞİ : ....
DAİRESİ : ....
İMZASI : ....

ADI SOYADI : ....
MESLEĞİ : ....
DAİRESİ : ....
İMZASI : ....

ONAY
....../......./......

Figure 2.2: Typical damage assessment form in Turkish (front side) (Prepared by former General Directorate of Disaster Affairs)

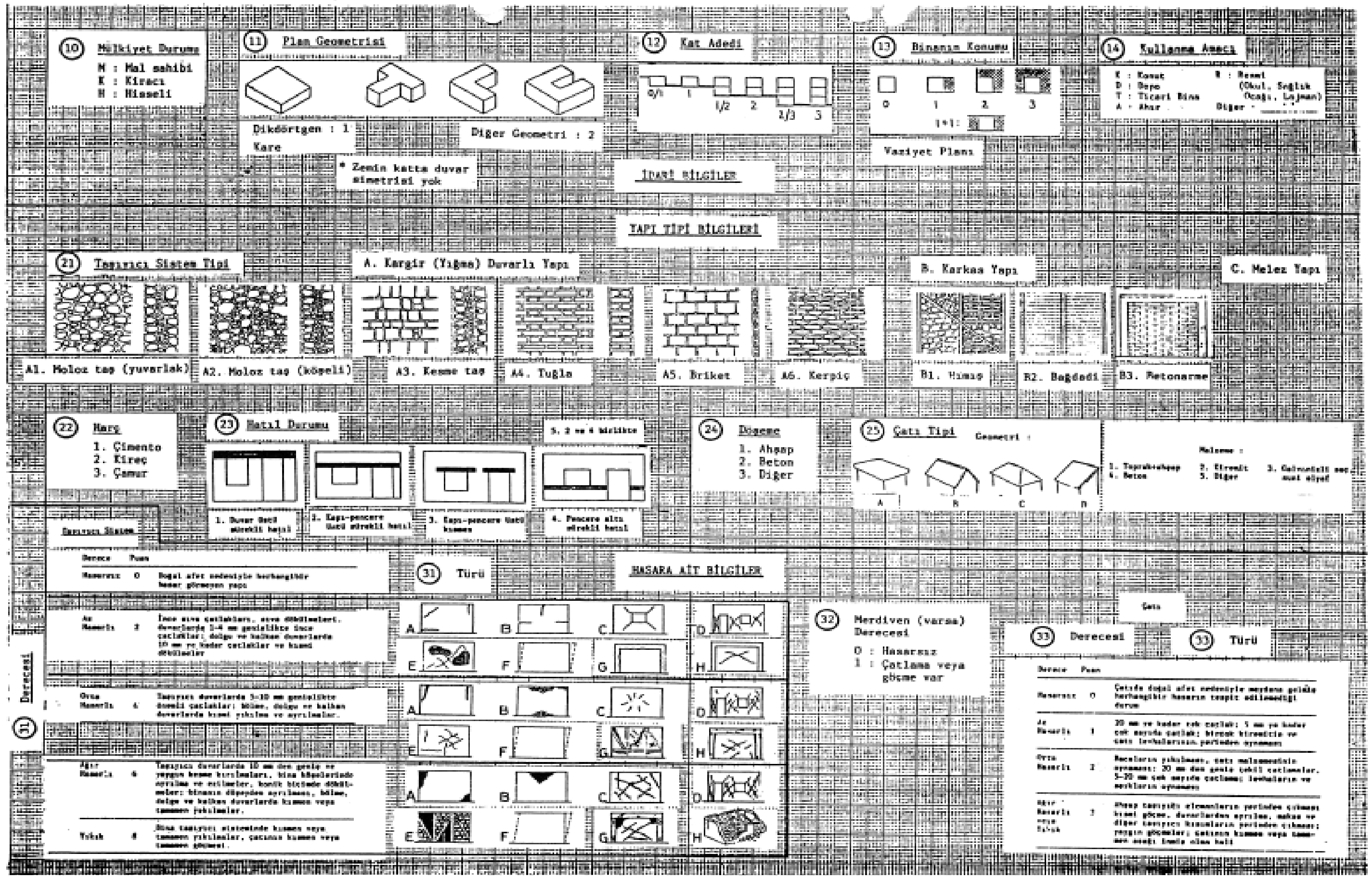


Figure 2.3: Typical damage assessment form in Turkish (back side) (Prepared by former General Directorate of Disaster Affairs)

Figure 2.4: A view from the damage archive in AFAD

Table 2.31: Mean damage ratios and damage probability columns for Bolu (MMI=VII) (Based on the damage database of the 17 August 1999 Kocaeli earthquake)

	CDR (%)	**Group O Buildings**	**B3 Type Buildings**
None	0	0.86	0.20
Light	5	0.06	0.16
Moderate	30	0.03	0.36
Heavy-Collapse	85	0.05	0.27
MDR (%)		5.50	34.64
Total number of households		12,661	7,814

Table 2.32: Mean damage ratios and damage probability columns for Kocaeli (MMI=IX) (Based on the damage database of the 17 August 1999 Kocaeli earthquake)

	CDR (%)	**Group O Buildings**	**B3 Type Buildings**
None	0	0.70	0.16
Light	5	0.12	0.30
Moderate	30	0.08	0.29
Heavy-Collapse	85	0.11	0.25
MDR (%)		11.91	31.75
Total number of households		14,086	25,351

Table 2.33: Mean damage ratios and damage probability columns for Sakarya (MMI=X) (Based on the damage database of the 17 August 1999 Kocaeli earthquake)

	CDR (%)	**Group O Buildings**	**B3 Type Buildings**
None	0	0.80	0.12
Light	5	0.08	0.22
Moderate	30	0.04	0.25
Heavy-Collapse	85	0.07	0.41
MDR (%)		7.51	43.28
Total number of households		78,444	22,463

It is observed that the MDR for reinforced concrete buildings (B3 type) in Sakarya is higher than that of Kocaeli and Bolu, whereas the MDR for masonry buildings in Kocaeli is the highest among all. The second observation for the masonry buildings is expected because the epicentre of the earthquake is closest to Kocaeli among all cities. However, it is interesting to obtain the greatest MDR value for reinforced concrete buildings not in Kocaeli but in Sakarya. This might be a result of the fact that the local soil conditions in Sakarya are worse than Kocaeli. The observed liquefaction patterns in Sakarya during the 17 August 1999 Kocaeli earthquake might have led to more severe damage in reinforced concrete buildings. If the MDRs for both types of structures are examined, it is possible to comment that, the local soil amplification in Sakarya affected reinforced concrete buildings worse than the masonry buildings. This might also be an indication of the resonance periods of soils in Sakarya coinciding with the fundamental periods of reinforced concrete buildings.

The results of this study at the city centre level are compared with that of Askan (2002), in Table 2.34. It is noted that the results are mostly consistent with each other with a minor difference between the MDRs from both studies. The MDR for Sakarya in this study is 43.28% whereas that is 39.55% in Askan (2002). It should be noted that the number of buildings used in this thesis is two times that was used in Askan (2002). Thus, it is believed that due to the increased sample size, results presented herein provide a more accurate MDR for Sakarya.

Table 2.34: Comparison of DPMs at city centre level obtained in this study for reinforced concrete buildings with that of Askan (2002)

Damage State	**CDR (%)**	**Sakarya (This thesis)**	**CDR (%)**	**Sakarya (Askan, 2002)**
None	0	0.12	0	0.04
Light	5	0.22	5	0.34
Moderate	30	0.25	30	0.27
Heavy	85	0.41	70	0.175
Collapse			100	0.175
MDR (%)		43.28		39.55

2.4.2 Comparisons with the Previous Studies and Updated Best Estimate DPMs for Reinforced Concrete Buildings

The overall empirical DPMs generated using the presented data in the previous section are given in Table 2.35 and Table 2.36.

Table 2.35: Empirical damage probability matrix for (O) type of structures from the 17 August 1999 Kocaeli earthquake (includes all districts)

		MMI		
	CDR (%)	**VII**	**IX**	**X**
None	0	0.86	0.72	0.80
Light	5	0.06	0.13	0.08
Moderate	30	0.03	0.07	0.04
Heavy-Collapse	85	0.05	0.09	0.07
MDR (%)		5.50	10.06	7.51
Total number of households		12,661	33,922	78,444

Table 2.36: Empirical damage probability matrix for (B3) type of structures from the 17 August 1999 Kocaeli earthquake (includes all districts)

		MMI		
	CDR (%)	**VII**	**IX**	**X**
None	0	0.20	0.16	0.12
Light	5	0.16	0.30	0.22
Moderate	30	0.36	0.29	0.25
Heavy-Collapse	85	0.27	0.25	0.41
MDR (%)		34.64	31.75	43.28
Total number of households		7,814	25,351	22,463

Next, these results are compared with the results from empirical DPMs of Askan (2002) in Table 2.37. It is noticed that the damage ratios are in general consistent with each other. Askan (2002) computed the mean damage ratio as 40.15% whereas in this study it is obtained as 31.75%. It is also remarkable that the distribution of single damage ratios (N, L, M, H&C) are very close. Comparing the sizes of database in each study, it can be argued that the results of Askan's study (2002) overestimate the mean damage ratio about 20.92% (relative error estimate). This difference indicates the significance of regional effects in the DPMs as Askan (2002) combines the damage rates from other events and regions, too. Another important point is that the increase in the MDR in the rightmost column is due to the fact that Askan (2002) used the Düzce damage database after the 12 November 1999 Düzce earthquake. As the buildings in Düzce had already been weakened by the 17 August 1999 Kocaeli earthquake, the damage states seem to be biased towards severe damage states. Such cases must be avoided whenever possible as these kind of bias could affect the outcomes significantly.

Table 2.37: Comparison of damage probability columns for MMI=IX case

Damage State	**CDR (%)**	**MMI=IX(This thesis)**	**CDR (%)**	**MMI=IX (Askan, 2002)**
None	0	0.16	0	0.08
Light	5	0.30	5	0.29
Moderate	30	0.29	30	0.27
Heavy	85	0.25	70	0.18
Collapse			100	0.18
MDR (%)		31.75		40.15

If the earthquake zone map of Turkey is examined, it is observed that all of the cities studied in this thesis lie on the first zone. Therefore, it is also possible to propose a best estimate damage probability matrix by combining the empirical DPM derived in this thesis with the subjective DPM of Gürpınar (1978). In Table 2.38, the corresponding empirical and subjective matrices are combined with weights of 0.75 and 0.25, respectively. The columns corresponding to MMI values which are not available in this study are taken from the best estimate DPM obtained by Askan (2002).

Table 2.38: Best estimate DPM for earthquake zone 1 (This Study)

		MMI (B3)					
	CDR (%)	**V**	**VI**	**VII**	**VIII**	**IX**	**X**
None	0	0.95	0.58	0.20	0.28	0.12	0.12
Light	5	0.05	0.29	0.18	0.39	0.24	0.22
Moderate	30	0.00	0.11	0.34	0.20	0.27	0.25
Heavy-Collapse	85	0.00	0.02	0.28	0.13	0.37	0.41
MDR (%)		0.25	6.45	34.62	19.00	40.50	43.28

2.4.3 Comparisons of the DPMs for Masonry Structures with the Previous Studies

The DPM obtained in this study for the masonry structures for earthquake zone 1 is given in Table 2.39. There is not a former study in terms of DPM for masonry structures in Turkey, but the previous fragility studies can always be converted to DPMs for comparison purposes.

Table 2.39: DPM Obtained for Group O Buildings (This Study)

		MMI (Group O Buildings)		
	CDR (%)	**VII**	**IX**	**X**
None	0	0.86	0.70	0.80
Light	5	0.06	0.12	0.08
Moderate	30	0.03	0.08	0.04
Heavy-Collapse	85	0.05	0.11	0.07
MDR (%)		5.50	11.91	7.51

As mentioned in Section 2.1, Erberik (2008b) obtained fragility curves for masonry structures. The buildings are coded according to the number of storeys (1-5), the construction style [(N)on-engineered, (E)ngineered] and the site it is built [(U)rban, (R)ural)]. For example, M2EU stands for the fragility analysis of two-storey, engineered masonry building in an urban site. In this study, the results are compared with non-engineered urban buildings. This is a valid assumption as most of the damaged buildings appear in city centres, and the buildings are mostly not designed with an engineering approach. The representative number of storeys (N) is obtained from the regional building census prepared by State Institute of Statistics Prime Ministry Republic of Turkey (2000). Then the corresponding fragility curves are selected accordingly.

The fragility curves of Erberik (2008b) use PGA to express the hazard levels for masonry structures. Thus, the corresponding PGA values recorded at the cities of interest are used. Finally, the damage probability matrix from Erberik (2008b) is obtained for Sakarya, Kocaeli and Bolu, from the fragility values corresponding to PGAs of 0.4g, 0.3g and 0.14g, respectively. These PGA values are the recorded values at the corresponding city centres during 17 August 1999 Kocaeli earthquake.

It must be noted that the fragility curves are obtained for two limit states LS1 and LS2. The limit states LS1 and LS2 originally are equivalent to none-light and heavy-collapse damage states in DPMs, respectively. The CDR for the combined none and light damage states is obtained by taking the average of corresponding CDR values based on the assumption that the number of none and lightly damaged structures are the same. The results of Erberik (2008) and this study for the three cities of interest are compared in Table 2.40 to Table 2.42.

Table 2.40: DPM for masonry structures obtained for Bolu (N≈2)

	CDR (%)	**O (M2NU)**	**O (this study)**
None-Light	2.5	0.91	0.92
Moderate	30	0.06	0.03
Heavy-Collapse	85	0.02	0.05
MDR (%)		6.15	7.45

Table 2.41: DPM for masonry structures obtained for Kocaeli(N≈1)

	CDR (%)	**O (M1NU)**	**O (this study)**
None-Light	2.5	0.90	0.81
Moderate	30	0.08	0.08
Heavy-Collapse	85	0.03	0.11
MDR (%)		6.89	13.78

Table 2.42: DPM for Masonry Structures Obtained for Sakarya (N≈1)

	CDR (%)	**O (M1NU)**	**O (this study)**
None-Light	2.5	0.75	0.89
Moderate	30	0.16	0.04
Heavy-Collapse	85	0.09	0.07
MDR (%)		14.60	9.38

It is observed that the results of this study and that of Erberik (2008b) match very closely for Bolu. However, the MDR values slightly differ for Kocaeli and Sakarya. It is believed that these small differences occur due to the bias in damage states within the sample space analysed in this thesis while deriving empirical DPMs.

It must be highlighted that it was not possible to obtain best estimate DPMs for masonry structures in this thesis since a subjective DPM is not available for masonry buildings Turkey.

To conclude, in this chapter regional empirical DPMs are expressed in terms of MMI. But as stated earlier, MMI is a subjective and qualitative measure. So it is better to express the probability of alternative damage states as a function of more quantitative indicators of the recorded ground motion levels. For this purpose and also for future ShakeMap applications, a relationship between MMI and instrumental peak ground motion quantities are proposed in the next chapter.

CHAPTER 3

RELATIONSHIPS BETWEEN FELT INTENSITY AND INSTRUMENTAL GROUND MOTION PARAMETERS FOR TURKEY

3.1 General

The degree of ground shaking can be identified by either qualitative or quantitative measures. The former is generally achieved through felt intensity and the latter is obtained via the recorded ground motion parameters. Felt intensity, which provides a subjective measure of the earthquake, is mainly based on human response to the shaking and evaluation of the damage to the structures. Intensity is commonly measured by Modified Mercalli Intensity scale (which was briefly explained in Chapter 2) and expressed in Roman numerals ranging between I and XII. Ground motion parameters on the other hand, are expressed by continuous numerical values in terms of peak ground acceleration (PGA), peak ground velocity (PGV), peak ground displacement (PGD) or the corresponding spectral quantities. These parameters give direct and physical measures of the recorded ground motions during an earthquake. In this chapter, the objective is to develop a relationship between felt intensity and instrumental ground motion parameters for Turkey.

Such a relationship is beneficial for several purposes. One of them is the need for a quantitative measure of shaking. For instance, in the previous chapter, the damage ratios are expressed in terms of MMI values. However, it is possible to relate damage directly to the observed peak ground motion parameters rather than a subjective measure. Another use of empirical MMI-PGA correlations is to estimate PGA data for historical earthquakes which have MMI information. Such relationships can also be extended to obtain PGA values in regions without dense strong ground motion networks where there is MMI information assigned in the field.

Another major area for use of such relationships is the ShakeMap applications. ShakeMaps are digital maps that indicate the meizoseismal area affected from an earthquake. They provide rapid assessment of shaking intensity and damage indirectly. ShakeMaps are useful for disaster management, mitigation and rapid response purposes. Minutes after an earthquake, these maps are generated for public use. They are expressed in terms of either subjective or quantitative measures of ground motions. Figure 3.1 and Figure 3.2 show example ShakeMaps in terms of PGA and MMI from a recent major event: 23 October 2012 Van earthquake (Mw=7.2), in Turkey.

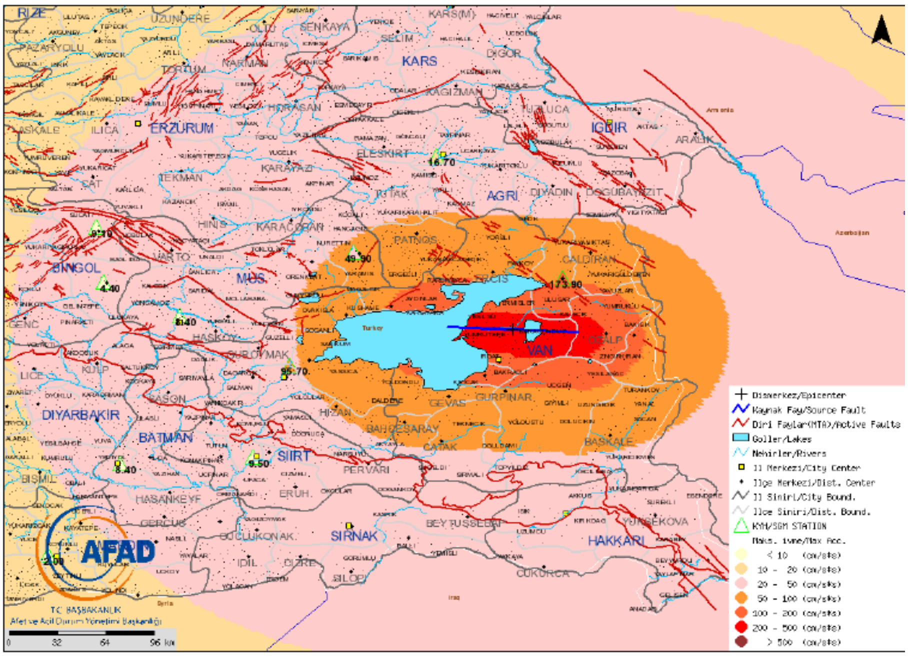


Figure 3.1: Digital intensity map of the 23 October 2011 Van earthquake in terms of PGA values (adopted from Van Earthquake Report, 2011, prepared by AFAD)

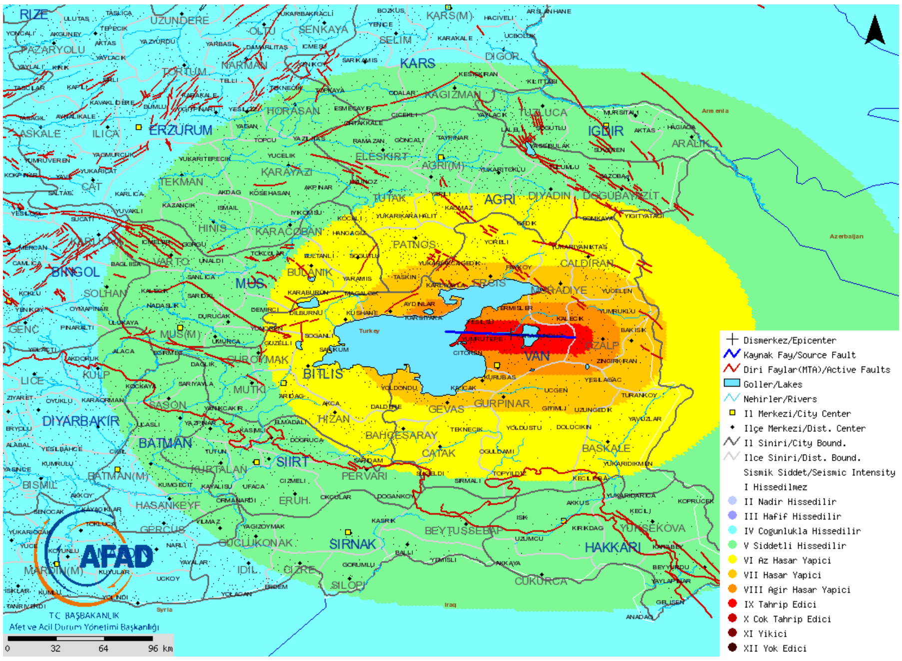


Figure 3.2: Digital intensity map of the 23 October 2011 Van earthquake in terms of MMI values (adopted from Van Earthquake Report, 2011, prepared by AFAD)

These ShakeMaps are prepared by the Earthquake Research Department of Prime Ministry Disaster and Emergency Management Presidency (AFAD, in Turkish). On the first map, each grid point is assigned a single PGA value by using one of the attenuation relationships (Ground Motion Prediction Equations, GMPE) available. For the maps prepared by AFAD, mostly the GMPE proposed by Fukushima and Tanaka (1992) is used. For the second map, each grid point is assigned an intensity value by using the MMI-PGA conversion equation proposed by Arıoğlu et al. (2001) after finding the PGA distribution from the selected GMPE.

In both steps of a ShakeMap application, it is best if the relationships are local: in other words both the GMPE employed and MMI-PGA or MMI-PGV relationships should be derived using local databases. In particular, correlations between MMI and measured ground motion parameters should be local as the MMI measures depend directly on regional damage characteristics. Thus, in this part of this thesis, a relationship is derived between MMI and PGA as well as PGV for a local dataset from recent events in Turkey.

Next section presents the corresponding literature survey which is followed by the data and method sections.

3.2 Literature Survey

There are several previous studies from all over the world, where either a predictive relationship in terms of MMI or a correlation of MMI with PGA or PGV are presented. In this section, some of them are discussed briefly.

3.2.1 Trifunac and Brady (1975)

Trifunac and Brady (1975) carried out a study on 57 earthquakes and 187 strong motion readings recorded in Western United States. They obtained a relationship between PGA and MMI. As a result of their study, the authors conclude that local soil condition is an important parameter in the correlation. This study provided one of the most commonly used relationships in the literature.

3.2.2 Murphy and O’Brien (1977)

In their classical study, Murphy and O’Brien (1977) obtained a relationship between the horizontal peak ground acceleration parameter and the felt intensity. The database consists of 875 worldwide data points with PGA values greater than 10 cm/sec². The reason for filtering below this limit is that the authors believe the ground motion amplitudes less than10 cm/sec² will be subjected to large uncertainties. The authors also highlight that, intensity is not directly proportional to the peak ground acceleration, thus a more appropriate relationship can be obtained using peak ground velocity instead of peak ground acceleration. It must be noted that this relationship was among the few available relationships for a long time and it was used globally for correlating MMI to PGA.

3.2.3 Wald et al. (1999)

Wald et al. (1999) obtained a relationship between felt intensity and PGA or PGV using the following significant California earthquakes: 1971 San Fernando (Mw=6.7), 1979 Imperial Valley (Mw=6.6), 1986 North Palm Springs (Mw=5.9), 1987 Whittier Narrows (Mw=5.9), 1989 Loma Prieta (Mw=6.9), 1991 Sierra Madre (Mw=5.8), 1992 Landers (Mw=7.3) and 1994 Northridge (Mw=6.7) earthquakes. These events are chosen because they provide a wide range of spatial distributions of intensity and recorded peak ground motions. In that study, it has been noticed that, for low intensities PGA correlates well with MMI, whereas for high intensities PGV correlates better with the MMI.

3.2.4 Atkinson and Sonley (2000)

Atkinson and Sonley (2000) obtained an empirical relationship between Pseudo Spectral Acceleration (PSA) (5% damped) and Modified Mercalli Intensity (MMI). The MMI data they employ are based on observations from 29 California earthquakes with moment magnitudes ranging from 4.9 to 7.4. In that study, it is discussed that the proposed relationship between MMI and PSA is suitable for regions other than California unless the structure types are very different. The authors conclude that the relationship between PSA at low frequencies and MMI significantly depends on magnitude, while it depends on distance for higher frequencies.

3.2.5 Arıoğlu et al. (2001)

Arıoğlu et al. (2001) proposed two relationships in their study based on the 14 ground motion records from 17 August 1999 Kocaeli earthquake. The first relationship indicates a correlation between the peak horizontal and vertical acceleration components. The second equation proposed by the authors relates PGA to MMI.

As it was mentioned before, Arıoğlu et al. (2001) is the only local MMI-PGA relationship for Turkey as of today. This relationship is currently used by AFAD in Turkey. However, 14 records from a single earthquake is not believed to be fully representative for a local MMI-PGA relationship. Thus, in this thesis a much larger dataset from different earthquakes is used to derive more extensive and robust correlations between MMI and PGA as well as MMI and PGV.

3.2.6 Wu et al. (2004)

Wu et al. (2004) investigated relationships between earthquake loss, intensity and peak ground motion parameters using data from 1999 Chi-Chi earthquake. Over 30000 digital strong motion records are obtained from the earthquake and its aftershocks. The mainshock is recorded at 441 stations. The regression analysis is performed for several ground motion parameters. The authors conclude that PGA and 1.0 sec SA are the two parameters that yield close correlations with intensity than the other parameters.

3.2.7 Atkinson and Kaka (2004, 2006, 2007)

The study carried out by Atkinson and Kaka (2004) provides a relationship between PGV and MMI using 18 significant earthquakes from eastern North America with magnitudes between 3.6 and 7.25. This relationship is verified by an implementation in Ontario ShakeMap. The results are also compared with relationships developed by Wald et al. (1999) and Atkinson and Sonley (2000) for California. The authors conclude that the relationships are significantly different in eastern North America than in California. In that study, it is also found that PGV is the best predictive measure of MMI as it has the lowest standard deviation.

Later, Atkinson and Kaka (2006) obtained a relationship between PGV and MMI based on the data from moderate earthquakes in the central US region that are also recorded by the strong motion recorders in New Madrid region.

Recently, Atkinson and Kaka (2007) developed a relationship for central US and California. The authors developed piecewise linear equations for the prediction of MMI from PGV. In that study, an average ground motion parameter is assigned to each intensity level. Better estimates are obtained with that approach.

3.2.8 Tselentis and Danciu (2008)

Tselentis and Danciu (2008) investigated the relationship between MMI and ground motion parameters such as peak ground acceleration (PGA), peak ground velocity (PGV) and peak ground displacement (PGD). Their database consists of 310 time histories from 89 earthquakes recorded from 4 November 1973 to 7 September 1999. The dataset is formed by Geodynamic Institute, National Observatory of Athens using questionnaires. The records are characterized as high frequency, low-energy content and short duration. The authors offer two sets of relationships; the former is based on mean values of ground motion parameters whereas the latter also takes magnitude, epicentral distance and local site conditions into account. The first relationship is based on the mean ground motion values observed at each MMI level, whereas the whole data are used obtaining the second relationship. It is observed that the soil conditions do not contribute significantly to the prediction of MMI from PGV.

3.2.9 Faenza and Michelini (2010)

Faenza and Michelini (2010) performed regression analyses between MCS intensity, I_{MCS} and PGA and PGV. The database consists of 266 data pairs. The results are tested in a USGS-ShakeMap application and the relationship is found to be consistent.

3.2.10 Other Relevant Studies in the World

In addition to the above mentioned relationships, following relevant studies are cited commonly in the literature: Kawasumi (1951) and Hershberger (1956). These are as well among the earliest available correlations between the instrumental and felt intensity measures.

3.3 Data and Resources

The objective of this chapter is to derive a local relationship between MMI and PGA as well as MMI and PGV using linear least-squares regression technique. The reason for providing two separate relationships for MMI in terms of both PGA and PGV is the following: Damage to different types of structures correlates well with either of these peak ground motion parameters. For instance, it is well known that for wall-bearing masonry buildings, PGA correlates better with damage while for reinforced concrete buildings, PGV is used as the main ground motion intensity parameter (Erberik, 2008a; 2008b). Thus, the fundamental objective herein is to provide both relationships so that for future studies researchers can pick the corresponding relationship for the structure type of interest.

In this study, ground motion records are obtained from the database of Prime Ministry Disaster and Emergency Management Presidency (AFAD in Turkish). The National Strong Motion Network for Turkey was established in 1973 and first ground motion data was recorded in 1976. As of 2011, the database is fed by 372 stations and data is available for both research purposes and public use at http://daphne.deprem.gov.tr.

The ground motion dataset is composed of 92 PGA and PGV values associated with 14 earthquakes with moment magnitudes ranging from 5.7 to 7.4. In the database, the earthquake ID is labelled by combining three letters of the city that the earthquake happened in with the month and year of the strike. Besides, every strong ground motion station has a specific ID code.

Except for the 23 October 2011 Van earthquake, intensity database is gathered from the unpublished bulletins and maps prepared by the Earthquake Research Department of AFAD. For the old earthquakes, the isoseismal maps were only obtained during site evaluations;

whereas for the recent earthquakes, the intensity values are assigned by the equation proposed by Arıoğlu et al. (2001) which was mentioned earlier in this chapter. In this thesis, only the actual (observed) MMI values are used for deriving relationships between MMI and PGA as well as PGV.

When the old intensity maps are investigated, it is observed that most of them are prepared based on the MSK scale. The scale, however, is converted to MMI in order to be consistent with the current studies worldwide. Musson et al. (2010) states that it is convenient to set both values equal to each other up to an intensity level of X. In this Chapter, as the intensity values range between I and X, this conversion is believed to contribute no significant error to the calculations. Finally, in this study MMI is used as the felt intensity scale and the conversion is performed using the proposed table by Musson et al. (2010) as previously given in Table 2.2. The intensity maps are given in Appendix A.

For the 23 October 2011 Van earthquake, the intensity data are gathered from Did You Feel It (DYFI) project of the United States Geological Survey (USGS). DYFI is an online questionnaire tool where the database is formed by the responses of the people who felt the seismic shaking during the earthquakes. Thus, an observed intensity value is paired with each of the 92 recorded PGA and PGV values. These data pairs are used in the regression analyses.

Information on felt intensities, events, stations and recorded peak ground motion parameters used in the analyses are given in Table 3.1 and displayed in Figure 3.3. Then, Figure 3.4 to Figure 3.8 display detailed information on data in terms of various data parameters.

Table 3.1: Information on the dataset used in the regression analyses

Record No.	Earthquake ID	Station ID	Mw	PGA N-S (cm/sec²)	PGA E-W (cm/sec²)	PGV N-S (cm/sec)	PGV E-W (cm/sec)	MMI
1	KOC8/99	1604	7.4	54.32	45.81	9.50	71.64	VI
2	KOC8/99	5903	7.4	90.36	101.36	20.67	12.80	VI
3	KOC8/99	3401	7.4	60.67	42.66	9.58	8.56	VI
4	KOC8/99	3403	7.4	118.03	89.61	14.99	16.59	VII
5	KOC8/99	1612	7.4	91.89	123.32	17.97	31.68	VII
6	KOC8/99	4106	7.4	264.82	141.45	97.09	127.90	VIII
7	KOC8/99	8101	7.4	314.88	373.76	59.53	52.64	IX
8	KOC8/99	4101	7.4	171.17	224.91	92.79	76.22	IX
9	KOC8/99	5401	7.4	0.21	407.04	8.11	82.27	X
10	KOC8/99	6001	7.4	0.85	1.16	1.81	1.86	II
11	KOC8/99	4302	7.4	50.05	59.66	9.41	17.15	IV
12	KOC8/99	0901	7.4	5.98	5.25	3.56	4.49	II

Table 3.1: (continued)

13	KOC8/99	2002	7.4	5.92	11.69	4.48	14.21	IV
14	KOC8/99	3502	7.4	9.89	10.80	3.92	3.20	IV
15	KOC8/99	3701	7.4	11.69	8.91	7.38	4.21	IV
16	KOC8/99	1701	7.4	24.57	28.63	10.52	6.39	V
17	KOC8/99	6401	7.4	11.20	14.31	3.57	7.36	IV
18	KOC8/99	1001	7.4	17.76	18.19	6.18	5.63	V
19	KOC8/99	301	7.4	13.50	15.00	442.37	199.83	V
20	KOC8/99	4501	7.4	12.50	6.50	681.79	792.94	IV
21	KOC8/99	1404	7.4	137.69	117.90	25.03	33.92	VII
22	AFY2/02	1006	6.5	1.62	1.59	0.71	1.36	I
23	AFY2/02	5401	6.5	1.04	1.19	1.53	0.64	I
24	AFY2/02	1001	6.5	1.62	0.89	1.42	0.61	I
25	AFY2/02	1502	6.5	2.59	2.44	0.61	6.11	III
26	AFY2/02	6401	6.5	7.66	6.17	1.88	1.24	III
27	AFY2/02	4302	6.5	23.13	20.78	3.02	4.34	IV
28	AFY2/02	301	6.5	113.50	94.00	25.93	42.03	V
29	BGA7/83	1002	6.1	22.55	20.71	15.67	5.79	VI
30	BGA7/83	1012	6.1	53.44	46.51	25.22	31.99	VII
31	BGA7/83	1013	6.1	27.78	25.38	3.74	4.91	V
32	BGA7/83	1014	6.1	50.11	46.77	45.69	53.93	VII
33	BGA7/83	5901	6.1	29.89	34.91	15.24	6.11	VI
34	DNZ8/76	2001	6.1	348.53	290.36	40.16	484.81	VI
35	MLT5/86	0203	6.0	114.70	76.04	26.60	27.80	V
36	MLT6/86	0203	5.8	68.54	34.43	10.84	12.37	V
37	MLT6/86	4402	5.8	23.57	24.81	56.79	17.33	IV

Table 3.1: (continued)

38	EZR10/83	2503	6.6	150.26	173.30	65.36	26.07	VI
39	EZR10/83	2502	6.6	35.49	24.99	7.50	2.70	IV
40	COR8/96	1902	5.7	15.65	30.88	3.98	3.66	IV
41	COR8/96	0502	5.7	27.00	53.50	1.73	4.43	III
42	ORT6/00	1801	6.0	62.46	63.16	8.50	7.09	VI
43	ORT6/00	1401	6.0	5.65	6.96	2.56	1.30	IV
44	ORT6/00	8101	6.0	4.06	4.21	1.08	1.07	III
45	ORT6/00	3701	6.0	11.75	12.12	2.48	0.95	V
46	ORT6/00	7801	6.0	4.72	6.53	0.92	0.86	V
47	ORT6/00	4302	6.0	4.46	3.39	3.76	2.60	III
48	ADN6/98	3301	6.2	119.29	132.12	25.03	27.45	III
49	ADN6/98	0202	6.2	4.50	3.00	18.71	20.87	II
50	ADN6/98	0105	6.2	223.28	273.55	29.10	28.10	VIII
51	ADN6/98	4603	6.2	8.00	8.50	45.46	48.17	II
52	ADN6/98	4605	6.2	4.70	5.16	2.69	3.88	II
53	ADN6/98	3102	6.2	27.10	25.82	2.68	4.78	III
54	ADN6/98	0110	6.2	28.50	33.10	20.00	15.81	V
55	IZM11/92	3507	6.0	16.65	37.81	4.01	9.43	V
56	IZM11/92	3501	6.0	30.49	38.34	11.45	10.36	V
57	IZM11/92	0905	6.0	83.49	71.80	13.23	14.60	VI
58	EZC3/92	2402	6.6	404.97	470.92	103.90	82.05	VIII
59	EZC3/92	2403	6.6	67.21	85.93	19.00	19.29	IV
60	EZC3/92	2405	6.6	39.38	26.97	15.18	11.42	III
61	DZC11/99	5902	7.1	5.71	6.10	2.08	1.61	V
62	DZC11/99	4302	7.1	17.12	20.69	5.69	10.21	III

Table 3.1: (continued)

63	DZC11/99	5401	7.1	17.33	24.72	4.81	5.17	VIII
64	DZC11/99	301	7.1	8.00	10.00	8.51	19.09	IV
65	DZC11/99	1604	7.1	9.31	8.00	2.58	2.65	V
66	DZC11/99	1701	7.1	3.94	3.33	1.86	2.12	IV
67	DZC11/99	2002	7.1	3.69	3.48	3.78	4.29	III
68	DZC11/99	1404	7.1	27.89	24.82	9.84	8.68	VII
69	DZC11/99	1406	7.1	120.99	58.34	17.68	32.09	VII
70	DZC11/99	1001	7.1	2.72	2.38	2.50	2.16	IV
71	DZC11/99	3502	7.1	1.59	1.86	1.56	2.56	III
72	DZC11/99	3701	7.1	7.93	7.63	3.06	3.59	III
73	DZC11/99	6401	7.1	3.05	3.08	2.91	1.53	II
74	DZC11/99	8101	7.1	407.69	513.78	66.47	90.78	X
75	DZC11/99	3401	7.1	8.97	5.25	2.18	4.29	V
76	DZC11/99	1401	7.1	739.51	805.88	57.78	66.60	X
77	VAN10/11	205	7.2	2.97	2.70	1.38	1.22	III
78	VAN10/11	208	7.2	1.12	0.74	0.52	0.44	III
79	VAN10/11	401	7.2	18.46	15.09	5.87	4.82	VI
80	VAN10/11	1206	7.2	7.53	11.08	3.26	4.00	VI
81	VAN10/11	1211	7.2	4.59	4.20	1.99	2.86	VI
82	VAN10/11	1302	7.2	89.67	102.24	8.35	7.59	VI
83	VAN10/11	2304	7.2	1.46	1.67	1.64	1.22	IV
84	VAN10/11	2305	7.2	1.20	1.19	0.77	1.23	IV
85	VAN10/11	2307	7.2	2.12	1.64	1.22	1.05	IV
86	VAN10/11	2401	7.2	1.54	1.29	0.95	1.16	IV
87	VAN10/11	2407	7.2	2.37	3.44	1.69	2.45	IV

Table 3.1: (continued)

88	VAN10/11	4404	7.2	1.00	1.00	0.85	0.50	IV
89	VAN10/11	4901	7.2	10.31	6.86	2.55	2.55	VII
90	VAN10/11	4902	7.2	44.50	56.00	12.16	13.86	VII
91	VAN10/11	6503	7.2	178.50	169.50	26.70	14.41	VIII
92	VAN10/11	7201	7.2	8.30	8.59	2.73	2.22	IV

Figure 3.3: Distribution of the earthquake locations, magnitudes and strong ground motion stations used in this study

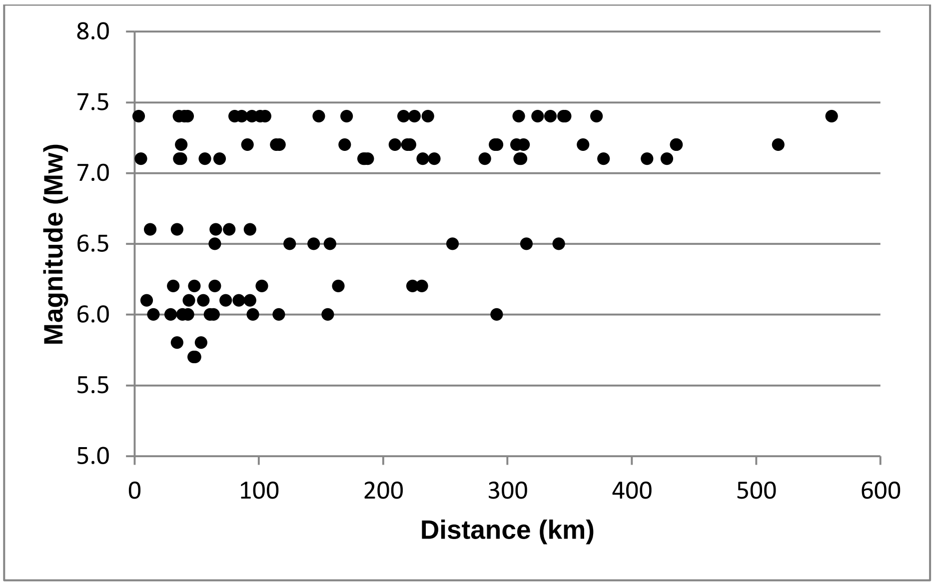


Figure 3.4: Magnitude-distance distribution of the dataset

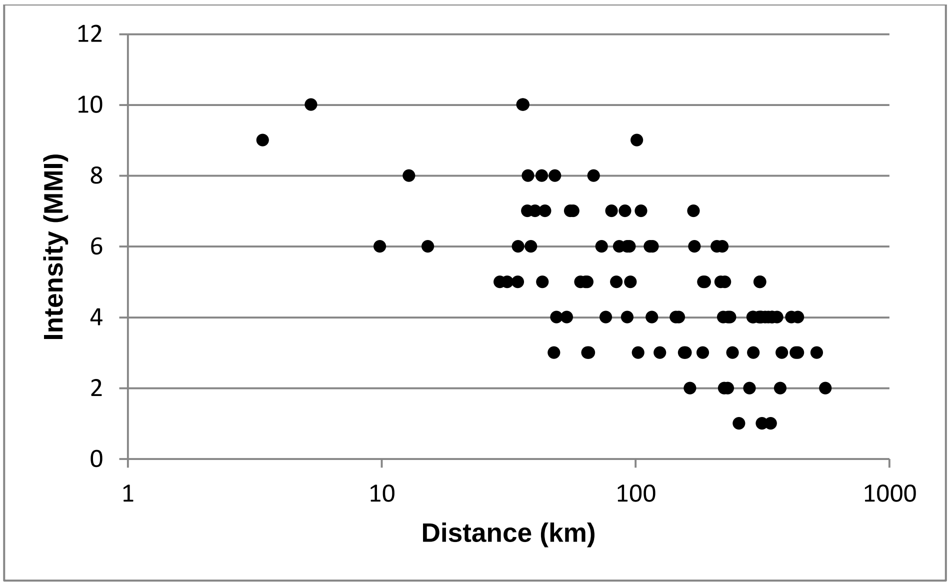


Figure 3.5: Intensity-distance distribution of the dataset

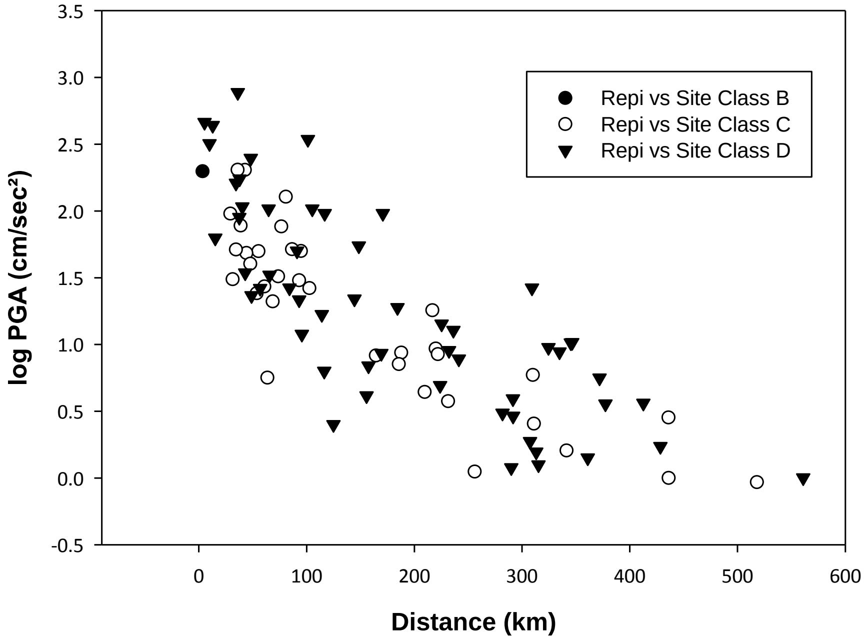


Figure 3.6: Peak ground acceleration-distance distribution of the dataset (NHERP site classes are used)

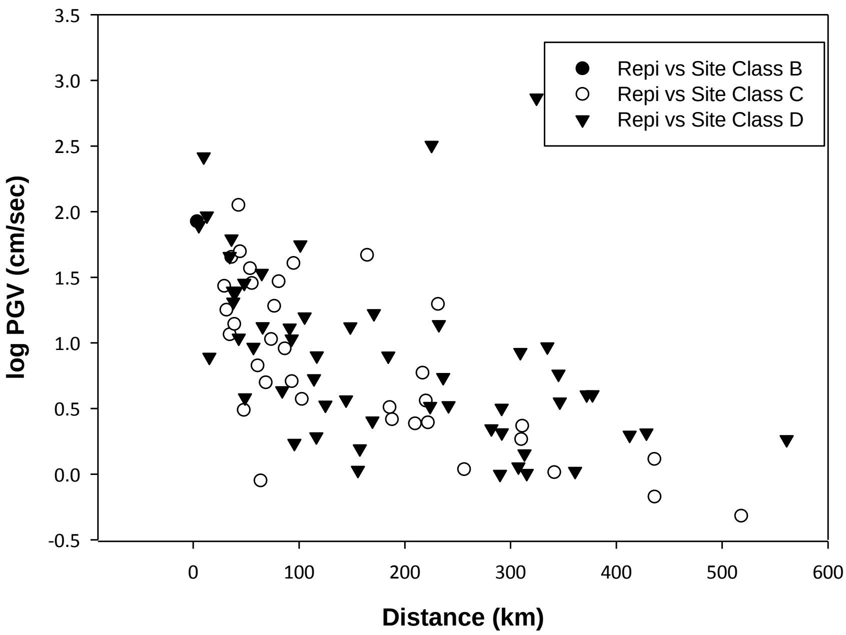


Figure 3.7: Peak ground velocity-distance distribution of the dataset (NHERP site classes are used)

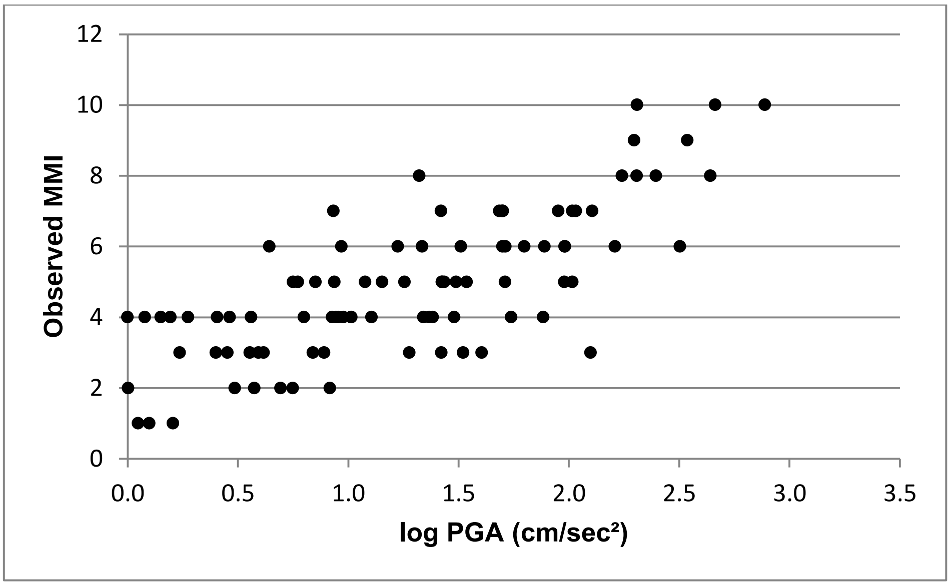


Figure 3.8: Intensity-peak ground acceleration distribution of the dataset

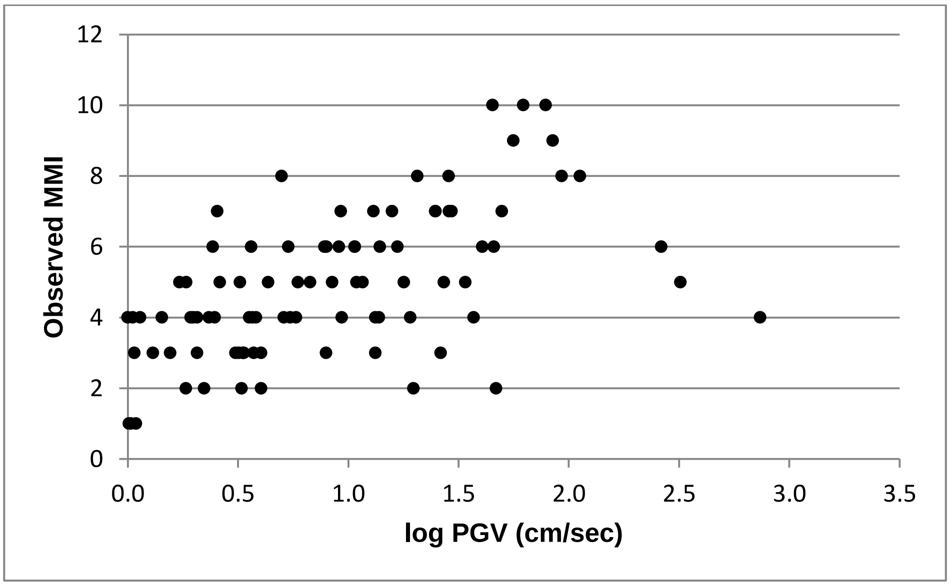


Figure 3.9 Intensity-peak ground velocity distribution of the dataset

3.4 Method: Linear Least-Squares Regression

In this study, simple least-squares regression is employed to obtain a correlation for MMI in terms of both PGA and PGV values. In order to account for the widely distributed PGA and PGV values, a mean value for both PGA and PGV are assigned to each corresponding MMI level. Another reason for using mean PGA and PGV values for each MMI is to force the curve to follow a better trend rather than being influenced by the uneven distribution of data.

The objective of linear least-squares regression is to obtain a relationship between a dependent variable y and one or more independent variables $x_1, x_2, \ldots, x_k$ in the following linear form:

$$y_i = C_0 + C_1 x_{1i} + C_2 x_{2i} + \cdots + \epsilon_i \tag{3.1}$$

where

x_{ji}:the i^th observed value of the independent variable x_j

y_i: the i^th observed value of the dependent variable y

ϵ_i: the error term or the residual

C_j: the regression slope for the variable x_j

C_0: the intercept of the regression line on the y-axis

Simple linear least-squares regression is performed with only one independent variable$x$. When the error terms are assumed to be normally distributed, the prediction equation becomes:

$$y_i = \text{Normal}(m * x_i + n, \sigma) \tag{3.2}$$

Where m is the slope of the line, n is the y-axis intercept and σ is the standard deviation of the variation of y about this line. Indeed, the simple least-squares regression finds the straight line which minimizes the sum of the squares of the errors, ϵ, (RMS error).

The total variation in the dependent variable$y$ aspredicted by the independent variable x is called thecoefficient of determination, R^2, which is used to describe how well a regression line fits a set of data. R^2 takes values between 0.0 and 1.0. Thus an R^2 near 1.0 shows that the regression is successful in fitting the data well; while an R^2 closer to 0 means the regression line does not fit the data closely. R^2 is defined as:

$$R^2 = 1 - \frac{SSE}{TSS} \tag{3.3}$$

In that equation TSS, the total sum of squares, is defined as:

$$TSS = \sum_{i=1}^{k} (y_i - \bar{y})^2 \tag{3.4}$$

Where $\bar{y}$ is the mean of the observed y data, and

SSE, the sum of squares of errors, is defined as:

$$SSE = \sum_{i=1}^{k} (y_i - \hat{y}_i)^2 \tag{3.5}$$

Where $\hat{y}_i$are the predicted values at each x_i:

$$\hat{y}_i = mx_i + n \tag{3.6}$$

For simple least-squares regression, the square root of R^2 is equivalent to the simple correlation coefficient, r.

The standard error of the estimated y values, σ, is calculated as:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{k} (y_i - \hat{y}_i)^2}{(k-2)}} \tag{3.7}$$

This is indeed equal to the standard deviation of the error terms, ϵ. These errors reflect the variability of the dependent variable $y$from the least-squares regression line.

It should be noted that the above formulation is accurate only when the errors are distributed normally.

3.5 Relationships between Felt Intensity and Peak Ground Motion Parameters for Turkey

MMI-PGA conversion equation proposed by Arıoğlu et al. (2001) is the most extensively used equation for ShakeMap applications in Turkey. The major shortcoming of this equation is that, the database involves only the 17 August 1999 Kocaeli earthquake and includes only 14 data pairs. In this thesis, a more extensive research is carried out for developing a relationship between MMI and PGA/PGV.

As stated earlier, regression is carried out using a processed database. Initially all PGA and PGV values are computed from the arithmetic mean of the two horizontal PGA and PGV values of each record. Then, each intensity level is assigned the averages of corresponding PGA and PGV values. The statistical parameters of mean representative PGA and PGV values corresponding to each MMI level are given in Table 3.2 and Table 3.3.

Table 3.2: Statistical parameters of mean representative PGA values corresponding to each MMI

MMI	**Average of log(PGA) (cm/sec^2)**	**Standard Deviation of Average of log(PGA)**	**Number of Observations**
I	0.117	0.081	3
II	0.570	0.315	6
III	0.891	0.607	14
IV	0.866	0.544	22
V	1.321	0.402	15
VI	1.651	0.510	13
VII	1.727	0.370	9
VIII	2.182	0.504	5
IX	2.417	0.170	2
X	2.620	0.292	3

Table 3.3: Statistical parameters of mean representative PGV values corresponding to each MMI

MMI	Average of log(PGV) (cm/sec)	Standard Deviation of Average of log(PGV)	Number of Observations
I	0.019	0.016	3
II	0.783	0.568	6
III	0.500	0.445	14
IV	0.663	0.668	22
V	0.891	0.636	15
VI	1.118	0.531	13
VII	1.233	0.378	9
VIII	1.497	0.548	5
IX	1.838	0.126	2
X	1.781	0.121	3

The regression equation is in the following form:

$$MMI_{est} = C_1 + C_2 * \log(PGA) \tag{3.8}$$

$$MMI_{est} = C_3 + C_4 * \log(PGV) \tag{3.9}$$

where

C_1, C_2, C_3 and C_4 are the regression coefficients, respectively.

The regression coefficients $C_1$and C_2 are found to be 0.287 and 3.625 for Equation (3.8); and C_3 and C_4 are calculated as 0.319 and 5.021 for Equation (3.9). Thus, the relationships are obtained as:

$$MMI_{est} = 0.287 + 3.625 * \log(PGA) \tag{3.10}$$

$$MMI_{est} = 0.319 + 5.021 * \log(PGV) \tag{3.11}$$

The coefficients of determination are obtained as ${R^2}_{PGA}$=0.986 and ${R^2}_{PGV}$=0.919 for Equations (3.10) and (3.11), respectively. Table 3.4 displays the regression coefficients and the standard errors of these equations.

Table 3.4: Regression coefficients and standard errors of Equations (3.10) and (3.11)

Ground Motion Parameter	Regression Coefficient	Value	Standard Error
PGA (cm/sec²)	C_1	0.287	0.247
	C_2	3.625	0.150
	$\sigma_{MMI-PGA}$		0.375
PGV (cm/sec)	C_3	0.319	0.616
	C_4	5.021	0.527
	$\sigma_{MMI-PGV}$		0.914

In Figure 3.10 and Figure 3.11, estimated versus observed intensity values are plotted. The data clustered around y=x line state how well the estimated MMI values correlate with the observed MMI values. It is observed from the Figure 3.11 that, the data points are spread far away from the y=x line. This result is expected since the correlation coefficient of Equation (3.11) is lower than that of Equation (3.10).

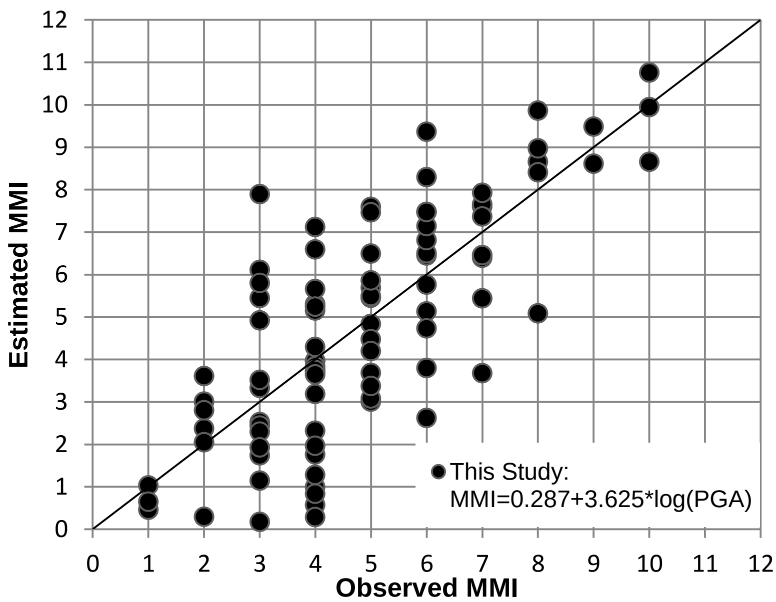


Figure 3.10: Observed versus estimated intensity values obtained using Equation (3.10)

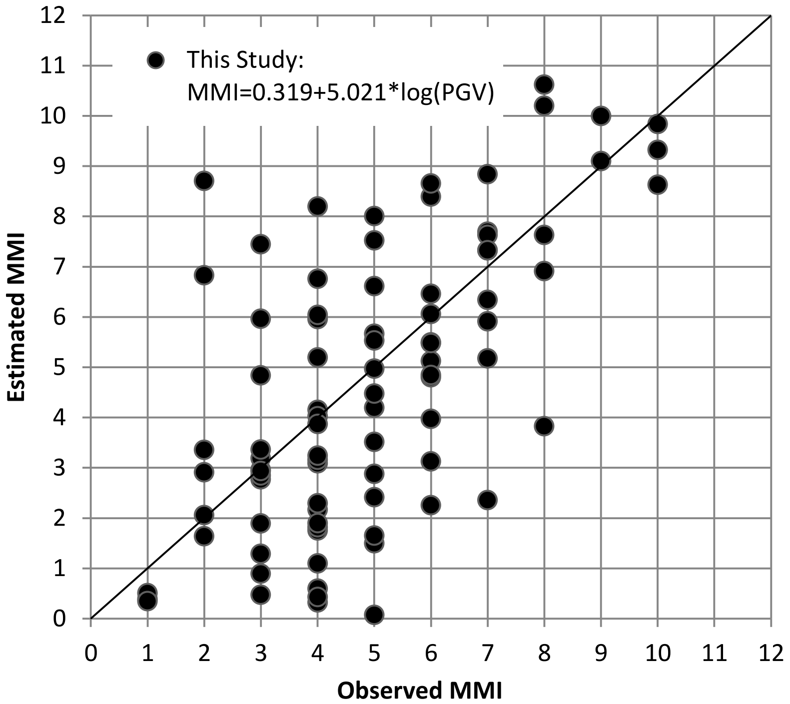


Figure 3.11: Observed versus estimated intensity values obtained using Equation (3.11)

It must be noted that the regression equations are obtained assuming that the errors are normally distributed. In order to verify this assumption, probability plots are used. A probability plot is in the form of a scatter of points along two axes, one of which is the observed value, and the other is the expected value. The P-P and Q-Q plots are commonly used in testing whether the assumed probability distribution of a variable is valid. A P-P plot is a plot of variable's cumulative proportions against the cumulative proportions of the test distribution. A Q-Q plot presents the quantiles of a variable's distribution against the quantiles of test distribution. Figure 3.12 to Figure 3.15 present the results of the P-P and Q-Q probability plots. It is observed that the errors of the MMI-PGA relationship are definitely normally-distributed. Thus, the MMI-PGA relationships can be used for further applications with confidence.

On the other hand, the P-P plot for the errors of MMI-PGV relationship does not fully indicate a normal distribution. Yet, the Q-Q plot and the high R^2 value for this relationship make it still usable for practical purposes.

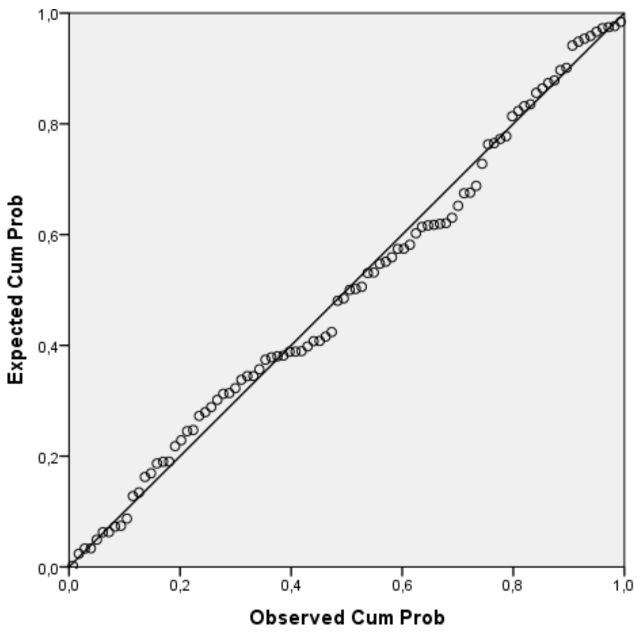


Figure 3.12: Normal P-P plot for errors in MMI-PGA relationship

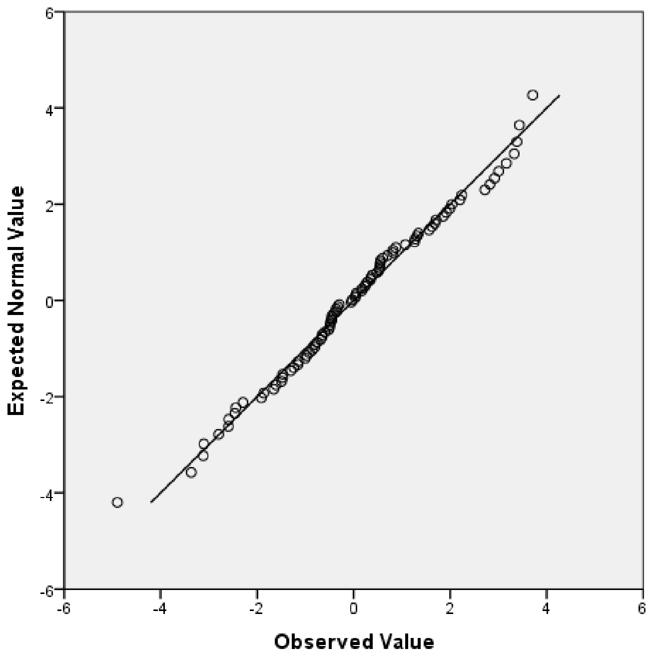


Figure 3.13: Normal Q-Q plot for errors in MMI-PGA relationship

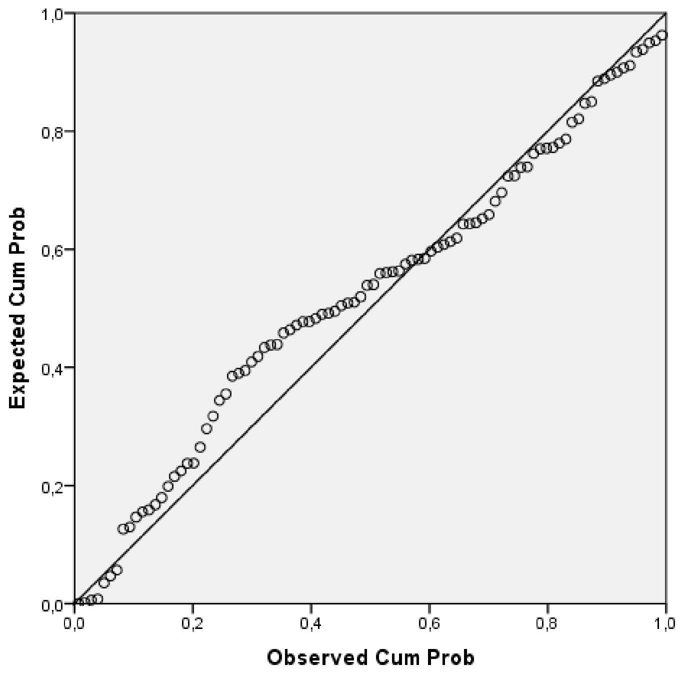


Figure 3.14: Normal P-P plot for errors in MMI-PGV relationship

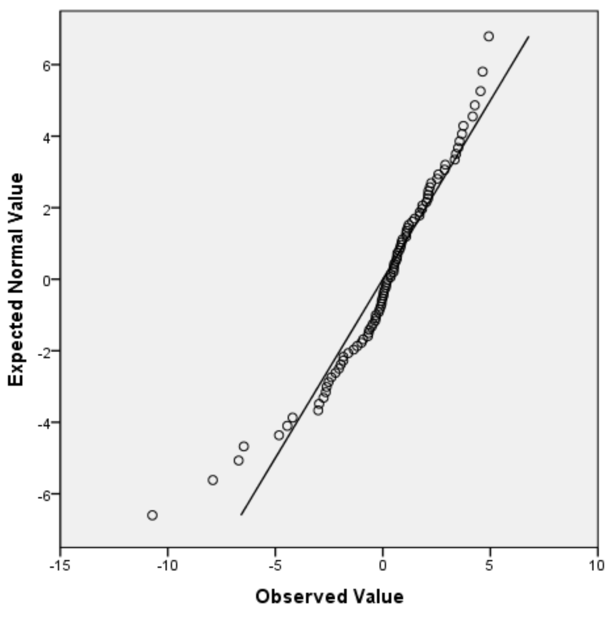


Figure 3.15: Normal Q-Q plot for errors in in MMI-PGV relationship

3.6 Comparison of the Proposed Equations with Previous Studies

The results of this study are compared with the results of previous studies worldwide. The MMI-PGA equation obtained in this study is compared with the following studies: Arıoğlu et al. (2001), Tselentis and Danciu (2008), Faenza and Michelini (2010), Murphy and O'Brien (1977), Trifunac and Brady (1975) and Wald et al. (1999). The proposed equation corresponding to each of these past studies is given in Table 3.5. Figure 3.16 to Figure 3.21 present the comparison of each study with the equation proposed in this thesis. Dataset used in this thesis is as well shown in these figures.

Table 3.5: Equations proposed for MMI-PGA relationships

No.	Name	Equation
1	This Study	MMI=0.287+3.625*log(PGA)
2	Arıoğlu et al. (2001)	MMI=1.748*ln(PGA)-1.078
3	Tselentis and Danciu (2008)	MMI=-0.946+3.563*log(PGA)
4	Faenza and Michelini (2010)	MMI=1.68+2.58*log(PGA)
5	Murphy and O'Brien (1977)	MMI=(log(PGA)-0.25)/0.25
6	Trifunac and Brady (1975)	MMI=(log(PGA)-0.14)/0.30
7	Wald et al. (1999)	MMI=3.66*log(PGA)-1.66

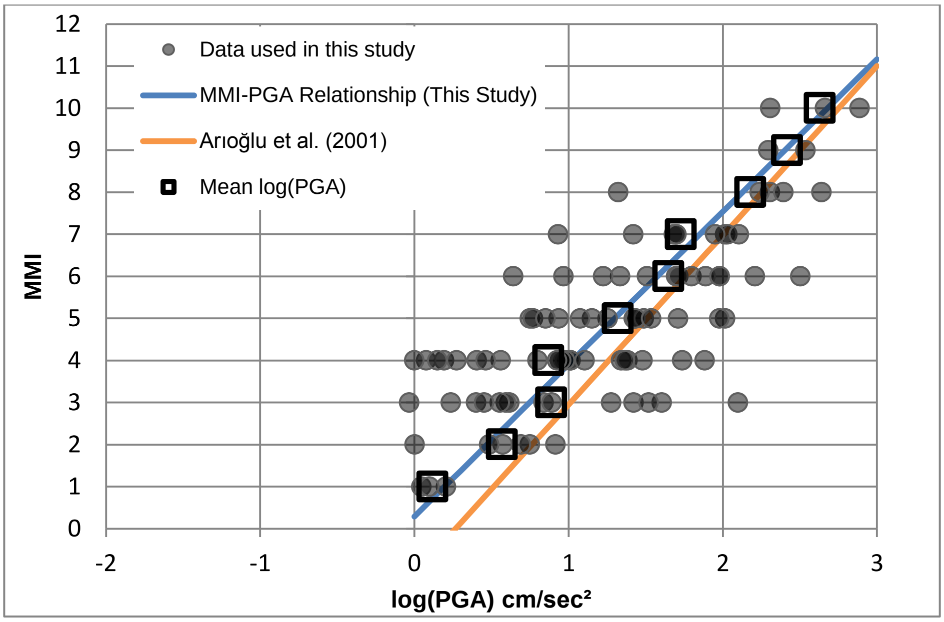


Figure 3.16: Comparison of the result of this study with that of Arıoğlu et al. (2001)

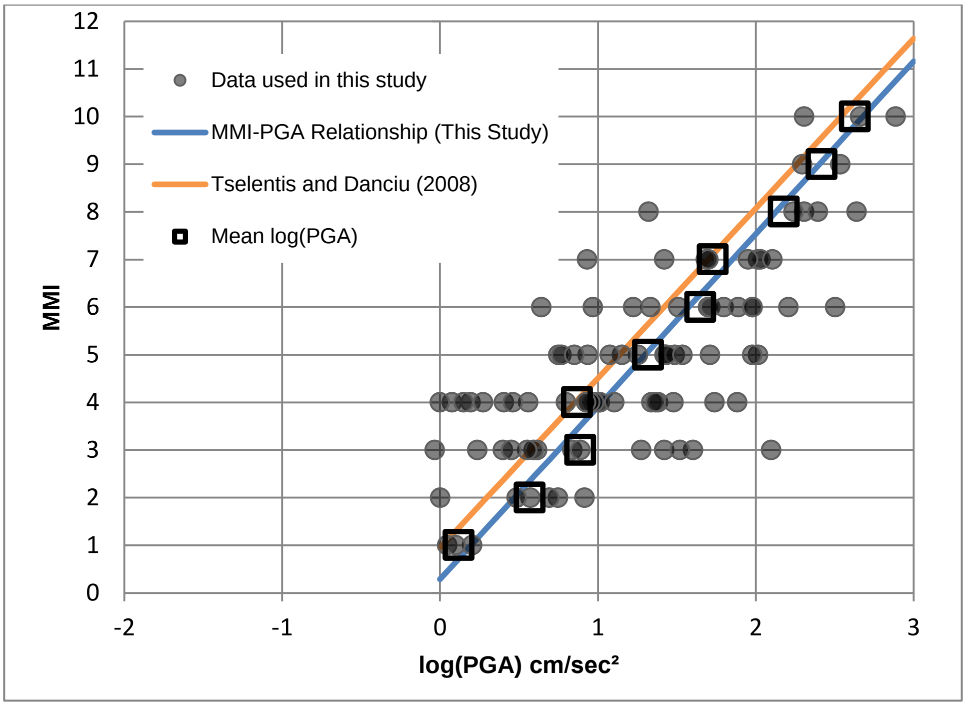


Figure 3.17: Comparison of the result of this study with that of Tselentis and Danciu (2008)

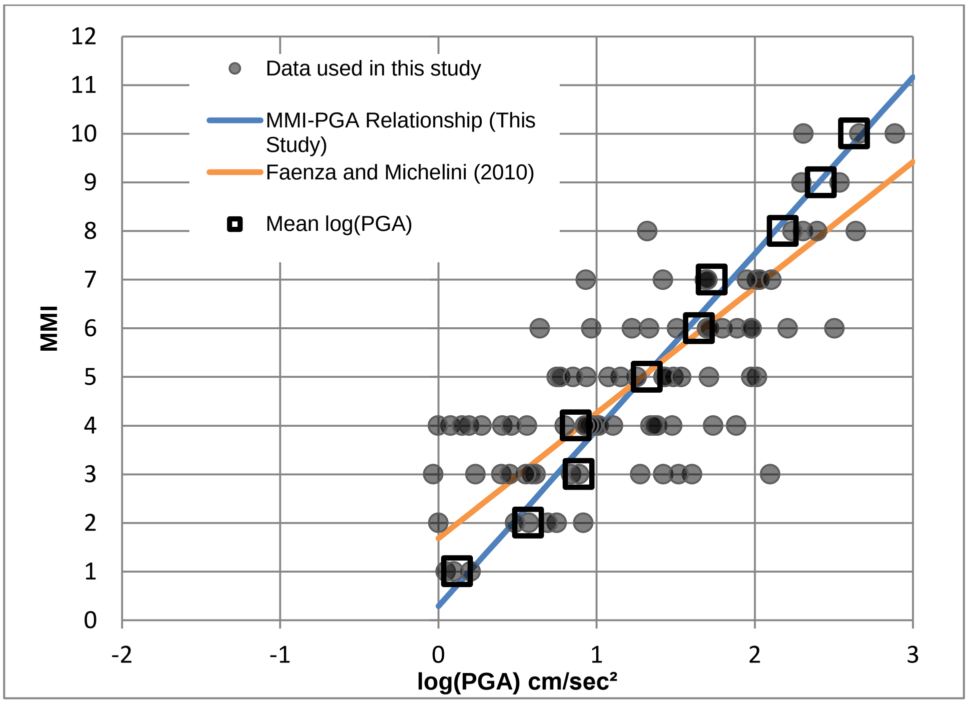


Figure 3.18: Comparison of the result of this study with that of Faenza and Michelini (2010)

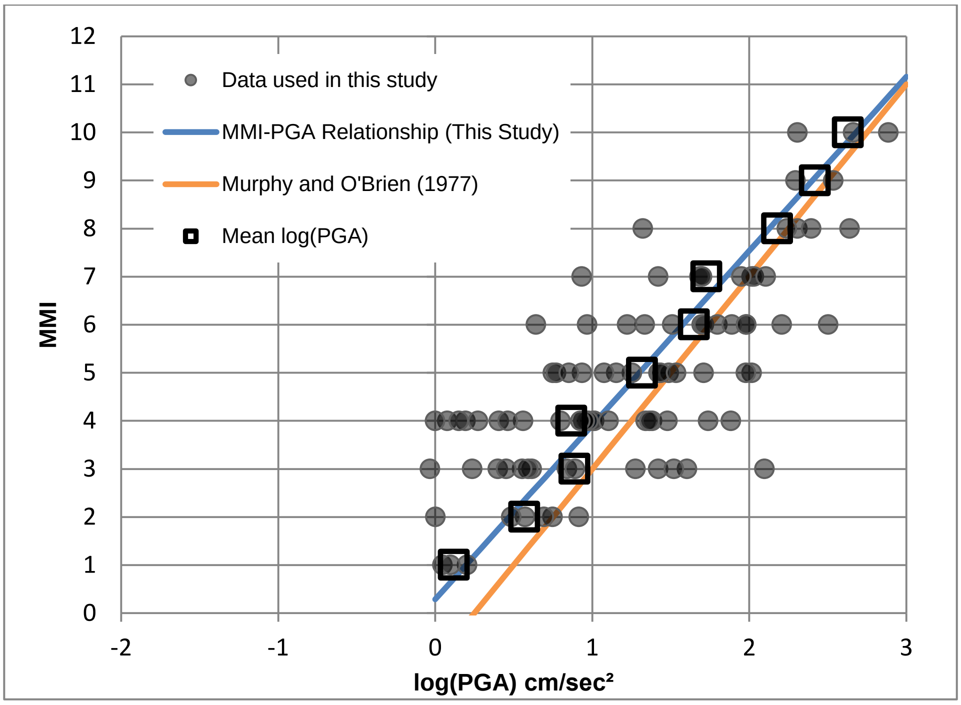


Figure 3.19: Comparison of the result of this study with that of Murphy and O'Brien (1977)

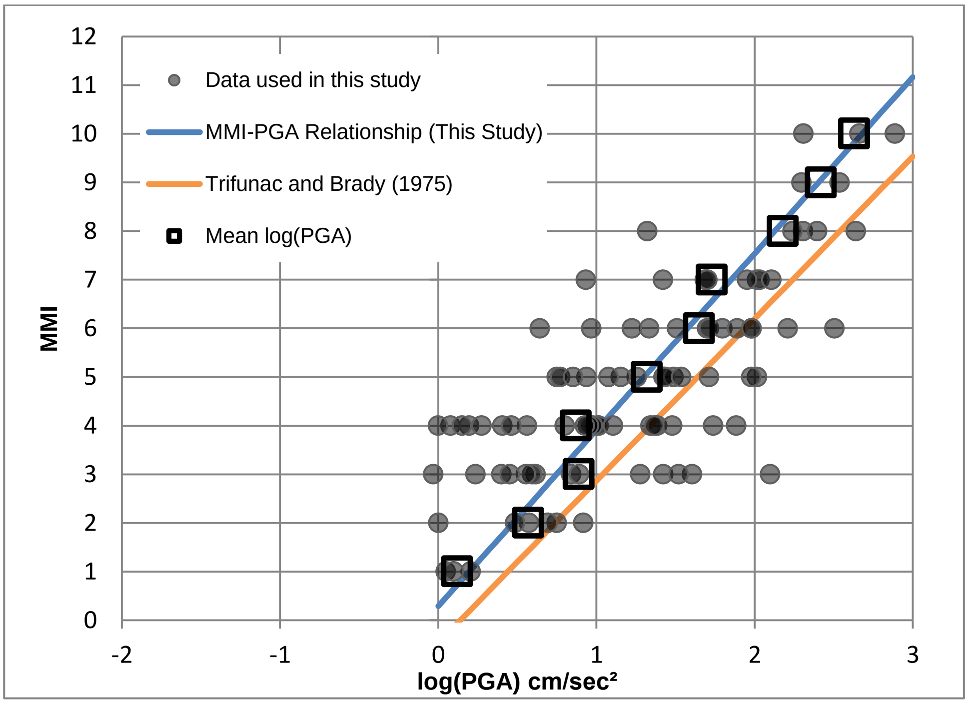


Figure 3.20: Comparison of the result of this study with that of Trifunac and Brady (1975)

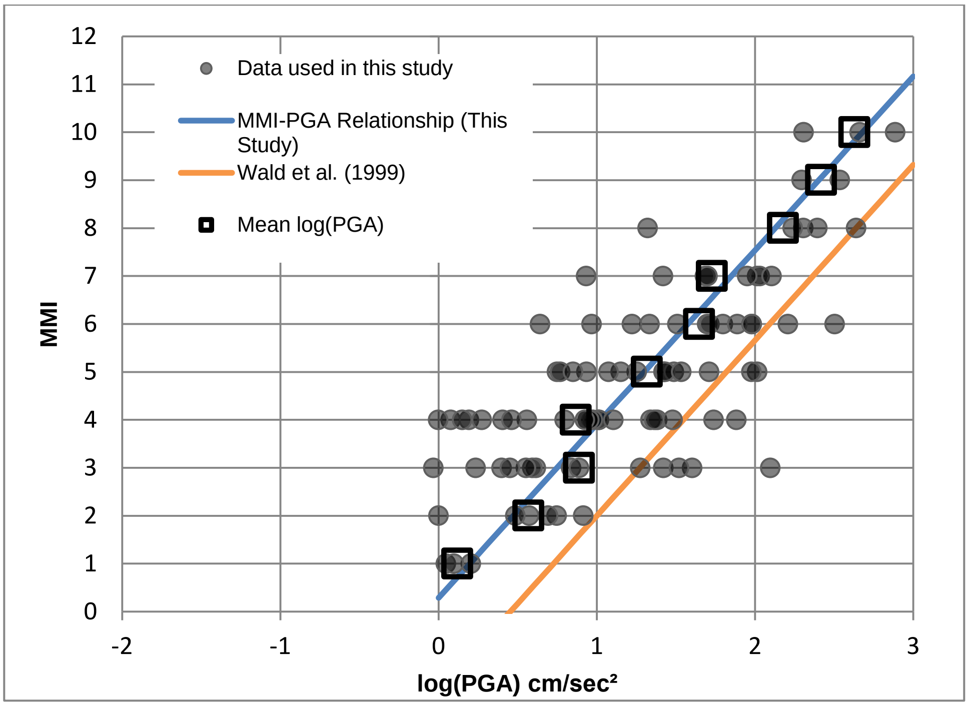


Figure 3.21: Comparison of the result of this study with that of Wald et al. (1999)

It is observed that, particularly the equations derived for California clearly underestimate the observed intensity values in the Turkish dataset. Despite the subjectivity in human response, it is believed that worldwide human perception of the same levels of ground shaking is more or less similar. Thus, this difference is believed to originate from the different building styles in different parts of the world as well as diverse damage types taken into consideration while assigning MMI values. Another possible reason is the following: since the buildings in California are more earthquake-resistant than the building stock in Turkey, generally lower MMI values are observed at the same levels of ground shaking.

On the other hand, it is noticed that the proposed equations by Faenza and Michelini (2010) and Tselentis and Danciu (2008) are indeed closer to the proposed equation than the other studies. Those studies are based on Italian and Greek damage databases which are believed to be similar to the dataset used in this study. This observation confirms that such relationships between felt intensity and instrumental ground motion parameters must be derived on local scales and they can only be used in regions with similar design and construction styles.

Finally, when Arıoğlu et al. (2001) and this study are compared, it is observed that the equation proposed by Arıoğlu et al. (2001) underestimates the intensity values by approximately an order of 1 intensity unit. This difference is mainly based on the fact that Arıoğlu et al. (2001) used data from only one event whereas this study considered 14 different earthquakes.

Next, the equation obtained for PGV is compared with the previous studies from the world. For comparison the following studies are used: Atkinson and Kaka (2004), Atkinson and Kaka (2007), Tselentis and Danciu (2008), Atkinson and Kaka (2006), Faenza and Michelini

(2010), and Wald et al. (1999). The proposed equation corresponding to each study is given in Table 3.6. The comparisons are plotted in Figure 3.22 to Figure 3.27.

Table 3.6: Equations proposed for MMI-PGV relationships

No.	Name	Equation
1	This Study	MMI=0.319+5.021*log(PGV)
2	Atkinson and Kaka (2004)	MMI=3.96+1.79*log(PGV)
3	Atkinson and Kaka (2007)	MMI=4.37+1.32*log(PGV) if log(PGV)≥0.48 cm/sec MMI=3.54+3.03*log(PGV) if log(PGV)≤0.48 cm/sec
4	Tselentis and Danciu (2008)	MMI=3.30+3.358*log(PGV)
5	Atkinson and Kaka (2006)	MMI=4.40+1.92*log(PGV)+0.28*(log(PGV))^2
6	Faenza and Michelini (2010)	MMI=5.11+2.35*log(PGV)
7	Wald et al. (1999)	MMI=3.66*log(PGA)-1.66

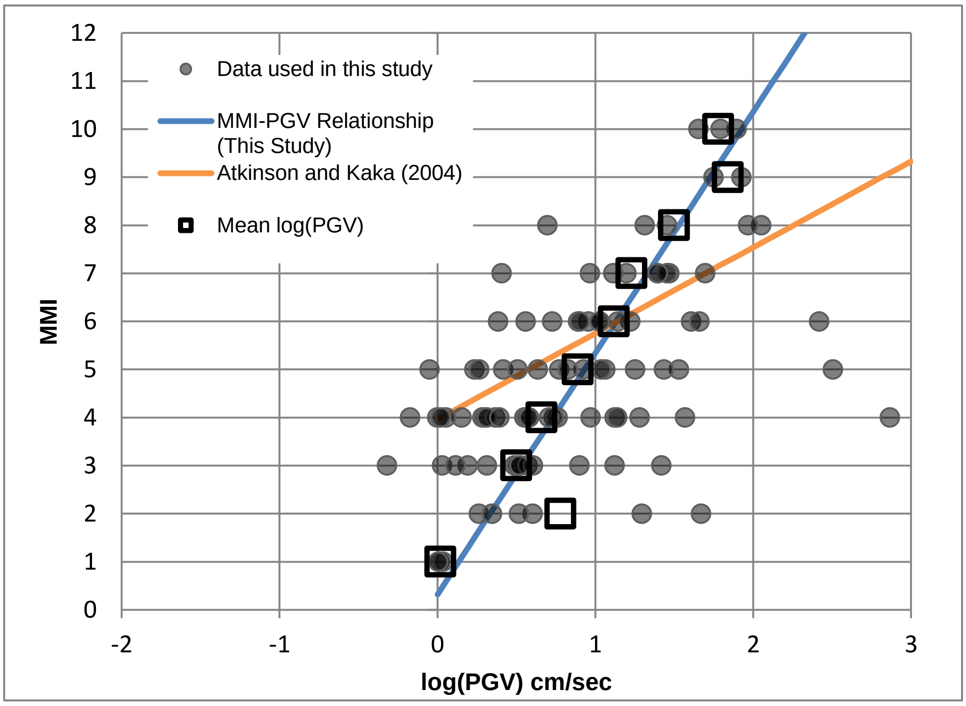


Figure 3.22: Comparison of the result of this study with that of Atkinson and Kaka (2004)

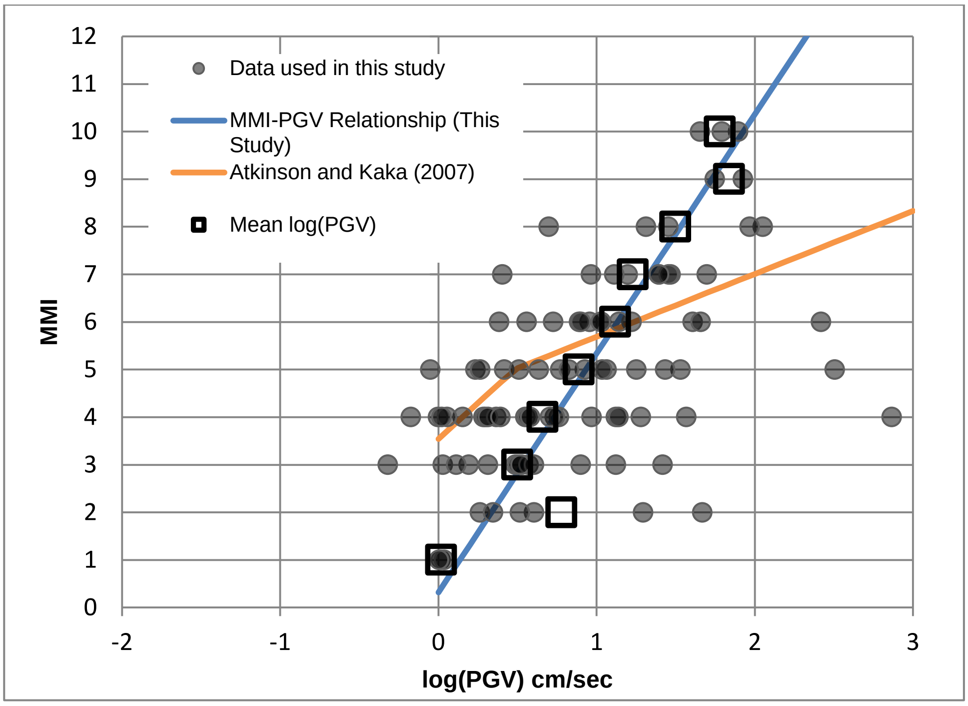


Figure 3.23: Comparison of the result of this study with that of Atkinson and Kaka (2007)

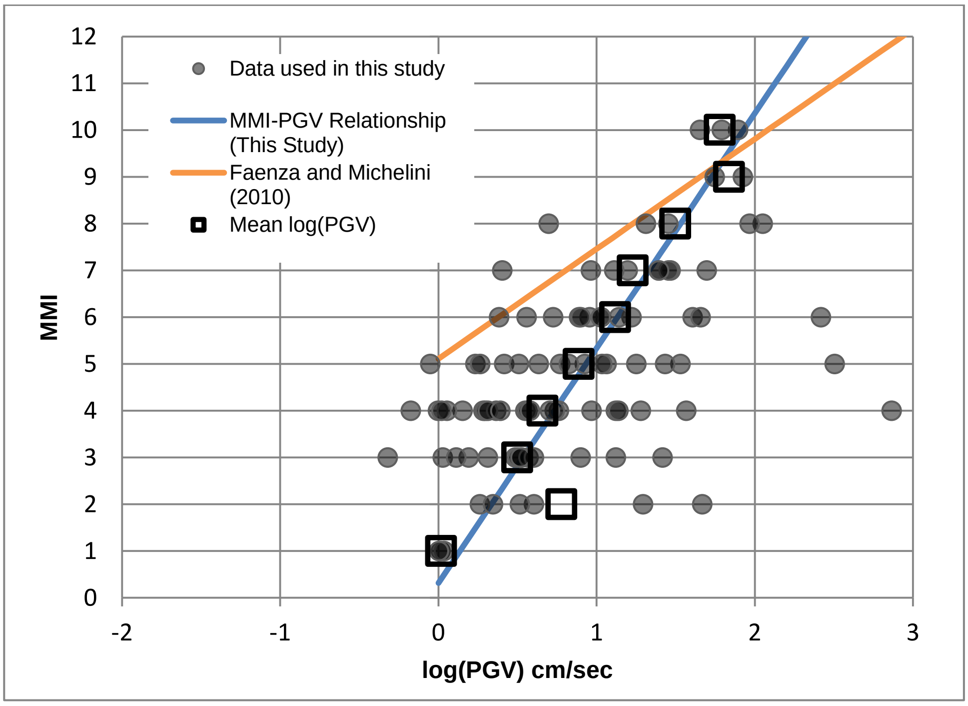


Figure 3.24: Comparison of the result of this study with that of Faenza and Michelini (2010)

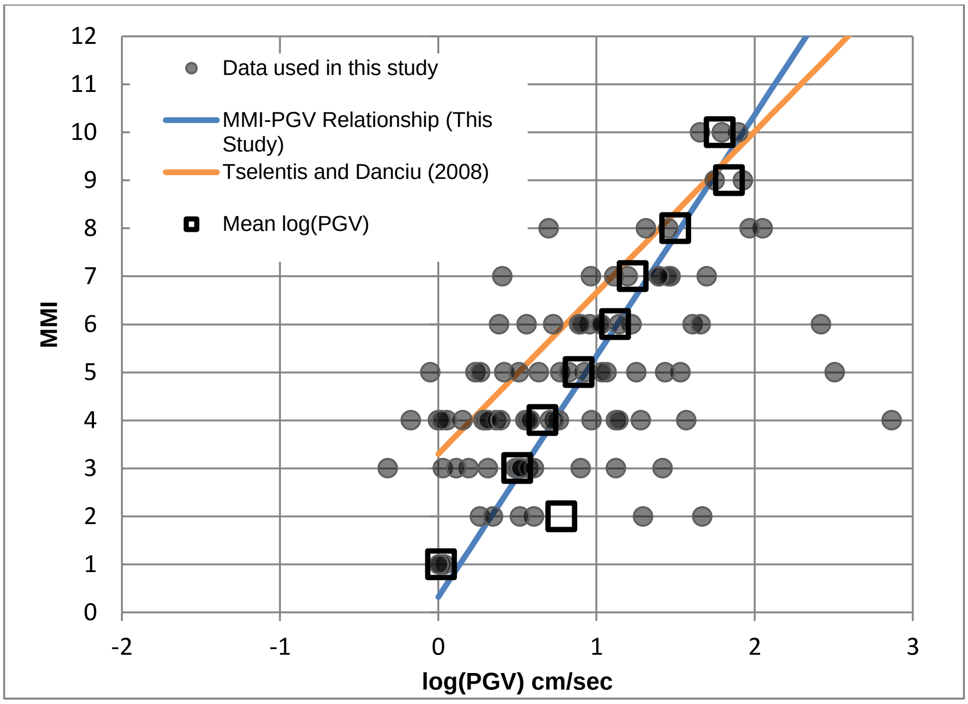


Figure 3.25: Comparison of the result of this study with that of Tselentis and Danciu (2008)

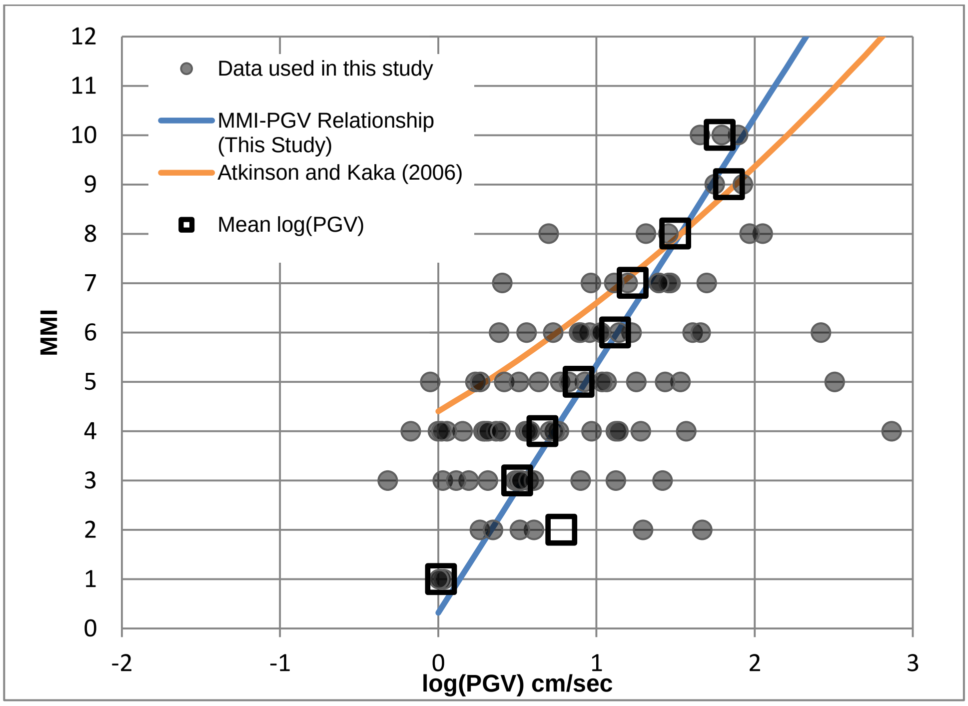


Figure 3.26: Comparison of the result of this study with that of Atkinson and Kaka (2006)

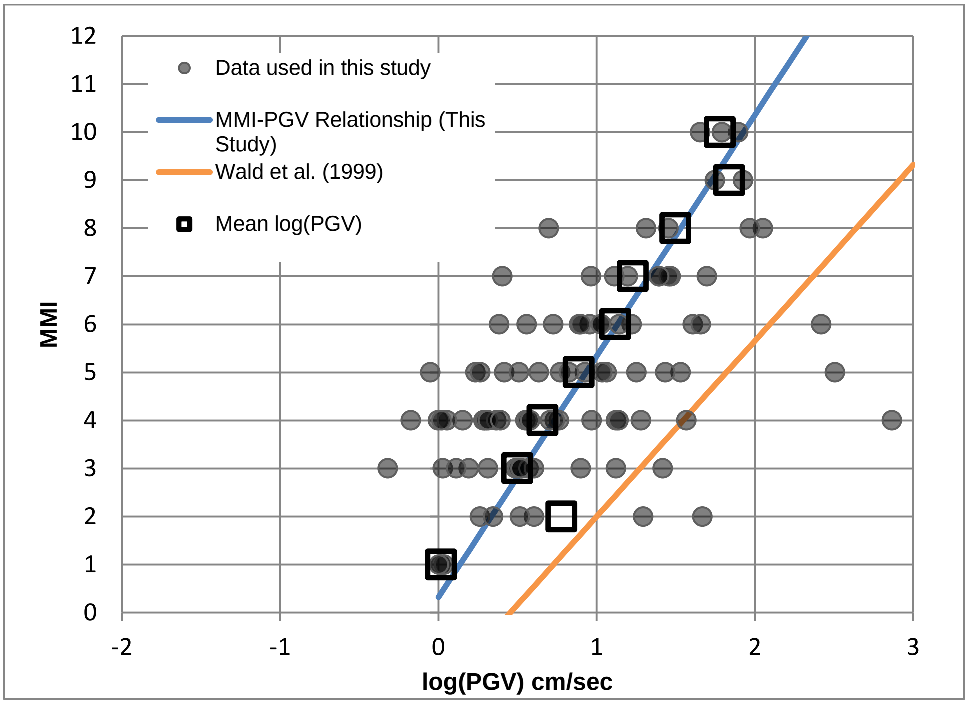


Figure 3.27: Comparison of the result of this study with that of Wald et al. (1999)

Interesting observations on MMI-PGV relationships arise. First of all, for the Turkish dataset even the MMI-PGV relationship proposed in this thesis does not exhibit as high correlation coefficient as the MMI-PGA relationship proposed here. This is expected to some extent since most of the buildings in Turkey are still non-ductile, brittle structures that are PGA sensitive. On the other hand, it is discussed in previous studies (e.g.: Wald et al., 1999; Atkinson and Kaka, 2007) that PGV correlates better with high MMI values. This is because the building stock of interest in those studies is more ductile with longer fundamental periods, thus the damage correlates better with PGV.

While comparing the results of this study with the previous ones in terms of MMI-PGV correlations, it is observed that the equations from other regions of the world overestimate the Turkish data at lower intensities but underestimate for higher intensities. This observation suggests that either the ground motion content quantified in terms of PGV is more variable than PGA or the building response to PGV measure is different. As a result, it is important to note that MMI-PGV correlations carry more regional characteristics and such relationships should not be adopted from a study based on data from elsewhere in the world.

Finally, for Turkey it is believed that PGA is a better global indicator of MMI mostly due to the building characteristics. One would expect that PGV would correlate better as there is a huge reinforced concrete building stock in Turkey. However, as of now it is obvious that the building stock in Turkey does not comply with the seismic code fully resulting in less ductile structures than the code specifies.

CHAPTER 4

SUMMARY AND CONCLUSIONS

4.1 Summary

In this thesis, first the existing empirical damage probability matrices for Turkey are updated using the detailed regional damage database of the 17 August 1999 Kocaeli earthquake. For this purpose, regional DPMs for both reinforced concrete and masonry structures are constructed from the mentioned database. Then, the obtained matrices are compared with the previous studies. Finally, a best estimate damage probability matrix for reinforced concrete structures is obtained by combining the empirical DPM proposed in this thesis with the subjective DPM from relevant studies.

In the second part of this thesis, a relationship is derived between instrumental ground motion parameters and felt intensity for Turkey: namely MMI is correlated with both PGA and PGV. As the MMI input data for these relationships, regional damage reports, surveys and previous isoseismal maps are employed. The ground motion parameters are obtained from the web page of the National Strong Motion Network of Turkey. The resulting equations are as follows:

$$MMI_{est} = 0.287 + 3.625 * \log(PGA) \qquad (3.10)$$

$$MMI_{est} = 0.319 + 5.021 * \log(PGV) \qquad (3.11)$$

With coefficients of determination as $R^2{}_{PGA}$=0.986 and $R^2{}_{PGV}$=0.919, respectively.

4.2 Conclusions

Following observations and conclusions are derived from the analyses performed in the first part of this study:

- Regional empirical DPMs constructed from a large dataset resulting from a major event is more accurate than the empirical DPMs that are formed by gathering scarce data from multiple events.
- Regional empirical DPMs better explain the damage patterns as they encounter local building properties.
- When the city-wise DPMs are compared for Bolu, Sakarya and Kocaeli, it is concluded that the local soil conditions in Sakarya affected the reinforced concrete building performance worse than the masonry buildings. Thus, it is concluded that local soil conditions can affect the damage probabilities of certain buildings types significantly.

- When compared with the analytically-formed DPMs from previous studies, empirical results are found to be mostly consistent for reinforced concrete buildings. However, for masonry structures some discrepancies are seen. These differences are believed to originate from the bias in damage states within the sample space analysed in this thesis while deriving empirical DPMs.

- After validations with future data, these regional DPMs can be used in calculation of earthquake insurance premiums.

Below are the conclusions derived in the second part of this study:

- For Turkey it is believed that PGA is a better global indicator of MMI mostly due to the building characteristics. One would expect that PGV would correlate better as there is a huge reinforced concrete building stock in Turkey. However, as of now it is obvious that the building stock in Turkey does not comply with the seismic code fully resulting in less ductile structures than the code specifies.

- When the MMI-PGA correlation obtained herein is compared with the previous studies worldwide, it is seen that particularly the equations derived for California clearly underestimate the observed intensity values in the Turkish dataset. This difference is believed to originate from the different building styles in different parts of the world as well as diverse damage types taken into consideration while assigning MMI values. Another reason could be the following: since the buildings in California are more earthquake-resistant than the building stock in Turkey, generally lower MMI values are assigned to the same levels of ground shaking.

- It is noticed that the proposed equations by past studies that are based on datasets with similar damage characteristics, are indeed closer to the MMI-PGA equation proposed herein. This observation confirms that such relationships between felt intensity and instrumental ground motion parameters must be derived on local scales and they can only be used in regions with similar design and construction styles.

- Finally, the proposed MMI-PGA relationship is compared with the corresponding equation in the study of Arıoğlu et al. (2001) which is the only local current relationship for Turkey. It is observed that the MMI-PGA relationship of Arıoğlu et al. (2001) underestimates the intensity levels by almost a unit of 1. This difference is mainly based on the fact that Arıoğlu et al. (2001) used data from only one event whereas this study considered 14 different earthquakes.

- As a result of the above conclusions, it is believed that the proposed equation can be used in future ShakeMap applications in Turkey.

- Results of this study and similar studies should be further validated with future data. In the long run, the results can be used in practice in Turkey for disaster mitigation and management purposes.

4.3 Future Work and Recommendations

The analyses presented in this thesis all depend on the datasets employed. As a result, there are certainly some limitations of the presented work. Recommendations regarding the data as well as the applied methods are presented below along with several recommendations:

- The accuracy of DPMs is completely dependent on the input data. Any bias or incompleteness in certain damage states could drastically change the DPM making it less accurate. Thus, while collecting the damage data, standard rules must be applied accurately. Damage data forms must be standardized and digitalized. Related educations must be provided to those engineers who collect damage data in the field in the aftermath of an earthquake.

- When forming the DPMs, not only the seismic zone and building type but also the local site conditions can be used as an independent variable. This way, more realistic damage probabilities could be obtained.

- One of the most challenging parts of this thesis was to gather MMI data from past studies. The data archives must be digitalized whenever possible for healthy data acquisition.

- In some communities, there is a wrong idea that due to the abundance of instrumental ground motion measures, felt intensity scales such as MMI is now unnecessary and outdated. This is actually very incorrect, as for rapid response systems even the most developed countries in the world (with dense accelerometric networks) use ShakeMaps in terms of MMI. Thus, in Turkey after major earthquakes, MMI must be measured based on damage observations in the field and questionnaires for human response whenever possible. As a result, felt intensity measures must be used together with the instrumental ground motion parameters.

- For the human response questionnaires for collecting MMI values, an online system such as the one used by the United States Geological Survey (Did You Feel It?) project could be implemented for Turkey and its use can be promoted at the country level.

- Augmenting the correlations between MMI and PGA or PGV is possible by increasing the number of data pairs for more accurate regressions. For this purpose, Strong Ground Motion Network should be widened as much as possible.

- Analyses presented in both part of this thesis (DPMs and MMI-PGA/PGV relationships) are indeed dynamic topics as the characteristics of the existing building stock could change in few decades. Thus, these research topics remain open for validations of the presented results and future updated applications.

REFERENCES

30 Ekim 1983 Erzurum-Kars Depremi Raporu, (1983). Ministry of Public Works and Settlement, 17, Ankara.

5 Temmuz 1983 Biga Depremi Raporu, (1983). İmar ve İskan Bakanlığı, 3, Ankara.

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

Alyamaç, K. E. and Erdoğan, A. S., (2005). Geçmişten Günümüze Afet Yönetmerlikleri ve Uygulamada Karşılaşılan Tasarım Hataları, *Deprem Sempozyumu Konferans Notları*, Kocaeli Turkey.

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.

Arıoğlu, E., Arıoğlu, B., Girgin, C., (2001). Doğu Marmara Depreminin İvme Değerleri Açısından Değerlendirilmesi, *Beton Prefabrikasyon*, **57-58**, 5-15.

Askan, A., (2002). Stochastic Methods for the Estimation of Potential Seismic Damage, *M. Sc. Thesis*, Middle East Technical University, Ankara.

Askan, A. and Yücemen, M. S., (2010). Probabilistic Methods for the Estimation of Potential Seismic Damage: Application to Reinforced Concrete Buildings in Turkey. *Structural Safety*, 32, 262-271.

Ateş, R., Bayülke, N., (1976). *Denizli Depremi 19 Ağustos 1976*, 62, Ankara.

Atkinson, G. M., and Sonley, E., (2000). Empirical Relationships between Modified Mercalli Intensity and Response Spectra, *Bulletin of Seismological Society of America*, **90-2**, 537-544.

Atkinson, G. M. and Kaka, S. L., (2004). Relationships between Instrumental Ground-Motion Parameters and Modified Mercalli Intensity in Eastern North America, *Bulletin of Seismological Society of America*, **94-5**, 1728-1736.

Atkinson, G. M. and Kaka, S. L., (2006). Relationships between Felt Intensity and Instrumental Ground Motion in Central United States and California, *Bulletin of Seismological Society of America*, **91-2**, 497-510.

Atkinson, G. M., and Kaka, S. L., (2007). Relationships between Felt Intensity and Instrumental Ground Motion for New Madrid ShakeMaps.

Bayülke, N., Büyükköse, N., İnan, E., Gencoğlu, S., Koşan, U., Hürata, A., Yılmaz, R., (1986). *5 Mayıs ve 6 Haziran 1986 Doğanşehir (Malatya) Depremleri Raporu*, Ankara.

Building Census Report, (2000). State Institute of Statistics, Prime Ministry Republic of Turkey, http://www.turkstat.gov.tr/Kitap.do?metod=KitapDetay&KT_ID=9&KITAP_ID=64.

Bulak, B. S., (1997).A Stochastic Methodology for the Estimation of Earthquake Insurance Premiums, *M. Sc. Thesis*, Middle East Technical University, Ankara.

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

Demirbaş, R., Iravul, Y., Erkmen, C., Baran, B., Yaman, M., Baykal, M., Kılıç, T., (2000). *06 Haziran 2000 Orta (Çankırı) Depremi*, 15, Afet İşleri Genel Müdürlüğü, Ankara.

Deniz, A. and Yücemen, M. S., (2009). Assessment of Earthquake Insurance Rates for the Turkish Catastrophe Insurance Pool. *Georisk*, **3**, 67-74.

Deniz, A., (2006). Estimation of Earthquake Insurance Premium Rates Based on Stochastic Methods, *M. Sc. Thesis*, Middle East Technical University, Ankara.

Efe, R., Sekin, S., (1998). *27 Haziran 1998 Adana-Ceyhan Depremi*, 39, İstanbul.

Erberik, M. A., (2008a). Fragility-Based Assessment of Typical Mid-Rise 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., Uçkan, E., Şeşetyan, K., Demircioğlu, M. B., Celep, U., Biro, Y., (2002). *February 3, 2002 Sultandağı (Turkey) Earthquake Report*, Department of Earthquake Engineering, Kandilli Observatory and Earthquake Research Institute, İstanbul.

Faenza, L. and Michelini, A., (2010). Regression Analysis of MCS Intensity and Ground Motion Parameters in Italy and its Application in ShakeMap, *Geophysical Journal International*, **180**, 1138-1152.

Gürpınar, A., Abalı, M., Yücemen, M. S., Yeşilçay, Y., (1978). Zorunlu Deprem Sigortası Uygunluğu, *Deprem Mühendisliği Araştırma Enstitüsü,* **78-05**, Orta DoğuTeknik Üniversitesi, Ankara.

Hershberger, J. (1956) A comparison of earthquake accelerations with intensity ratings. *Bulletin of the Seismological Society of America*, **46**, 317-320.

İnan, E., (1996). *14 Ağustos 1996 Çorum-Amasya (Salhançayı) Depremi Raporu*, 11, Ankara.

Kafalı, C. and Grigouri, M., (2004). Seismic Fragility Analysis, *Proceedings of the 9th ASCE Specialty Conference on Probabilistic Mechanics and Structural Reliability*, Rome, Italy, 19-23 June, 2005.

Kawasumi, H. (1951) Measures of earthquake danger and expectancy of maximum intensity throughout Japan as inferred from the seismic activity in historical times. *Bulletin of the Earthquake Research Institute*, Tokyo University, Tokyo, 469-482.

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

Murphy, J. R. and O'Brien, L. J., (1977). The Correlation of Peak Ground Acceleration Amplitude with Seismic Intensity and Other Physical Parameters, *Bulletin of Seismological Society of America*, **67-3**, 877-915.

Musson, R. M. W., (2000). Intensity-based Seismic Risk Assessment, *Soil Dynamics and Earthquake Engineering*, **20**, 353-360.

Musson, R. M. W., Grünthal, G., Stucchi, M., (2010). The Comparison of Macroseismic Intensity Scales, *Journal of Seismology,* **14**, 413-428.

November 6, 1992 (Ms: 6.0) İzmir Earthquake: A Preliminary Reconnaissance Report, (1993), Kandilli Observatory and Eartquake Research Institute, 46, İstanbul.

Özmen, B., (1999). Iso-intensity map of İzmit Earthquake, Earthquake Research Department, General Directorate of Disaster Affairs, Ankara.

Özmen, B., Bağcı, G., (2000). *12 Kasım 1999 Düzce Depremi Raporu*, Bayındırlık ve İskan Bakanlığı, Ankara.

Özmen, B., (2002), 3 Şubat 2002 Çay (Afyon) Depreminin Eşşiddet Haritası ve Hasar Durumu (Rakamsal Verilerle), Afet İşleri Genel Müdürlüğü Deprem Araştırma Dairesi, Ankara.

Shiga, T., (1977). Earthquake Damage and the Amount of Walls in Reinforced Concrete Buildings, *Proceedings of 6th World Conference on Earthquake Engineering*, 2467-2472, India.

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

Tselentis, G. and Danciu, L., (2008). Empirical Relationships between Modified Mercalli Intensity and Engineering Ground-Motion Parameters in Greece, *Bulletin of Seismological Society of America*, **98-4**.

Ünal, E., Cindemir, H., Ergünay, O., Yıldız, M., Kozacı, H., Tekeli, S., Ceyhan, R., Aytaç, E., (1993). *13 Mart 1992 Erzincan Depremi*, 6, Ankara.

Van Depremi (23 Ekim 2011) Raporu, (2011).Deprem Dairesi Başkanlığı, Afet ve Acil Durum Yönetimi Başkanlığı, Ankara.

Wald, D. J., Quitoriano, V., Heaton, T. H., Kanamori, H., (1999). Relationships between Peak Ground Acceleration, Peak Ground Velocity, and Modified Mercalli Intensity in California, *Earthquake Spectra*, **15-3**, 557-564.

Whitman, R.V., (1973). Damage Probability Matrices for Prototype Buildings, *Structures Publication*, **380**, MIT, Boston.

Wu, Y., Hsiao, N., Teng, T., (2004). Relationships between Strong Ground Motion Peak Values and Seismic Loss during the 1999 Chi-Chi Taiwan Earthquake, *Natural Hazards*, **32**, 357-373.

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

Yücemen, M. S., Bulak, B. S., (2000). Yapılarda Deprem Hasarının Tahmini: Hasar Olasılık Matrisleri, *KTMMOB Bülteni*, **3**, 15-22, Lefkoşa, KKTC.

Web References:

Least-Squares Linear Regression Notes, Vose Software, http://www.vosesoftware.com/ModelRiskHelp/index.htm#Probability_theory_and_statistics/The_basics/Probability_theorems_and_useful_concepts/Least_Squares_Linear_Regression.htm. (last accessed 04 January 2013).

M7.1-Eastern Turkey, Did You Feel It, United States Geological Survey, http://earthquake.usgs.gov/earthquakes/dyfi/events/us/b0006bqc/us/index.html. (last accessed 08 January 2013).

Medvedev–Sponheuer–Karnik Scale, http://en.wikipedia.org/wiki/MSK_scale (last accessed 28 October 2012).

Web Page of Strong Ground Motion Database of Turkey, http://daphne.deprem.gov.tr (last accessed 08 January 2013).

APPENDIX A

INTENSITY MAPS USED IN THIS THESIS

A.1 General

In this section isoseismal intensity maps used to form the MMI database are presented.

Figure 6.1 Regional map of İzmir, indicating the villages visited.

Figure A.1: Intensity map of the 6 November 1992 İzmir earthquake

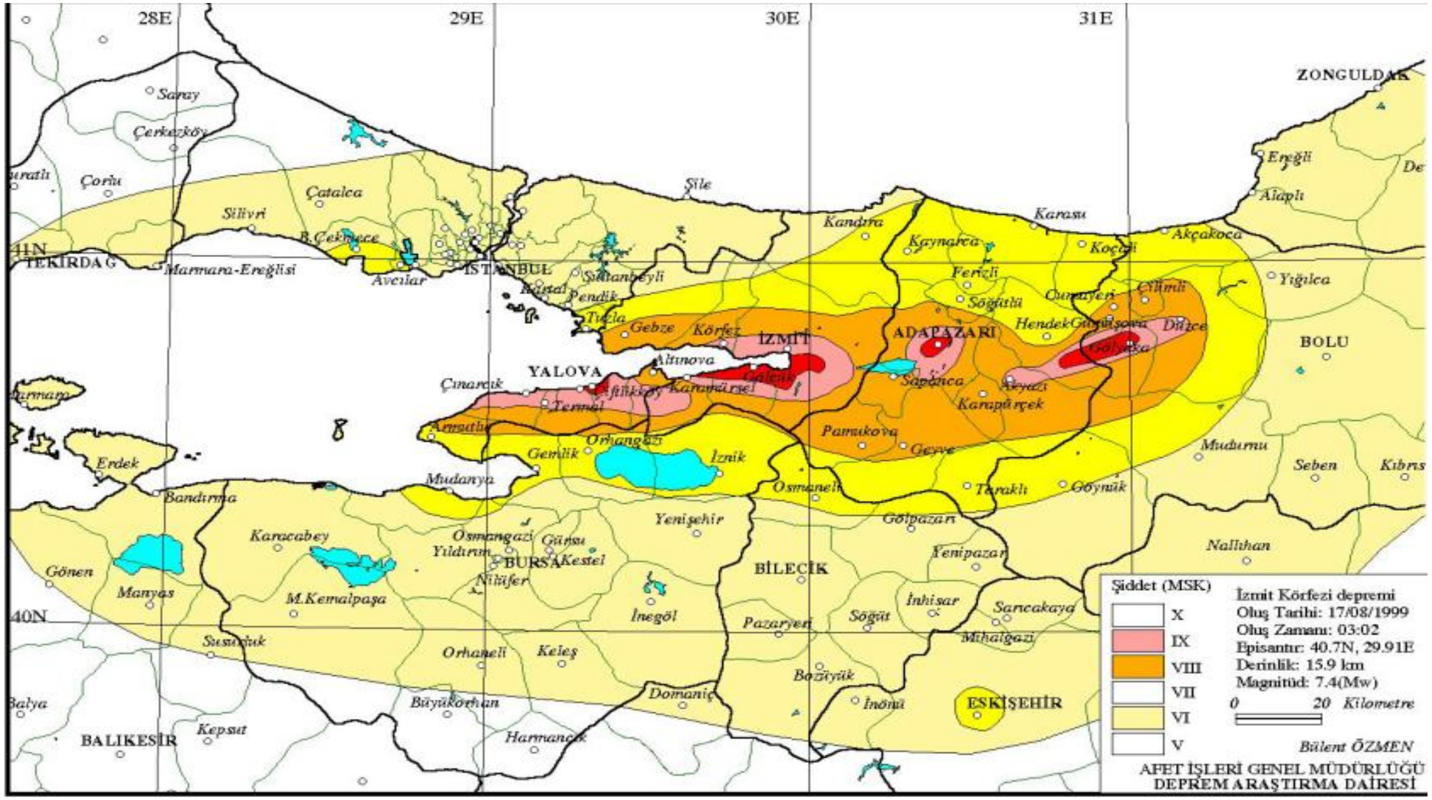


Figure A.2: Intensity map of the 17 August 1999 Kocaeli earthquake

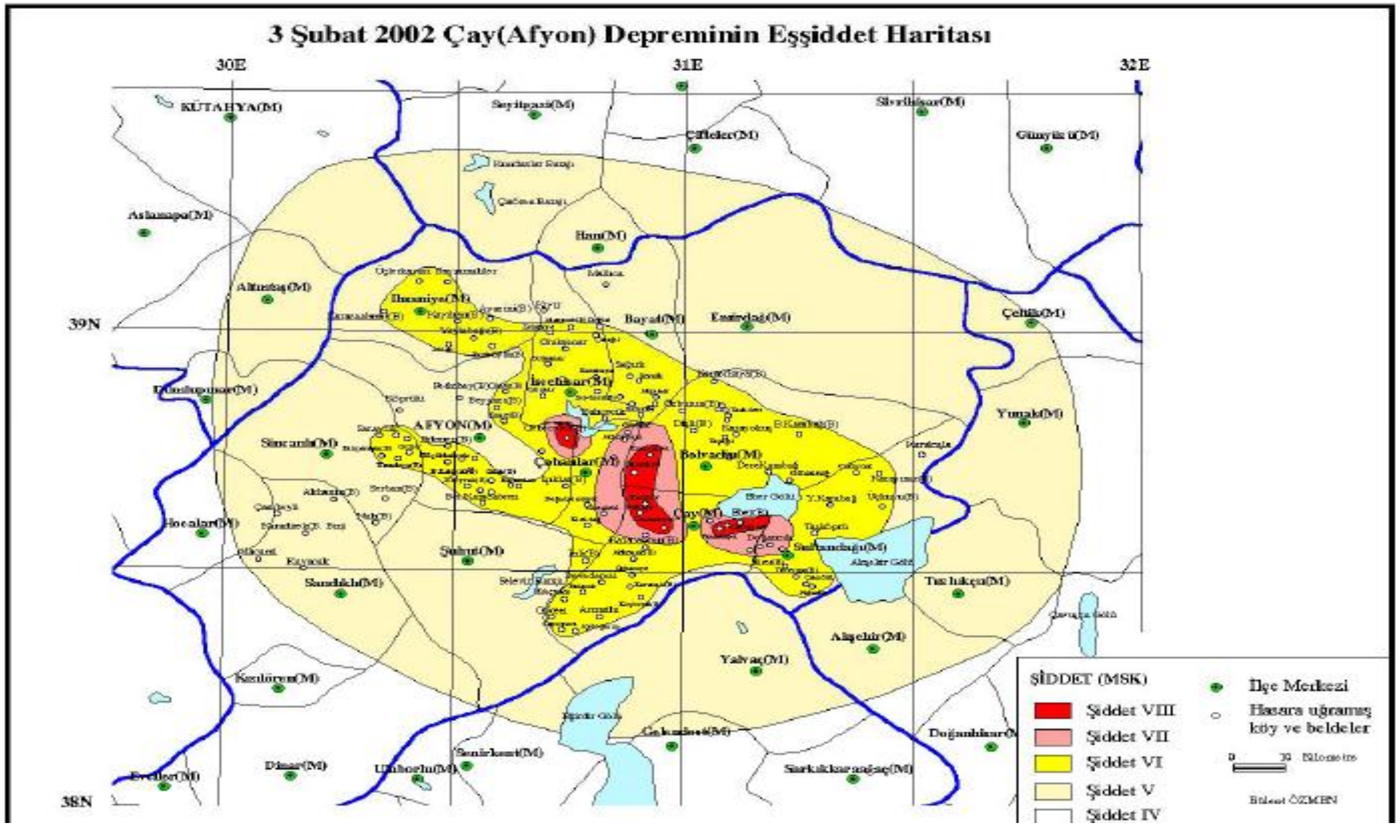
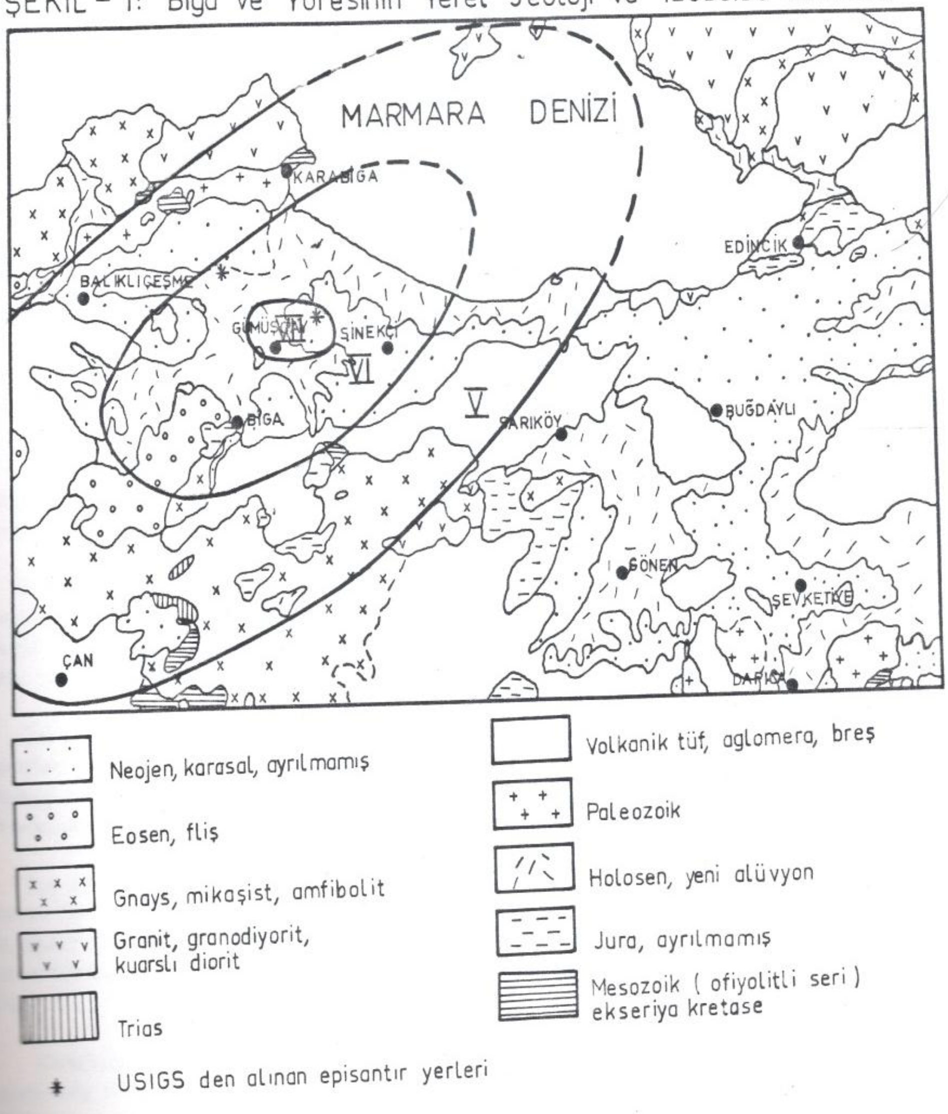


Figure A.3: Intensity map of the 03 February 2002 Çay earthquake

ŞEKİL – 1: Biga ve Yöresinin Yerel Jeoloji ve İzoseist Haritası



Ölçek: 1/500.000

Figure A.4: Intensity map of the 05 July 1983 Biga earthquake

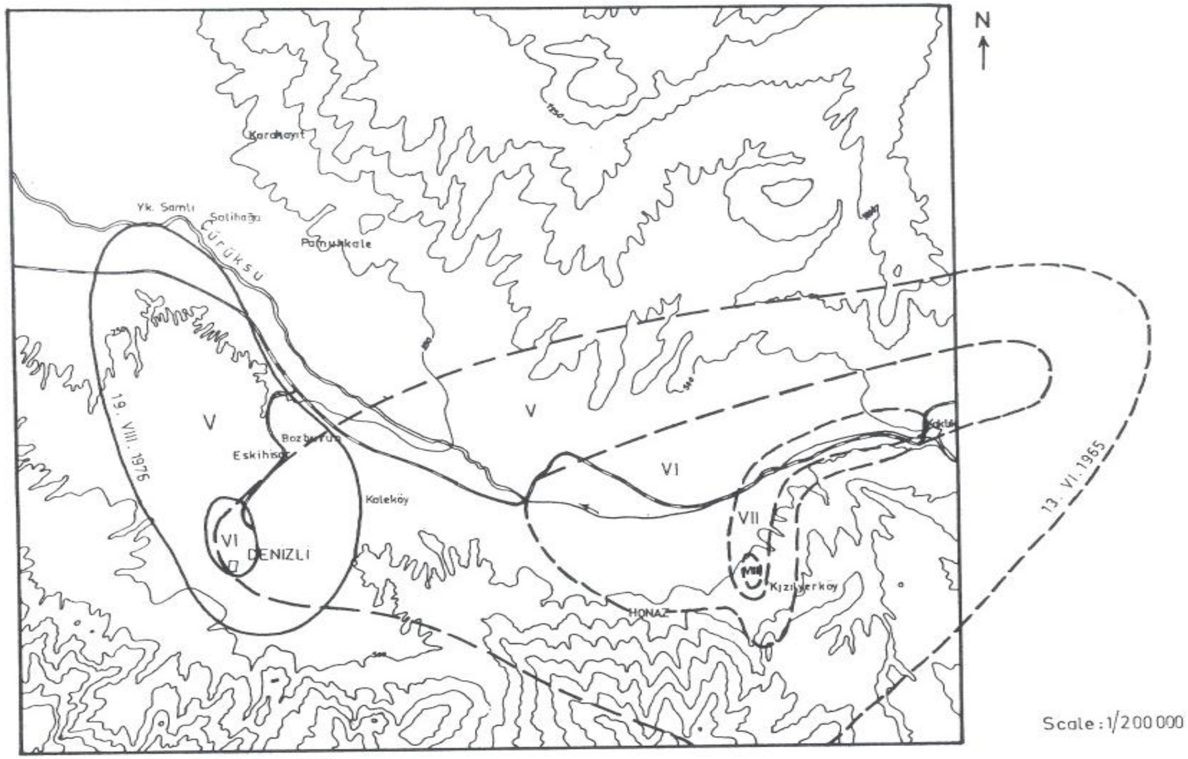


Figure A.5: Intensity map of the 19 August 1976 Denizli earthquake

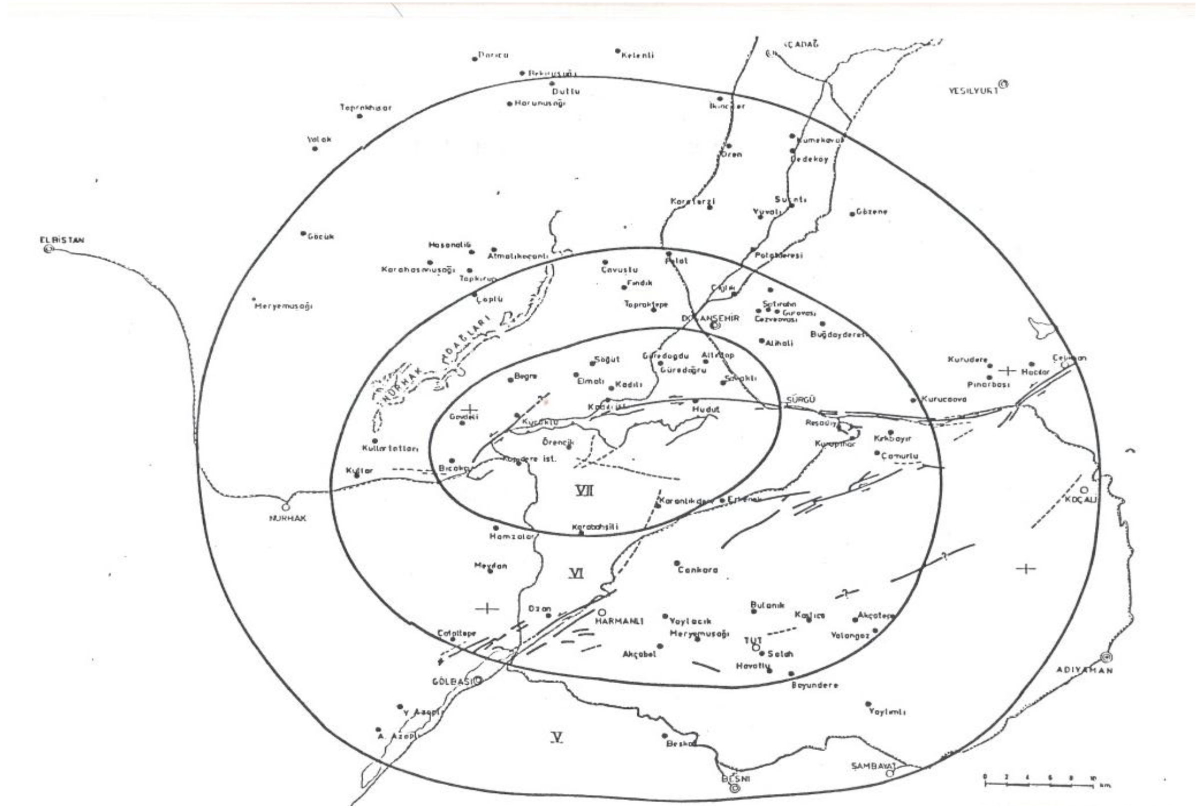


Figure A.6: Intensity map of the 05 May 1986 Doğanşehir Malatya earthquake

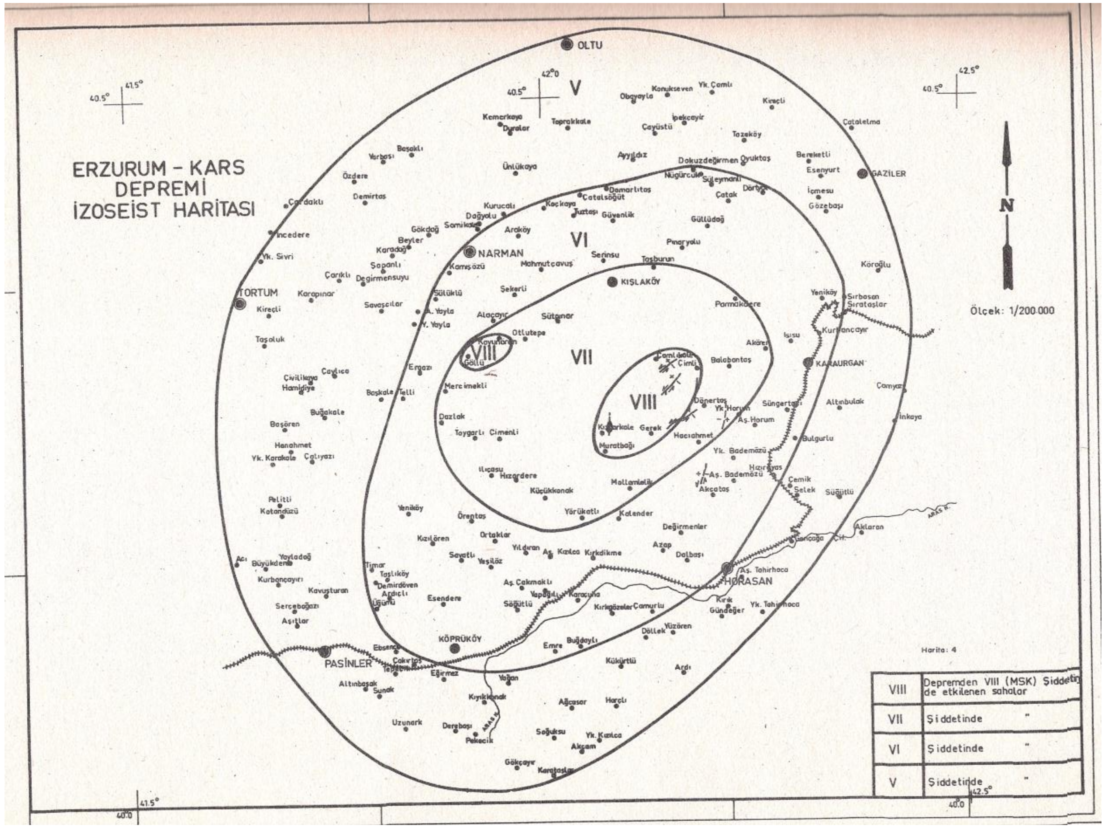
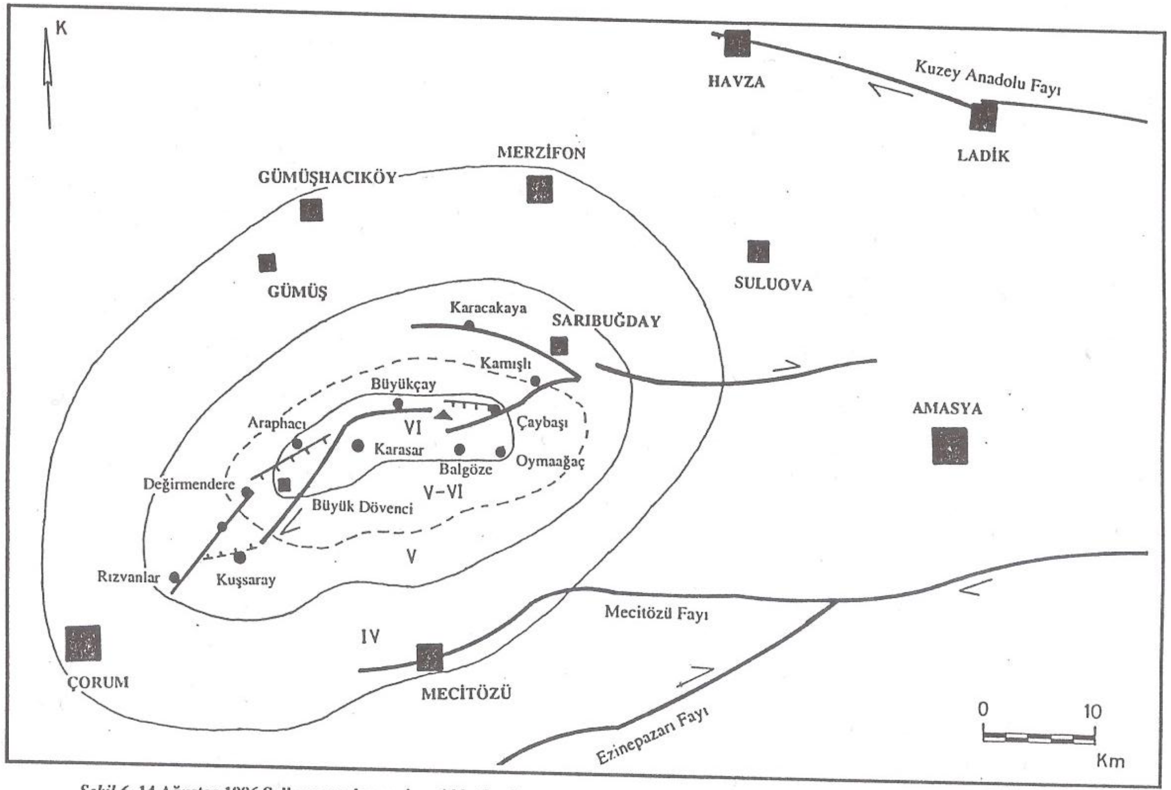
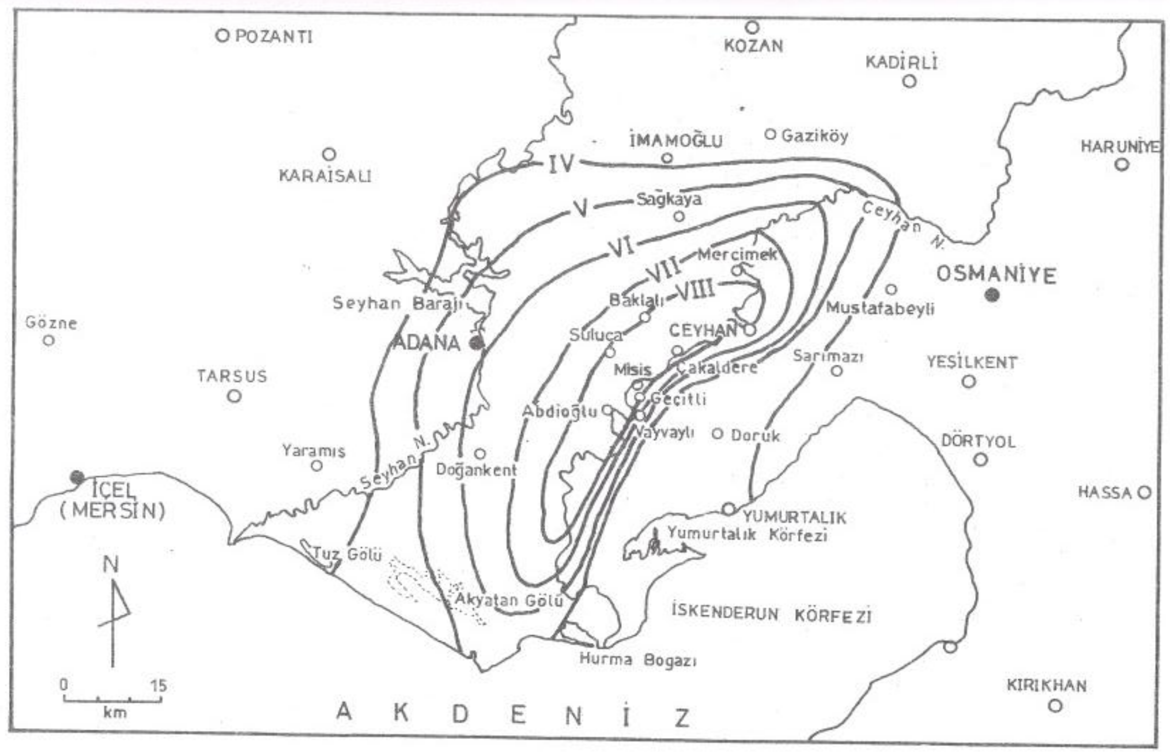


Figure A.7: Intensity map of the 30 October 1983 Erzurum Kars earthquake



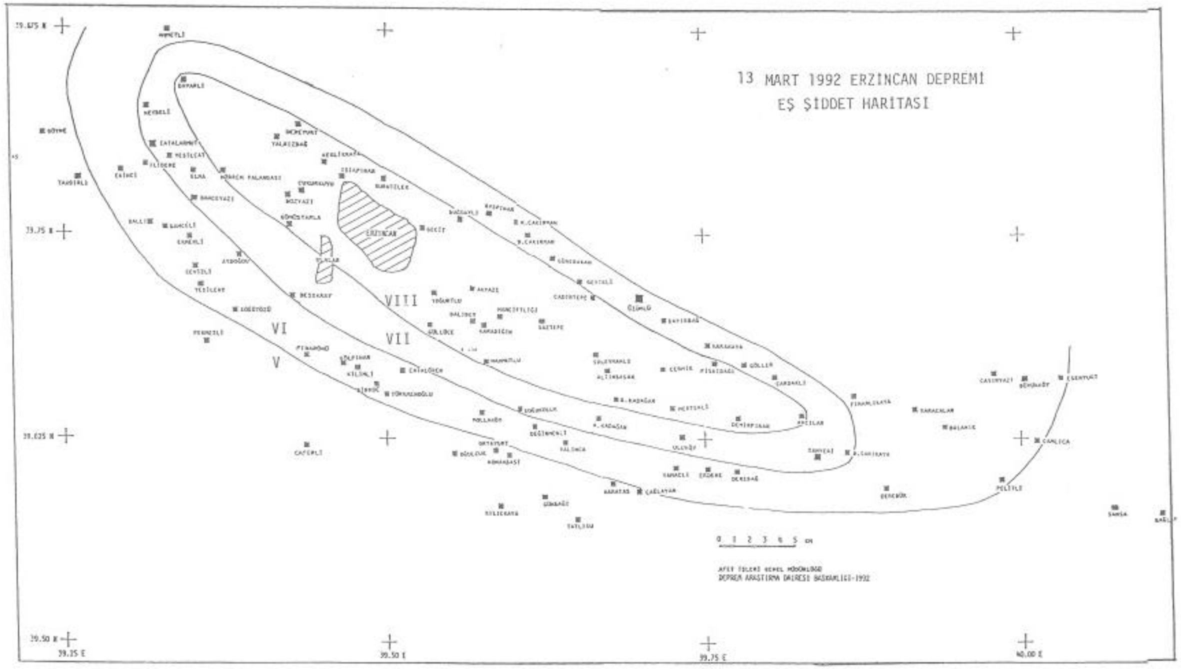
Şekil 6. **14 Ağustos 1996 Salhançayı depremi eş-şiddet haritası.**

Figure A.8: Intensity map of the 14 August 1996 Çorum earthquake



Şekil 10: Adana-Ceyhan Depremi izoseist (şiddet dağılış) haritası

Figure A.9: Intensity map of the 27 June 1998 Adana Ceyhan earthquake



Şekil - 5   13 Mart 1992 Erzincan Depremi Eşşiddet Haritası

Figure A.10: Intensity map of the 13 March 1992 Erzincan earthquake

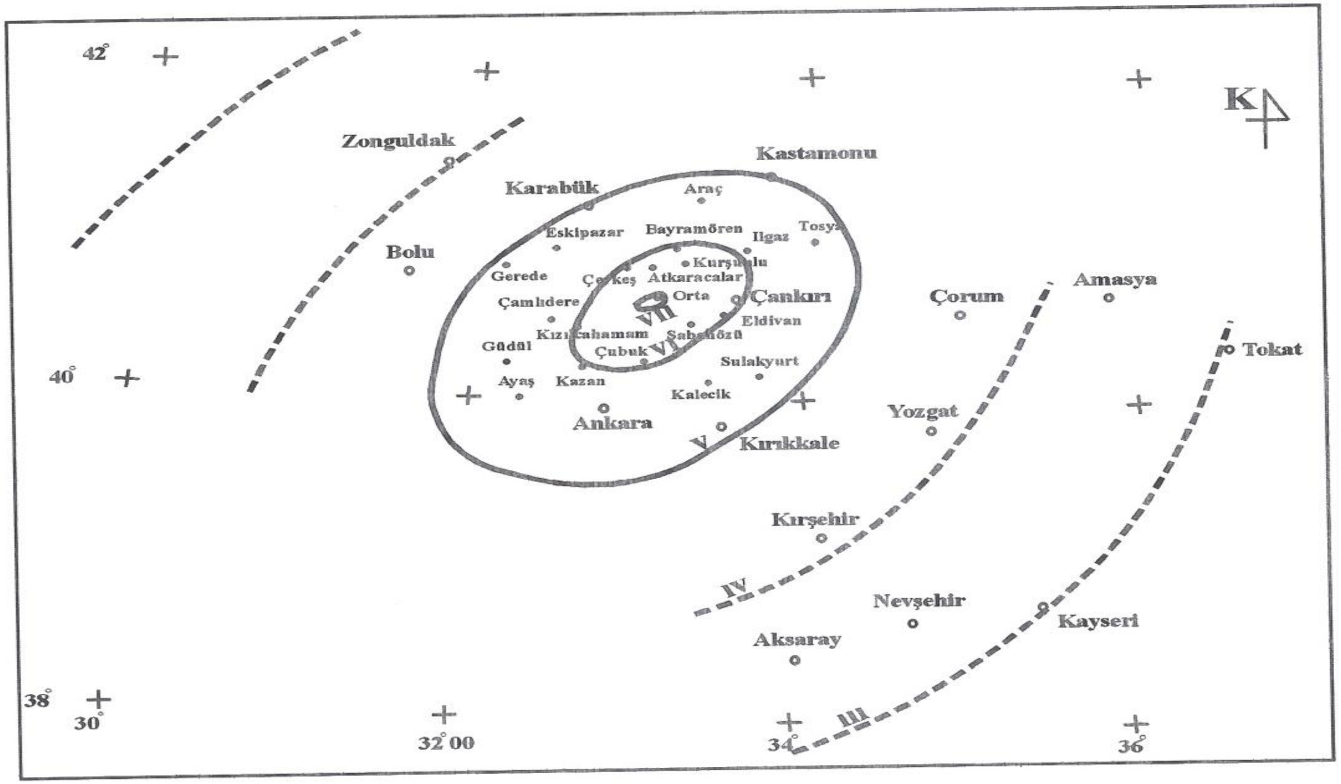


Figure A.11: Intensity map of the 06 June 2000 Çankırı earthquake