# PROBABILISTIC SEISMIC HAZARD ASSESSMENT FOR ESKİŞEHİR

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Approval of the Graduate School of Natural and Applied Sciences.

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I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science.

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This is to certify that we have read this thesis and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

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## ABSTRACT

PROBABILISTIC SEISMIC HAZARD ASSESSMENT FOR ESKİŞEHİR



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The purpose of this study is to develop probabilistic hazard maps for Eskişehir including ‘Peak Ground Acceleration’ values for 10% probability of exceedance in 50-year and 100-year periods at different site classes.

A seismotectonic map has been prepared in the Geographical Information Systems environment by compiling instrumental seismicity and neotectonic data for the study area.

The seismic sources have been defined spatially in six areal zones, characterized by a commonly used recurrence law and a maximum magnitude value.

Four attenuation relationships have been selected being one of them totaly developed from the strong-motion records of Turkey.

After the implementation of a seismic hazard model by using SEISRISK software, the probabilistic seismic hazard curves and maps were developed based on the selected attenuation relationships, at ‘rock’ and ‘soil’ sites, with a probability of exceedance of 10% in 50-year and 100-year periods. At rock sites the highest levels of hazard were calculated based on the predictive relationship of Abrahamson and Silva (1996), whereas the lowest ones based on the one of Boore et al. (1996). On the other hand the highest hazard levels were determined at soil sites based on the attenuation relationship of Ambraseys et al. (1996), whereas the lowest ones based on the one of Boore et al. (1997).

For Eskişehir, the peak ground acceleration values calculated based on attenuation relationship by Boore et al. (1997) were found to be applicable for 10% probability of exceedance in 50 and 100 years, taking into consideration the fact that a considerable portion of the city is founded over alluviums.

Key words: Eskişehir, hazard map, hazard curve, attenuation relationship, peak ground acceleration.

**ÖZ**

ESKİŞEHİR İÇİN OLASILIĞA DAYALI SİSMİK TEHLİKE ANALİZİ

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Bu çalışmanın amacı Eskişehir için değişik zemin sınıflarında, %10 aşılma olasılığı için, 50 ve 100 yıllık sürelerde ‘En Büyük Yer İvmeleri’ni’ içeren olasılığa dayalı tehlike haritalarının geliştirilmiştir.

Coğrafi Bilgi Sistemleri ortamında çalışma alanı için deprem ve neotektonik verileri derlenerek bir sismotektonik harita hazırlanmıştır.

Sismik kaynaklar geometrik olarak altı alan kaynak şeklinde tanımlanmış, sıkça kullanılan bir tekrarlanma ilişkisi ve maksimum büyüklük değeri ile karakterize edilmiştir.

Bir tanesi tamamen Türkiye’deki deprem kayıtlarından geliştirilmiş olan, dört adet azalım ilişkisi seçilmiştir.

SEISRISK yazılımı kullanılarak bir sismik tehlike modeli oluşturulmasının ardından, kaya ve toprak zeminlerde, %10 aşılma olasılığı için 50 ve 100 yıllık sürelerde, seçilen azalım ilişkilerine dayanarak, olasılığa dayalı sismik tehlike eğrileri ve haritaları oluşturulmuştur. Kaya zeminlerde, en yüksek tehlike seviyeleri Abrahamson ve Silva’nın (1997) önerdiği azalım ilişkisine dayanarak hesaplanırken, en düşük seviyeler Boore vd.’nin (1997) önerdiği azalım ilişkisiyle hesaplanmıştır. Diğer taraftan, toprak zeminlerde en yüksek tehlike seviyeleri Ambraseys vd.'nin (1996) önerdiği azalım ilişkisiyle, en düşük seviyelerse Boore vd.'nin (1997) önerdiği azalım ilişkisiyle hesaplanmıştır.

Eskişehir için, şehrin büyük bir kısmının alüvyon zeminler üzerinde konuşlandığı dikkate alındığında, 50 ve 100 yıllık sürelerde %10 aşılma olasılığına sahip, Boore et al. 'ın (1997) önerdiği azalım ilişkisi kullanmak suretiyle hesaplanan en büyük yer ivmesi değerleri uygulanabilir bulunmuştur.

Anahtar Kelimeler: Eskişehir, tehlike haritası, tehlike eğrisi, azalım ilişkisi, en büyük yer ivmesi.

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# CHAPTER I

# INTRODUCTION

## 1.1. Purpose and Scope

The two recent Kocaeli and Düzce earthquakes of Turkey, which occurred on 17 August 1999 and 12 November 1999 showed again and again that almost all of the settlement areas established and developed in seismically active areas are under serious threat. It is evident that without considering the reality that Turkey is an earthquake country and without careful examination of available earthquake precautions together with the new, innovative prevention and/or prediction techniques, severe damages and losses of lives will be unfortunately expected in the future as well. So first of all, the consciousness of the earthquake hazard and its drastic probable consequences should be manipulated to the people.

In that sense Eskişehir, being one of these industrialized cities of Turkey, is rapidly expanding due to an increase of its population. However, based on the earthquake zonation map of Turkey (Ministry of Public Works and Settlement Divides, 1996), the city is situated within the second degree earthquake region, and in addition to that between different fault systems defined by distinct fault characteristics with respect to each other. It is located within the transition zone between North Anatolian Fault System and West Anatolian Fault System (WAFS).

The purpose of this study is to perform a probabilistic seismic hazard analysis for the Eskişehir metropolitan area. The principle aim of this study is to provide the seismic hazard curves and the hazard maps for the study area in terms of 'Peak Ground Acceleration' for %10 probability of exceedance, for different time periods of 50, 100 years and different site classifications(classes) such as ‘rock’, ‘stiff site’ and ‘soft site’.

The study was carried out in four stages. In the first step, the seismic source zones have been identified and characterized based on a seismotectonic map, which was prepared after a comprehensive survey. This survey consisted of a literature review of available instrumental earthquake records (seismicity), geological data and neotectonic data of Eskişehir and its vicinity with their evaluation. The second step of the study has been performed to define the earthquake recurrence characteristics of each source zone separately by the aid of a commonly used recurrence relationship of Gutenberg and Richter (1944). The third step consisted of the estimation of the earthquake effect, based on the selection of an appropriate attenuation relationship or a set of attenuation relationships. The final step included the determination of the hazard at the sites of interest in the study area. This process of determination consisted of the preparation and presentation of the seismic hazard curves and the seismic hazard maps.

Since the analysis used in this study is a probabilistic analysis and contains the results of some unpredictable processes, it is evident that the concept of ‘uncertainty’ and its requirements have been carefully included in every step of this methodology.

### 1.2. Location and Accessibility of the Study Area

The study area, which is located in the western Central Anatolia Region, is a rectangular area situated between the latitudes of N 38 14 29.4 and N 40 51 31.6 and the longitudes of E 28 07 35.8 and E 32 44 56.8 and consists of the municipal boundaries of Eskişehir (Figure 1.1).

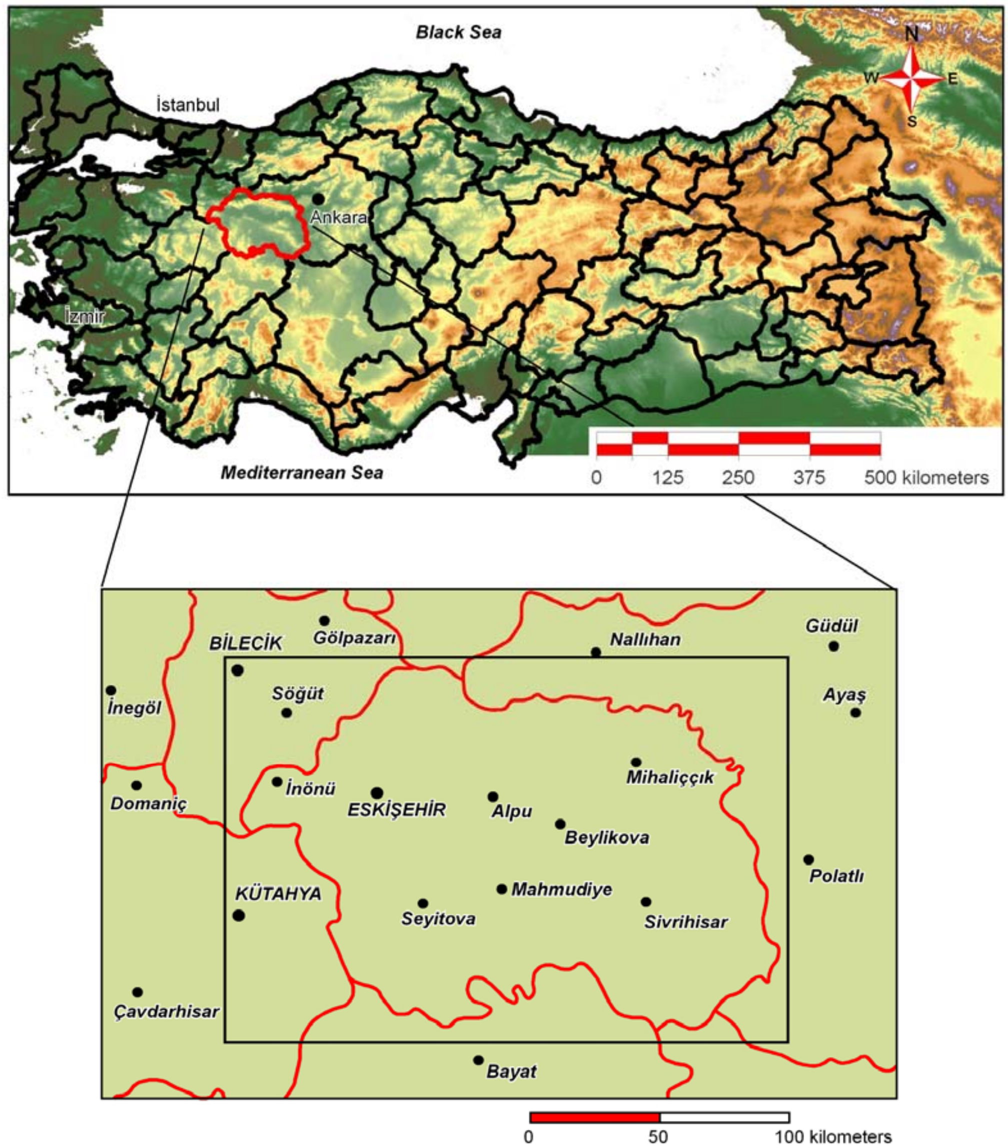


**Figure 1.1.** Location map of the study area.

The city of Eskişehir is at the junction of both the highway and railway transportation. The public highways between Ankara and Bursa and Ankara Kütahya have passed through the Eskişehir downtown area. Besides it has an important mission as a central station for the rail lines between both Ankara and İstanbul, Ankara and İzmir.

### 1.3. Geology of the Study Area

#### 1.3.1. General Stratigraphy of Eskişehir and Its Surroundings

In this study, for the description of the geological units in and around Eskişehir, the nomenclature proposed by Gözler et al. (1996) is adopted. The stratigraphical columnar section and the geological map of the study area are shown in Figures 1.2 and 1.3, respectively.

The lithostratigraphical units of the study area are composed of various metamorphic, volcanic, sedimentary rock sequences and Quaternary alluviums. The oldest units forming the elevated land in the north of the study area are grouped into a tectonic unit consisted of Triassic schist and marble, ophiolitic melange and metadetritic rocks. The metamorphic series which is one of these units having tectonic relationships between each other was named as Eskişehir metamorphics and it is presented by garnetiferous amphibolite, quartzite, glaucophone glawsonite greenschist, epidote-albite greenschist and marbles (Gözler et al., 1996). Although they do not show uniform layering, the ophiolitic rocks of the same age comprise radiolarite, radiolarite limestone, mudstone, diabase, serpentinite, the blocks of schist, peridotite and gabbros. The metadetritics of Triassic age, metasandstone, metamicroconglomerate, phyllite, metabasic and crystallized limestones are even the oldest units in the region. Above these units, Zeyköy Formation, which is composed of the members of conglomerate, sandstone, clayey limestone and limestones, situated in the northwest and southwest overlies the older units unconformably. Since the age of Zeyköy Formation was determined as Jurassic, the age of the tectonic unit composed of metamorphic, ophiolite and metadetritics is accepted to be pre-Jurassic or Triassic (Gözler et al., 1996). This upper Cretaceous formation crops out in a small region, in the south of the study area. But it shows widespread exposures near Ilıca and contains conglomerates and sandstones whose gravels are formed of schist, marble, radiolarite, spillite, granite and sepentinite. The formation was named as Orbucak Ridge Formation (Gözler et al., 1996). In the southern parts of the study area, the granitic rocks cut across the ophiolitic rocks and Paleocene-Eocene conglomerates. An age of Early Eocene was assigned to these rocks. In the south of Eskişehir, near Meşelik locality, and Karacaşehir and Mamuca Villages the Lower-Eocene Mamuca Formation unconformably overlies Orbucak Ridge Formation. The formation has a thickness ranging between 20 and 400 m, and is composed of members of conglomerate, sandstone, clay, marl and limestones with nummulites. The Upper Miocene Porsuk Formation consisting of conglomerate, claystone, marl, tuff and limestone members crops out as a belt trending E-W and covering wide areas in the south of the study area. The volcanic rocks forming the upper levels of Late Miocene consist of andesite, andesitic tuff, agglomerate and basalt. These rocks produce widespread exposures both at the south and north of Eskişehir. The Pleistocene age old alluviums are observed as terrace deposits in the southwest of the study area. They exhibit a relatively rough topography than the recent, Holocene alluviums, which are observed along flat areas (Gözler et al., 1984 and 1996).

A considerable portion of the city of Eskişehir is founded over Quaternary alluviums. Basically six lithological units were distinguished by Ayday et al. (2001) and Koyuncu (2001), in the downtown area of Eskişehir. These units are,

(a) Conglomerate member of the Lower Eocene Mamuca Formation
(b) Conglomerate-sandstone, claystone-marl-tuff-tuffite and limestone members of the Upper Miocene Porsuk Formation
(c) Old and recent Quaternary alluviums

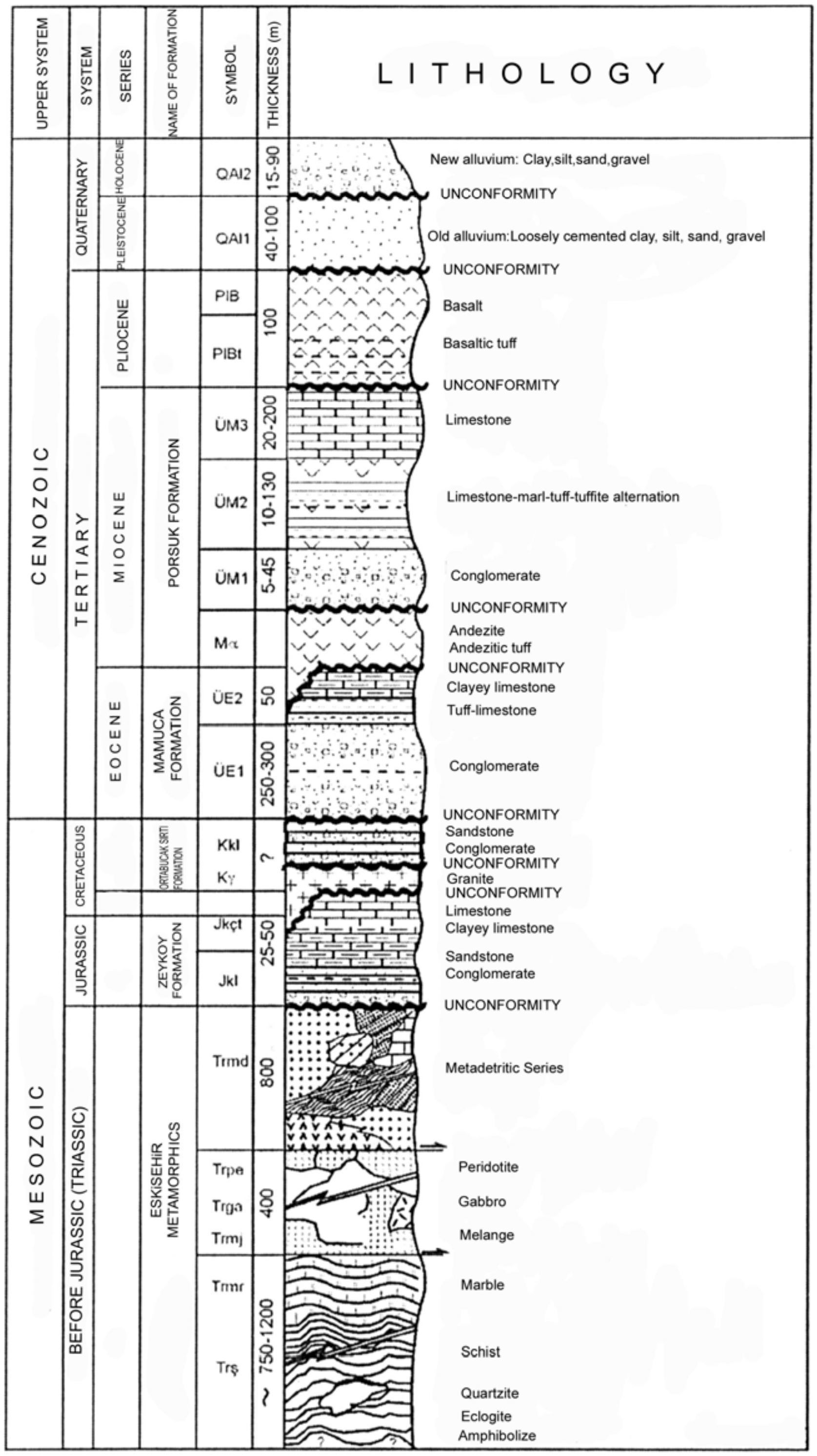


**Figure 1.2.** Stratigraphical Columnar Section of the study area (Gözler et al., 1984, 1996).

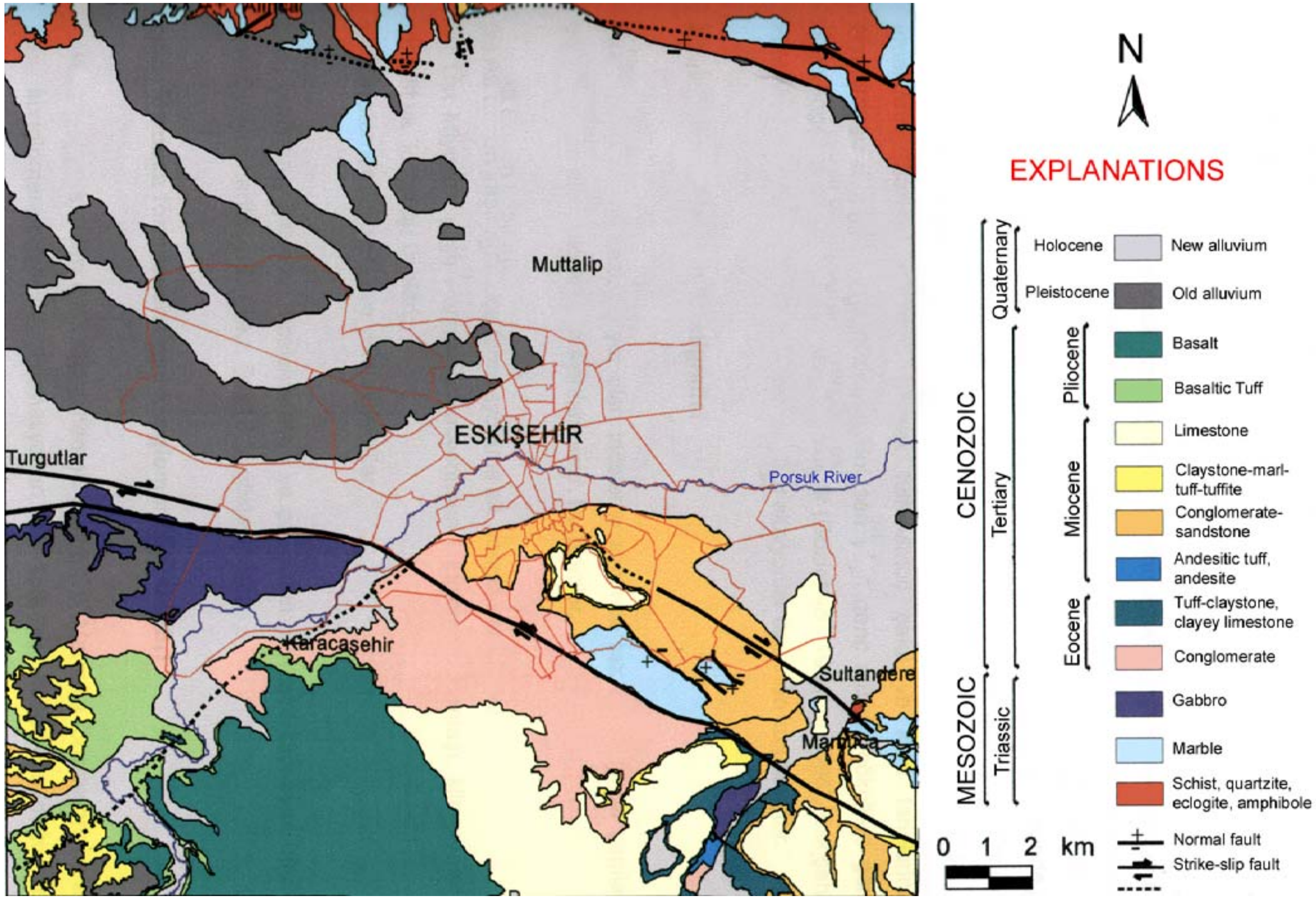


**Figure 1.3.** Geological Map of Eskişehir and its close vicinity (Ayday et al., 2001)

# CHAPTER II

# LITERATURE REVIEW

The scientific pubications or researches about (the subject of) the Seismic Hazard Assessment could be basically grouped into four categories:

(a) The publications on the determination and application of deterministic seismic hazard analysis and its considerations in a particular region of the world

(b) The publications on the formation of Probabilistic Seismic Hazard Assesment, its development through time; the challenges in it, beginning from very recent times, back in the history

(c) The publications on the consideration of uncertainties inherent in seismic hazard assesments; like in all of the probabilistic analyses, and the discussion of the effects of the different types from a scientific perspective

(d) The publications on the integration and/or the combination of these two methods and the discussion of their advantages (beneficial usages) and/or their handicaps

In fact there is a few number of publications written on the subject of Deterministic Seismic Hazard Analysis. Although it is not a complete (specific) deterministic approach, the study of Chandler et al. (2001) could be mentioned here as an example application from Hong Kong. In their study, the recent regional studies, which evaluate the seismic hazard parameters required to assess the seismic risk to engineering construction in the Coastal Region of South China (CRSC) including Hong Kong (HK), have been reviewed and compared. Since the potential threat to lives and properties of the unprepared community in the region from moderate to large earthquakes has been a growing concern in recent years they presented a simplified, pseudo-probabilistic approach to the evaluation of seismic hazard and engineering risk assessment for the HK region. This approximate analysis has aimed to quantify first the magnitude–distance (M–R) combinations associated with certain probabilities of exceedance (PE) of magnitude *M* within a defined circular source area then the PEs associated with events of different magnitudes and source areas, and finally the bedrock ground motions and design acceleration levels associated with such events together with the relation of the design-level scenario events to structural performance objectives, in order to formulate a policy for seismic risk reduction. After formulated a group of realistic design-level earthquake events have been presented in the form of deterministic magnitude–distance pairs associated with earthquake magnitudes having a range of magnitude recurrence intervals. The peak (effective) ground accelerations predicted by the scenario earthquake events were estimated for 500-year earthquake events and for 1000-year events were estimated by this pseudo probabilistic approach (Chandler et al., 2001).

On the other hand, a number of studies (e.g. Orozova and Suhadolc, 1999; Romeo and Prestininzi, 2000; Krinitzsky, 2002) exist in the literature which have been trying to integrate both of the approaches; the probabilistic and the deterministic one in a sophisticated engineered framework. In their study, Orozova and Suhadolc (1999) have criticized the deterministic seismic hazard approaches since they made use of a controlling earthquake instead of the frequency of earthquake occurrence and they proposed a methodology which allows to estimate both the ground motion due to large and rare events as well as that due to small and frequent earthquakes so that the obtained results can be easily compared with the probabilistic studies for standard return periods. The method proposed by them has two sights; one from a deterministic perspective consisting of a fixed ground motion due to a fixed event and the other one from a probabilistic perspective providing an annual average number of events, or probability of ground motion exceedance over a given time period. So, a 'deterministic–probabilistic' approach comprising the advantages of both the probabilistic and deterministic methods has been applied to estimate the seismic hazard for the region of eastern Sicily in Italy. Finally they have claimed that the method proposed had overcome one of the most significant criticisms of the deterministic approaches, and at the same time maintains their advantages of being clear and realistic in the estimation of engineering parameters needed in the calculation of Seismic Risk (Orozova and Suhadolc, 1999). On the other side, Romeo and Prestininzi (2000) has proposed a methodology to determine design earthquakes for site-specific studies such as the siting of critical structures, strategic structures or for seismic microzoning studies, matching the results of probabilistic seismic hazard analyses. They tried to reach to this goal (aim) by calculating the source contribution to hazard and the magnitude-distance deaggregation. They showed that the reference earthquakes could be changed, by means of some observations of the variations in the selected frequency and the level of hazard. A methodology minimizing the residuals between the uniform hazard spectrum and the design earthquake spectrum has been adopted to provide a specific earthquake scenario encompassing all the frequencies of the target motion so that the influences exerted by ground motion uncertainties on hazard deaggregation would be outlined. In this approach deterministic reference events are selected on a probabilistically-based procedure, coupling the concepts of Maximum Credible Earthquake and maximum probable earthquake over all the frequencies of engineering interest that is over all the Uniform Hazard Spectra at the selected exceedance probability within a reference time period (Romeo and Prestininzi, 2000).

In addition to the several studies providing challenging approaches for seismic hazard analysis either probabilistic or deterministic, there are a lot of researches conducted by different analysts ( Grandori et al., 1998; Krinitzsky, 2002; Bommer, 2003) concerning the ‘uncertainty’ assumed to be involved in all of the probabilistic analyses. In their study, Grandori et al., (1998) have illustrated three important statements particularly concerning the adoption of the coefficient of variation as a measure of uncertainty which is assumed to include all the randomness due to both the choice of the model and the estimate of the parameters. These vital statements presented and proved by them were:

(a) In theory, when the modelling uncertainty is involved the use of coefficient of variation is not appropriate

(b) In practice the usage of the coefficient of variation under these circumstances can provide unreliable results to the analysts

(c) If both the uncertainties in modelling and in parameters' estimate should be considered with different approaches separately, the analysis of uncertainties could satisfy the results and the researches (Grandori et al., 1998).

On the other hand, Krinitzsky (2002) stated that the uncertainty is a buzz word adapted by seismic probabilists who have been claiming that everything is uncertain, therefore, only a probability could express it, meaning that seismic probability must be used. According to him the process of seismic probability itself constitutes the greatest uncertainty which is noted to have blossomed into the dual aspects of epistematic and aleatory contributions. In his paper, by an opposite approach to the probabilistic methodology, he has given some protesting answers to the conflicts in the minds of the 'seismic probabilists'. So it claimed that uncertainty is accounted for more logically, more simply and more accurately by the deterministic method, which seismic probabilists choose to ignore (Krinitzsky, 2002). Another research (opinion paper) has been conducted (published, written) by Bommer (2003) in an engaging and lively prose as a welcome change from so much of the scientific literature (against a series of publications in defence of a deterministic approach to seismic hazard assessment). According to him, both the probabilistic and deterministic elements are needed together with a state of practice not with respect to the approach to adopt but with regard to the use of terminology and, particularly, the presentation of process and results. He claimed that being clear about the uncertainties in seismic hazard assessment will not only make things more certain, but also it will certainly make things clearer. So the discussions on how to move seismic hazard assessment forward can focus on the core issues of obtaining more reliable estimates of ground motions and adapting them to the evolving demands of earthquake engineering and can be more productive with these concepts' clear definitions so that the fights could be avoided at cross purposes (Bommer, 2003).

There are a few number of analysts (e.g. Castanos and Lomnitz, 2002) still discussing the scientific background of probabilistic seismic hazard approaches and even whether they could be assumed to be scientific! Castanos and Lomnitz (2002) compared the probabilistic and deterministic procedures and declared the problems mostly associated with probabilistic seismic hazard analysis (PSHA) which could be originated from their inadequate data and their defective logic and they have proved the deterministic procedures especially when coupled with engineering judgment to be more reliable and more scientific.

Other than the main publications published on the development of some methodologies of seismic hazard (deterministic or probabilistic or combined of both of them) and its inherent uncertainties, there are a number of researchers who have been studying the different concepts of a seismic hazard analysis separately. Hamdache et al., (1998) and Manakou and Tsapanos (2000) applied different methods from the conventional ones to estimate seismic hazard parameters such as the parameter *b* of the Gutenberg-Richter relationship, the annual activity rate *l* of event and the maximum possible magnitude. The method proposed by former one has an ability to estimate these parameters from incomplete and uncertain data files by incorporating the uncertainty of earthquake magnitude, and accepting mixed data containing large historical events and recent complete catalogue, and very like the previous one; the latter estimated nearly all of the parameters from mixed data files composed of historical and instrumental data.

On the other side, Meletti et al. (2000) first described the procedures for constructing a seismotectonic model of Italy, designed to be used as a basis for hazard assessment and figured out the results of their seismotectonic analysis, which has (had) essentially been based on a GIS-aided cross-correlation of data sets, as synthesized in a zonation of Italy. In addition to these studies, under the light of the important role played by the return period in seismic hazard analysis, Tsai (2001) applied two types of statistical analyses; Gutenberg–Richter's law and Markov chain in which a past event has an influence on a subsequent event with an element of randomness or unpredictability to study the earthquake periodicity in the Chiayi–Tainan area. Additionally, he performed the substitutability analyses applicable to earthquake data, which suggest high similarity for low-magnitude earthquakes and dissimilarity for high-magnitude earthquakes, to study the statistical property of earthquake occurrences. Finally he demonstrated that the result from these statistical approaches for earthquake occurrences has lead to a conceptual model inferring fault behavior which is also supported by the recent geologic findings; potentially useful in earthquake hazard assessment (Tsai, 2001).

The majority of the publications in the subject of seismic hazard analysis basically concentrate on the application of the probabilistic approaches at different parts of the world and new challenges in the methodologies used in its development since its formation (Cornell, 1968; Veneziano et al., 1984; Kebede and van Eck, 1996; Theodulidis et al.,1998; Kijko and Graham, 1998, 1999; Eck and Stoyanov, 1999; Lindholm and Bungum,2000; Stirling et al., 2002; Tsapanos, 2003). The theoretical base of 'deductive' method developed for seismic hazard analysis was formulated by C.A. Cornell (Cornell, 1968) and it was called as 'deductive' because by applying this procedure, the causative sources, characteristics, and ground motions for future earthquakes are deducted. This approach has permitted the incorporation of geological and geophysical evidence to supplement the seismic event catalogues. It is still evident that deductive procedures of PSHA are dominant and remain the most commonly used method worldwide (Cornell, 1968). On the other side, the second category of PSHA has been composed of 'historic' methods (Veneziano *et al*., 1984), which are originally nonparametric. They basically require input data, such as information about past seismicity only, and do not require specification of seismogenic zones and the designation of the model which could be seen as major advantages (Veneziano *et al*., 1984). In 1997, Kebede and van Eck (1997) performed a probabilistic seismic hazard assessment for the horn of Africa based on seismotectonic regionalisation. The results have been presented as the regional hazard maps for 0.01 annual probability for intensity and peak ground acceleration, the hazard curves and as the response spectra for six economically significant sites. They have also analyzed the model uncertainties with respect to seismicity in a novel approach by means of a sensitivity analysis quantifying them in the probabilistic seismic hazard analysis (Kebede and van Eck, 1997). The purpose of the study by Theodulidis et al. presented in their paper (1998) has been to suggest a probabilistic seismic hazard analysis based on the local attenuation relations for peak ground acceleration and peak ground velocity and to propose the region-specific elastic design spectra for the buildings of Kozani and Grevena regions based on two factors; the 'observed spectral acceleration amplification values' and the 'expected peak ground acceleration for mean return period of 500 years'. Their study of hazard assessment could be outlined in three basic steps; the formation and representation of an adequate model representing the seismic sources with their potential to affect the site of interest, the determination of an appropriate earthquake recurrence model in order to supplement this seismic source model and the derivation of a realistic attenuation relation in order to transfer ground motion from source to site of interest (Theodulidis et al.,1998). In their study, Kijko and Graham (1998, 1999) have described a new methodology for probabilistic seismic hazard analysis (PSHA) which combines the best features of the 'deductive' and 'historical' procedures and they called this new approach as 'parametric-historic' procedure. Part I of their study presents some of the statistical techniques used for the assessment and evaluation of the maximum regional magnitude which is of paramount importance in this approach. In Part II the approach of a probabilistic seismic hazard assessment which permits the utilization of incomplete earthquake catalogues and which takes into account uncertainty in the determination of the earthquake magnitude is described. Their technique has provided specifically the estimation of seismic hazard at individual sites, without the subjective judgment involved in the definition of seismic source zones, in which specific active faults have not been mapped and identified, and where the causes of seismicity are not well understood (Kijko and Graham, 1998 and1999). Eck and Stoyanov (1999) performed a probabilistic seismic hazard analysis (PSHA) for southern Bulgaria which represents a typical case of seismic hazard for a tectonically complex region with large uncertainties in model parameters. They showed by using a Monte Carlo approach, that large uncertainties in seismic characteristics have relatively little effect on the PSHA output, especially when compared with the uncertainties associated with the attenuation function. Finally they claimed that some future improvements could be handled first by the development of more accurate regional attenuation models, second by the addition of some constraints on the seismic zones and last by a better constrain of magnitude-frequency distributions (Eck and Stoyanov, 1999). In their paper (study or publication) Lindholm and Bungum (2000) presented some examples from Norway within a seismological frame by the aid of a probabilistic seismic hazard. They highlighted the subject of how a combined seismicity analysis using both modern network data and historical data can be utilized in order to provide realistic insights into location precision and to establish magnitude homogeneity. In fact their aim has been to improve the reliability of the seismic source models (i.e. the activity parameters), and to rehabilitate the spatial differentiation of the seismogenic zones, without over-interpretation the earthquake catalogue data. So by the objective of this study they demonstrated how a seismic hazard analysis critically depends on proper analysis of the underlying seismological information such as the seismicity catalogue, the attenuation relationships and the magnitude conversions (Lindholm and Bungum, 2000). On the other hand, Stirling et al. (2002) have presented a new probabilistic seismic approach for probabilistic seismic hazard analysis (PSHA) to be applied in New Zealand. This new challenge added as an important feature in the analysis has been the application of a new methodology which combines the modern method based on the definition of continuous distributions of seismicity parameters with the traditional method based on the definition of large area sources and the associated seismicity parameters for the treatment of the historical seismicity data. So their PSHA has combined the modelled seismicity data with geological data representing the location and the earthquake recurrence behaviour of different active faults and then incorporated new attenuation relationships specifically developed for New Zealand to these elements. They stated that the resulting maps have been currently used for the revision of the building code of the country (Stirling et al., 2002). Tsapanos (2003) has also developed a site-specific seismic hazard scenario to be applied to the sites located in the main cities of Crete Island in Greece in order to compute the probabilities of exceedance of specific peak ground acceleration (PGA) values and to predict the maximum possible PGA at each site of interest. According to Tsapanos (2003), since the methodology utilized does not rely on the definition of seismic source zones has allowed the use of historical or instrumental data or a combination of both (Tsapanos, 2003).

In addition to all these above mentioned publications, there is another one written by Abrahamson (2000) that should not be ignored because of some significant points criticizing the state-of-the-practice of seismic hazard analysis. This scientific paper mainly focuses on the ‘approaches to developing design ground motions’, ‘common misunderstandings in the definition of predictor variable terms or in usage of the different aspects of seismic hazard analysis such as the attenuation relations ’, ‘attenuation relations’, ‘deterministic seismic hazard analysis’, ‘probabilistic seismic hazard analysis’ and ‘comparison of the deterministic and probabilistic approaches’. And it was concluded that in fact there is no state-of-the-practice of seismic hazard evaluations because of wide variability in them! In this publication the sources of the problems leading to the large variability in practice were basically and briefly discussed together wit their reasons (Abrahamson, 2000).

Finally it would be necessary to mention about some examples of seismic hazard analysis projects carried out for Turkey in recent time. One of these assessments was carried out by the agreement between İzmir Municipality and Boğaziçi University in the context of a project so-called RADIUS In this project’s context both deterministic and probabilistic analyses were performed (Erdik et al., 2001). The other one which was a typical probabilistic one was performed for Turkey and neighbouring regions by Erdik et al. (1999) and it was published then to serve as a reference for more advanced approaches and to stimulate discussion and suggestions on the database, assumptions and the inputs, and to pave the way for the probabilistic assessment of seismic hazard in the site selection and the design of engineering structures (Erdik et al., 1999). And the third one was developed in both of the types (either deterministic or probabilistic) by Anadolu University in the context of a project so-called ‘Eskişehir Yerleşim Yeri Mühendislik Jeolojisi Haritasının Hazırlanması’ by ‘T.C. Anadolu Üniversitesi Araştırma Fonu’ (Ayday et al., 2001).

# CHAPTER III

# METHODOLOGY

## 3.1. Introduction to Seismic Hazard Analysis

Today, nowhere in the world, the short-term earthquake prediction in the hours and days prior to fault rupture by means of the recognition of the physical precursors is issued as a reliable seismic hazard mitigation method. Even if it is eventually used, it will be neither a long-term solution nor a practical mitigation technique to the existing problems of planning, seismic design and construction in the context of structural reliability. The ultimate question that should be answered is whether the structures will be sufficiently safe when the expected earthquake does happen suddenly and if so, whether the proper preparatory efforts have already been completed before the event.

Seismic hazard assessment is analogous to long-term earthquake prediction whose ‘’cook book’’ method does not currently exist with a complete confidence since it is still an ongoing research field nowadays (Yeats et al., 1997). In a general sense, seismic hazard is a broad term usually utilized to refer to the potentially damaging phenomena associated with the earthquakes. These earthquake related hazards could be ground shaking, liquefaction, landslides and tsunami hazards. However, in a specific manner, the seismic hazard could be defined as the likelihood of experiencing a specified intensity of any damaging phenomenon at a particular site or all over a particular region during a considered period of time. (Chen and Scawthorn, 2002)

The development of the methodology for analyzing the probability of seismic hazards has originated from the engineering needs for better designs (Cornell, 1968, 1969). These assessments are mostly performed for the purpose of leading decisions associated with the mitigation risk. On the other hand, the probabilistic methods are comprised by compelling structured frameworks where the quantification of the scientific uncertainties is involved by the hazard estimation processes. Although the scientific knowledge for the accurate quantification of these hazards is always limited, this limitation could be balanced somehow by the technical judgment. (Chen and Scawthorn, 2002)

In fact, earthquake hazard assessment is naturally and necessarily based on one of the geological rules of 'uniformitarianism' which was proposed by James Hutton and could be opened as ''the present is the key to the past''. However, in this case, this old geological adage has to be explored as ''the past is the key to the future''; that is, the likelihoods of the similarities between the recent past earthquakes and near future ones could be considered to be very high. In addition to these facts it is evident that the past history consists of the historical and prehistorical periods (Yeats et al., 1997).

On the other hand, in the early years of geotechnical earthquake engineering practice, prior to the common use of probabilistic seismic hazard analysis for the earthquake hazard assessments, deterministic methods became dominant in such analyses. Deterministic analyses take into consideration the effect at a site of either a single scenario earthquake or a relatively small number of individual earthquakes. (Chen and Scawthorn, 2002) That is; for the most part they make use of single-valued, discrete models to end up with scenario-like descriptions of earthquake hazard. These analyses require the specification of three basic elements; an earthquake source, a controlling earthquake of specified size, a parameter of hazard definition such as ''the peak ground acceleration'' at the considered distance to the site of interest (Reiter, 1990).

The difficulties in hazard assessment studies basically focus on the selection of this above mentioned representative earthquake satisfying a codified or regulatory definition, on which the method would be based. These types of selection could be somehow more ambiguous at best when compared with those of the probabilistic ones, because the deterministic earthquake scenarios could be seen as a subset of the probabilistic methodology (Chen and Scawthorn, 2002).

The basic steps involved in the process of deterministic seismic hazard assessment can be categorized as follows:

1. Definition of an earthquake source or sources: These sources could be either clearly understood and defined faults or less well understood and less well defined geologic structures or seismotectonic provinces of many thousands of square kilometers. The individual sources could be configured as points, lines, areas or volumes (Reiter, 1990).
2. Selection of the 'controlling earthquake': This selection stands at the core of a deterministic earthquake hazard analysis, at least from the earth scientist's point of view because the earthquake potential of each source specified in the first step should be defined in terms of a maximum earthquake (Reiter, 1990 and Yeats et al., 1997). This earthquake could be defined as either 'maximum credible earthquake', which is the maximum earthquake capable of occurring in a given area or on a given fault during the current tectonic regime or by some other type of earthquake description such as 'maximum expectable earthquake', 'maximum earthquake', 'maximum probable earthquake', 'design earthquake'. In addition to these definitions, in some cases two levels of maximum earthquakes could be considered as in the case of the U.S. Nuclear Regulatory Commission: 'Safe Shutdown Earthquake' and 'Operating Basis Earthquake' (Yeats et al., 1997). Since the ground motion of one of these postulated earthquakes that could be estimated as (for example) the controlling earthquake will dominate the effects of all the earthquake source-size pairs being specified, the specific criterion chosen to define this controlling earthquake is critically important in the determination of the general level of conservatism. When one source is as important as another one, different earthquakes could control the different measures. So in that sense, there may exist more than one controlling earthquake associated with the largest ground motion at the

site of interest at both the selection stage and at the conclusion of the analysis.

3. Determination of the earthquake effect (some type of ground motion, at the site): This is typically performed by means of an earthquake ground motion attenuation relationship which estimates the ground motion for an earthquake of a given magnitude at different distances.
4. Definition of the hazard at the site: This could be simply stated as the hazard at the site of interest represented by specific peak ground acceleration and/or velocity value or other measure such as response spectrum ordinate values, describing the earthquake effects (Reiter, 1990).

Deterministic seismic hazard analysis provides a simple framework for the evaluation of the worst-case ground motions associated with the catastrophic failure damages of the large engineering structures such as nuclear power plants and large dams. However, it presents no information on the subjects such as the likelihood of occurrence of the controlling earthquake, the probable level of shaking expected to occur during a finite period of time and of course the effects of uncertainties in each and every step needed to compute the resulting ground motion characteristics.

Perhaps the most important thing that should be kept in mind is that deterministic seismic hazard analysis is always associated with the subjective predictive decisions, regarding for instance the earthquake potential, of the combined opinions and judgments of seismologists, engineers, risk analysts, economists, social scientists and finally government officials. This variation in the backgrounds and divergent goals can cause some difficulties in combining under a common consensus on the earthquake potential (Kramer, 1996).

## 3.2. Probabilistic Seismic Hazard Analysis

### 3.2.1. Introduction to Probabilistic Seismic Hazard Assessment

The probabilistic seismic hazard analysis which could be seen as a rational solution to the different types of dilemmas posed by uncertainty permits the multi-valued or continuous competing models to be used together with their uncertainties. The hazard descriptions in the probabilistic seismic hazard analysis include the effects of all the earthquakes which may be capable of threating the site of interest in contrast to the typical deterministic ones restricted to the scenario-like statements. There are also two distinguishing advantages of probabilistic seismic hazard analysis when compared with the deterministic seismic hazard analysis. The first one of most importance is that the probability of different magnitude (or intensity) earthquakes could be incorporated into the analysis. The second advantage is that it results in an estimate of the likelihood of earthquake ground motion assumed to occur at the site of interest and this permits the incorporation of seismic hazard into the seismic risk estimates and the comparison of different options quantitatively in decision-making criteria.

The first methodology applied to the most of the probabilistic seismic hazard analyses was defined by Cornell in 1968 but in fact the basic steps have not been challenged since then. These steps can be grouped into four categories and shown in Figure 3.1.

***1. The definition of earthquake sources:*** The types of the sources may range from small planar faults to large seismotectonic provinces. But it is sure that the chance of an earthquake of a given size which is expected to occur in the future is the same within the source, that is, the sources are expicitly defined as being of uniform earthquake potential. In contrast to the deterministic analyses which try to pick one controlling earthquake or one maximum earthquake for each source seperately, each source is characterized by an earthquake probability distribution or simply by a recurrence relationship in probabilistic analyses. A recurrence relationship shows the chance of an earthquake of a given size expected to occur anywhere within the source, during a specified time period, most of the time one year. For each source, a maximum or upper bound earthquake is selected as the representative maximum event but it does not represent the only considered event, but rather the upper limit of the earthquakes of all sizes that will be incorporated into the analysis.

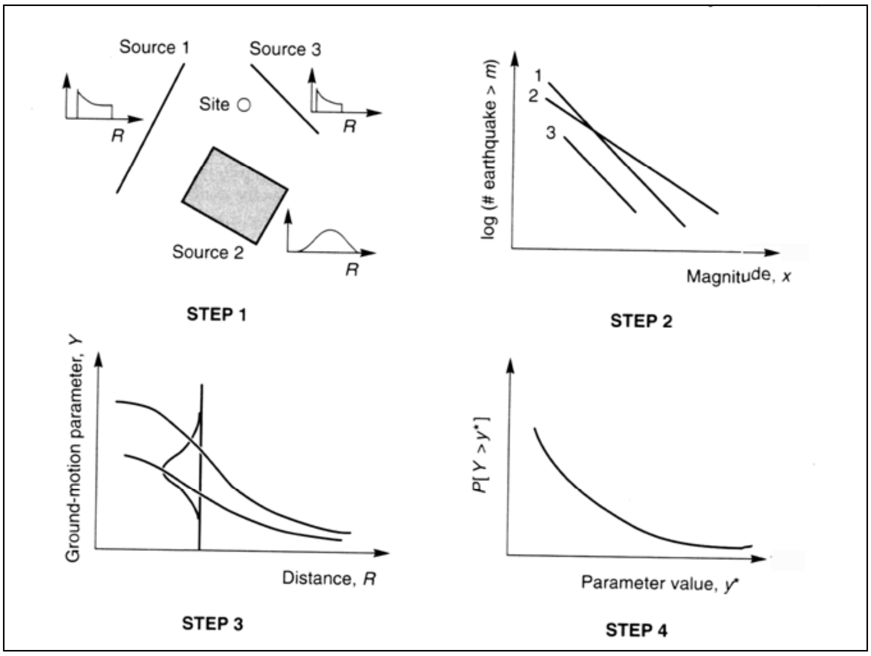


**Figure 3.1.** Four Steps of a probabilistic seismic hazard analysis (Kramer, 1996).

The recurrence relationship curve is usually, simply presented by a straight line whose ordinate shows the logarithm of the number of earthquakes of a given size or larger and whose abscissa shows the size of the earthquakes (magnitude or sometimes epicentral intensity). The recurrence curve has an equation:

$$LogN = A - BM \tag{3.1}$$

$N$ = Cumulative number of earthquakes of a given magnitude or larger which are expected to occur during a specified time period or
The number of earthquakes in a defined magnitude interval around M (Convenient when the recurrence relationship is written in its incremental form)

$A$ = Logarithm of the number of earthquakes of magnitude zero or greater which are expected to occur during the specified period of time

$B$ = The slope of the curve which considers the proportion of large earthquakes to small earthquakes

$M$ = Magnitude

The distances from all possible locations to the site within the earthquake source should be certainly considered since these earthquakes are assumed to happen anywhere within that source. Although in deterministic analysis the distance parameter is defined only as the closest distance from each source to the site of interest, in the probabilistic one a range of different descriptions of the distance parameter and the associated probability of occurrence of these earthquake size-site distance pairs could be taken into consideration.

***2. The estimation of the earthquake effect:*** A set of earthquake attenuation or ground motion curves; relating a ground motion parameter to distance for an earthquake of a given size is required.

***3. The determination of the hazard at the site of interest:*** The hazard curve which integrates the effects of all the earthquakes of different sizes, occurring at different locations within different earthquake sources at different probabilities of occurrence is formed to show the probability of exceeding different levels of ground motion levels at the site during a specified time period. This can be expressed by the equation given below together with some assumptions (Reiter, 1990):

$$E(z) = \sum_{i=1}^{N} \alpha_i \int_{m_0}^{m_u} \int f_i(m) f_i(r) P(Z \rangle z | m, r) dr dm \qquad (3.2)$$

$E(z) =$ The expected number of exceedances of ground motion level z during a specified period of time t

$\alpha_i$ = The mean rate of occurrence of earthquakes between lower and upper bound magnitudes ($m_o$ and $m_u$) in the *i* th source

$f_i(m)$ = The probability density distribution of magnitude (recurrence relationship) within source *i*

$f_i(r)$ = The probability density distribution of site to source distances

$P(Z \rangle z | m, r)$ = The probability that a given earthquake of magnitude m and distance (epicentral) r will exceed ground motion level z

When carrying out a probabilistic analysis, the usual assumption that the earthquakes have no memory and that each earthquake occurs independently of any other earthquake,  should be overseen. This assumption of no memory is called the Poisson Process and it makes use of some other efficient approximations.

On the other hand, the return period of an event in years exceeding a particular ground motion level is the reciprocal of its annual probability of exceedance. So the probability of exceeding some level of ground motion during some finite period of time T which means the return period can be expressed as (Reiter, 1990):

$$\text{Return Period} = -T / \ln(1 - P(Z \rangle z)) \quad (3.3)$$

$P(Z \rangle z)$ = The desired probability of exceedance during the time interval T

### 3.2.2. Issues in Probabilistic Seismic Hazard Analysis

Probabilistic seismic hazard analysis yields a framework in which the uncertainties in the size, location and rate of recurrence of earthquakes and in the alteration of ground motion characteristics with earthquake size and location could be explicitly taken into account. (Reiter, 1990)

Although the information needed to develop a probabilistic seismic hazard analysis or deterministic seismic hazard analysis is essentially the same for both, except the concept of ‘recurrence relationships’, their evaluation and/or their process before providing them as ‘inputs’ to the scientists and/or engineers differs between probabilistic seismic hazard analysis and deterministic seismic hazard analysis (Reiter, 1990).

In fact, this variation comes from the nature of probabilistic seismic hazard analysis such as;

(a) Probabilistic results are expressed as ‘likelihoods’ or ‘probabilities’.
(b) Multiple models or sources could be adapted.
(c) Some of the definitions of the input parameters such as ‘maximum magnitude’ could be altered or even modified.

One of the greatest and most troubling aspects of probabilistic seismic hazard analysis is that various effects of the input assumptions and its reflections on the results may be quite different; that is; it is not always apparent to the analyst which assumption or assumptions do affect the results the most. So this lack of transparency is sometimes a problematic issue in probabilistic seismic hazard analysis (Reiter, 1990).

#### 3.2.2.1. Seismic Source Zones

The first step of both types of seismic analyses is the definition of the earthquake sources that could most probably affect the site of interest at which the seismic hazard will be calculated. So it will be useful to understand the meaning and the real concept of a seismic source zone. A seismic source is usually called a seismotectonic source which is activated by tectonic forces and whose concept is a relatively modern one. In fact, the characterization of seismic source zones depends on the interpretation of the geological, geophysical and seismological data obtained by many tools such as tectonic theory, seismicity, surface geological investigations and subsurface geophysical techniques (Reiter, 1990).

As stated above, although the recent ability of identifying and locating all earthquake sources is a relatively new development, the clues of the earthquake activity may take the form of the geologic and tectonic evidence, instrumental seismicity or preinstrumental (historical) seismicity records (Kramer, 1996).

#### 3.2.2.1.1. Clues of the Earthquake Activity

##### 3.2.2.1.1.1. Geologic Evidence

The fact that the occurrence of earthquakes is recorded in the geologic record, particularly in the form of the offsets or relative displacements of various strata is assured by the 'Plate Tectonics' theory. This geologic record of the past earthquake activity whose study is called 'Paleoseismology' by Wallace (1981) could be either easily accessible somewhere or it could be hidden or very complex somewhere else and so it may not be easily interpreted by the earthquake geologist. In fact, the use of geologic evidence in the identification of the seismic sources is often very complicated and difficult part of a seismic hazard analysis.

The recognition of the faults is the center of the search for geologic evidence of the earthquake sources. Different kinds of tools and techniques such as the review of the published literature, the interpretation of the air photos and the remote sensing imagery, the field reconnaissance consisting logging of the trenches, geophysical techniques and test pits or borings exist for the geologist. Although various criteria are explained, in detail, in numerous publications (on geomorphology, field geology and structural geology), here one of the several lists of the features suggested by Reiter (1990) is given as an example. According to him, the characteristic features suggesting faulting could be:

(a) Directly observable fracture surfaces and indicators of fracturing; including the slickensides, the fault gouge and the fault breccias.

(b) Geologically mappable indicators; consisting of the juxtaposition of distinct units, missed or repeated strata and the truncation of the strata or the structures.
(c) Surface landform and topographic indicators; comprising topographic scarps or triangular facets, the offset streams or drainage, the changes or the tilting in the elevation of terraces or shorelines, sag ponds.
(d) Secondary geologic features; including the abrupt changes in groundwater levels, gradients and chemical composition, the alignment of the volcanic vents or springs and the presence of hot springs.
(e) The lineaments caused by the topography, the vegetation or the tonal contrasts on the remote sensing imagery.
(f) The geophysical indicators of the subsurface faulting; consisting of the steep linear gravity or magnetic gradients, the offset of the seismic reflection horizons and the differences in seismic wave velocities.
(g) The geodetic indicators including the fault movement which appears as the tilting and the changes in the distance between the fixed points in the geodetic surveys (Kramer, 1996).

**Fault Activity**

The notion of 'fault activity' is very important in the issue of the indication of the future possible earthquakes' occurrence because the mere presence of a fault does not state the future probable earthquake locations.

Although there is a consensus as to how the terms 'active fault' and 'inactive fault' should be utilized, there are several different formal definitions of the 'fault activity'. An active fault is defined as one that has produced surface displacement within Holocene time (approximately the past 10000 years) by the California Division of Mines and Geology. This time period is stated differently for the dams as 35000 years by the U.S. Army Corps of Engineers and as 100000 years by the U.S. Bureau of Reclamation (Idriss, 1985). On the other hand, 31 different explanations of the term 'active fault', most of which were based on the elapsed period of time since the most recent fault movement, were found by Slemmons and McKinney (1977).

In fact, since the faults do not suddenly become inactive at these stated periods of time; that is they may pass from active to inactive states over geologic time period, the evaluation or the identification of the fault activity by means of these specified periods of the time is not a very realistic approach (Cluff et al., 1972; Cluff and Cluff, 1984). Depending upon the relativity of the fault activity, Cluff and Cluff (1984) proposed six categories for the fault activity which were based on the characteristics such as the 'slip rate', the 'slip per event', the 'rupture length', the 'earthquake size' and the 'recurrence interval'. However, it should be kept in mind that; these sophisticated approaches, which are expected to provide a more satisfying framework, can be hardly implemented in the political and economic environment which sometimes necessitates many seismic hazard analyses (Kramer, 1996).

**Magnitude Indicators**

Very like the recognition of the faults, the magnitude of the past earthquakes could be also estimated by the use of geologic evidence. It has been shown by the worldwide studies that the faults do not always rupture over their entire lengths or areas during one single event, it is the individual fault segment or succeeding fault segments which rupture(s) repeatedly. So, the correlation of magnitude with the deformation characteristics such as the rupture length, the rupture area and the fault displacement, evaluated by postearthquake field geological investigations could finally present an estimate of the expected value of the magnitude. When applying these correlations, the uncertainties should be considerably recognized during the estimation processes.

The fault rupture length is one of these characteristics which has been usually utilized to estimate the earthquake magnitude; as illustrated by a number of studies showing the nature of its relationship with the magnitude (e.g., Bonilla et al., 1984; Wells and Coppersmith, 1994). It is evident that the variations in the width of the rupture surface have not been taken into consideration in these estimations, so these correlation methods could be well suited to the cases containing the rupture surfaces which are fairly narrow and typically less than approximately 20 km (Bonilla et al., 1984) and which usually extend to the ground surface.

On the other side, the fault rupture area could be expected to be more related to the magnitude parameter than the fault rupture length itself because of its close relationship to seismic moment and in contrast to the fault length, it is still more convenient for the faults of width greater than approximately 20 km (Wells and Coppersmith, 1994). Instead of the average fault displacement whose determination could be unavailable or impossible, maximum surface displacements (Slemmons, 1982; Wells and Coppersmith, 1994) could be correlated to the magnitude also (Kramer, 1996).

#### 3.2.2.1.1.2. Tectonic Evidence

The earthquakes are told to occur in order to release their strain energy which has been accumulated on them by the relative movement of the plates with respect to each other (Kramer, 1996). Therefore, the rate of movement should be correlated to the rate of strain energy accumulation and to the rate of strain energy release also (Smith, 1976; Idriss, 1985). For example Ruff and Kanamori (1980) developed a relationship correlating the maximum magnitude to both the rate of convergence and the age of the subducted slab for the major subduction zones:

$$M_w = -0.0089T + 0.134V + 7.96 \qquad (3.4)$$

$M_w$ : Moment Magnitude

$T$ : Age in millions of years

$V$ : Rate of convergence in cm/year

#### 3.2.2.1.1.3. Historical Seismicity

The records of the preinstrumental (historical) seismicity may be used to identify the earthquake sources by means of the historical accounts of the ground-shaking effects which could confirm the occurrence of the past earthquakes and sometimes estimate their geographic distributions of the intensity. Although the maximum intensity may be used to assess the epicentral location and the magnitude of a specific earthquake event, the accuracy of this location found by this method depends strongly upon the population density and the rate of the earthquake recurrence. However, the geographic distribution of the historic epicenters still provides a good evidence for the existence of the earthquake source zones, at least it can be used to evaluate the rate of recurrence of the earthquakes or simply the 'seismicity' in some areas (Kramer, 1996).

#### 3.2.2.1.1.4. Instrumental Seismicity

Although the instrumental records of the large earthquakes have been available since about 1900 (lots of them before 1960 are incomplete or of uneven quality), they represent the best, the most significant information for the evaluation of the earthquake sources. The most important disadvantage of using these records is the short period of time when compared with the average time interval between the large earthquakes. But, still the alignment of the instrumentally located epicenters or even hypocenters together with the analysis of the aftershocks can help in the subjects of the detection and the delineation of the earthquake source zones.

After the interpretation of the geological, geophysical and seismological data obtained by many tools, the characterization of an earthquake source first demands the consideration of the spatial characteristics of this source, the distribution of the earthquakes within that source, the distribution of the earthquake sizes for each source then the distribution of these earthquakes with time. It is evident that these characteristics should involve specified, required uncertainties (Kramer, 1996).

#### 3.2.2.1.2. Spatial Uncertainty

The earthquake sources are classified into three categories according to their geometries, which are based upon the tectonic processes involved in their formulation:

1. Point Sources: Small areas near the volcanoes such as the ones in which the earthquakes associated with the volcanic activity could generally originate
2. Areal Sources: Two- dimensional well-defined fault planes
3. Volumetric Sources: Areas where the earthquake mechanisms are poorly defined or faulting is so extensive that the distinction between the individual faults is very hard (Kramer, 1996).

The examples of some of the source zone geometries are shown in Figure 3.2.

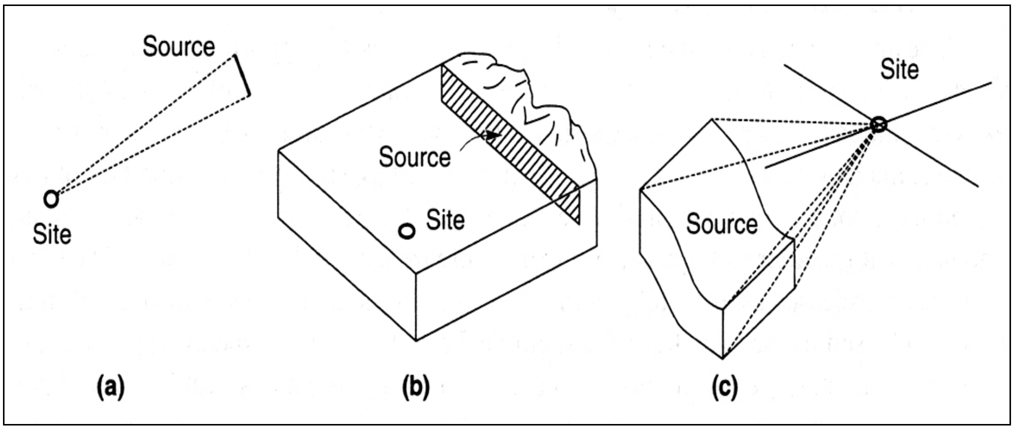


**Figure 3.2.** Examples of some of the source zone geometries (a) short fault modeled as a point source; (b) shallow fault modeled as a linear source; (c) three-dimensional source zone (Kramer, 1996).

The predictive relationships represent the ground motion parameters in terms of some measure of the site-to-source distance. So, the spatial uncertainty which could be involved in the distance parameter must be described by a ‘probability density function' (Kramer, 1996). A few examples of variations of source-to-site distance for different source zone geometries are shown in Figure 3.3.

In probabilistic seismic hazard analysis, the size of maximum earthquake together with all other earthquake generating properties is defined explicitly. So, a seismic source either a linear or areal source is a configuration in which it is assumed that earthquakes occur at the same rate of magnitudes or any other size parameter regardless of their location. However, this assumption of uniform earthquake potential in a defined seismic source zone is not so sharp that the recurrence parameters could vary spatially within the individual zones.

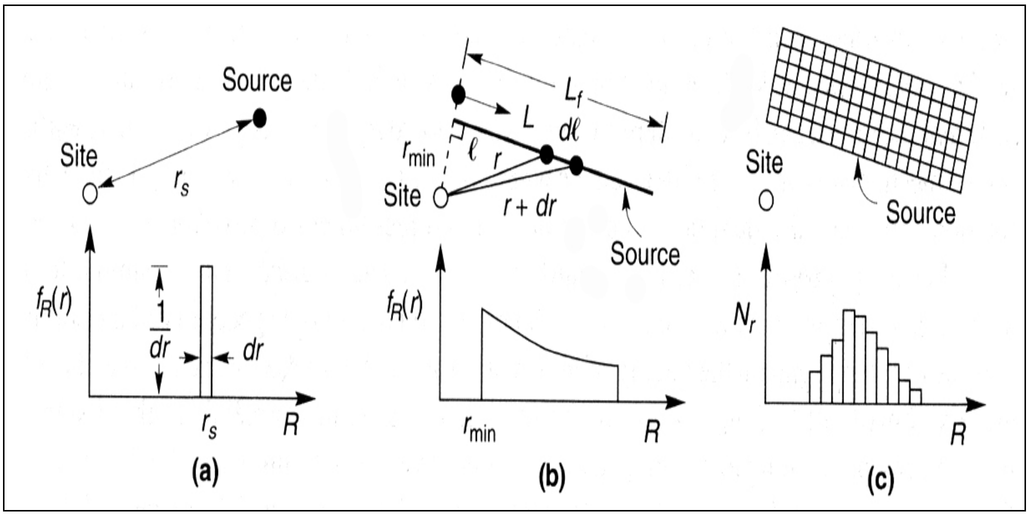


**Figure 3.3.** Examples of variations of source-to-site distance for different source zone geometries (Kramer,1996)

On the other hand, the seismic sources are defined with a certain limited level of detail and resolution based upon the available information, the analytical tools at hand and the specific needs of the analysis itself. So, even when very detailed information is known about the source, it should be kept in mind that only large scale variations could be often taken into account by the hazard models or more simply by the earthquake ground motion models.

Single or multiple sets of seismic source zones which are considered as a combination of a wide range of regional source models could be utilized depending upon the extent of the modeling uncertainty and of course of the purposes for which the map will be prepared. For example; for the assessment of the hazard for noncritical facilities such as engineering structures, it would be appropriate to use one single set of seismic source zones rather than using many different sets of distinct source zone configurations. Since the surface faults which are active are relatively well defined, the variations of models are usually dominated by the maximum earthquake potential to be generated by these faults and configuration of the subsurface sources such as subduction zones and blind thrusts.

The definition of the multiple source zones incorporates two important aspects; one is the modeling of the uncertainty and the other one is the diverse views of a single expert or a group of experts mostly seismologists or earth scientists who are provided with some feedback on the implications of the assumptions on seismic hazard analysis calculations for the selected sites of interest (Reiter, 1990).

But, in fact to develop a model, sometimes a highly structured interactive methodology; relying on the opinions of the various interdisciplinary teams comprising geologists, geophysicists and seismologists has been emphasized. The general scope of this methodology is based first on the determination of a tectonic framework and afterwards on the construction of a specific matrix indicating different probabilities of the seismological activities of the hypothetical features which are associated with some specific characteristics (Reiter, 1990).

#### 3.2.2.1.3. Size Uncertainty

##### 3.2.2.1.3.1. Recurrence Relationships

The recurrence relationships which provide the descriptions of the whole earthquake history to be incorporated into a seismic hazard analysis by means of a specified tool and which are largely data dependent elements constitute the central part of a probabilistic seismic hazard analysis. These relationships are coming from a data base comprising the seismic record either historical or instrumental and sometimes the paleoseismic information whose uniformity and characteristics are very important (Reiter, 1990).

During the formation process of these recurrence relationships, one of the most important problems could be related to the necessity of utilizing a long, 'non-uniform' earthquake history; including different intensity or magnitude scales. So a more or less uniform, entire earthquake history has to be defined by the aid of some conversion relationships and a more structured analysis should consider the uncertainty associated with these conversions relations.

Another problem facing the expert, especially in a probabilistic analysis which is related to the earthquake data set is the removal of the dependent events that could be the aftershocks and/or the foreshocks. They are said to be the likely sources of a principal confusion, even if they are very important in the prediction of future large earthquakes and in the definition of the source geometry and other mainshock characteristics, respectively. Unfortunately, a condition of the exceedance of a specified ground motion level during a specified period of time in the case of an occurrence of a large earthquake is usually not assumed anyway. But various techniques exist to remove these types of dependent events varying from the simple examination and culling of the record by the expert, to the highly sophisticated processes containing some additional statistical analyses. What is astonishing for the analysts is that the impact of the removal of these dependent events on the results (the probabilities of exceeding a certain ground motion value or values) is not that much great (Reiter, 1990).

In the definition of the recurrence relationships, the completeness which is the extent of an earthquake catalog is perhaps the most important problem associated with the data base in a probabilistic analysis. Since any recurrence relationship curve has to be or must be skewed by the problem of the incompleteness between any ranges of magnitudes or intensities, the key factors that determine the extent of this artificial tilting (skewness) such as the detection capability for the instrumental data or the population density or the record for the historical data should be carefully examined and interpreted. Before fitting a line to the data on the curve, the probable underestimations or overestimations in the number of the earthquakes either small or large should be taken into consideration (Reiter, 1990).

Several approaches of correction exist for this problem of completeness; such as the one suggested by Stepp (1972) and more sophisticated ones developed specifically for different purposes. A recurrence relationship could be figured out by means of a complete, consistent enough data set culled of dependent events (Reiter, 1990). This relationship which is proposed by Gutenberg and Richter (1944) is defined by a simple, semi-logarithmic equation (Equation 3.1).

In fact, it is very important to know the expressions for a seismic hazard analysis given by these above stated parameters. For instance the parameter ‘A’ could vary greatly from region to region and could be a significant indicator of seismic hazard. On the other hand a ‘B’ value which is relatively lower (shallow slope) would indicate a significantly higher portion of large earthquakes than a high ‘B’ value (steep slope). It should be convenient to state that the ‘B’ value is usually around 1.0 when the ‘magnitude’ parameter is utilized as the measure of the earthquake strength. The estimated number of the events of a given size occurring per year or the inverse of this number which is so-called the average recurrence interval for an earthquake of this size in the area of interest could be possibly affected by the changes in the ‘A’ and ‘B’ parameter values (Reiter, 1990).

Since the recurrence intervals of the large earthquakes are sensitive to even the relatively smaller changes in the values of ‘B’, their definitions and their derivation methods become a really important matter of fact. So, there exist different methods used for the definition of the ‘B’ value. These methods are:

(i) Maximum Likelihood Method
(ii) Least Square Method
(iii) Extreme Value Theory

In the ‘Maximum Likelihood’ method, each earthquake is treated equally and a ‘B’ value is chosen to maximize the product of the probabilities of having each observed earthquake. So, the estimated ‘B’ value is less dependent on the few events constituting high intensity or magnitude bands in the method. On the contrary, the method of ‘Least Squares’ treats each magnitude or intensity band equally, no matter the number of the individual earthquakes or the gaps are stated to be (Reiter, 1990).

‘Extreme Value Theory’ developed by Gumbel (1959) is only dependent upon the largest event occurred in a year or in a restricted period of time and this fact could be a very useful advantage so that the incompleteness of the data at smaller magnitudes will no longer be a great problem anymore. In fact, the plot of the ‘Extreme Value Theory’ can be utilized to determine ‘A’ and ‘B’ values of the exponential Gutenberg Richter equation (Reiter, 1990). But Knopoff and Kagan (1977) have pointed out that the seismicity parameters which are estimated by this theory could lead to many unacceptably big errors.

#### 3.2.2.1.3.2. Lower and Upper Bound Magnitudes

In order to assess the impact of the lower and upper bound magnitudes on the calculated hazard, first of all, the definitions of them should be clearly stated. The lower bound or the minimum magnitude, which is not an issue in deterministic seismic hazard analysis, is the level of the earthquake size below which there is no engineering interest or insufficient data, whereas the upper bound or the maximum magnitude represents the largest earthquake specified for a particular source zone (Reiter, 1990).

Since they are the least likely events which may influence ground motions, the common belief that the lower bound magnitudes do not have significant influence on probabilistic seismic hazard analysis, is not necessarily true. It should be kept in minds that, the lower bound magnitudes could be extended to as low as the data allows, if the separation between the non-damaging peak accelerations coming from the smaller earthquakes and the more damaging ones resulting from the relatively larger earthquakes could be perfectly done (Reiter, 1990).

In contrast to the one of the lower bound magnitudes, the definition of the upper bound magnitude is so difficult that it is highly dependent on the zone and engineering significance and it has usually been derived by the extrapolation from the sparse data. To do this, there are different methods which are essentially the same; however, there is such a practical difference in deterministic seismic hazard analysis that in these methods the maximum magnitude, which is chosen, directly controls the result no matter the likelihood of occurrence is. So, the scientist should judge the credibility or the likelihood of a specific maximum earthquake before choosing it. Whereas, in probabilistic seismic hazard analysis since the likelihood of occurrence is specifically considered in the analysis, the upper bound earthquake may be the maximum possible ‘finite’ earthquake that could happen during the specified period of time in a given tectonic regime (Reiter, 1990).

In recent probabilistic analyses incorporating also the uncertainty, the maximum historic earthquake is thought to be almost always the lower limit to the upper bound earthquakes. Within the scope of the subject of selecting the maximum historic earthquake or the maximum possible earthquake, one of the most important things which has to be taken into consideration carefully by the analyst, is that the recurrence interval of the maximum historic earthquake should be well established with a little variation and should be relatively longer than the time period of interest, if the maximum historic earthquake occurred recently (Reiter, 1990).

Although the selection of the maximum or the upper bound earthquake in deterministic seismic hazard analysis is so significant that it could directly scale the seismic hazard, its effect on a probabilistic analysis could be quite complex. Because, the final hazard in probabilistic seismic hazard analysis is a conclusion which is contributed by various complex interactions of the diverse elements; such as the earthquakes of different sizes, at different frequencies of occurrence and at different locations (Reiter, 1990).

The seismic hazard at a site is a conclusion predicted by many different sources, so the amount of increase in total seismic hazard resulted most probably by the increase in upper bound magnitude of a ‘constant seismicity model’ is balanced and predicted by the percentage of these contributions from various sources to the total hazard (Reiter, 1990).

#### 3.2.2.2. Ground Motion

In the evaluation of probabilistic seismic hazard analysis; most of the discussions focus on two important issues which are namely ‘the source zonation’ and ‘the maximum magnitude determination’. However, the significance and the importance of all these issues together with the other ones previously described in detail in this chapter may be clarified and controlled by of course the ground motion models. Unfortunately, in contrast to the deterministic analysis, in probabilistic seismic hazard analysis, which is stated to have an integrative nature, the effects of distinct ground motion models could be assessed and sometimes reassessed after the examination of the results and the application of sensitivity analyses. Since the uncertainties associated with the ground motion models could dominantly affect the low probabilities of exceedance and relatively less dominantly the high probabilities of exceedance, the concept of ‘uncertainty’ and the variations in it should be clarified and its extent should be identified in detail very carefully (Reiter, 1990).

There are two different types of uncertainty which are namely:

(a) The 'Random Uncertainty' and

(b) The 'Modeling Uncertainty'

The 'Random Uncertainty' is the inherent uncertainty included in the estimation of ground motion in which the occurrence of an earthquake of a specified size and at a specified distance is given. It is assumed to have a lognormal distribution almost in all the cases and to include the elements of the source and the propagation path properties. The breadth of this distribution is defined as 'standard deviation'. In the studies where the random uncertainty is not included, a large reduction in the calculated seismic hazard could be caused and logically observed. It is evident from various examples that, the effect when uncertainty is included into the analysis increases with the ground motion level's increase or the probability of exceedances decreases. For instance, the seismic hazard with no consideration of the uncertainty at high ground motion levels may most probably be governed by the median high ground motions produced by the events of the unlikely but huge or nearby smaller earthquakes. On the other hand, the effect of low likelihood high ground motion resulted from the high likelihood but smaller and/or more distant earthquakes may also be taken into account with the consideration of the uncertainty. So it is apparent that as the random uncertainty becomes larger the effect of the maximum magnitude becomes smaller (Reiter, 1990).

The 'Modeling Uncertainty', which is another type of the uncertainty used in several sophisticated analyses, is formed by the contribution of several seismic models and their parametric variations chosen by the analyst or the analysts.

In probabilistic seismic hazard analysis, additional attention should be given to the possibility of occurrence of extremely large ground motions. Since in the theory, the lognormal plot of the ground motion model extends out to infinity, in practice there has to be a limitation in the value of a ground motion that can be resulted from a specified earthquake. In the deterministic analyses, one standard deviation is assumed to be sufficient to express the conservatism that is expected in the final estimations on the ground motion parameter. Whereas in probabilistic analyses, since the very low likelihood accelerations should be taken into consideration, the extents of truncation of the high range of ground motion must be defined clearly. In some of the analyses, the upper bound of the truncated range of ground motion has been proposed to be called as 'engineering effective acceleration' or the 'acceleration cutoff' which is mainly the maximum effective acceleration associated with the maximum magnitude. Sometimes an acceleration cutoff is implemented by limiting the number of standard deviations used in the ground motion calculations (Reiter, 1990).

In fact, the problem arises from the fact that the limitations of ground motion parameters are sometimes mixed with the engineering applications and the expert judgment conflicts between seismologists and engineers. Because the seismologists have usually been claiming that very high accelerations are often possible, in contrast to the engineers who have been thinking about the implications of the delimitations on the ground motion measures.

The 'uniform hazard response spectrum' is defined as a multi-parameter description of the ground motion, generated from probabilistic seismic hazard analyses but in reality, it has also a different meaning in the deterministic analyses. In deterministic analyses, a response spectrum usually distinguishes period or frequency dependent levels of ground motion response; describing the controlling earthquake with an appropriate level of conservatism. The local site effects can be important. First the analysis is carried out by the assumption of a rock site, and then a correction factor, whose impact would lead to the different shapes of uniform hazard response spectra depending on the depth of soil assumed, could be possibly used to account for local site conditions. In probabilistic seismic hazard analysis, a response spectrum has only one requirement that it should be made up of the ordinates having an equal likelihood of being exceeded. In fact, these ordinates may be independent of each other (Reiter, 1990).

#### 3.2.2.3. Seismic Hazard Computation with the Assumption of Modeling Uncertainty

The seismic hazard computation is based on two important aspects:

(i) A computational framework which provides a systematic way of integrating interdisciplinary judgment

(ii) An assumption that each expert taking part in this framework is knowledgeably capable to provide inputs in the 'required elements' of the seismic hazard estimation; reserved by them without giving the chance of mixing the effects of 'seismic zonation', 'recurrence relationship' and 'ground motion estimation'

In fact in a seismic hazard analysis, there is a variety of combinations of possible seismic source zonations, recurrence parameters and ground motion estimates so their incorporation into the analysis could be quite useless with the utilization of the 'modeling uncertainty'. But these inputs are combined by a mostly commonly used method which is so-called 'logic tree' approach. The logic tree is described by Coppersmith and Youngs (1986) as a decision flow path consisting of the nodes and the branches. These branches express some discrete choices of a given parameter such as upper bound magnitude, with a likelihood of occurrence besides. On the other hand the nodes which are the connection points between the various input elements are determined by the logical succession of the assumptions and the specifications required as a result of a specific branch. It is evident that in a full logic tree showing all the branches and nodes, the sum of all the likelihoods of the branches in an element joined together at a node should be equal to 1.0 and the likelihood of a specific scenario to be true is basically the product of the likelihoods associated with each branch consisting the scenario (Reiter, 1990).

A logic tree very conveniently displays the input parameters, the optional choices of the different scenarios and their associated likelihoods, and then the analysis could be simply disassembled; that is the effect of each element on the final hazard at a particular node point could be assessed. It is evident that the final number of calculations could be significantly high and cost-ineffective with the increase in the number of the branches and node points (Reiter, 1990).

# CHAPTER IV

# SEISMIC SOURCES

The seismicity of Eskişehir and its vicinity is controlled mainly by seven different seismic sources;

1) North Anatolian Fault Zone (NAFZ)
2) Eskişehir Fault Zone (EFZ)
3) Gediz Fault and Simav Fault (Simav Graben)
4) Kütahya Fault Zone
5) Akşehir Afyon Graben Bounding Faults (Akşehir-Afyon Graben)
6) Gediz Graben Northern Bounding Faults (Gediz Graben)

## 4.1. North Anatolian Fault Zone (NAFZ)

### 4.1.1. Geodynamics and Active Tectonics

The current tectonic regime controlling mainly northwestern Turkey is composed of the interaction of an extensional tectonic regime which causes N–S extension of western Anatolia and the Aegean Sea area, and the strike–slip tectonics exerted by the NAFZ; the former being effective in a broad zone from Bulgaria in the north to the Hellenic trench in the south (McKenzie, 1972).

About the ages of the initiation of the strike-slip and extensional tectonic regimes, different opinions exist. The extensional regime in western Anatolia started in the Early Miocene and has been continued according to Seyitoglu and Scott (1991). On the other hand Bozkurt (2000, 2001 and 2002) suggests that the extensional regime in Western Anatolia is episodic and has been active since the early Miocene but was interrupted by a period of compression that took place in the Early Pliocene. However, there is a common idea about the commencement age of the NAFZ as post-middle Pliocene (Şaroğlu, 1988;

Bozkurt, 2000, Bozkurt, 2001); that is the Anatolian block has begun to move west, along the NAF, during the Pliocene some 5 my. ago (Barka, 1997).

In addition to that, although there are a lot of different opinions, the NAFZ which is a dextral intra-continental transform fault zone of about 1500 km long and of few hundred meters to 40 km wide (Bozkurt, 2001) is thought to be extending from the Karlıova triple junction, where it meets the sinistral East Anatolian Transform Fault Zone, to the Saros Gulf in the west of Turkey. In the west of the Saros Gulf, the NAFZ becomes extension dominated and it extends along the North Aegean trough to the west, mainland Greece (Okay et al, Okay et al and Anastasia and Louvari, 2001). Morphologically narrow and relatively deep NAFZ is divided into two branches in the west of Dokurcan and it splits further into sub-branches in the Marmara Sea Region which are called from north to south as; the northern branch, the middle or the central branch and the southern branch respectively. The northern branch has been indicated to be more active by historical seismicity records (Honkura and Işıkara, 1991).

The northern branch which is characterized by a wide, graben-like structure (Honkura and Işıkara, 1991) is considered to be a sequence of three, small `en échelon' pull-apart basins formed by the right stepping of the NAFZ; which are named as the Çınarcık Basin, the Central Basin and the Western Basin (Barka, 1997). Each of them has a depth of more than 1100 m. It passes through the İzmit and Karamürsel Basins and enters into the northern margin of the Marmara Sea. Since 3-4 m.y., 15 km openings which are actually lower than the expected values from a slip rate of 1.5 cm $year^{-1;}$ obtained by GPS displacement measurements (Reilinger et al., 1995; and Straub, 1996) of these pull-apart basins have been estimated to occur (Barka, 1997). The submarine part of this northern branch composed of a system of three, large pull-apart basins which have a depth of 1200 m and which are related to right steps along the fault (Barka and Kandinsky-Cade, 1988). Then the fault extends inland along the segment between Gaziköy and Saros which was activated during the 1912 earthquake. For the northern branch of the NAF, a total right offset of 65-70 km for the last 5 m.y., which gives rise to an average slip rate of 1.3-1.4 cm $year^{-1}$, is proposed in the recent study of Armijo et al. (1999). This proposition was based on the displaced and folded deposits from Eocene to Miocene, along the fault, at the Gelibolu Peninsula. This value is close to the present value of 2.4 cm $year^{-1}$; obtained from the GPS measurements for the Anatolia with respect to Eurasia, including the slip along the central and southern branches of the NAF.

The central branch which dominates the southern Marmara Sea area extends along Geyve Basin at the southern border of İznik Lake. At Gemlik Bay where a number of approximately E–W trending faults with chiefly normal components dominate (Kurtuluş, 1985), it enters the southern border of Marmara Sea. As a sequence of three, shallow `en échelon' pull-apart basins, it continues between the Armutlu and Kapıdağ Peninsulas. Then passing through Can and Bayramiç and entering the Aegean Sea at Ezine, it crosses the Biga Peninsula in a direction of SSW, as in the form of minimum three segments (Gürbüz et al., 2000).

The southern branch which is a simple, continuous strand and which is displaced right-laterally passes through the Bursa and Manyas-Karacabey basins, then crosses the Biga Peninsula by running along Gönen and Pazarköy. Then it enters the Aegean Sea at Edremit Bay in the direction of the Skyros Basin. There also exist the offset features of Holocene age; indicating that the strike-slip faulting has been dominant (Honkura and Işıkara, 1991).

Between the current studies in the Marmara Sea region, there is mainly a dense concentration on the studies of the Northern branch of the NAFZ, because of its possible potential seismic risk for the city of İstanbul, in contrast to the few number of studies on the southern and central branches of the North Anatolian Fault Zone and on the southern part of the Marmara Sea(e.g. Barka and Reilinger, 1997)

### 4.1.2. Seismicity of the Marmara Region

Along The North Anatolian Fault Zone, which is one of the well-known strike-slip faults throughout the world by its considerable damaging seismic activity, numerous large earthquakes have been produced both in recent and in historical times by the deformations along its branches. Some of these important historical earthquakes; such as the large 1737 event, were reported to have been produced by the southern strand of NAFZ which could result in a large magnitude earthquake in the future, because of its paucity (Ambraseys and Finkel, 1995). A large cluster of seismicity which is more distributed towards west, is observed to be produced by the southern branch of the NAFZ, near the city of Bursa (29°0.2E, 40°0.2N) (Sellami et al., 1997). Although for the central branch, the only remarkable event is the large 1737 event, there are significant, strong events already recorded, for example; in the Gemlik area in 128 AD, in Erdek, NW of Gönen in 155 AD and again in Cyzicus in 543 AD. So it is thought to be active between 28°0.6E and 29°0.4E. In addition to that, the distribution of epicenters becomes more diffuse towards the west, in contrast to the northern branch. On the other hand an interaction between the central and southern branches of the NAF in the Biga Peninsula could be suggested by the surface ruptures of the 1953 and 1964 earthquakes (Gürbüz et al., 2000)

However, in contrast to the diffused seismic activity along the central and southern part of the NAFZ, the northern branch of the NAFZ, which corresponds to the northern part of the Marmara Sea, shows a linear epicentral orientation in the E-W direction, from İzmit to Gaziköy. Two other important clusters of seismicity; one near İzmit (29°0.9E, 40°0.7N) at the boundary of the rupture regions of the 1754 and 1878 earthquakes and the other one in the NW of Yalova (29°0.1E, 40°0.7N), which might be accepted to cover the late aftershocks of the 1963 earthquake (M=6.2) could be followed (Gürbüz et al., 2000). Three seismic gaps at the place of the 1719 and 1754 earthquake ruptures and at the site of the 1912 Gelibolu earthquake; originated from Ganos fault are also observed. It is shown by GPS measurements (Straub, 1996), geomorphology, bathymetry, the thickness of sediments in the basins and historical earthquake records (Ambraseys and Finkel, 1991) in the eastern Marmara Sea region, the slip rate along the Northern branch is relatively higher than the central and southern branches. Taking into consideration its historical activities (Ambraseys and Finkel, 1995), it is the most active strand with a high earthquake risk potential for the coming years (Barka and Kuşçu, 1996).

The recent destructive earthquakes, which ruptured the two westernmost segments of the Northern branch of the NAFZ, happened on 17 August 1999 ($M_w$ =7.4) and on 12 November 1999 ($M_w$ =7.1).

#### 4.1.2.1. Seismic Activity: İzmit 1999 Earthquake

The most recent historical earthquake in İzmit Bay is comparable in magnitude to 2 September 1754 earthquake (Ambraseys and Finkel, 1995). The 1999 Kocaeli earthquake associated with the westward propagation of the activity of the North Anatolian Fault zone is thought to happen on a 150-km-long ''seismic gap''. This gap is located between 1963 Çınarcık ($M_s$=6.3) earthquake and 1967 Adapazarı ($M_s$=7.2) earthquake. It was proved that the focus of Kocaeli earthquake was approximately 17 km deep, in the elastic-brittle layer of the lithosphere and its epicenter was close to the town of Gölcük (40.7°N and 29.9°E). In addition to that, the moment magnitude of this earthquake was stated to be 7.4, and it caused a right-lateral movement on the fault in the E-W direction.

The field surveys have shown that the observed displacements between Düzce and Arifiye were basically of two different characters; the transtensional and/or pure strike-slip and mainly transtensional between İzmit and Yalova-Çınarcık region. The average right-lateral offset was between 2.5 and 3 m and the lateral surface displacement in the town of Arifiye reached its maximum offset of 4.9 m (Barka, 1999). The maximum dip slip offset of about 2.5 m was found on the Kavaklı Fault segment (Altınok et al., 2001).

Although the aftershock activities were highly concentrated along the main fault and especially at both ends of the ground ruptures, no aftershock activity was observed along the Çınarcık Fault which had been reactivated in 1963 by the Çınarcık Earthquake ($M_s$ = 6.3 ) (Özel et al., 2000).

## 4.2. Eskişehir Fault Zone

### 4.2.1. Tectonics and Seismicity

Anatolia is one of the regions throughout the world where tectonic deformation is intense (Jackson and McKenzie, 1988). Eskişehir Fault Zone is located between the strike-slip North Anatolian Fault Zone and Aegean extensional regime characterized by normal faults. For about 30 years, there are a lot of opinions or suggestions supporting the fact that Anatolian Block; containing Aegean Region and Central Anatolia has been moving west along North Anatolian Fault Zone and East Anatolian Fault Zone (McKenzie, 1972, 1978; Dewey and Şengör, 1979; Şengör, 1982; Şengör et al., 1985). However, according to Barka et al. (1995), western Anatolia has been separating from Central Anatolia with the Fethiye-Burdur Fault Zone and WNW-ESE trending Eskişehir Fault Zone. Eskişehir Fault Zone was exhibited to be a right-lateral strike-slip fault zone with a normal component (Şengör et al., 1985; Barka et al., 1995; and Şaroğlu et al., 1992) and it is moving more rapidly towards W-SW. The motion rate of western Anatolian block towards west increases from north to the south; for example the motion rate in the north would be less than 20 mm/year; whereas in the south, it is more than 30-40 mm/year (Jackson, 1994; Barka et al., 1995).

If the earthquake activity of Turkey is taken into consideration, Eskişehir region is not located in the first degree earthquake region, according to earthquake risk potential. But, Eskişehir is located in a transition between Aegean Region, which is stated to be the first degree earthquake region, and the NAFZ. According to the present earthquake catalogs (Ergin et al., 1967; Soysal et al., 1981), there is no significant earthquake record belonging to the period before 1900, around

Eskişehir and its surroundings. However, both existence of mud dykes in Pleistocene units and deformation of Holocene deposits in front of fault scarps indicate that fault segments are active in this area and several M≥ 6 earthquakes occurred in the last 10 000 years. On the other hand, large and medium scale earthquakes had occurred for the last 100 instrumentally recorded years and the largest magnitude earthquake that occurred during this period is 20 February 1956 earthquake ($M_s$=6.4) which gave rise to various damages in the downtown areas of Eskişehir, Bilecik and Bozüyük and in their vicinities. Fault plane solution of the 1956 earthquake and field observations indicated that the Eskişehir Fault Zone which played an important role in the development of Eskişehir and İnönü plains is a transtensional fault zone (Öcal, 1959). Öcal (1959) having completed macro and microseismic investigations has shown that the epicenter of this earthquake is near Çukurhisar which is 10 km west of Eskişehir, but he did not mention anything on which fault the earthquake had occurred and whether surface rupture was produced because of the fact that the city had been covered by snow. The 20 February 1956 earthquake could be expected to occur most probably on the segment between Oklubal and Turgutlar, in the south of Çukurhisar and to produce a surface rupture of at least 10 km. After this earthquake, the largest damage was observed in the villages of Çukurhisar and Satılmış which are located in the west of Eskişehir (Öcal, 1959).

#### 4.2.1.1. Eskişehir Fault Zone Between İnönü and Sultandere

WNW-ESE trending fault zone which is extending from Uludağ in the west to Kaymaz in the east was named in three parts, separately as İnönü-Dodurga fault zone, Eskişehir fault zone and Kaymaz fault zone on the active fault map of Turkey; prepared by Şaroğlu et al. (1992). However, Şengör et al. (1985) and Barka et al. (1995) named this fault extending between Uludağ and Kaymaz as Eskişehir Fault Zone. Eskişehir Fault Zone continues from Sultandere towards İnönü in succeeding segments. Although the general trend of Eskişehir fault is WNW-ESE, it may change between E-W and NW-SE when analyzed in a more detailed manner. Eskişehir Fault Zone, trends NW-SE in the west of İnönü, approximately E-W in between İnönü and Oklubalı, WNW-ESE between Oklubal, Turgutlar and Eskişehir, approximately E-W in the south of Eskişehir and NW-SE between Eskişehir and Sultandere. The width of the plain ranges between 2 and 12 km. The deepest (790 m) and the largest (12 km) section of the plain is located right in the downtown area of Eskişehir (Altunel and Barka, 1998).

#### 4.2.1.2. İnönü-Çukurhisar Segment

This segment which is bounding İnönü plain in the south, trends approximately in the E-W direction between İnönü and Oklubal and WNW-ESE between Oklubal and Satılmış. This fault bifurcates into two segments in the south of İnönü. It is shown by the horizontal fault lines on the vertical surface of the Triassic limestones that trend N142°. Right-lateral strike-slip, southern branch has no normal component. Another branch bounding İnönü plain in the south and trending approximately E-W between İnönü and Oklubalı is located obliquely according to this southern branch. In the south of İnönü, there are also normal faults, having strikes changing between N80° and N124° and dips between 48° and 86° (Altunel and Barka, 1998).

#### 4.2.1.3. Turgutlar-Eskişehir Segment

This fault extending from İnönü towards East steps over right in the south of Satılmış and starts again in the west of Turgutlar village and then it aligns through Eskişehir. WNW-ESE trending fault, disappears in the east of Turgutlar village without extending to Eskişehir. On the other hand, another WNW-ESE trending segment starting from the south of Turgutlar village trends approximately E-W near Eskişehir and NW-SE between Eskişehir and Sultandere. This fault forms the southern boundary of Eskişehir Plain. Around this fault, between the eastern Turgutlar and Sultandere, there is a dense settlement (Altunel and Barka, 1998).

In the south of the fault bounding the southern Eskişehir Plain, another fault is located cutting across the Eocene limestones. This fault trends approximately E-W in the west and NW-SE in the southern Eskişehir and extends to the SE, by passing through the southern Sultandere. However, no fault surface could be clearly observed along these alignments (Altunel and Barka, 1998).

Based on these observations matching with the ones from previous studies, it could be stated that Eskişehir Fault Zone is transtensional. The deformation rate on the Eskişehir Fault Zone is low (Barka et al., 1995) so it leads to the fact that the recurrence intervals of large earthquakes become wider. Eskişehir Fault Zone is composed of succeeding geometric segments and the segments forming a fault zone can be broken during different time intervals. Each segment of Eskişehir Fault Zone, lying between İnönü and Sultandere could be considered as a potential earthquake risk but the segment between Turgutlar and Eskişehir is thought to be the one on which earthquake risk is at the highest level (Altunel and Barka, 1998.

Syndepositional and postdepositional faults cutting Pleistocene and Holocene units indicate that the Eskişehir Fault Zone has been active since at least Pleistocene (Altunel and Barka, 1998).

### 4.3. Akşehir-Afyon Graben

#### 4.3.1. Neotectonics and Main Faults of Akşehir-Afyon Graben

The Akşehir-Afyon Graben, which is a NW trending depression, has a width ranging between 4 and 20 km, and a length of 130 km. It separates Central Anatolia in the NE from the Isparta Angle in the SW. The northeast edge of the outer Isparta Angle is determined by the southwestern margin-bounding fault of Akşehir-Afyon Graben (Koçyiğit and Özacar, 2003).

Total throw amount accumulated on the Akşehir Master Fault (AMF), which is the southwestern margin-bounding fault, is 870 m and it is 200 m since the Late

Pliocene and Early Pleistocene on the Karagöztepe Master Fault (KMF) which is the northeastern margin-bounding fault. Under the assumption of a uniform motion, these values indicate the motion rates of 0.3 mm/year and 0.2 mm/year, respectively. According to Koçyiğit and Özacar (2003), an oblique-slip motion with a minor right-lateral strike-slip component, and a NE-SW directed extension were observed and these observations were supported by kinematic analysis of surface slip data of both the Akşehir Master Fault and Karagöztepe Master Fault.

The Akşehir-Pınarkaya and Sultandağı-Maltepe sections of the Akşehir Master Fault are thought to be the sources of reactivation, leading to two recent seismic events which are respectively 15 December 2000 Sultandağı earthquake ($M_w$=6.0) and the 3 February 2002 Çay-Eber earthquake ($M_w$=6.5).

The principal discussions on the kinematic natures of the western and eastern edges of the Isparta Angle and the type of neotectonic regime can be grouped into two main categories:

The first group of researches (Boray et al. 1985; Barka et al. 1995; Uysal 1995; Altunel et al. 1999) think that the western edge of the outer Isparta Angle could be defined kinematically as the ''Fethiye-Burdur fault zone'', which is a NE-trending, left-lateral strike-slip fault and its eastern edge as ''Sultandağ Thrust'' which is a NW-trending thrust fault and the type of neotectonic regime controlling Isparta Angle is interpreted as compressional. The second group of researches (Koçyiğit 1996; Glover and Robertson 1998) suggest contrarily that the Isparta Angle has passed an extensional tectonic regime rather than a compressional one and the western and eastern bounding faults of outer Isparta Angle are oblique-slip normal faults as determined by field and seismicity data (Koçyiğit 1983, 1984, 1996, 2000; Koçyiğit et al. 200a, b; Kocaefe and Ataman 1976;McKenzie 1978; Taymaz and Price 1992; Price and Scott 194; Yılmaztürk and Burton 1999; Cihan and Koçyiğit 2000; Özacar and Koçyiğit 2000). In addition, Akşehir Fault Zone (AFZ), which defines the eastern edge of the outer Isparta Angle, is an active oblique-slip normal fault (Koçyiğit and Özacar, 2003).

#### 4.3.1.1. Graben Structure

##### 4.3.1.1.1. Akşehir Fault Zone

Graben-facing, Akşehir Fault Zone, which is composed of southern margin-bounding step-like normal faults of Akşehir-Afyon Graben, has a width of 2–7 km, an approximate length of 200 km and strike variations of 285º-320º-270º from west towards east, (resulting in a "Z"-shaped outcrop pattern). It is an oblique-slip normal fault zone, dipping at an average value of 60º NE with a minor dextral and/or sinistral strike-slip component, as proved by the stereographic plots and kinematic analysis of synthetic normal faults and focal mechanism solution of two very recent seismic events. (The 15 December 2000 Sultandağı and the 3 February 2002 Çay-Eber earthquakes)

Although the Akşehir Fault Zone comprises many second to third order, closely spaced, synthetic normal faults, having ranges of length from 2 to 50 km, in the east-southeast, it basically bifurcates into two major segments which are namely, the Argıthanı and the Doğanhisar faults. Since the total throw on the western section of the Akşehir Fault Zone has been indicated as 870 m since at least the Late Pliocene, the maximum rate of motion along this section may be about 0.3 mm/year (Koçyiğit and Özacar, 2003).

##### 4.3.1.1.2. Karagöztepe Fault Zone

The northern margin of the Akşehir-Afyon Graben is determined by relatively NW-, NS- and NE- trending three sets of closely spaced, synthetic to antithetic, oblique-slip normal faults, whether short (1-5 km) or long (up to 40 km). It has been divided into numerous second-order horsts and grabens, such as Emirdağları, Adakale, Aladağ, Dededağ and Karadağ horsts and Kızılboğaz, Yunak and Ilgın subgrabens.

Karagöztepe Fault Zone which is a key structure of the northern margin of the Akşehir-Afyon Graben is a WNW- and ENE-trending fault zone, with a width of

1-10 km and a length of 90 km. It consists of various, closely spaced, synthetic to antithetic fault segments; either short (1 km) or long (up to 25 km).

The master fault of the Karagöztepe Fault Zone is stated to be an ENE and SSW oblique-slip normal fault with average dip angles of 56º–61º SSE and WSW, respectively, as shown by stereographic plots and kinematic analysis (Koçyiğit and Özacar, 2003).

The total throw of 200 m, since the Early Quaternary, on the northern margin-bounding faults of the Akşehir-Afyon Graben yields a rate of subsidence of 0.2 mm/year. If these values of rates of subsidence for northern and southern margin are compared separately, it may be figured out that the Akşehir-Afyon Graben has experienced an asymmetrical evolution during the extensional neotectonic regime (Koçyiğit and Özacar, 2003).

### 4.3.2. Seismicity

#### 4.3.2.1. Historical Earthquakes

Seven seismic events of intensities varying from VI to X have been reported for the period between 94 A.D. and 1899 B.C., at the towns of Afyon, Şuhut and Ilgın (Ergin et al., 1967). Unfortunately no reliable data exist on various parameters such as the exact location of the epicenter, the depth of the hypocenter, time, magnitude and source of the earthquake, damage to various structures or the number of casualties caused by these seismic events. Nevertheless, Şuhut graben which is located 7 km south of Akşehir Fault Zone was proved to be the epicenter of the 1862 earthquake of intensity ‘’X’’. During this earthquake, the town of Şuhut was devastated by numerous foreshocks followed by the mainshock, eight hundred people died and several damages were observed such as ground ruptures and liquefaction in the water-saturated fill of the Şuhut Graben. (Ergin et al., 1967)

#### 4.3.2.2. Earthquakes in the Period 1900–1999

During this period, 36 earthquakes with magnitudes ranging between 4.0 and 6.8 occurred in the Akşehir-Afyon Graben and its surrounding areas. It is shown by the distribution of these shallow-focused earthquake epicenters that NW-trending graben bounding faults and a majority of the NE-trending second order faults are seismically active. The 26 September 1921 Argıthanı-Akşehir earthquake (M=5.4) and the 21 February 1946 Ilgın-Argıthanı earthquake (M=5.5), which were both occurred in the eastern part of the Akşehir Afyon Graben, led to several, significant damages in the area. However, no information on the ground rupture has been reported. On the other hand, in spite of the lack of reliable and accurate instrumental seismic records before 2000's, it can be stated by the present field data and the distribution of the epicenters of these earthquakes that these two devastating earthquakes may have originated from the fault segments of the Akşehir Fault Zone; the so-called Argıthanı and Doğanhisar fault segments (Koçyiğit and Özacar, 2003).

#### 4.3.2.3. Recent Seismicity: 15 December 2000 Sultandağ and 3 February 2002 Çay-Eber (Afyon) Earthquakes

In 15 December 2000, at 18:44 (local time), Sultandağı earthquake of moment magnitude 6.0, with a shallow focus of between 5.8 and 15 km occurred at the southern margin of Eber Lake located in the Afyon Akşehir Graben (Harvard University, 2000; Taymaz and Tan, 2001). There is no observation on the ground rupture which could be created by this earthquake. Since the epicenters of the aftershocks are cumulated between Eber Lake and the southern margin of Akşehir Lake, a 30 km long linear seismic belt which is parallel both to the Akşehir Master Fault of the Akşehir Afyon Graben at the south and to its Karagöztepe Master Fault (of the Akşehir Afyon Graben) in the north could be observed to be displayed by the distribution of these earthquakes. 15 December 2000 Sultandağı earthquake was implied to be originated from Akşehir-Pınarkaya section of the Akşehir Master Fault of 30 km long.

A second destructive, shallow-focus (H=5-15 km), moderate-size earthquake ($M_w$=6.5) which was so-called 3 February 2002 Çay-Eber (Afyon) earthquake again occurred at the southern margin of Eber Lake which is very close to the epicenter of the first event, at 9:11 on local time (Koçyiğit and Özacar, 2003).

#### 4.3.2.4. Ground Deformation (and the Source of Sultandağı and Çay Earthquakes)

Based on their orientations and places of formation, the discontinuous surface ruptures which have been led by the Çay-Eber earthquake in contrast to the Sultandağı earthquake were categorized from east to west in four sets (of ground ruptures) as:

(i) Sultandağı ruptures, which consist of a series of closely spaced en-echelon cracks of 2 to 4 cm long; trending approximately N75ºW, have been observed to be of 200 m total length and to have 2.5 cm throw on its northern down-dropped block.
(ii) Oğuzhüyüğü ruptures consist of en-echelon cracks of 2 to 4 cm long; trending approximately NNE (N-N10ºE), have been observed to be of 250 m total length and to have 2.0 cm throw on its northern block.
(iii) Çay ruptures, which consist of a series of closely spaced (2-20 cm) en-echelon, open cracks of 10 to 18 m long; trending approximately N50º-70 ºE have been observed to be of 4 km total length and to have throw amounts of 19-22 cm and 1-2 cm at the southern and northern margin respectively.
(iv) Maltepe ruptures consist of a series of parallel to subparallel, closely spaced (5 cm-5 m) en-echelon, open cracks of 12 cm to 33.4 m long, have been observed to produce throw amounts of 11-17 cm on northern down-dropped blocks.

So as an average, total observable length of discontinuous ground ruptures at four different localities (Sultandağı, Oğuzhüyüğü, Çay and Maltepe) of about 10 km has been followed along the southern margin-bounding master fault, along a distance of about 32 km (Koçyiğit and Özacar, 2003).

### 4.4. Seismotectonics of Gediz and Its Surroundings

Gediz and its surroundings are predicted to be seismically active regions by means of either historical or instrumental earthquake records. 23 March 1969 Demirci Earthquake (M: 5.6-6.1); 28 March 1969 Alaşehir-Sarıgöl Earthquake (M=6.0) and 28 March 1970 Gediz Earthquake (M=7.1) are very typical examples of this activation or reactivation (Tokay and Doyuran, 1979).

#### 4.4.1. General Tectonic Pattern

The existence of grabens which forms the typical tectonic<structure of the Aegean region of Turkey has been known for years (Arpat and Bingöl, 1970). Büyük Menderes, Küçük Menderes, Alaşehir, Simav, Gediz, Bergama and Edremit could be stated as the typical examples of these grabens whose general directions are determined to be approximately E-W. But, in addition to these generally E-W directed grabens, other numerous types of faults having different directions were seen on the tectonic map of Gediz and its surroundings. These fauls developed in the directions of approximately WNW-ESE and NE-SW. This variation may show that this region could have been affected by complex block faultings (Tokay and Doyuran, 1979).

The region has been generally dominated by oblique-slip normal faults. Gediz and its surroundings are controlled by extensional neotectonic regime; as indicated by the existence of typical grabens of western Anatolia (Tokay and Doyuran, 1979).

### 4.4.2. Seismotectonic Pattern

Ambraseys and Tchalenko (1972) have claimed that a great number of the epicenters of the aftershocks occurred after the 1970 Gediz earthquake, through one year, were scattered in an earthquake belt of 300 km long which extends through the Edremit Bay.

This belt, established by the distribution of these earthquake epicenters, includes some of the WNW-ESE trending faults such as Gediz and Simav faults and also E-W trending Emet fault. The existence of various earthquake epicenters aligned along these faults may prove that these faults could be active. But on the other hand, NE-SW trending faults could be accepted as seismically less valuable than the others.

### 4.4.3. Gediz Graben

Gediz Graben is a structure of about 200 km long which extends from Pamukkale all the way to Manisa. The master fault of this graben aligns through its southern edge, whereas the antithetic component of this fault lies along the northern edge. The 28 March 1969 Alaşehir earthquake (M=6.5), which occurred within this graben, resulted in surface ruptures of 36 km long, trending in a direction of N70°-80°W and a (vertical) throw of 3 to 13 cm was observed on these surface ruptures. (Arpat and Bingöl, 1969; Ergin et al., 1971) After this earthquake, a dense accumulation of aftershock activities was observed in the southern region of the graben.

The master fault separating Neogene deposits of the Gediz Graben from the metamorphic basement; so-called Menderes Massif is called as Southern Boundary Fault (Seyitoğlu and Scott, 1996) or Karadut Fault (Emre, 1996). A semi-parallel fault, bounding the Neogene and Quaternary deposits, exists near the interior parts of the graben (Seyitoğlu and Scott, 1996).

#### 4.4.4. Simav Graben

Simav Graben trends WNW and its master fault is bounding its southern edge (Seyitoğlu, 1998). 1942 Bigadiç; 1969 Demirci and 1970 Gediz earthquakes are among the most destructive earthquakes of the Simav Graben which occurred during this century (Eyidoğan and Jackson, 1985). Before these earthquakes, a large amount of micro earthquake activities has been observed for the last 30 years (Üçer et al., 1997).

# CHAPTER V

# PREPARATION OF THE SEISMOTECTONIC MAP

Although the seismic data obtained from instrumental records has been proved to be the main probabilistic tool for reflecting future events, the geological data; especially fault slip-rate data, have captured an increasing trend and so a more dominant role. This astonishing and well innovative trend could be certainly related to the worldwide availability of the Global Positioning Satellite (GPS) data.

In the content of this thesis, a seismotectonic map of the study area was prepared based on two main stages and it is demonstrated in Figure 5.1. The first stage consists of the studies for determining the fault lines and the second stage comprises the collection of the data associated with the earthquake epicenters from the earthquake catalogs.

First of all, for the assessment of the active faults bounded by the study area, a number of studies which were already conducted within the limits of the study area have been carefully analyzed. These studies include the technical reports of earthquakes, the scientific publications from the journals both national and international, some of the collected works in the area of interest and finally the geological maps. As a result, the fault lines detected by these studies were compiled on a base map by means of a GIS Software named as TNTmips (Ref; User's manual). The fault lines which were stated to be active and enclosed within the NAFZ and Kütahya Fault Zone were collected from the geological map (scale: 1/25000) prepared by MTA. The Gediz Fault, Simav Fault and Emet Fault which appeared to align along Gediz and its surroundings were gathered together from the study of Tokay and Doyuran (1979). On the other side, Eskişehir Fault Zone was drawn on the base map from the study of Altunel and Barka (1998). Finally, the fault lines bounding Akşehir-Afyon Graben and its surroundings were taken from the study of Koçyiğit and Özacar (2001).

Secondly, the earthquake epicenters from the instrumental records, between the dates of (1913-2003) within the study area were provided to be presented on the base map by means of the earthquake catalog of Boğaziçi University, Kandilli Obsevatory and Earthquake Research Institute Seismology Laboratory. It is evident that there is no available instrumental record before 1913 for the earthquakes which were named as ‘historical’ or ‘preinstrumental’. So the determination of the epicenter and intensity of these earthquakes were entirely based on the damage observations. As a result, they were artificially dislocated towards the downtown areas where destructive consequences could be naturally expected to occur thus it became a very complicated and hard issue to define the maximum intensity properly (Gürpınar et al., 1978). Taking these implicit inconveniences into consideration and the difficulties encountered during the compilation of the research for finding historical records, the preinstrumental data were not utilized in the evaluation stage but they were mentioned somehow shortly on the context of the chapter; ‘Seismotectonics’.

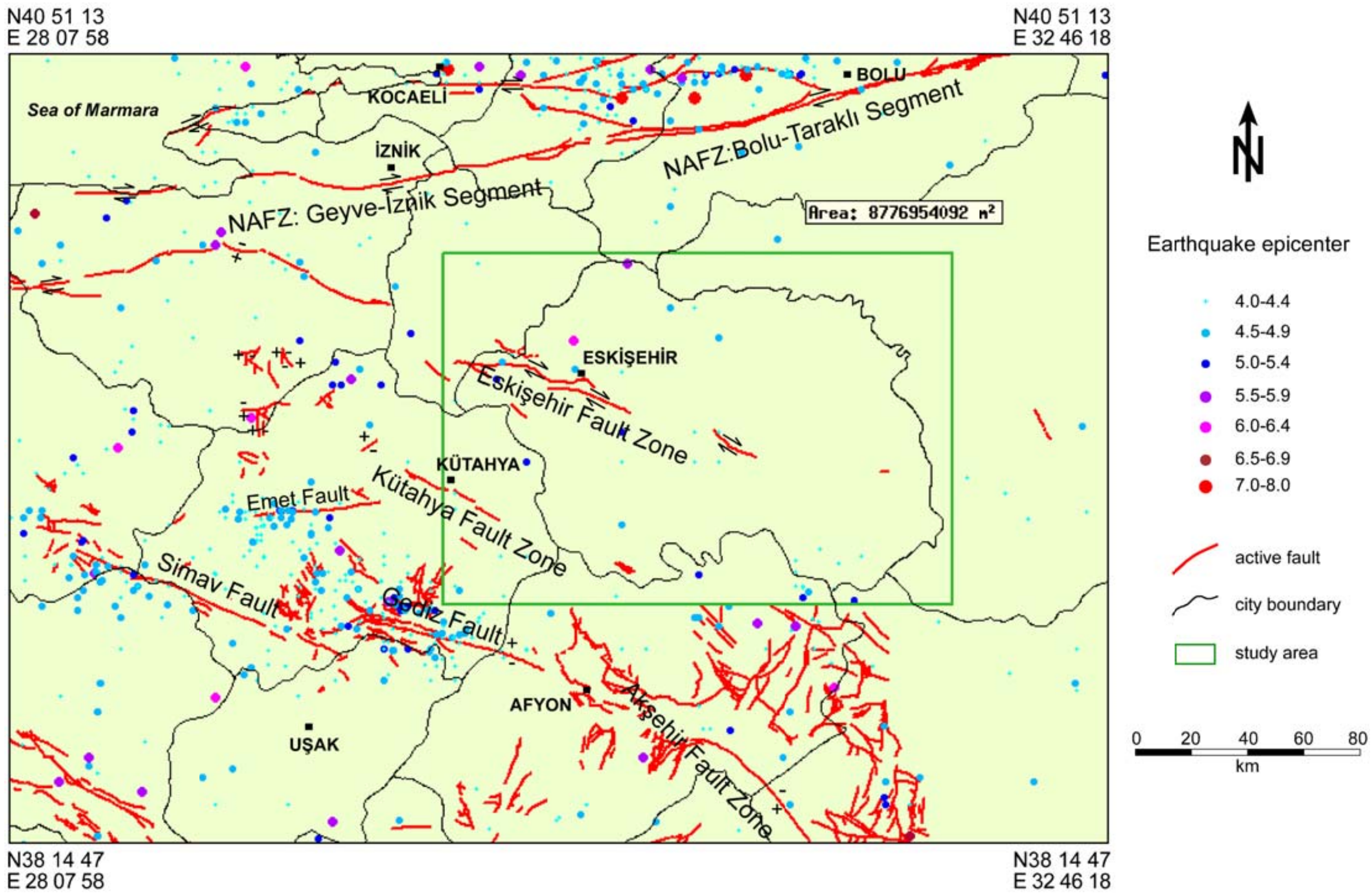


**Figure 5.1.** Seismotectonic map of the study area.

# CHAPTER VI

## EARTHQUAKE SOURCE CHARACTERIZATION

Earthquake source characterization of the study area and its environments requires two main considerations; namely the prediction of the spatial distribution of earthquakes within these sources and their occurrence(s) with time. These are respectively the definition of the earthquake source zones and the application of the appropriate earthquake recurrence relationship to the earthquakes happened within them. This must be accomplished by means of a predictive, well structured (engineered) model, based on the available seismological and regional tectonics data which are smart enough to consider the inherent uncertainties also.

So, taking into consideration the seismicity of the region and understanding its tectonic structures from a broad, detailed technical literature review, a consistent model was developed. The model consists of six earthquake source zones:

1. North Anatolian Fault Zone (Bolu-Taraklı and Geyve-İznik Segment )
2. Eskişehir Fault Zone
3. Kütahya Fault Zone
4. Gediz Fault and Simav Fault (Simav Graben System)
5. Akşehir-Afyon Graben System
6. Gediz Graben System

They were all geometrically defined as two-dimensional 'areal sources' and represented in Figure 6.1.

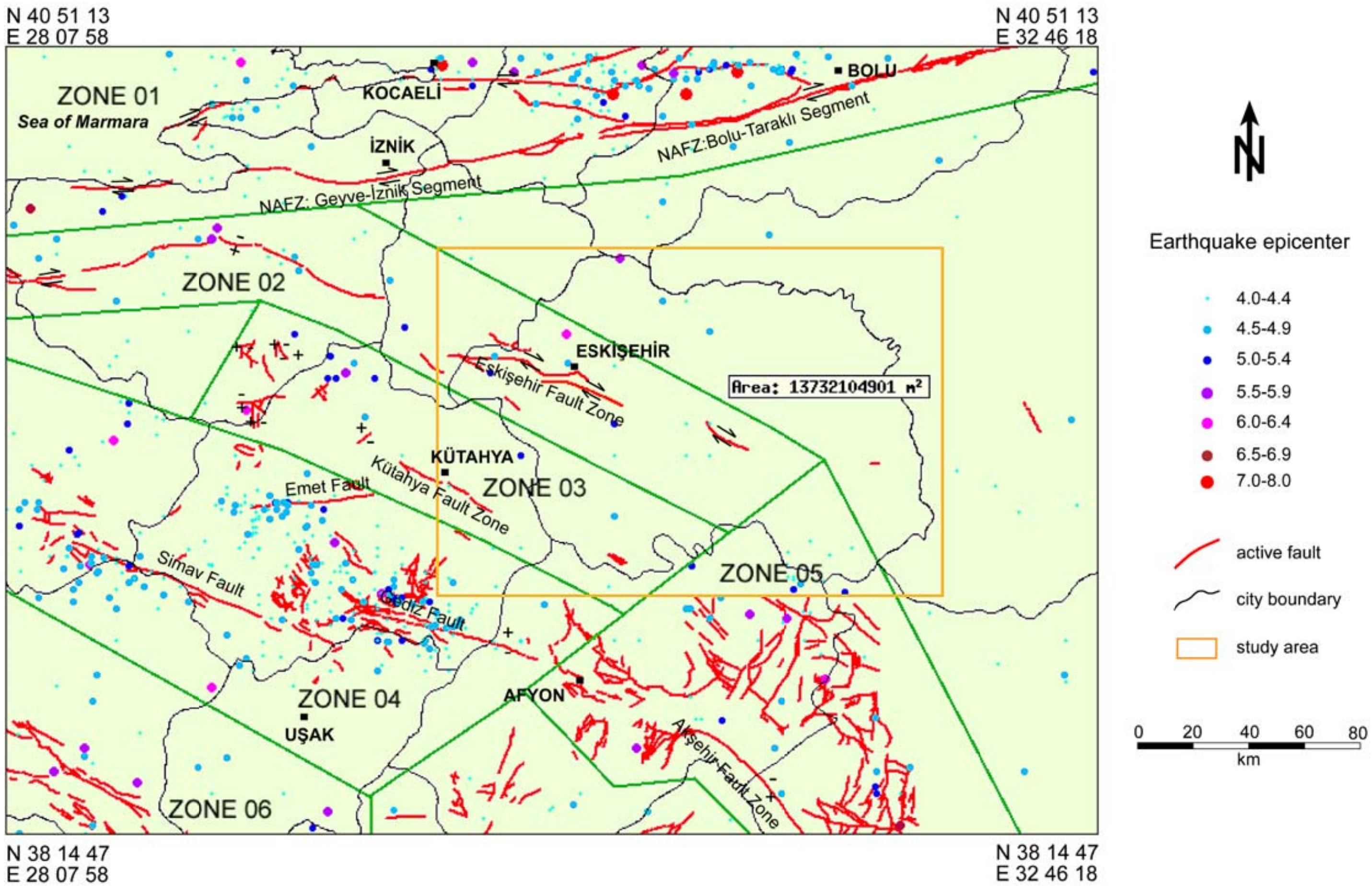


**Figure 6.1.** Seismic Source Zones.

The model of earthquake recurrence is selected as the Gutenberg-Richter relationship (1944) for all the earthquake source zones. Besides, Gutenberg and Richter (1944) collected data from southern California earthquakes for many years and then organized the data according to the number of earthquakes exceeding different magnitudes over this period of time. They divided the number of exceedances of each magnitude by the length of the time period to define a 'mean annual rate of exceedance', $\lambda_m$ of an earthquake of magnitude *m*. The reciprocal of the annual rate of exceedance for a particular magnitude is commonly called as the 'return period' of earthquakes exceeding that magnitude. After the logarithm of the annual rate of exceedance of these southern California earthquakes had been plotted against earthquake magnitude, the resulting linear 'Gutenberg-Richter law' for earthquake recurrence was expressed as (Kramer, 1996)

$$Log\lambda_m = a - b\lambda_m \qquad (6.1)$$

$\lambda_m$ = Mean annual rate of exceedance of magnitude *m* (or epicentral intensity)

$10^a$ = Mean yearly number of earthquakes of magnitude greater than or equal to zero

$b$ = Constant describing the relative likelihood of large and small earthquakes

On the other hand, this model is thought to be applied within a magnitude interval whose lowest limit was set to be the minimum magnitude as 4.0 and whose highest limit; the maximum magnitude as the largest earthquake capable of occurring in each source zone.

There are many regression equations, for the determination of the maximum earthquake for known active faults, relating earthquake size to the fault characteristics such as 'fault rupture length', 'fault rupture area', 'fault rupture displacement' and 'average fault rupture displacement' or 'maximum surface displacement(Reiter, 1990). But, in this study, the 'fault rupture length' and 'maximum magnitude' relationship has been chosen to be the appropriate one in estimating the maximum earthquake magnitude. It is selected as the principle regression type since it is most probably the most commonly employed and it appears to be very useful for all fault types except the ones with a large normal component (Reiter, 1990). One way of using this type of regression, if the data are available, is to identify the segments of the fault which seem to have ruptured as unit segments in single earthquakes and utilize their lengths to determine the maximum magnitude (Reiter, 1990). The other way is to compare the projected rupture length of a given fault likely to rupture in a future earthquake with the ones, actually observed during past earthquakes and to estimate the expected level of magnitude associated with these historic earthquakes and so the future ones (Yeats, 1997). Within the scope of this thesis, one of these regression relationships for worldwide earthquakes, which has been tabulated by Wells and Coppersmith (1994) is selected. In their study, Wells and Coppersmith (1994) used 216 historic earthquakes in which at least some source parameters were very well documented. This regression relationship of surface rupture length on moment magnitude was expressed for worldwide earthquakes of all slip types as (Wells and Coppersmith, 1994):

$$M = 5.08 + 1.16 Log(SRL) \quad (6.2)$$

$$Log(SRL) = -3.224 + 0.69M \quad (6.3)$$

*M* = Moment Magnitude
*SRL* = Surface Rupture Length (km)

This relationship was also expressed differently for each fault movement together with its uncertainty by Wells and Coppersmith (1994) as in the following table (Table 6.1.)

In the following paragraphs, the determination of the maximum magnitude and the graphical and mathematical representation of the selected earthquake recurrence relationship will be explained for each areal source zone, separately.

**Table 6.1.** Emprical Relationships between Moment Magnitude and Surface Rupture Length (Wells and Coppersmith, 1994)

| Fault Movement | Relationship |
|---|---|
| Strike-slip | $M_w = 5.16 + 1.12 \log L$<br>$\log L = 0.74 M_w - 3.55$ |
| Reverse | $M_w = 5.00 + 1.22 \log L$<br>$\log L = 0.63 M_w - 2.86$ |
| Normal | $M_w = 4.86 + 1.32 \log L$<br>$\log L = 0.50 M_w - 2.01$ |

## 6.1. North Anatolian Fault Zone (NAFZ) (Geyve-İznik and Bolu-Taraklı segments)

The NAFZ contains few master segments (around 10); 4 of them being greater than 100 km in length and several small segments shorter than 100 km long which include some subsegments toward their both ends. From east to west, its master segments include the Erzincan Segment of 350 km long, the Ladik-Tosya segment of 260 km, the Gerede segment of 180 km, and the Saros segment of at least 100 km. The other segments are situated at the eastern end (Varto segment) and at the western end (Mudurnu Valley segment). On the western branches, the northern strand is called as Sapanca-İzmit and the southern one as İznik-Mekece (Demirtaş and Yılmaz, 1995).

However, in contrast to the diffused seismic activity along the central and southern part of the NAFZ, the northern branch of the NAFZ, which corresponds to the northern part of the Marmara Sea, shows a linear epicentral orientation in the E-W direction, from İzmit to Gaziköy. Two another important clusters of seismicity could be observed; one being near İzmit and the other one in the NW of Yalova. (Demirtaş and Yılmaz, 1995).

### 6.1.1. Maximum Magnitude

Within the boundaries of the NAFZ, the very significant recorded past earthquakes occurred on the Saros, Gerede, Yenice-Gönen, Mudurnu Valley and Manyas segments are in 1912, 1944, 1953, 1957, 1964, respectively. In this zone, the longest observed surface faulting was reported as 160 km and this length was assumed to be accompanied with Gerede segment of NAFZ. (Demirtaş and Yılmaz, 1995). In addition to these past earthquakes, the very recent and biggest earthquakes recorded along this zone are the 17 August 1999 Kocaeli earthquake of magnitude 7.4 and the 12 November 1999 Düzce earthquake of magnitude 7.2. ''The Kocaeli Earthquake involved two main shocks, which have ruptured several fault segments lying between Gölyaka and Karamürsel. It has been assumed to produce an approximate surface rupture length of 120 kilometers between Gölyaka and Karamürsel and several different right-lateral offsets as large as 4.5 m'' (Demirtaş and Yılmaz, 1995).

In this study, the master segments within this stated zone are Geyve-İznik and Bolu-Taraklı segments of about 130 and 100 km long; measured from 1:25 000 scale MTA geological map. So it would not be unrealistic to assume that the master Geyve-İznik segment whose length was measured as approximately 130 km will not rupture as a single segment in a single earthquake shock. So based on the empirical relationship in Table 6.1. between magnitude and surface rupture length, a maximum moment magnitude of 7.5 could be assigned to this areal source.

### 6.1.2. Earthquake Recurrence Relationship

Gutenberg-Richter recurrence relationship equation and Gutenberg-Richter recurrence relationship curve (its graphical representation) which were both constructed based on instrumental records of last 100 years (Table 6.2.) are shown in Figure 6.2 below for NAFZ Geyve-İznik and Bolu-Taraklı Segments (Source Zone 1).

**Table 6.2.** Quantitative distribution of instrumental records of last approximately 100 years within considered magnitude intervals for NAFZ Geyve-Iznik and Bolu-Taraklı segments

| | MAGNITUDE | | | | | | |
|---|---|---|---|---|---|---|---|
| TIME (YEARS) | 4,00 | 4,5 | 5 | 5,5 | 6 | 6,5 | 7 |
| **100** | **223,00** | **94** | **40** | **15** | **7** | **6** | **5** |
| **1** | **2,23** | **1,14815** | **0,4** | **0,15** | **0,07** | **0,06** | **0,05** |

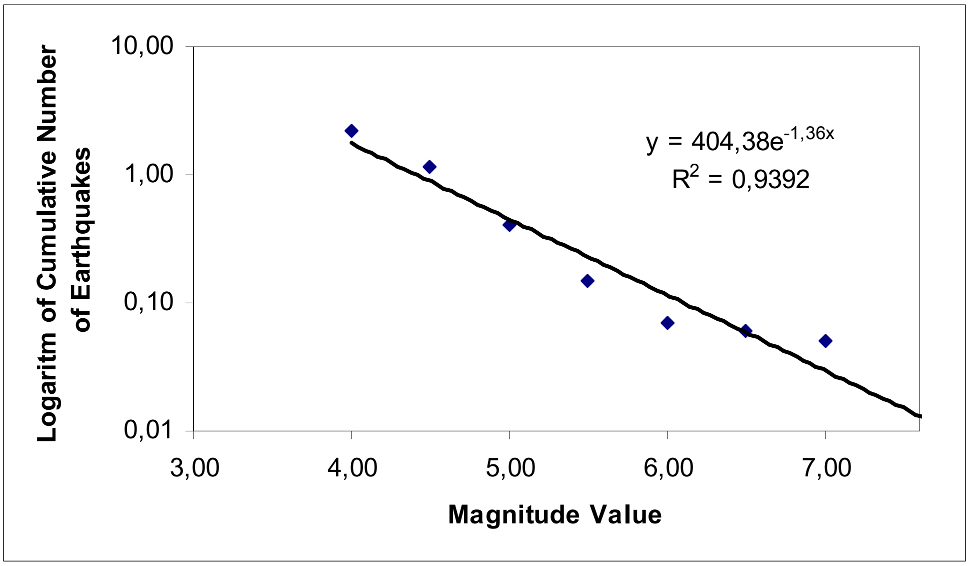


**Figure 6.2.** Gutenberg-Richter recurrence relationship curve for source zone 1

### 6.2. Eskişehir Fault Zone

400 km long İnegöl-Eskişehir fault set is located between the Tuzgölü fault to the east and İnegöl to the west (Gülkan et al. 1993). It is composed of numerous short fault segments and dominantly right lateral strike-slip faults (Demirtaş and Yılmaz, 1995).

Eskişehir Fault Zone is the nearest fault zone to the Eskişehir downtown area. So, it is one of the most important fault zone controlling the sesimicity of the Eskişehir municipal area.

### 6.2.1. Maximum Magnitude

‘’Every segment of Eskişehir Fault Zone between İnönü and Sultandere could create a potential earthquake risk but the risk near Turgutlar and Eskişehir is relatively higher’’ (Barka and Altunel, 1998).

The largest earthquake along the Eskişehir Fault Zone was reported to be the 20 February 1956 earthquake (M = 6.4) which was assumed to produce a surface rupture of at least 10 km (Barka and Altunel, 1998). However, nobody can claim that the longest segment of approximately 30 km, lying south of Eskişehir downtown area (the closest one to the Eskişehir downtown area) cannot rupture at one time; in a single earthquake. So, based on the selected empirical regression relationship (Wells and Coppersmith, 1994) between surface rupture length and magnitude, a maximum magnitude 6.8 is assigned to this source zone. This empirically calculated magnitude value has also found to be consistent with 1964 earthquake which was assumed to happen on a shorter segment which ruptured a relatively smaller length.

### 6.2.2. Earthquake Recurrence Relationship

Gutenberg-Richter recurrence relationship equation and Gutenberg-Richter recurrence relationship curve (its graphical representation) which were both constructed based on instrumental records of last 100 years (Table 6.3.) are shown in Figure 6.3 below for Eskişehir Fault Zone ( Source Zone 2) .

**Table 6.3.** Quantitative distribution of instrumental records of last approximately 100 years within considered magnitude intervals for Eskişehir Fault Zone

| | MAGNITUDE | | | | |
|---|---|---|---|---|---|
| **TIME (YEARS)** | 4 | 4,5 | 5 | 5,5 | 6 |
| 100 | **45** | **22** | **10** | **3** | **1** |
| 1 | **0,45** | **0,22** | **0,1** | **0,03** | **0,01** |

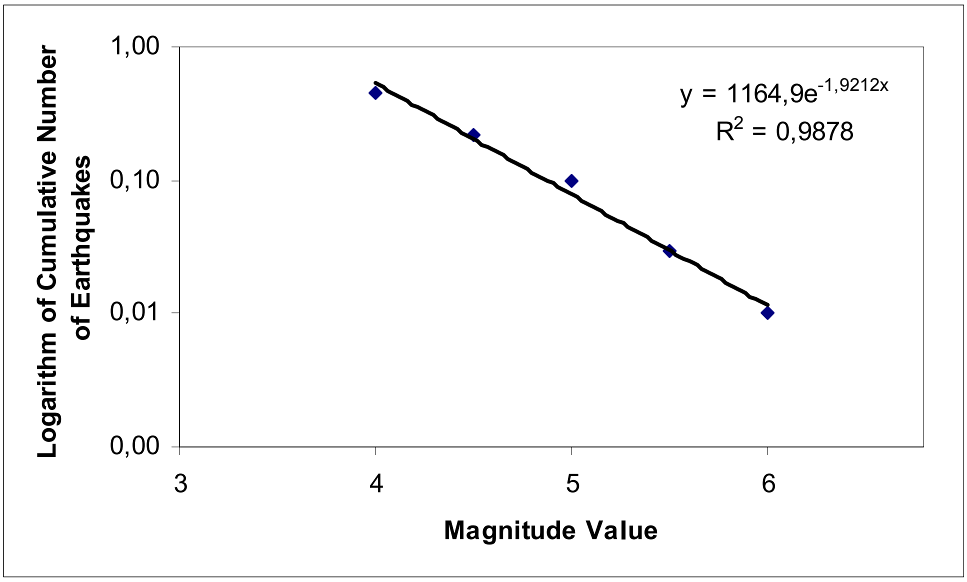


**Figure 6.3.** Gutenberg-Richter recurrence relationship curve for source zone 2 (Eskişehir Fault Zone).

### 6.3. Kütahya Fault Zone

Kütahya Fault Zone is located at the southwest of Eskişehir. It is composed of three main segments (Koyuncu, 2001 and 1/25000 Map of MTA). Each segment could be a major threat for Eskişehir. The maximum magnitude earthquake recorded around this fault was Çavdarhisar earthquake (1970) of magnitude 5.9, with a focal depth of 18 km.

### 6.3.1. Maximum Magnitude

Taking into consideration all the fault segments, which constitute Kütahya Fault Zone and are stated to be possibly close to the study area, the maximum length of the fault segment is measured as approximately 14 km from Figure 6.1. So, if this largest segment is assumed to rupture in a single event in the future, the maximum observable moment magnitude could be calculated by Wells and Coppersmith (1994) regression relationship relating moment magnitude to the 'rupture length' as 6.4.

### 6.3.2. Earthquake Recurrence Relationship

Gutenberg-Richter recurrence relationship equation and Gutenberg-Richter recurrence relationship curve (its graphical representation) which were both constructed based on instrumental records of last 100 years (Table 6.4.) are shown in Figure 6.4 for Kütahya Fault Zone (Source Zone 3).

**Table 6.4.** Quantitative distribution of instrumental records of last approximately 100 years within considered magnitude intervals for Kütahya Fault Zone

| | **MAGNITUDE** | | | | |
|---|---|---|---|---|---|
| **TIME (YEARS)** | 4 | 4,5 | 5 | 5,5 | 6 |
| 100 | **27,00** | **12,00** | **8,00** | **3,00** | **1,00** |
| 1 | **0,27** | **0,12** | **0,08** | **0,03** | **0,01** |

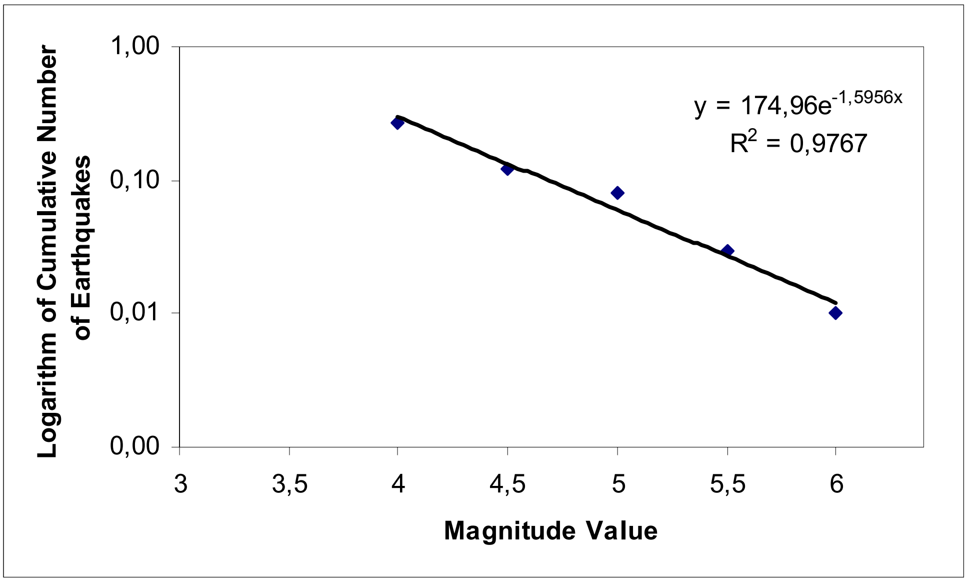


**Figure 6.4.** Gutenberg-Richter recurrence relationship curve for source zone 3 (Kütahya Fault zone).

### 6.4. Gediz Fault and Simav Fault (Simav Graben System)

The Simav graben is about 100 km long and runs along the Simav Creek (Gülkan et al., 1993). Simav and Gediz are very typical graben systems of the Western Anatolia which are mainly controlled by the extensional neotectonic regime of the Aegean Region of Turkey. These E-W directed tectonic structures are associated with numerous, dominantly oblique-slip, WNW-ESE and E-W directed normal faults such as Gediz and Simav Faults. (Tokay and Doyuran, 1979).

After 28 March 1970 Gediz earthquake, the aftershocks were aligned within a belt of 300 km long which accommodates some important faults such as Gediz , Simav and Emet (Ambraseys and Tchalenko, 1972).

Although in the Aegean Graben System exhibiting a very complex tectonic structure, the earthquakes are generally concentrated at the ends of the major grabens, they have been scattered all along the Simav graben and at the western end of Gediz graben (Demirtaş, 1995).

### 6.4.1. Maximum Magnitude

The largest recorded earthquakes within the Gediz and Simav grabens were 23 March 1969 Demirci Earthquake (M=5.6-6.1), 28 March 1969 Alaşehir-Sarıgöl Earthquake (M=6.0), and 28 March 1970 Gediz Earthquake (M=7.1) (Tokay and Doyuran, 1979).

The 1942 Bigadiç; 1969 Demirci and 1970 Gediz earthquakes are among the most important earthquakes of Simav Graben, at this century (Eyidoğan and Jackson, 1985).

These graben bounding faults are composed of various segments connected with steps and bends. So an earthquake occurred on one segment may trigger the adjacent one or ones that could be reactivated independently later on. Based on this hypothesis, the earthquakes occurred in this century are assumed to form a pair (Demirtaş, 1995). Therefore, there is no reason to believe that approximately 70 km long Gediz Fault (Figure 6.1.) and 73 km long Simav Fault (Figure 6.1.) will not rupture all along their lengths seperately in individual events. Based on the empirical relationship between magnitude and surface rupture length, a maximum magnitude of 7.3 could be assigned to this areal source.

### 6.4.2. Earthquake Recurrence Relationship

Gutenberg-Richter recurrence relationship equation and Gutenberg-Richter recurrence relationship curve (its graphical representation) which were both constructed based on instrumental records of last 100 years (Table 6.5.) are shown in Figure 6.5 for Simav Graben System (Source Zone 4).

**Table 6.5.** Quantitative distribution of instrumental records of last approximately 100 years within considered magnitude intervals for Simav Graben System

| | **MAGNITUDE** | | | | |
|---|---|---|---|---|---|
| **TIME (YEARS)** | 4 | 4,5 | 5 | 5,5 | 6 |
| 100 | **309,00** | **128,00** | **31,00** | **8,00** | **3,00** |
| 1 | **3,09** | **1,28** | **0,31** | **0,08** | **0,03** |

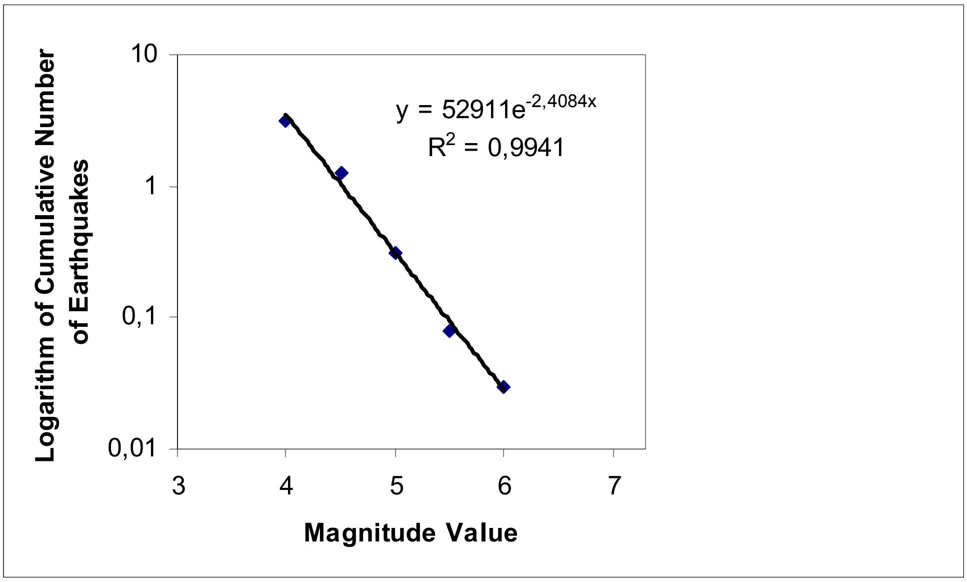


**Figure 6.5.** Gutenberg-Richter recurrence relationship curve for source zone 4 (Simav Graben System).

## 6.5. Akşehir-Afyon Graben System

The Akşehir-Afyon Graben, a NW trending depression, has a width ranging between 4 km and 20 km, and a length of 130 km. Its southern and northern margins are bounded by two fault zones which are the southern margin bounding oblique-slip normal faults and northern margin bounding, closely spaced, synthetic to antithetic fault segments; either short or long (Ref Koçyiğit and Özacar).

### 6.5.1. Maximum Magnitude

The maximum earthquakes recorded within the Akşehir-Afyon Graben are the 15 December 2000 Sultandağı earthquake ($M_w$ = 6.0) and 3 February 2002 Çay earthquake ($M_w$ = 6.5). The responsible sources of these two recent earthquakes were considered as the Akşehir-Pınarkaya and Sultandağı-Maltepe sections of the Akşehir Master Fault of 30 km long. In addition to these earthquakes, the 26 September 1921 Argıthanı-Akşehir earthquake (M=5.4) and the 21 February 1946 Ilgın-Argıthanı earthquake (M=5.5) were the significant past earthquakes of the eastern part of the Akşehir Afyon Graben. Based on the field data and the distribution of the epicenters, it is assumed that these may have been originated from the fault segments of the Akşehir Fault Zone; the so-called Argıthanı and Doğanhisar fault segments (Koçyiğit and Özacar, 2003).

In fact, oblique-slip normal Akşehir Fault Zone, which consists of southern margin-bounding step-like normal faults of 2 to 50 km long, has an approximate length of 200 km. Its two major segments were named as Argıthanı and the Doğanhisar faults (Koçyiğit and Özacar, 2003).

On the other hand, Karagöztepe Fault Zone which consists of northern margin-bounding fault segments of 1 to 25 km long has an average length of 90 km (Koçyiğit and Özacar, 2003).

If Akşehir Master Fault of approximately 30 km will rupture all through its alignment at one time in the future, it would be inevitable to assign a maximum moment magnitude of 6.8 to this areal zone.

### 6.5.2. Earthquake Recurrence Relationship

Gutenberg-Richter recurrence relationship equation and Gutenberg-Richter recurrence relationship curve (its graphical representation) which were both constructed based on instrumental records of last 100 years (Table 6.6.) are shown in Figure 6.6 for Akşehir-Afyon Graben System (Source Zone 5).

**Table 6.6.** Quantitative distribution of instrumental records of last approximately 100 years within considered magnitude intervals for Akşehir-Afyon Graben System

| | MAGNITUDE | | | | | |
|---|---|---|---|---|---|---|
| **TIME (YEARS)** | 4 | 4,5 | 5 | 5,5 | 6 | 6,5 |
| 100 | **56** | **26** | **15** | **6** | **3** | **1** |
| 1 | **0,56** | **0,26** | **0,15** | **0,06** | **0,03** | **0,01** |

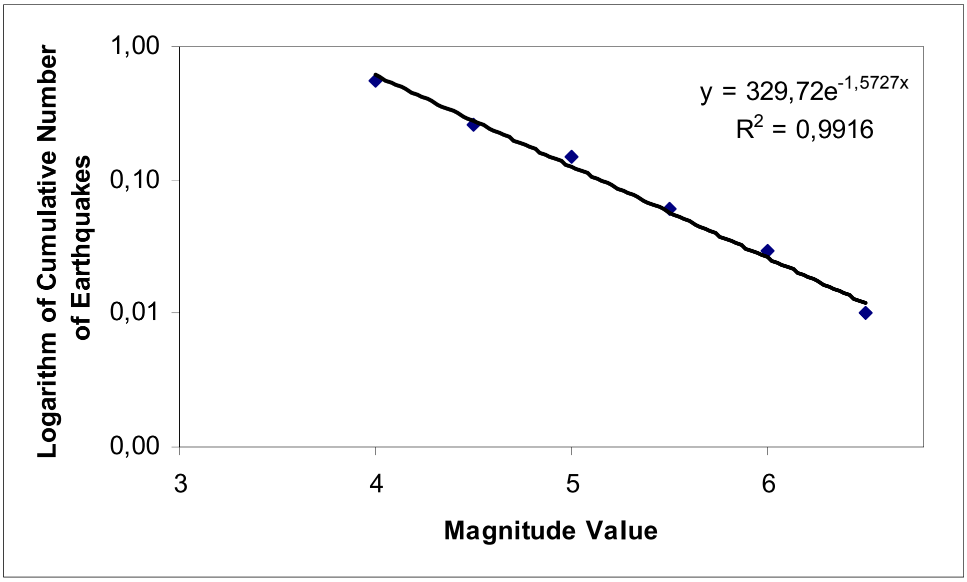


**Figure 6 6.** Gutenberg-Richter recurrence relationship curve for source zone 5 (Akşehir-Afyon Graben System)

### 6.6. Gediz Graben System (Gediz Graben Northern Bounding Fault)

WNW-ESE trending Gediz graben forms a depression 10 to 20 km wide and 140 km long. Vertical displacement occurred since Pliocene time is estimated to be approximately 1.5 km (Gülkan et al., 1993).

#### 6.6.1. Maximum Magnitude

A surface rupture of about 36 km was observed in the 28 March 1969 Alaşehir earthquake (M=6.5) occurred within the Gediz graben (Arpat and Bingöl, 1969; Ergin et al., 1971) and thereafter a numerous aftershock activities were observed in the southern region of the graben. (Tokay and Doyuran, 1979). If in this zone, the longest fault segment of 36 km long is assumed to rupture in a single event, a magnitude of 6.9 could be assigned as the maximum magnitude representing this source.

### 6.6.2. Earthquake Recurrence Relationship (Frequencies)

Gutenberg-Richter recurrence relationship equation and Gutenberg-Richter recurrence relationship curve (its graphical representation) which were both constructed based on instrumental records of last 100 years (Table 6.7.) are shown in Figure 6.7 below for Gediz Graben System (Source zone 6).

**Table 6.7.** Quantitative distribution of instrumental records of last approximately 100 years within considered magnitude intervals for Gediz Graben System

| | **MAGNITUDE** | | | |
|---|---|---|---|---|
| **TIME (YEARS)** | 4 | 4,5 | 5 | 5,5 |
| 100 | **21** | **14** | **5** | **4** |
| 1 | **0,21** | **0,14** | **0,05** | **0,04** |

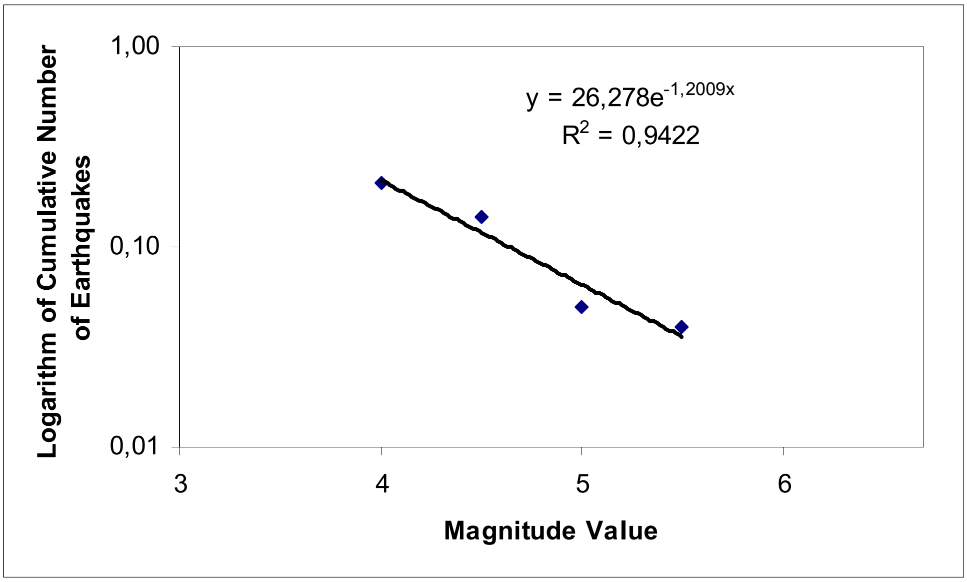


**Figure 6.7.** Gutenberg-Richter recurrence relationship curve for source zone 6 (Gediz Graben System)

# CHAPTER VII

# STRONG GROUND MOTION

The earthquake-resistant structures and the facilities will be subjected to the different levels of ground shaking. So the methods of estimation of these levels which are most conveniently described in terms of some ground motion parameters is required for a proper design (Kramer, 1996). 'Predictive relationships' have been developed to estimate ground motion parameters, by expressing a particular ground motion parameter by means of some significant quantities characterizing the earthquake source, geologic conditions of the site, and the length of the propagation path between the source and the site (Gülkan and Kalkan, 2002; Kramer, 1996).

They are often obtained empirically by least-squares regression on a defined set of strong motion data. Although there are nearly always some attempts to remove questionable data, some amount of scatter resulting from the randomness in the mechanics of rupture, from the variability and heterogeneity of the source, travel path and site conditions is inevitable in the data. But this scatter in the data can be quantified by some confidence limits (Campbell, 1985) or by the standard deviation of the predicted parameter. The inclusion of this considerable amount of uncertainty plays an important role in computation of seismic hazard analyses and so in seismic design (Kramer, 1996).

## 7.1. Selection of the Attenuation Relationships

For this study, four attenuation relationships have been basically selected. These are the relationships proposed by Gülkan and Kalkan (2002), Boore et al. (1997), Abrahamson and Silva (1997), and Ambraseys et al. (1996).

In the following sections, the reasons of their selections and their characteristic features will be clarified, somewhere together with their comparisons with the other ground motion relationships.

## 7.2. Attenuation Modeling of Recent Earthquakes in Turkey by Gülkan and Kalkan (2002)

Estimation of ground motion, either implicitly through the use of special earthquake codes or in a more detailed manner from site-specific investigations is essential for the design of engineered structures. The development of design criteria requires, as a minimum, a strong motion attenuation relationship to estimate earthquake ground motions (Gülkan and Kalkan, 2002).

The estimates and uncertainties in the ground motion parameters which were predicted in a functional form are described by Gülkan and Kalkan (2002), to be used in probabilistic hazard studies and other earthquake engineering applications. The Kocaeli 1999 earthquake was the largest event that occurred in Turkey within the last 50 years, and that was the first well-studied and widely recorded large NAF (North Anatolian Fault) earthquake. So, the occurrence of this largest event and the Düzce 1999 earthquake motivated somehow the effort of providing the values of the predictor parameters based on the models which were developed by an extensive analysis of ground motion data and its relevant information (Gülkan and Kalkan, 2002).

The data set consists of the records from the earthquakes of moment magnitude greater than about 5, and different site conditions which were characterized as ‘soft soil’, ‘soil’ and ‘rock’ with closest distances less than about 150 km. The fixed recording stations, most of which have several records have also led to a possibility of analyzing the effects of local site conditions on the attenuation of earthquake ground motions. So, the procedure for estimating ground motion at various soil sites by means of the equations describing attenuation functions and their associated values of uncertainties is described (Gülkan and Kalkan, 2002).

### 7.2.1. Strong Motion Database

The strong motion database of this attenuation analysis (Gülkan and Kalkan, 2002) is composed of a total of 93 records from 47 horizontal components of 19 earthquakes between 1976-1999 after careful researches of the strong motion database of whole Turkey. In order to lower the complex propagation effects coming from long distances to a minimum level and to avoid somehow the influence of regional differences, recordings from small earthquakes were limited to the closer distances than large earthquakes.

In the data set, earthquake size is characterized by moment magnitude $M_w$, and the magnitudes are restricted to about $M_w$ = 5.0 to focus on those ground motions having greatest engineering interests, and to limit the analysis to the more reliably recorded events. One of the most important parameters on which the distribution of these earthquakes is basically based is the 'source distance'. The 'source distance' ($r_{cl}$) is defined as the closest horizontal distance between the recording station and a point on the horizontal projection of the rupture zone on the earth's surface. Since the rupture surfaces have not been defined clearly for some of the smaller events, epicentral distances are used instead. The use of epicentral distances is not believed to introduce a significant bias because the dimensions of the rupture area for small earthquakes are usually much smaller than the distance to the recording stations. Normal, reverse or strike-slip earthquakes were combined into a single fault category after an examination of the peak ground motion data from the small number of normal-faulting and reverse faulting earthquakes in the data set showing that they were not significantly different from ground motion characteristics of strike-slip earthquakes (Gülkan and Kalkan, 2002).

Peak horizontal ground acceleration (PGA) and pseudo response spectral acceleration (PSA) are represented as both maximum and random horizontal components (Gülkan and Kalkan, 2002).

The data used in the analysis comprise only main shocks of 19 earthquakes. The fact that these earthquakes were recorded mostly in small buildings which were built as meteorological stations up to three stories tall, causes modified acceleration records. This is one of the major unavoidable uncertainties involved in this study. On the other hand one of the other attributes that should be mentioned is the omission of aftershock data most of which come from the two major 1999 earthquakes and the omission of some records for which the peak acceleration caused by the main shock is less than about 0.04 g (Gülkan and Kalkan, 2002).

The effects of geological conditions on ground motion and response spectra are usually considered based on a widely accepted method of classifying the recording stations according to the shear-wave velocity profiles of their substrata. Since the detailed site description and the actual shear-wave velocity profiles are not available for most of the stations in Turkey, the site classification is estimated by analogy with information in similar geologic material types under the recording sites. In fact, they were obtained by various ways such as; the collection and reinterpretation of the various geological maps, past earthquake reports, also geological references prepared for Turkey and of course the consultation with geologists at Earthquake Research Division of Ministry of Public Works and Settlement should not be ignored at all. Finally a group of geological materials for Turkey which consist of soft soil, soil and rock according to their average shear wave velocities of 200, 400 and 700 m/s respectively was formed (Gülkan and Kalkan, 2002).

### 7.2.2. Attenuation Relationship Development

For the development of the attenuation relationships the same general form of the equation proposed by Boore et al. (1997) was used. The ground motion estimation equation is expressed as follows (Gülkan and Kalkan, 2002):

$$LnY = b_1 + b_2(M-6) + b_3(M-6)^2 + b_5 \ln r + b_v \ln(V_S / V_A) \qquad (7.1)$$

$$r = \sqrt{r_{cl}^{2} + h^{2}} \qquad (7.2)$$

$Y$ = Ground motion parameter (peak horizontal acceleration (PGA) or pseudo spectral acceleration (PSA) in g);

$M$ = Moment magnitude;

$r_{cl}$ = Closest horizontal distance from the station to a site of interest in km;

$V_S$ = Shear wave velocity for the station in m/s;

$b_1, b_2, b_3, b_5, h, b_V$ and $V_A$ = The parameters to be determined;

$h$ = Fictitious depth and

$V_A$ = Fictitious velocity that are determined by regression.

The coefficients in the equations for the prediction of the ground motion were determined by using nonlinear regression analysis which is a method of trying to find out a nonlinear model of the relationship between the dependent variable and a set of independent variables. Because, unlike the traditional linear regression, restricted to linear models' estimation, models with arbitrary relationships between independent and dependent variables could be estimated by nonlinear regression (Gülkan and Kalkan, 2002).

For the development of the attenuation curves a procedure of two stages (Joyner and Boore, 1993) is followed. The first stage comprises the development of the attenuation relationships for PGA and spectral acceleration values by selecting the acceleration values in the database as maximum horizontal components of each recording station, afterwards, a nonlinear regression analysis was performed. The next stage consists of the selection of the random horizontal components for the acceleration values in the database then the application of regression analyses (Gülkan and Kalkan, 2002).

In the context of this study, the coefficients used in the prediction of horizontal peak ground acceleration values are selected for zero period and taken as in the following Table 7.1.

**Table 7.1.** The coefficients for estimating the maximum horizontal-component pseudo-acceleration response by Equation (7.1) (Gülkan and Kalkan, 2002)

| Period, s | b1 | b2 | b3 | b5 | $b_V$ | $V_A$ | h | $\sigma_{\ln(Y)}$ |
|---|---|---|---|---|---|---|---|---|
| 0 (PGA) | –0.682 | 0.253 | 0.036 | –0.562 | –0.297 | 1381 | 4.48 | 0.562 |

After the estimation of the maximum horizontal-component pseudo-acceleration response by Equation (7.1.) and by means of the tabulated coefficients, the results were used to compute errors for PGA and PSA at individual periods. It should be kept in minds that, the standard deviation of the residuals, $\sigma$, expressing the random variability of ground motions, is an important input parameter in probabilistic hazard analysis. In this study, the observed value of $\sigma$ (ln Y) lies generally within the range of 0.5 to 0.7 (Gülkan and Kalkan, 2002).

### 7.2.3. Uncertainty and Reliability

Uncertainty is a condition associated with essentially all aspects of earthquake related science and engineering. Since the basis of the regression analysis is a stochastic method, it is unavoidable to observe some errors in the obtained final attenuation formula. These errors are called uncertainties that could most probably originate from the lack of and/or the imperfect reliability of the available data concerning the characterization of site geology, calculation of closest distances, determination of seismic shaking properties, and of the geotechnical properties of earthquake motion monitoring sites. And unfortunately, they could affect all the applied analytical methods and procedures. Although the attenuation relationships presented in this study could not directly eliminate these uncertainties, they could provide more sophisticated approaches than do traditional linear analysis procedures through the use of nonlinear regression analyses. The results presented in tabular and graphical form become meaningful only in the context of the error distributions that are associated with each variable. In general, the results possess larger deviations in comparison with, e.g., Boore et al. (1997). This is plausible because of the smaller number of records from which they have been derived. In view of the limited number of records utilized in this study it may not be appropriate to expect the distributions to conform to the normal distribution. This analysis was performed as a vehicle that permits a direct comparison to be made between these results and those of Boore et al. (1997) (Gülkan and Kalkan, 2002).

### 7.2.4. Comparison with Other Ground-Motion Relationships

When the equations developed by Gülkan and kalkan (2002) were compared to those recently developed by Boore et al. (1997) and Ambraseys et al. (1996), some simple differences could be observed at first sight. Basically, they could originate from the fact that the site classes were divided into four groups according to their shear wave velocities (in the relations of Boore et al., 1997; Ambraseys et al., 1996) (Gülkan and Kalkan, 2002).

The other differences between the values of PGA and PSA, calculated by distinct relationships at different periods could be judged to be reasonable since each attenuation model contains different databases, regression models and analysis methods, different definitions for source to site distance and magnitude parameters among the relationships (Gülkan and Kalkan, 2002).

It is preferable to use attenuation equations based on the records taken from the region in which the estimation equations are to be applied because differences among attenuation of strong motions from one region to another have not been definitely proven (Gülkan and Kalkan, 2002).

### 7.2.5. Discussions

The attenuation relationship presented in the study of Gülkan and Kalkan (2002) has been recommended for the estimation horizontal components of peak ground acceleration, and 5 percent damped pseudo acceleration response spectra for earthquakes with magnitude in the range $M_w$ 5 to 7.5 and $r_{cl}$<150 km for soft soil, soil and rock site conditions, in active tectonic regions of Turkey (Gülkan and Kalkan, 2002).

Although the aftershock data has been excluded and the peak values of less than about 0.04 g have been omitted, it is evident that there are some handicaps of this relationship coming from poor distribution, and arbitrary location of the records, near-total lack of knowledge of local geology, and possible interference from the response of buildings where the sensors have been stationed. In addition to these handicaps, since more than half of the records have been recovered from two M > 7 events of 1999, the regression equations are heavily dominated by this data (Gülkan and Kalkan, 2002).

When the equations developed are compared with the other ones not specifically developed from the records of Turkey itself, it is clear that the attenuation relations from other environments overestimate the peak and spectral acceleration values for up to about 15–20 km but for larger distances the opposite is true (Gülkan and Kalkan, 2002).

The attenuation relationship which gives the best match among the others has been stated to be the one by Ambraseys et al. (1996) for European earthquakes, but the reason could not be found from different perspectives except from the one, showing the fact that the Ambraseys study utilized data recorded also in Turkey (Gülkan and Kalkan, 2002).

It should be predictable that the attenuation relationships derived in this study can be progressively modified and improved, and their uncertainties reduced, as additional strong motion records, shear wave velocity profiles for recording sites, and better determined distance data become available for Turkey (Gülkan and Kalkan, 2002).

## 7.3. Empirical Attenuation Relations for Shallow Crustal Earthquakes by Abrahamson and Silva (1997)

Some empirical models for the attenuation of response spectral values for both the average horizontal and the vertical components were developed to be applied to the shallow crustal events in active tectonic regions like Western North America by Abrahamson and Silva (1997).

### 7.3.1. Strong Motion Data Set

The data set used for the derivation of PGA equation by Abrahamson and Silva (1997) consist of a worldwide data of strong ground motions from shallow crustal events up through the 1994 Northridge earthquake, occurred in active tectonic regions. The subduction events were excluded. The final, reduced data set from 853 to 655 recordings, after the exclusion of some of the recordings with unknown and poor estimates of the magnitude, mechanism distance and/or site conditions, contains 58 earthquakes with magnitude greater than 4.5 (Abrahamson and Silva, 1997).

**Site Classification**

The site classification used in the publication of Abrahamson and Silva (1997) resembles to the modified Geomatrix site class (Table 7.1.). Because, Geomatrix site class C and D have been combined into a single deep soil site category and A (rock) and B (shallow soil) classes of the Geomatrix have also been combined into a single ‘rock’ site category (Abrahamson and Silva, 1997).

**Table 7.2.** Site Classification (from Geomatrix, Abrahamson and Silva, 1997)

| | |
|---|---|
| A | Rock ($V_s$ > 600 m/s)<br>Or very thin soil (< 5 m) over rock |
| B | Shallow Soil<br>Soil 5-20 m thick over rock |
| C | Deep Soil in narrow canyon<br>Soil > 20 m thick<br>Canyon < 2 km wide |
| D | Deep Soil in Broad Canyon<br>Soil > 20 m thick<br>Canyon < 2 km wide |
| E | Soft Soils ($V_s$ < 150 m/s) |

**Distance Definition**

It has been known that there are several distinct definitions of the 'distance' term for the development of the attenuation relations. Specifically for this relationship, the closest distance to the rupture plane ($r_{rup}$) as used by Idriss (1991) and Sadigh *et al.* (1993) was utilized (Abrahamson and Silva, 1997).

### 7.3.2. Development of Attenuation Relations

#### 7.3.2.1. Regression Method

A random effects model which is based on a maximum likelihood method has been used for the regression analysis. It actually accounts for all the correlations in the data set recorded by a single earthquake. That is; if an earthquake has a higher than average stress drop, then the ground motions at all sites from this event would be expected to become higher than the average one (Abrahamson and Silva, 1997).

#### 7.3.2.2. Regression Model

The general functional form of the regression equation which combines some features previously used in recent studies is given by (Abrahamson and Silva, 1997):

$$LnS_a(g) = f_1(M, r_{rup}) + Ff_3(M) + HWf_4(M, r_{rup}) + Sf_5(pga_{rock}) \quad (7.3)$$

$S_a(g)$ = Spectral acceleration in g

$M$ = Moment magnitude

$r_{rup}$ = Closest distance to the rupture plane in km

$F$ = Fault type (1 for reverse, 0.5 for reverse/oblique and 0 otherwise)

$HW$ = Dummy variable for hanging wall sites (1 for sites over the hanging wall, 0 otherwise)

$S$ = Dummy variable for the site class (0 for rock or shallow soil, 1 for deep soil)

For the horizontal component, the geometric mean of the two horizontals is used). For the function $f_1(M, r_{rup})$ which is the basic functional form of the attenuation for strike-slip events recorded at rock sites, the following form has been used:

For $M \le c_1$

$$f_1(M, r_{rup}) = a_1 + a_2(M - c_1) + a_{12}(8.5 - M)^n + (a_3 + a_{13}(M - c_1))\ln R \quad (7.4)$$

For $M \rangle c_1$

$$f_1(M, r_{rup}) = a_1 + a_4(M - c_1) + a_{12}(8.5 - M)^n + (a_3 + a_{13}(M - c_1))\ln R \quad (7.5)$$

where

$$R = \sqrt{r_{rup}^{\;2} + c_4^{\;2}} \quad (7.6)$$

**Style-of- Faulting Factor**

The style-of-faulting factor is actually the difference in ground motion between reverse and strike-slip events. Although most attenuation relations have considered a constant style-of-faulting factor; applicable to all magnitudes, distances and periods, the distinction between ground motions from strike-slip and reverse faults has become common in recent attenuation relations (e.g., Idriss, 1991; Sadigh et al., 1993; Boore et al., 1997; Campbell and Bozorgnia, 1994). Sadigh et al. (1993) and Campbell and Bozorgnia (1994) developed a magnitude and distance dependence of the style-of-faulting for peak acceleration, whereas Boore et al. (1997) included a period dependence to the style-of-faulting factor (Abrahamson and Silva, 1997).

The following functional form allowing for a magnitude and period dependence of the style-of-faulting factor is given by (Abrahamson and Silva, 1997):

$$f_3(M) = a_5 \quad \text{for } M \le 5.8 \tag{7.7}$$

or

$$= a_5 + \frac{(a_6 - a_5)}{(c_1 - 5.8)} \quad \text{for } 5.8 < M < c_1$$

or

$$= a_6 \quad \text{for } M \ge c_1$$

**Hanging Wall Effect**

To model the differences in the motion on the hanging wall and foot wall of dipping faults, the approach of Somerville and Abrahamson (1995) was followed. The hanging wall effect, rather than both the hanging wall and footwall effects together, is stated to be mainly a geometric effect resulting from the distance definition used in this study because the significant increase in ground motion was systematic for the sites over the hanging wall, whereas the decrease in ground motion was not as significantly systematic for the sites on the footwall as in the case of the ones on the hanging wall. So the functional form for the hanging wall effect is modeled as separable in magnitude and distance as (Abrahamson and Silva, 1997):

$$f_4(M, r_{rup}) = f_{HW}(M) f_{HW}(r_{rup}) \tag{7.8}$$

where

$$= 0 \quad \text{for } M \le 5.5$$

$$f_{HW}(M) = M - 5.5 \quad \text{for } 5.5 < M < 6.5$$

$= 1$ for $M \geq 6.5$

and

$$f_{HW}(r_{rup}) = \begin{cases} 0 & \text{for } r_{rup} < 4 \\ a_9 * \frac{r_{rup} - 4}{4} & \text{for } 4 < r_{rup} < 8 \\ a_9 & \text{for } 8 < r_{rup} < 18 \\ a_9 \left(1 - \frac{(r_{rup} - 18)}{7}\right) & \text{for } 18 < r_{rup} < 24 \\ 0 & \text{for } r_{rup} > 25 \end{cases}$$

**Site Response**

For the development of a functional form accommodating non-linear soil response which is a key aspect, the approach of Youngs (1993) was followed. In this approach that allows a single regression for both soil and rock while preserving the differences between soil and rock attenuation, the soil amplification is a function of the expected peak acceleration on rock. The non-linear soil response is modeled by (Abrahamson and Silva, 1997):

$$f_5(PGA_{rock}) = a_{10} + a_{11} \ln(PGA_{rock} + c_5) \tag{7.9}$$

$PGA_{rock}$ = Expected peak acceleration on rock in g

The only addition to the functional form proposed by Youngs (1993) is the $c_5$ term (Abrahamson and Silva, 1997).

### 7.3.3. Standard Error

In this study, both of the standard errors; the inter-event (τ) and the intra-event (σ) standard errors which are dependent on the magnitude are modeled as follows (Abrahamson and Silva, 1997):

$=b_1$ for M ≤ 5.0

$\alpha(M) = b_1 - b_2(M-5)$ for 5.0 <M< 7.0

$= b_1 - 2b_2$ for M ≥ 7.0

and

$= b_3$ for M ≤ 5.0

$\tau(M) = b_3 - b_4(M-5)$ for 5.0 <M< 5.0

$=b_3 - 2b_4$

The total standard error computed by adding the variance of the two error terms was smoothed and appeared in the form of (Abrahamson and Silva, 1997):

$=b_5$ for M ≤ 5.0

$\sigma_{total}(M) = b_5 - b_6(M-5)$ for 5.0 <M< 7.0

$=b_5 - 2b_6$ for M ≥ 7.0

### 7.3.4. Discussion of the Empirical Model

There are some limitations of this empirical model and they should be taken into account for its application to the engineering projects (Abrahamson and Silva, 1997). First of all the site response factor ($f_5$) is only dependent on the expected peak acceleration on rock rather than possessing a magnitude dependence (Abrahamson and Silva, 1997). Secondly, the style-of-faulting factor ($f_3$) has significant magnitude dependence. This effect is about 30% for large magnitude events but an approximate factor of 2 is assigned for small magnitude events (Abrahamson and Silva, 1997). Finally, although the B class consists of soils up to 20 m thick, most of the sites are for much shallower soils. Since, the rock relation developed by this study combines the rock (class A) and shallow soil (class B) sites, more significant site response differences for predicting ground motions for a 20 m thick soil site could be expected than are predicted by the rock relation of this study (Abrahamson and Silva, 1997).

**Attenuation Relations from Western North American Earthquakes by Boore et al. (1997)**

The design of any engineered structure is based on an estimate of ground motion, through basically two ways of either implicit use of building codes or explicit searches in the site-specific design of large or particularly critical structures. Since there are a few number of ground-motion recordings near a specified site which allow a direct empirical estimation of the motions expected for a design earthquake, it is necessary to develop relationships, in the form of equations or graphical representations, which correlate some important variables such as magnitude, distance and site conditions. This is important for site-specific design as well as for hazard mapping (Boore et al., 1997).

### 7.4.1. Ground-Motion Data

The data set consists of the shallow earthquakes which are defined as those for which the fault rupture lies mainly above a depth of 20 km in Western North America with moment magnitude greater than 5.0 (Boore et al., 1997).

**Predictor Variables**

As predictor variables; the moment magnitude as the measure of earthquake size and the closest horizontal distance from the station to a point on the earth's surface lying directly above the rupture ($r_{jb}$) as the distance measure are used respectively. Since all of the earthquakes in the data set are either strike-slip or reverse-slip except the one which appears to be normal-slip, the normal-slip earthquakes have not been attempted to be included in the equations for estimating ground motions (Boore et al., 1997).

As the (a) variable to represent site conditions, shear-wave velocity averaged over the upper 30 m was utilized in the analyses. For the assignment of the site classifications, the measurements from boreholes at the strong-motion sites were used if they were available, otherwise the site classifications were estimated by analogy with borehole measurements in similar geologic materials (Boore et al., 1997).

Of the four site classes listed according to their ranges of shear velocities as A ,B, C, and D. Class D in Boore et al. (1993) was poorly represented and so it was not included in the analysis (Boore et al., 1997). The recommended values of average shear velocity for use in equation 7.13. are given in Table 7.2.

**Table 7.3.** Recommended values of average shear velocity (Boore et al., 1997)

| | |
|---|---|
| NEHRP site class B | 1070 m/sec |
| NEHRP site class C | 520 |
| NEHRP site class D | 250 |
| Rock | 620 |
| Soil | 310 |

In this study, it is evident that very few data are available for distances beyond about 80 km and it is recommended that these equations should not be used for magnitudes less than 5.5 (Boore et al., 1997).

### 7.4.2. Method

The ground motion estimation equation is modeled by as follows (Boore et al., 1997):

$$\ln Y = b_1 + b_2(M-6) + b_3(M-6)^2 + b_5 \ln r + b_V \ln \frac{V_S}{V_A} \tag{7.13}$$

$Y$ = Ground-motion parameter (peak horizontal acceleration or pseudoacceleration response in g)

$M$ = Moment magnitude

$r$ = Distance in km

$V_S$ = Average shear-wave velocity to 30 m, in m/sec

$b_{1SS}, b_{1RS}, b_{1ALL}, b_2, b_3, b_5, b_V, V_A$ = Coefficients to be determined

$h$ = Fictitious depth to be determined by the regression

where

$$r = \sqrt{r_{jb}^{\ 2} + h^2} \tag{7.14}$$

And

$$b_1 = \begin{cases} b_{1SS} & \text{for strike-slip earthquakes} \\ b_{1RS} & \text{for reverse-slip earthquakes} \\ b_{1ALL} & \text{if mechanism is not specified} \end{cases} \qquad \text{……………. (7.15)}$$

The coefficients in the equations for predicting ground motion were determined using a weighted, two-stage regression procedure; based on the maximum-likelihood method (Joyner and Boore, 1993, 1994). First, the distance and site-condition dependence were determined along with a set of amplitude factors, one for each earthquake. Secondly, the magnitude dependence was determined along with these amplitude factors (Boore et al., 1997).

For the context of this master thesis, particular coefficients (entries) for zero period were selected to represent the ones for peak horizontal acceleration from the smoothed coefficients of Boore et al. (1997) for use in equation 7.13 to estimate pseudoacceleration response spectra (g) for the random horizontal component at 5 percent damping. These selected zero period entries are given in Table 7.4. below.

**Table 7.4.** The coefficients for estimating peak horizontal acceleration

| Period | $B_{1SS}$ | $B_{1RV}$ | $B_{1ALL}$ | $B_2$ | $B_3$ | $B_5$ | $B_V$ | $V_A$ | h | $\sigma_{lnlY}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.000 | -0.313 | -0.117 | -0.242 | 0.527 | 0.000.. | -0.778 | -0.371 | 1396 | 5.57 | 0.520 |

### 7.4.3. Standard Error

The standard error (one sigma value of the natural logarithm of the ground-motion value from equation (1)) is the square root of overall variance of the regression and it is given by (Boore et al., 1997):

$$\sigma^2{}_{l\,nY} = \sigma^2{}_r + \sigma^2{}_e \tag{7.16}$$

$\sigma^2{}_e$ = Earthquake-to-earthquake component of the variability; determined in the second stage of the regression

$\sigma^2{}_r$ = All other components of variability

$$\sigma^2{}_r = \sigma^2{}_1 + \sigma^2{}_c \tag{7.17}$$

$\sigma^2{}_1$ = Variance from the first stage of the regression

$\sigma^2{}_c$ = Correction needed to give the variance corresponding to the randomly-oriented horizontal component and it is represented for the horizontal components by the following formula (Boore et al., 1997):

### 7.4.4. Comparison with Other Relationships

There are basically three main differences between this relationship and those already developed by most other authors. They could be numbered and explained in detail step by step as follows (Boore et al., 1997):

First, the distance parameter ($r_{jb}$) has been selected to be defined as the closest horizontal distance from the station to a point on the earth's surface lying directly above the rupture;

$$r = \sqrt{{r_{jb}}^2 + h^2} \tag{7.18}$$

*h* = Depth constant to be determined in the regression

Whereas the closest distance in three dimensions from the station to the rupture has been used by some researches (*e.g.*, Abrahamson and Silva, 1997). On the other hand, Campbell (1997) introduced the concept of 'seismogenic rupture' and has been using the closest distance to this rupture whose top lies at a depth of 3 km or more. So in contrast to these points of view, since the distribution in depth of source strength is unknown, the horizontal source distance in conjunction with an effective depth which has been chosen to fit the strong-motion data is used instead. This definition of distance yields higher ground-motion values over the hanging wall of dipping faults than over the footwall. So one of the most important problems associated with this definition is that it may lead to overestimates of the ground motion at sites directly over the downdip edges of the faults extending to depths near 20 km.

The second difference is that these relationships have the same magnitude scaling at all source distances, in contrast to the other relationships which have smaller magnitude scaling at short distances than at long distances. The reason lying behind this usage is that the magnitude scaling was indicated not to be statistically very different at short distances from what were found for the whole data set by some earlier approaches.

The last important difference is that the regression analysis of response spectra is performed at each period independently. This approach requires that the regression coefficients are smoothed over period. On the other hand, some of the researches do the regression analysis on normalized spectral ordinates (and) then multiply the results by the value of peak acceleration (given by regression analysis of acceleration data), the others (e.g., Abrahamson and Silva, 1997) do a multiple-step regression analysis; that is the peak acceleration is fit in the first step and some of he parameters values are then fixed for subsequent steps (Boore et al., 1997).

### 7.4.5. Dependence of Variance on Magnitude and Amplitude

The opinion that the variance of peak horizontal acceleration depends on magnitude (*e.g.,* Idriss, 1985, and Youngs et al., 1995) has been suggested by a number of authors and another opinion that it depends on the value of peak acceleration (Donovan and Bornstein, 1978; Campbell and Bozorgnia, 1994) has also been suggested by others. After the examination of these suggestions for this data set in terms of both peak acceleration and response spectra, the results are summarized briefly (Boore et al., 1997):

(a) As Youngs et al. (1995) stated, for peak acceleration $\sigma_{\ln}Y$ is found to decrease with increasing magnitude and most of the effect appears below magnitude 6.0. In addition to this resemblance, very like Campbell and Bozorgnia (1994) $\sigma_{\ln}Y$ decreases with increasing peak acceleration and for this data set, most of the effect comes from records with peak values less than 0.1 g.

(b) For response spectral values, no significant dependence of variance on either magnitude or amplitude could be observed since there are relatively few records in the response spectral data set from earthquakes with magnitude less than 6.0.

### 7.4.6. Limitations of the Boore et al.'s Relationship (1997) and Prospects for Improvement

#### Few Response Spectral Data Below Magnitude 6.0

The response-spectral data set includes only seven records with magnitudes less than 6.0; one record from a magnitude 5.3 earthquake and six records from a magnitude 5.8 earthquake. It is evident that the prediction of ground motion for the smaller earthquakes is less important but it would be desirable to increase the number of data for small earthquakes so that they could be less-poorly represented in the data set (Boore et al., 1997).

**Effect of Site Conditions on Short-Period Motion**

By the addition of new data including a broader range of site conditions, the differences between site classes for peak acceleration and response spectra at all periods are shown by the equations developed from the current data set. However, some additional variables associated with site conditions, unfortunately not being able to be included in the prediction equations, could affect the short-period motions. The thickness of attenuating material under each site could be one of these variables and it should be known because two sites may have the same average shear velocity over the upper 30 m but the thicknesses of underlying attenuating material could be different anyway. It should be taken into account that for a large enough thickness, the effect of anelastic attenuation on short-period motions may largely offset. So a variable representing this thickness parameter to the equations should be tried after the addition of all the recently-recorded earthquakes to the data set and compilation of all the available geologic site data again (Boore et al., 1997).

**Averaging Velocity Over 30 m**

The ideal parameter to characterize site conditions would be the average shear-wave velocity to a depth of one-quarter wavelength for the period of interest, as was used by Joyner and Fumal (1984). By this rule for example, 30 m is the appropriate depth for a period of 0.19 sec for a typical rock site with an average velocity of 620 m/sec and for a period of 0.39 sec for a typical soil site with an average velocity of 310m/sec. So the use of average shear wave-velocity to a depth of 30 m as a variable has been chosen because of the relative unavailability of velocity data for greater depths. In fact, since it has a high correlation with the average over other depths, it may be a reasonable solution for different periods until the development of the estimates of average shear wave-velocity to greater depths at a sufficient number of sites (Boore et al., 1997).

**Distance Limitations**

Due to the scarcity of data, most probably aggravated by regional difference in wave propagation caused by variations in crustal structure, there is a significant uncertainty in ground-motion estimates at large distances. It is sure that the uncertainty in estimates for smaller distances is more significant than for larger distances but it could still be important under some conditions. Since very few recordings exist in this data set for distances greater than 80 km, it is not recommended to use these equations for greater distances. This limitation in the number of recordings is inherent in the strong-motion data set because of the usage of conventional triggered instruments (Boore et al., 1997).

## 7.5. Prediction of Horizontal Response Spectra in Europe by Ambraseys et al. (1996)

### 7.5.1. Data

The data set of this study comprises 422 available triaxial records which were generated by 157 earthquakes in Europe and adjacent areas, with surface wave magnitude ($M_s$) between 4.0 and 7.9 and focal depth less than or equal to 30 km (Ambraseys et al., 1996).

**Source Distance**

The source distance was defined as the closest distance to the projection of the fault rupture as adopted by Joyner and Boore (1981). Although there are adequate data for most of the larger earthquakes in this dataset to estimate accurately the source distances of strong-motion stations, the definition of the source distance parameter is stated to be complicated for small magnitude earthquakes. It should be kept in mind that for the small magnitude crustal earthquakes, the source distance is very approximate to the epicentral distance but still the exact locations of some of the smaller earthquakes are poorly known (Ambraseys et al., 1996).

**Focal Depth**

The depth of the earthquake is proved to be the poorly determined (least well-determined) parameter during the re-examination of the locations (re-location studies). So the interval between the triggering time and the first S-wave arrivals ($S_t$) was used to determine an approximate hypocentral distance. It was figured by the distribution of the earthquakes within the dataset with respect to their focal depths, the majority (81%) of the focal depths (h) range between 5 and 15 km (Ambraseys et al., 1996).

**Local Soil Conditions**

207 of the 212 permanent and temporary strong-motion stations in this dataset have been classified into four categories which are similar to those used by Boore et al., (1993) based on shear wave velocities, $V_s$, averaged over the upper 30 m of the site. These classes are respectively defined as rock (R); stiff soil (A); soft soil (S) and very soft soil (L) by the following ranges of average $V_s$, 750 m/s or higher; 360-750 m/s; 180-360 m/s; 180 m/s or lower. Except 53 sites whose local soil and velocity profiles are known in detail, the conditions of the other sites have been recognized in a more general sense. There are 106, 226, 81 and 3 records in the (R), (A), (S) and (L) categories respectively in the dataset (Ambraseys et al., 1996).

**Magnitudes**

Taking into account some important restrictions, surface wave magnitude ($M_s$) has been chosen to be adapted to all magnitudes as a magnitude scale. One of these restrictions depends on the lack of the local magnitude ($M_L$) determinations for the earthquakes already happened in some parts of the study area like in Algeria, Iran, Turkey and the former USSR. The other one comes from the poor estimation or the lack of the available seismic moment ($M_o$) in the dataset which could be well correlated to a size estimate.

These restrictions and both of the facts that $M_s$ is assumed to be the best estimator of the size of a crustal earthquake and that the seismicity in Europe is generally evaluated in terms of $M_s$ significantly justify the choice of $M_s$.
Moment magnitude **M** is considered by Hanks and Kanamori (1979) to be equivalent to $M_s$ in the range $5 \leq M_s \leq 7.5$ (Ambraseys et al., 1996).

**Strong-motion Records**

Although some of the records come from the basements or ground floors of relatively small structures and tunnel portals, most of them are from free-field stations. By the distribution of the dataset with respect to $M_s$ and source-site distance, it can be observed that the data consists of the distances up to 200 km from the earthquake source and a range of $M_s$ from 4.0 to 7.5 (Ambraseys et al., 1996).

### 7.5.2. Development of Attenuation Model of Peak Ground Acceleration

In Ambraseys et al.'study (1996), the two-stage regression technique (Sarma, 1994) to decouple the determination of distance dependence from the determination of magnitude dependence was applied as originally suggested by Joyner and Boore (1981).
The following equation was obtained (Ambraseys et al., 1996):

$$\log(a) = -1.39 + 0.266 M_s - 0.922 \log(r) + 0.25P \quad (7.19)$$

with $h_o = 3.5$

$$r = \sqrt{d^2 + h_o{}^2} \quad (7.20)$$

On the other hand, the following type of equation was found with the analysis performed by using a direct one-stage regression (Ambraseys et al., 1996):

$$\log(a) = -1.52 + 0.261M_s - 0.00045(r) - 0.815\log(r) + 0.25P \quad (7.21)$$

$$h_o = 3.5$$

#### 7.5.2.1. Inclusion of the Site Geology in the Attenuation Model

Even if the conditions under which site geology may amplify peak ground motion values have not been established yet, it is evident that local site geological characteristics are very important in the determination of the shape and amplitude of the response spectrum. The method applied for the regression analysis has the same logic as the two-stage procedure defined previously.
The following equation was obtained (Ambraseys et al., 1996):

$$\log(a) = -1.48 + 0.266M_s - 0.922\log(r) + 0.117S_A + 0.124S_S + 0.25P \quad (7.22)$$

where still $h_o = 1.9$

$S_A$ = 1 if the site is classified as stiff soil
= 0 otherwise

$S_S$ = 1 if the site is classified as soft soil
= 0 otherwise

### 7.5.3. Discussion

The current engineering practice in Europe is to construct elastic design spectra by anchoring a standard response shape to an effective peak ground acceleration. In this relationship as an alternative, frequency-dependent attenuation relations that allow for the direct construction of hazard-consistent design spectra have been provided and the equations for the prediction of peak ground acceleration based on the response spectra data set have also been presented so that the records are demonstrated to represent the region.

When compared with the equations developed for western North America, larger values of peak acceleration at very short distances, particularly for larger magnitudes are predicted in this study but the equations developed in this study attenuate more rapidly than the equations of western North America. In fact, the differences are not very large except in the very near-field (<5 km) of large magnitude events. On the other hand, the European equations demonstrate much less site-dependence, particularly for soft soil, than the equations for western North America (Ambraseys et al., 1996).

## CHAPTER VIII

## SEISMIC HAZARD CALCULATION

### 8.1. Probabilistic Approach

In order to quantify the level of seismic hazard at the selected sites within the study area, a probabilistic seismic hazard methodology has been applied by a computer program developed for seismic hazard estimation which is called SEISRISK III (Bender and Perkins, 1987).

Initially, the capabilities of this program and how this probabilistic hazard estimation model especially for homogeneous sources is implemented will be explained. Seisrisk III is a computer program for seismic hazard analysis which aims specifically to compute maximum ground-motion levels, having a defined probability of not being exceeded during a specified time period or periods at each and every set of sites which are uniformly spaced on a two-dimensional grid. Its major capabilities can be grouped in four steps:

1. Seisrisk III still underlies the assumption of uniform seismicity within a seismic source zone that every point in a source zone has the equal probability of representing the epicenter of a future earthquake. But, so that this concept does not give rise to abrupt, unreasonable changes in the probabilistically calculated values of ground motion at the source zone boundaries; climbing to 50-80 percent or more for relatively longer exposure times at sites 20 km away from a seismic source boundary. Seisrisk III allows the earthquakes to be distributed normally rather than uniformly. This means that each point within a seismic zone is assumed to be the ‘mean’ of a future earthquake and this is the locations of actual earthquakes which are normally distributed with a standard deviation about their mean locations. Since seismicity varies smoothly, the resultant acceleration values and the projected rates of earthquakes also

vary relatively more smoothly near the boundaries. This option which is called as ‘earthquake location uncertainty’ is very crucial in Seisrisk III.

2. If the presence and hence the orientations of the faults are said to be known by geological evaluations and if the fault pattern is in such a complex active fault zone that many different faults are spread over it, Seisrisk III may model ‘artificial’ parallel faults which are spaced equidistantly. In addition to that, by means of a simulation of a finer spacing between parallel faults it can perform a partial ‘distance smoothing’ process.
3. For every site, intermediate calculations between source zones; to accumulate ground motions from successive sources, can be saved in the forms of two-dimensional arrays in the memory of Seisrisk III.
4. In the scope of the ‘fault rupture model’, Seisrisk III introduces a concept so-called; ‘partial magnitude smoothing’. This means that, it treats the closest distance ruptures as if they occurred over a range of magnitudes and then it smoothes the acceleration densities which result from these so-called ruptures.

Like in most seismic hazard analyses, in Seisrisk III, earthquakes are modeled as finite-length ruptures that could be centered randomly somewhere along the linear fault segments or simply as points; assumed to obtain the same probability of representing the epicenter of a future earthquake, in quadrilateral, seismically homogeneous source areas. This issue of randomness forms the basis of probabilistic models mostly used in the lack of knowledge about the exact locations and sizes of future earthquakes. No one would argue that an earthquake will most probably happen at one point in a zone than in another one.

Although there is no single procedure or method by which seismic source zones could be delineated and drawn across nations, the scientists or engineers benefit from the same type of information such as; earthquake catalogues and/or geological, geophysical, and other types of available data. But it should be kept in mind the fact that the studies of zonation depend on not only the uniformity level of existent information, especially from enormously differing tectonic settings, but also on the expert judgement or opinion.

In Seisrisk III, any one of the ground motion parameters such as acceleration, velocity or any other measure of ground shaking could be used equally. In Seisrisk III, earthquake occurrences and rates are assumed to have a Poisson distribution, so they remain constant during the specified time intervals. Mean or median ground motion parameters increase with increasing magnitudes and decreasing site-to-source distances.

For each zone or fault, a magnitude interval bounded by a minimum and a maximum magnitude value is assumed and there are no restrictions about the uniformity of these intervals for different seismic source zones; they may change successively. But seismicity which is equivalent to the average rate of earthquakes per unit time for each magnitude remains absolutely constant during the specifically defined time intervals.

In fact, there is no single value of acceleration results assumed by described ground-motion computations from earthquakes of each magnitude and distance, there is a range. A model describing this variability in acceleration is constituted by means of an assumption that accelerations from earthquakes of a given magnitude and distance are lognormally distributed with a logarithmic standard deviation which is assumed to be independent of magnitude and distance.

There are mainly five input parameters which are basically required to run SEISRISK III. Taking into account their meaning for this program and their significant roles, they have been first determined and then carefully listed in the input file. These basic input parameters tabulated in the input file of this study are;

(a) Coordinates of two points as 28.1 39.6 and 32.8 39.6 in terms of longitude latitude coordinate system on a great circle that becomes the equator in a transformed coordinate system.

(b) Coordinates (long., lat.) of two opposite corners namely the upper left and the lower right corner of the seismic felt area as 28.13 40.86 and 32.75 38.24 and grid spacing of 0.09 decimal degrees in longitude and latitude.

(c) Areal source computations: Total number of sets of quadrilaterals, the number (identifier) of current set, the number of the pairs of quadrilateral corner points in this current set and the coordinates of the pairs of quadrilateral corner points for each seismic source zone. (Because each seismic source zone is defined as seismically homogeneous area enclosed by one or more arbitrary quadrilaterals; either connected or disjoint)

(d) The number of years over which the earthquake occurrences take place as 1 year, the centers of magnitude intervals for which a stated number of events occur as and the number of events expected in a particular number of years in each and every magnitude interval for earthquake occurrences as.

(e) Table of median ground-motion values calculated from four different attenuation relationships (Peak Ground Acceleration values) as function of 7 number of magnitudes and a 12 number of distances.

So, the measures of probabilistic seismic hazard are input as the peak ground acceleration values with 475-year and 1000-year return periods at different site classes; 'soft', 'stiff' and 'rock' sites. For the selected site at the downtown area of Eskişehir, the annual frequencies of exceedance for a number of ground motion levels were calculated by the model implemented in the SEISRISK IIII. The seismic hazard curves for these different classes of sites have been developed and figured out for four different selected attenuation relationships. After the estimation of maximum acceleration levels expected to be exceeded in 50 and 100 (105) years, with a chance of %10, the probabilistic seismic hazard maps for all the sites at the intersections of grid lines were developed. They represent the levels of peak ground acceleration (PGA) with return periods of 475 years (i.e., 10% probability in 50 years), and 1000 years (%10 probability in 105 years).

The earthquakes of magnitudes greater than 4.0 were included in the analysis and the uncertainty in the estimates of ground motion from four different attenuation relationships (Abrahamson and Silva, 1997; Boore et al., 1997, Ambraseys et al., 1996, Gülkan and Kalkan, 2002,) has been accounted in the calculation of probabilistic seismic hazard.

### 8.1.1. Results

The probabilistic seismic hazard maps of the levels of 'Iso-Peak ground acceleration(PGA)' contours, which were estimated by the emprical relationship of Abrahamson and Silva (1997), Boore et al. (1997), Ambraseys et al. (1996) and Gülkan and Kalkan (2002), with approximate return periods of 475 years and 1000 years (10% probability of exceedance in 50 and 105 (in about 100) years respectively) are shown in Figures 8.1, through 8.8 for 'rock' sites. The highest hazard levels have been observed (at the) South South East (SSE) of the study area which is located at a very proximate situation to the Akşehir-Afyon Graben. The lowest hazard levels have been observed in the Nort North East (NNE)of the study area very close to the Eskişehir Fault Zone and NNW of the study area in these above mentioned maps except the ones (maps) developed by the relationship of Gülkan and Kalkan (2002)

Also the other maps for 'rock' sites showing the levels of PGA which have been developed by the logic tree method taking into consideration equal contributions of three attenuation relationships of Abrahamson and Silva (1997), Boore et al. (1997), Ambraseys et al. (1996) with the same return periods, are shown in Figures 8.9 and 8.10 It is not very surprising to observe the very close and average levels of hazard as in the maps constructed by the individual contribution of each seperate predictive relationship. But it is also evident that except the areas of the highest and lowest levels of hazard, the hazard especially in the central part of the study area is distributed smoothly and uniformly across within the study area.

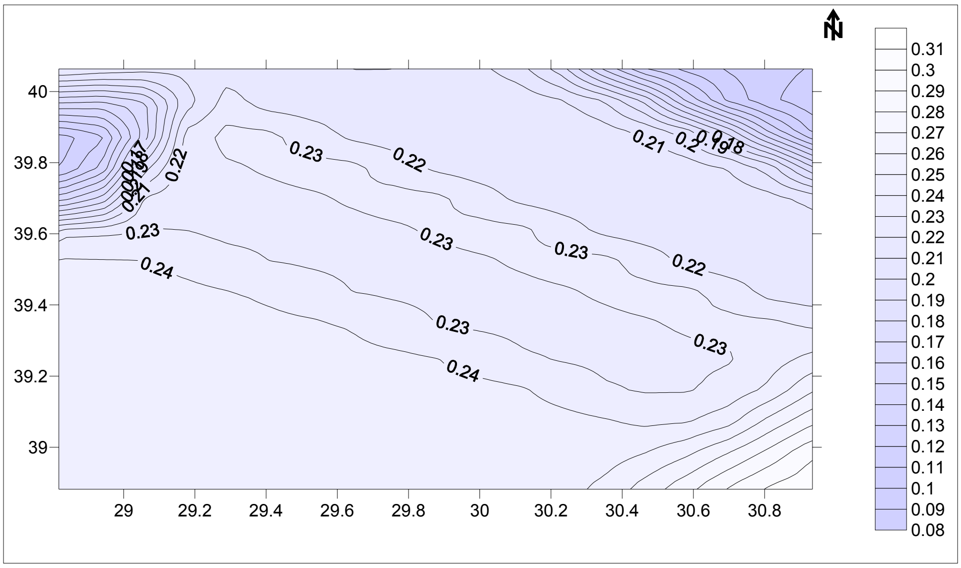


**Figure 8.1.** PSH Map for rock sites based on Abrahamson and Silva attenuation relationship (1997) (475-year return period)

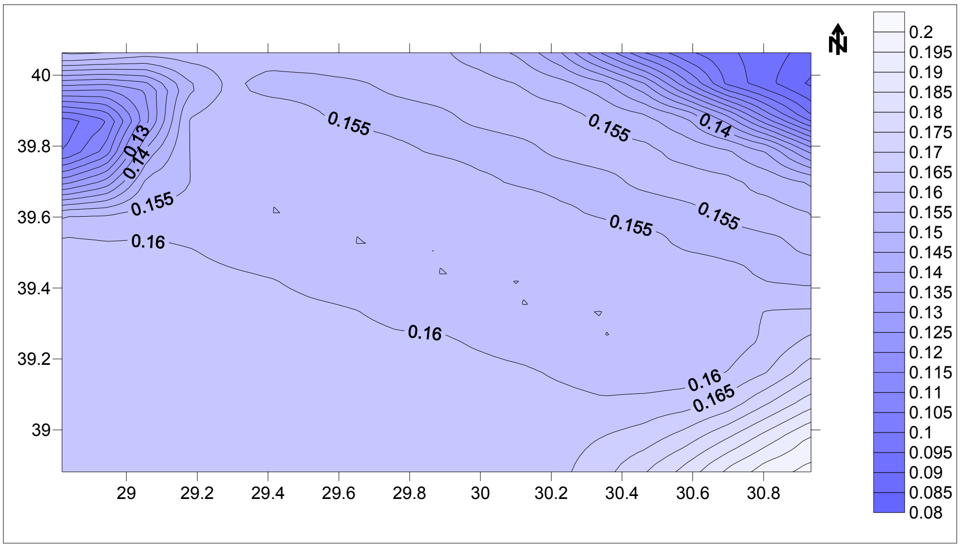


**Figure 8.2.** PSH Map for rock sites based on Boore et al. attenuation relationship (1997) (475-year return period)

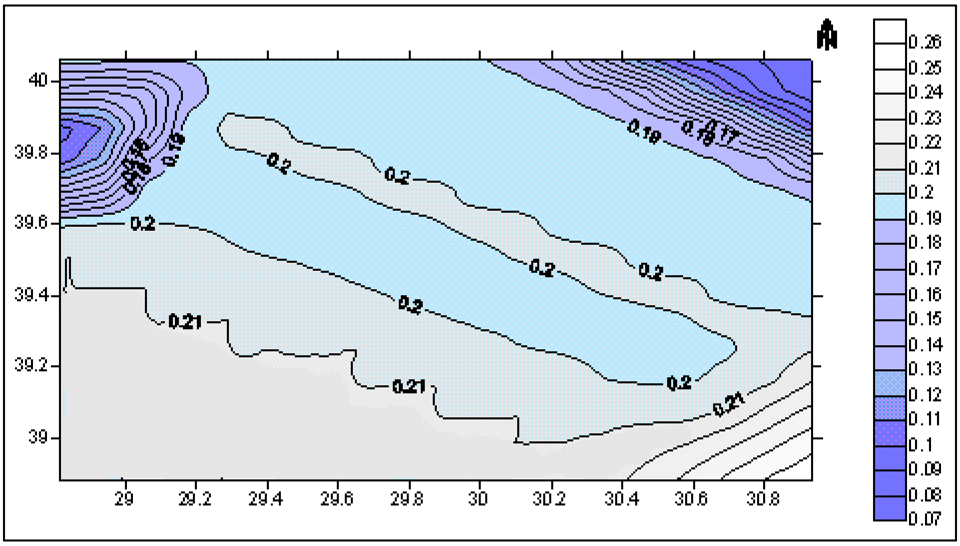


**Figure 8.3.** PSH Map for rock sites based on Ambraseys et al. attenuation relationship (1996) (475-year return period)

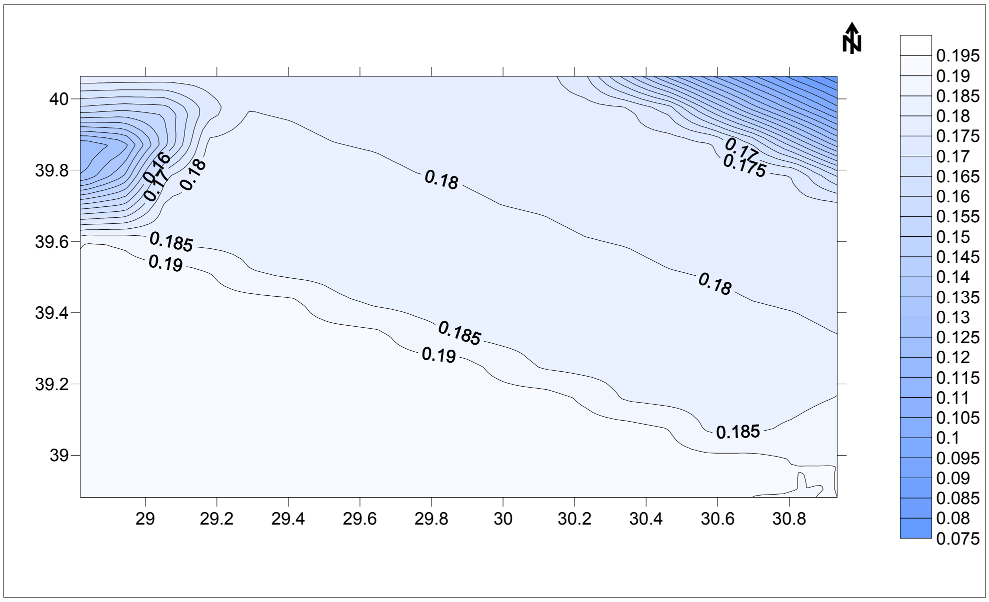


**Figure 8.4.** PSH Map for rock sites based on Gülkan and Kalkan attenuation relationship (2002) (475-year return period)

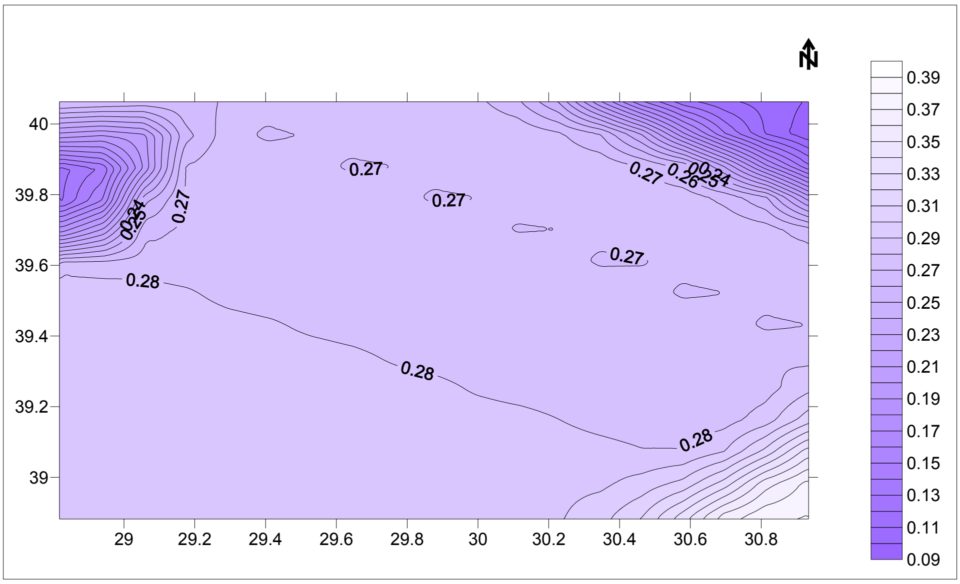


**Figure 8.5.** PSH Map for rock sites based on Abrahamson and Silva attenuation relationship (1997) (1000-year return period)

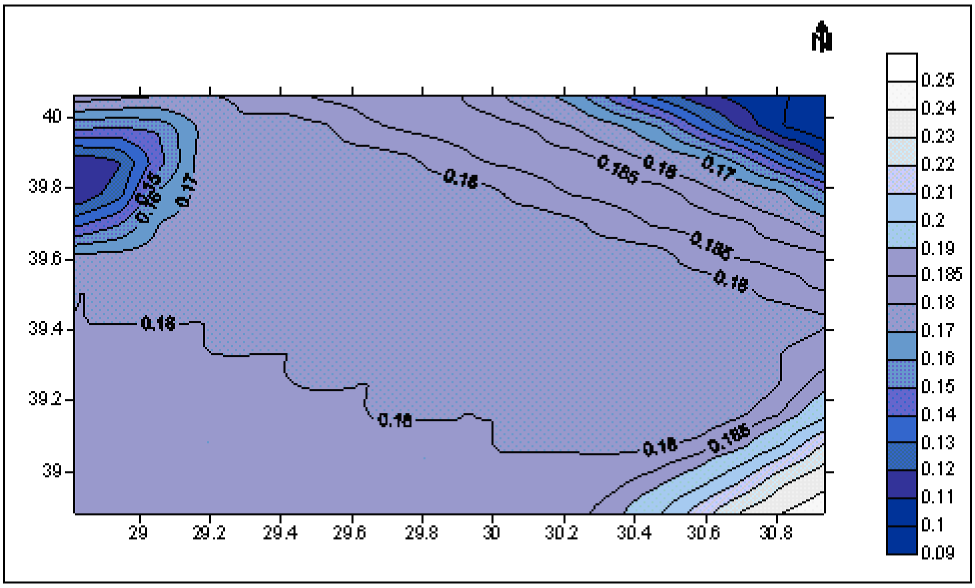


**Figure 8.6.** PSH Map for rock sites based on Boore et al. attenuation relationship (1997) (1000-year return period)

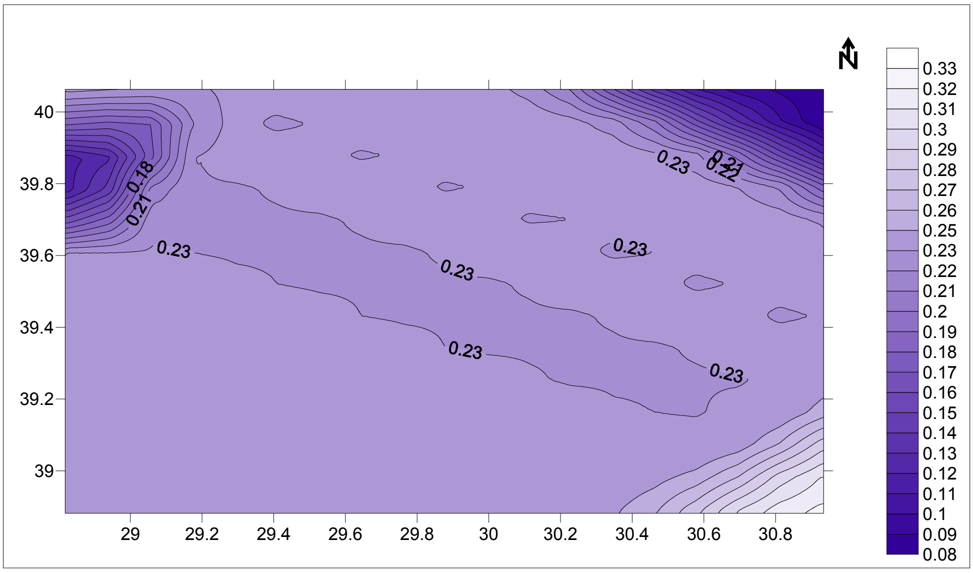


**Figure 8.7.** PSH Map for rock sites based on Ambraseys et al. attenuation relationship (1996) (1000-year return period)

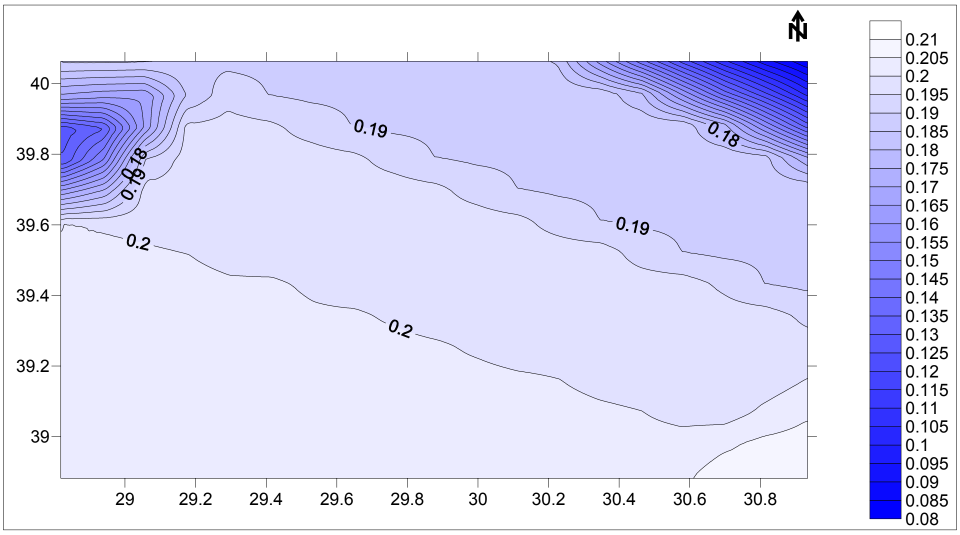


**Figure 8.8.** PSH Map for rock sites based on Gülkan and Kalkan attenuation relationship (2002) (1000-year return period)

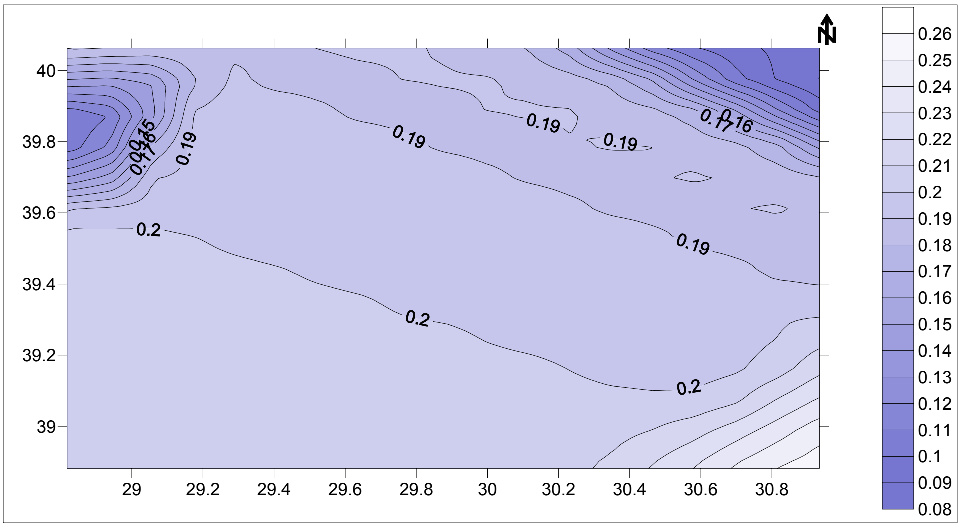


**Figure 8.9.** PSH Map for rock sites by Logic Tree method for 475 year return period

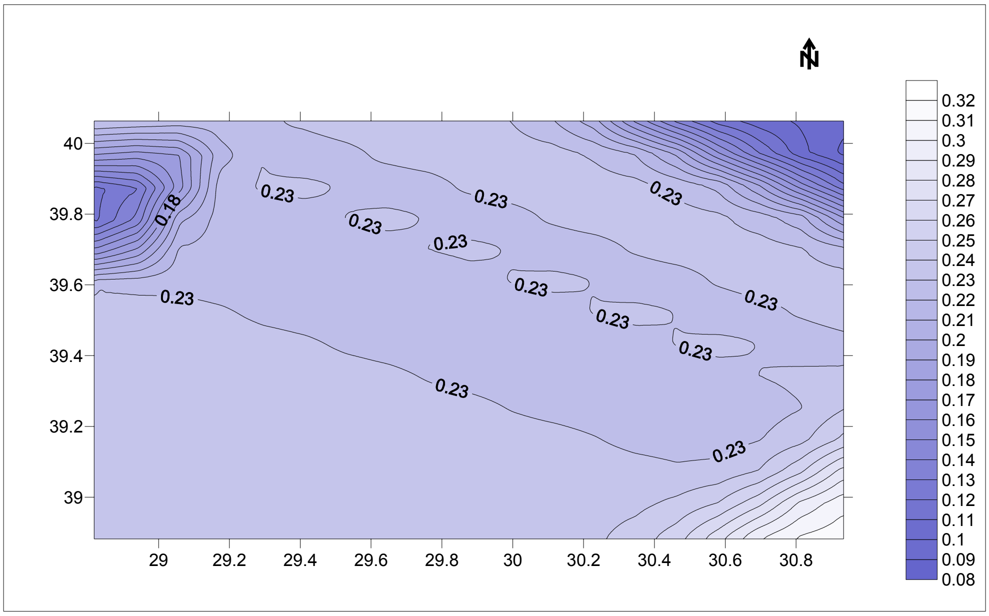


**Figure 8.10.** PSH Map for rock sites by Logic Tree method for 1000 year return period

In addition to these maps of expected PGA values for a defined gridwork of 'rock' sites; for a total number of 6006 computation nodes with a grid spacing of 0.09 decimal degrees in longitude and latitude, the PGA hazard curves or mainly the probabilistic seismic hazard models developed by the four relationships, at the Eskişehir downtown area (longitude:30.52, latitude:39.78) are shown in Figures 8.11 through 8.14. In Figure 8.15 all four of the hazard curves are demonstrated on the same graph so that they could be compared. This figure shows that after a certain level of peak ground acceleration (approximately 0.2 g) the hazard predicted by Abrahamson and Silva (1997) is overestimated whereas the one predicted by Boore et al. (1997) and Gülkan and Kalkan (2002) is underestimated and the other one is in between. To account for the conribution of different seismic source zones into total seismic hazard Figure 8.16 is drawn by considering Abrahamson and Silva (1997) relationship. So when the hazards led by different seismic source zones are deaggragated, it has been observed that the hazard at a site near the Eskişehir downtown area is mainly dominated by Eskişehir Fault Zone and in decreasing order the North Anatolian Fault Zone, Kütahya Fault Zone, Akşehir-Afyon Graben bounding faults and finally Gediz and Simav Faults dominate this calculated hazard. Then at Eskişehir downtown area, the peak ground acceleration values expected to occur for 10% probability of exceedance in 50 and 100 year periods for 'rock' sites have been given in Table 8.1. below.

**Table 8.1**. Peak ground acceleration values (g) for 10% exceedance in 50 and 100 years, calculated by three selected attenuation relationships for rock sites

| **Attenuation Relation** | %10 PE in 50 years | %10 PE in 100 years |
|---|---|---|
| Abrahamson and Silva (1997) | **0.218** | **0.279** |
| Boore et al. (1997) | **0.156** | **0.186** |
| Ambraseys et al. (1997) | **0.194** | **0.239** |
| Gülkan and Kalkan (2002) | **0.177** | **0.189** |

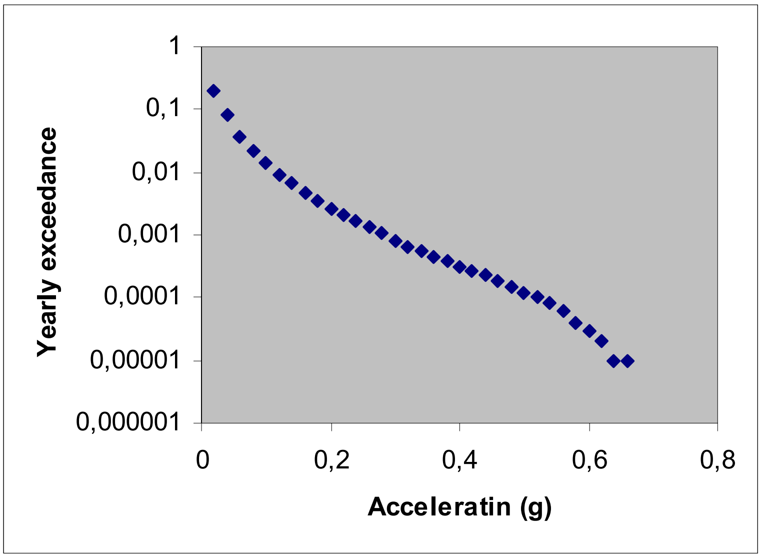


**Figure 8.11.** PGA Hazard Curve based on Abrahamson and Silva attenuation relationship (1997) for rock sites

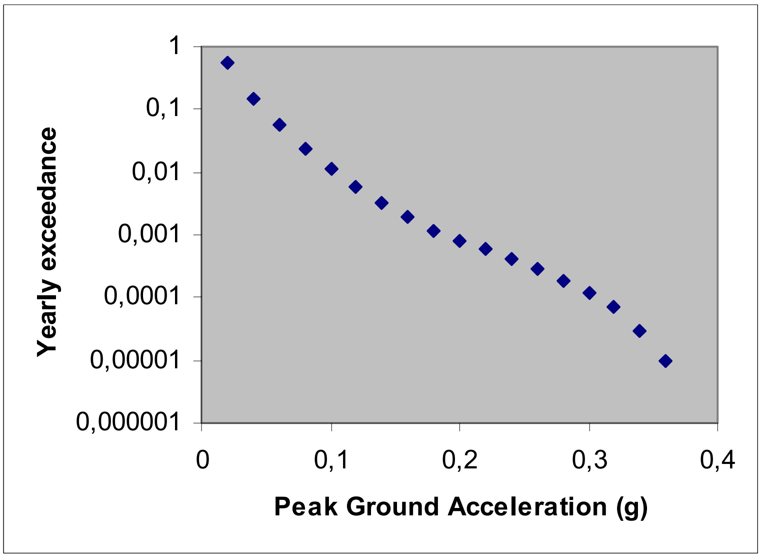


**Figure 8.12.** PGA Hazard Curve based on  Boore et al. attenuation relationship (1997) for rock sites

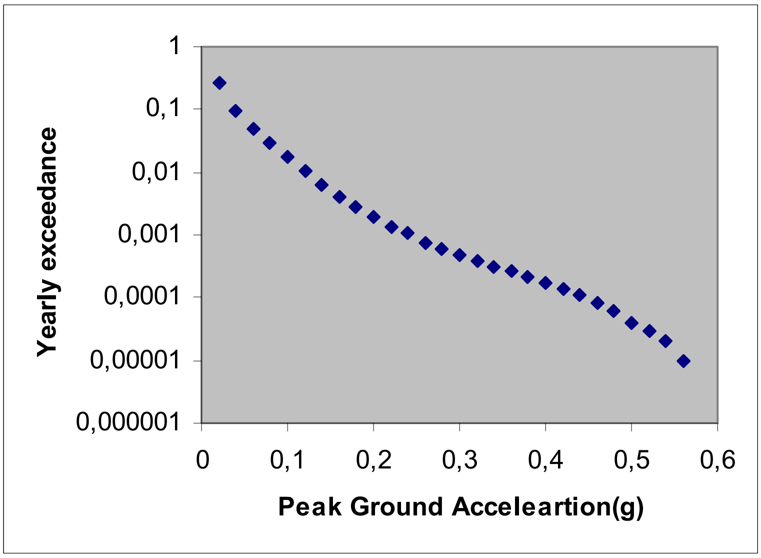


**Figure 8.13.** PGA Hazard Curve based on Ambraseys et al. attenuation relationship (1996) for rock sites

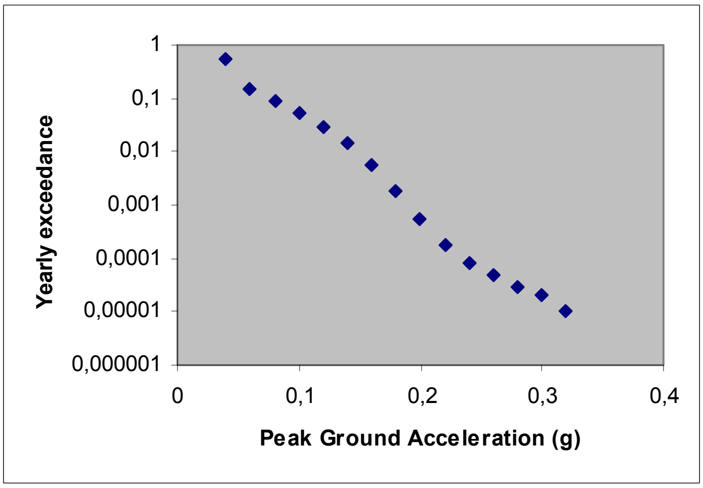


**Figure 8.14.** PGA Hazard Curve based on Gülkan and Kalkan attenuation relationship (2002) for rock sites

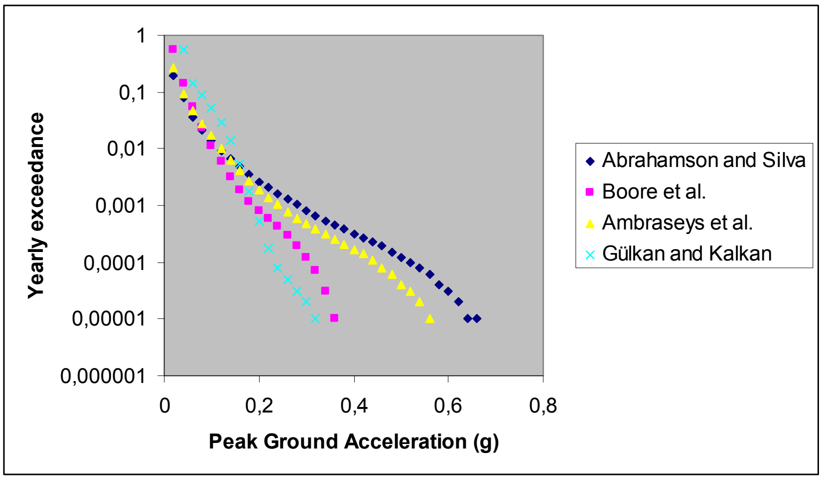


**Figure 8.15.** PGA Hazard Curves for rock sites

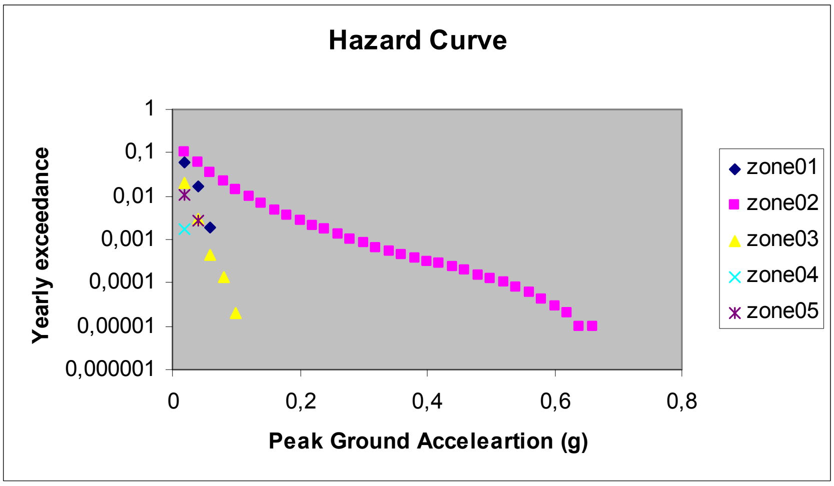


**Figure 8.16.** Deaggregation of seismic sources

On the other hand, in order to compare the effects of the minimum magnitude selection on the calculated total seismic hazard and to satisfy the Poissonian distribution, which requires the removal of dependent events such as the foreshocks and aftershocks , the PSH individual maps developed by the attenuation relationships of Abrahamson and Silva and Boore et al. (1997) and the maps prepared by the equal weight of these two relationships, have been redeveloped this time with different minimum magnitudes; selected specifically for each source zone but with the same return-periods for 'rock' sites. (Figures 8.17 through 8.22). In fact the removal of aftershocks and foreshocks does not lead to significantly different results in Turkey except in some of the seismic areas where the earthquakes cause long series of aftsershocks; such as the NAFZ and some parts of Aegean Region (Erdik et al., 1999) So the minimum magnitude has been chosen to be 5.5 for North Anatolian Fault Zone and for Gediz and Simav Faults but as 4.3 for the rest. Finally it has been observed that the distributions of the hazard levels have not changed significantly when compared to the previosly formed PSH maps with the same return-periods.

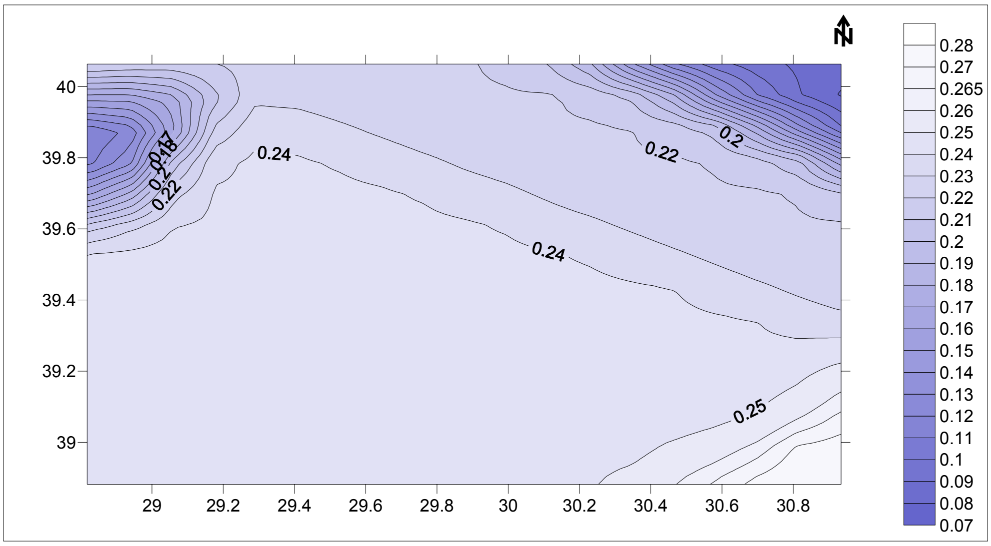


**Figure 8.17.** PSH Map based on Abrahamson and Silva attenuation relationship (1997) with a minimum magnitude variation for rock sites (475-year return period)

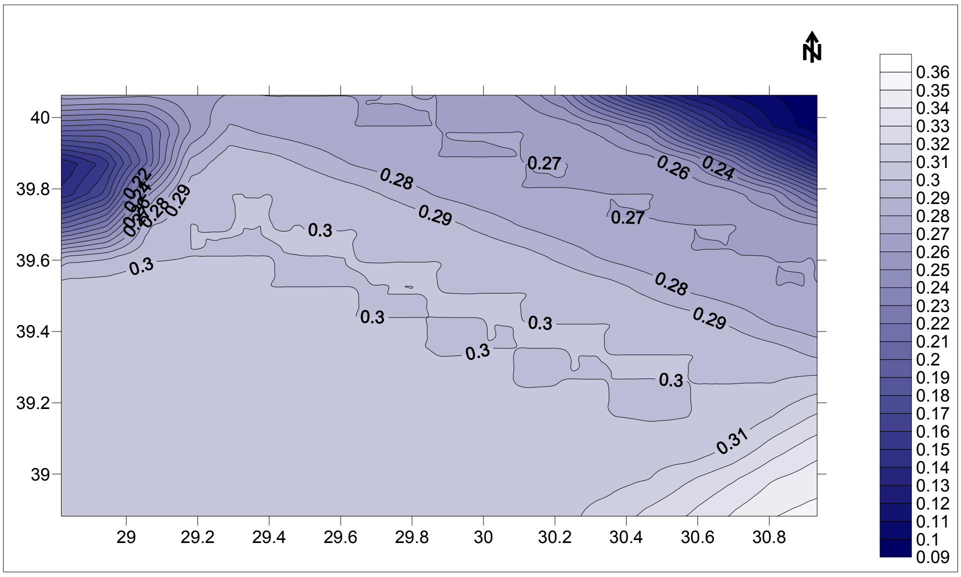


**Figure 8.18.** PSH Map based on Abrahamson and Silva attenuation relationship (1997) with a minimum magnitude variation for rock sites (1000-year return period)

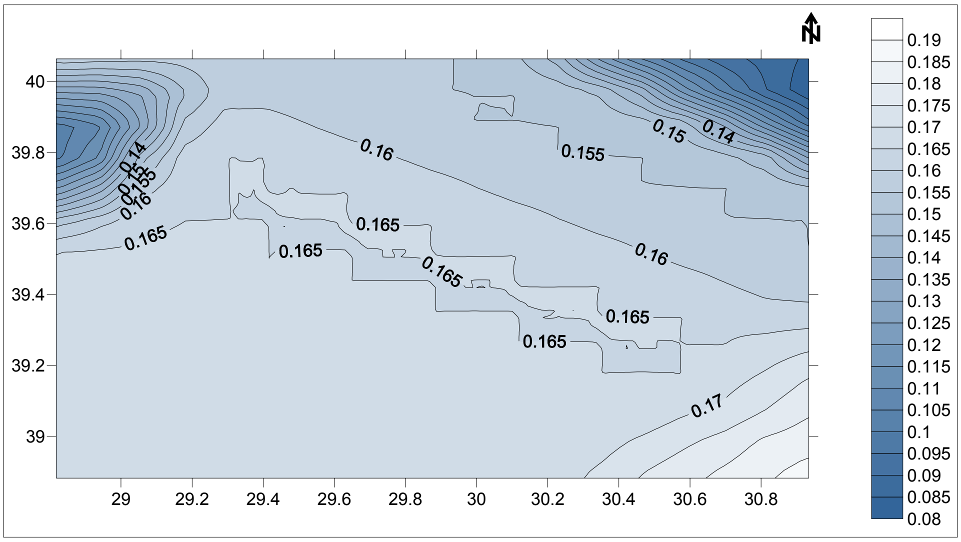


**Figure 8.19.** PSH Map based on Boore et al. attenuation relationship (1997) with a minimum magnitude variation for rock sites (475-year return period)

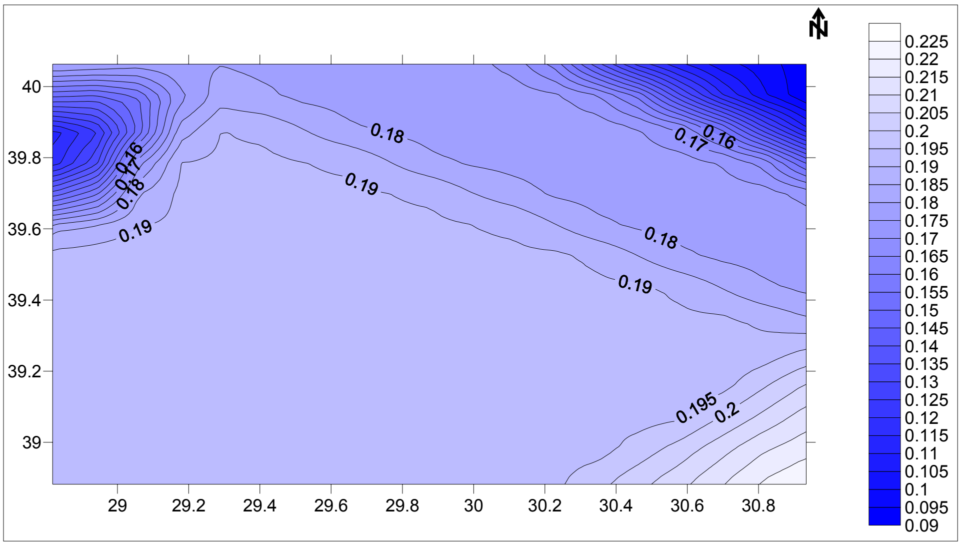


**Figure 8.20.** PSH Map based on Boore et al. attenuation relationship (1997) with a minimum magnitude variation for rock sites (1000-year return period)

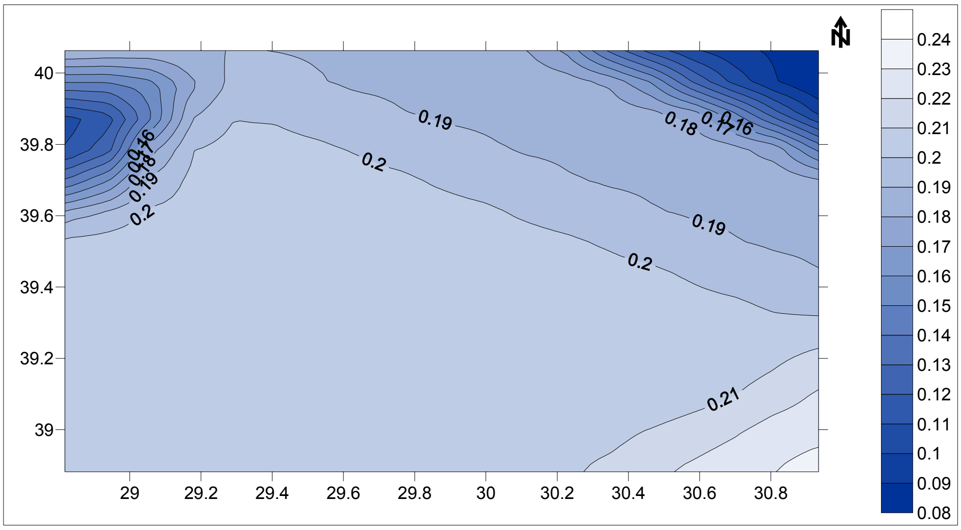


**Figure 8.21.** PSH Map by logic tree method with Boore et al. (1997) and Abrahamson and Silva (1997) attenuation relationships with a minimum magnitude variation for rock sites (475-year return period)

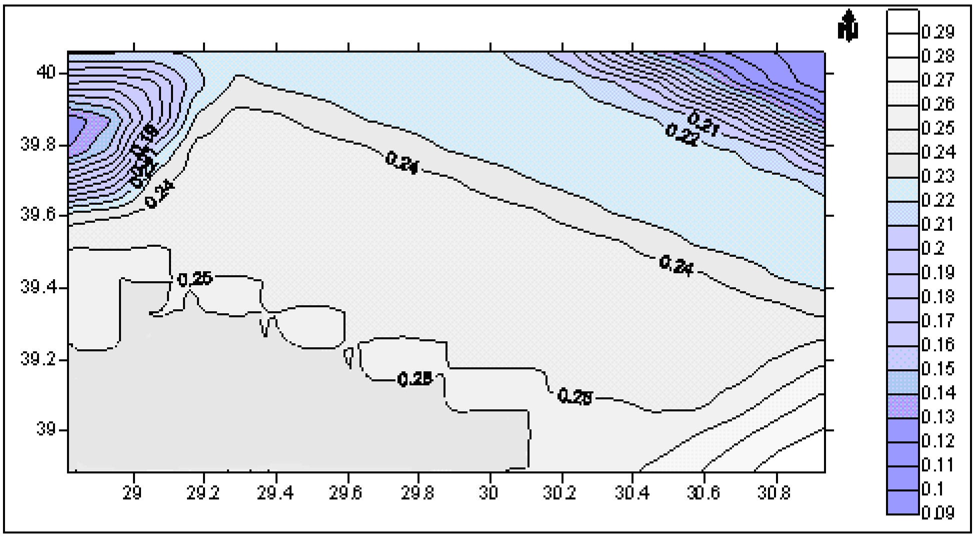


**Figure 8.22.** PSH Map by logic tree method with Boore et al. (1997) and Abrahamson and Silva (1997) attenuation relationships with a minimum magnitude variation for rock sites (1000-year return period)

In addition to the seismic hazard maps developed for rock sites, similar maps for two types of soil classes; for soil sites with an average $V_s$ of 250 m/s(Site Class D) and soil sites with an average $V_s$ of 520 m/s(Site Class C) or for stiff and soft soils were developed by means of two selected attenuation relationships (Boore et al., 1997 and Ambraseys et al. 1996) with a 10% probability of exceedance in 50 and 100 years (Figures 8.23 through 8.30). Because as a predictive variable 'site classification' or 'site class' has been relatively well defined and developed in these relationships when compared with the one (Abrahamson and Silva, 1997) which used only two classes ; 'rock' or 'shallow soil' and 'deep soil' and the other one (Gülkan and Kalkan, 2002) which categorized the sites as 'soil', 'soft soil' and 'rock'. In that sense by these simple-defined parameters, these last-mentioned relationships do not consider totally the classes of sites according to their stiffness based on the ranges of shear wave velocity. It was observed that the hazard maps developed by the predictive relationship of Boore et al. (1997) for site class C with an average shear wave velocity of 520 m/s show very close hazard levels when compared with the ones specifically developed by Boore et al. (1997) for rock site class. On the other hand, the maps predicted for site class D represent a two-fold increase in hazard levels when compared with that of the relatively stiff soil sites (Class C). However, this observation could not be made for the maps prepared by Ambraseys et al. (1996) for specifically stiff and soil sites because the differences in the levels of hazard for stiff and soft soil sites have not been that much significant. In contrary, the calculated PGA values are very close to each other.

At Eskişehir downtown area, the calculated peak ground acceleration values based on these two above mentioned attenuation for 10% probability of exceedance in 50 and 100 year periods for two fifferent 'soil' sites have been given in Table 8.2. and 8.3. below.

**Table 8.2.** Peak ground acceleration values (g) calculated based on Boore et al attenuation relationship (1997) for %10 PE in 50 and 100 years at 'soil' sites

| **$V_s$(m/s)** | %10 PE in 50 years | %10 PE in 100 years |
|---|---|---|
| 250 | **0.219** | **0.239** |
| 520 | **0.166** | **0.181** |

**Table 8.3.** Peak ground acceleration values (g) calculated based on Ambraseys et al attenuation relationship (1996) for %10 PE in 50 and 100 years at 'soil' sites

| **Soil Class** | %10 PE in 50 years | %10 PE in 100 years |
|---|---|---|
| Soft soil | **0.232** | **0.271** |
| Stiff soil | **0.230** | **0.268** |

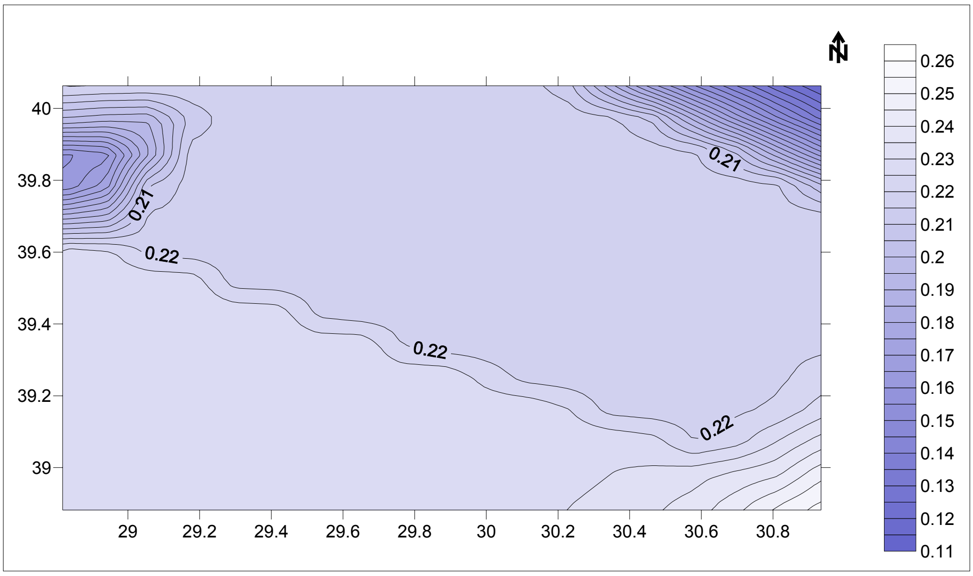


**Figure 8.23.** PSH map for site class D (Vs=250 m/s) based on Boore et al. attenuation relationship (1997) (475-year return period)

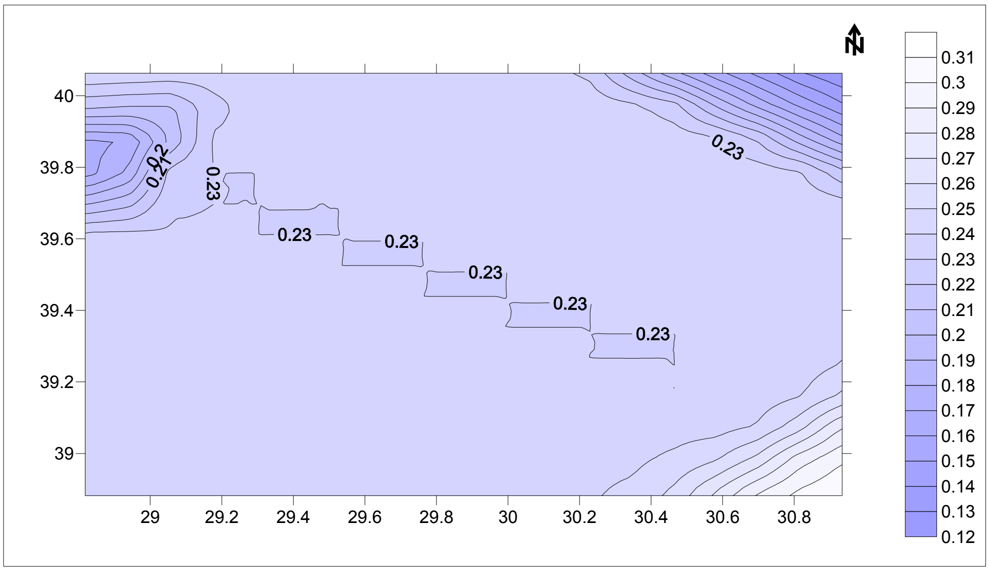


**Figure 8.24.** PSH map for site class D (Vs=250 m/s) based on Boore et al. attenuation relationship (1997) (1000-year return period)

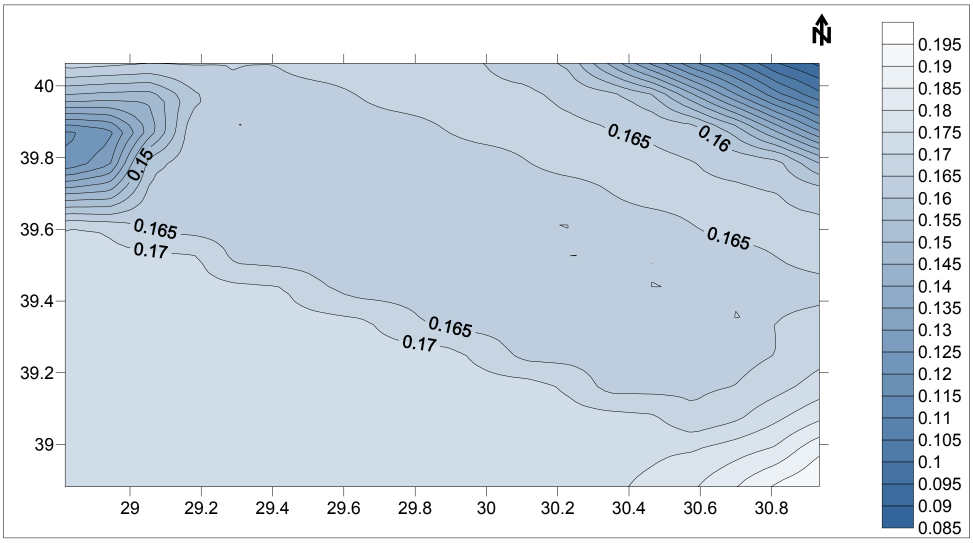


**Figure 8.25.** PSH map for site class C (Vs=520 m/s) based on Boore et al. attenuation relationship (1997) (475-year return period)

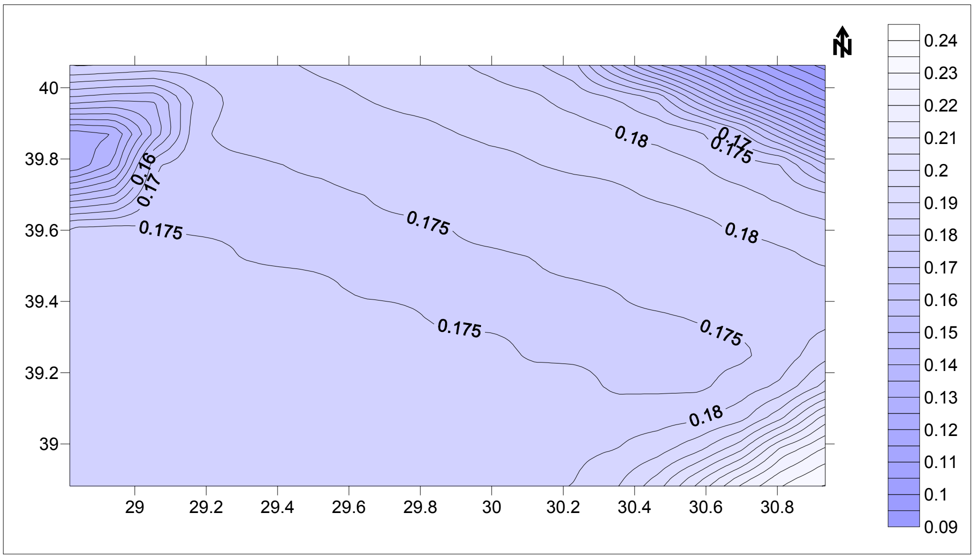


**Figure 8.26.** PSH map for site class C (Vs=520 m/s) based on Boore et al. attenuation relationship (1997) (1000-year return period)

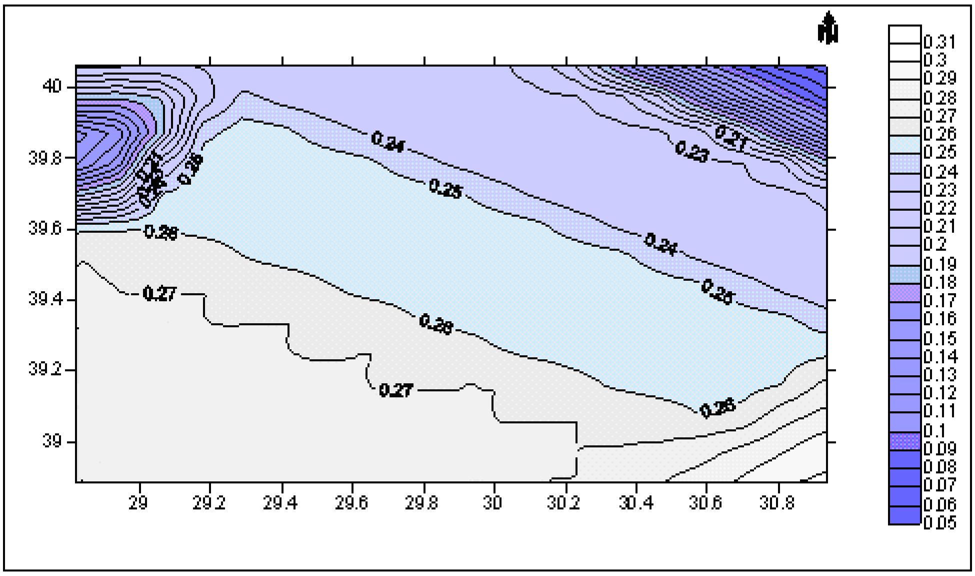


**Figure 8.27.** PSH map for ‘soft’ site class based on Ambraseys et al. attenuation relationship (1996) (475-year return period)

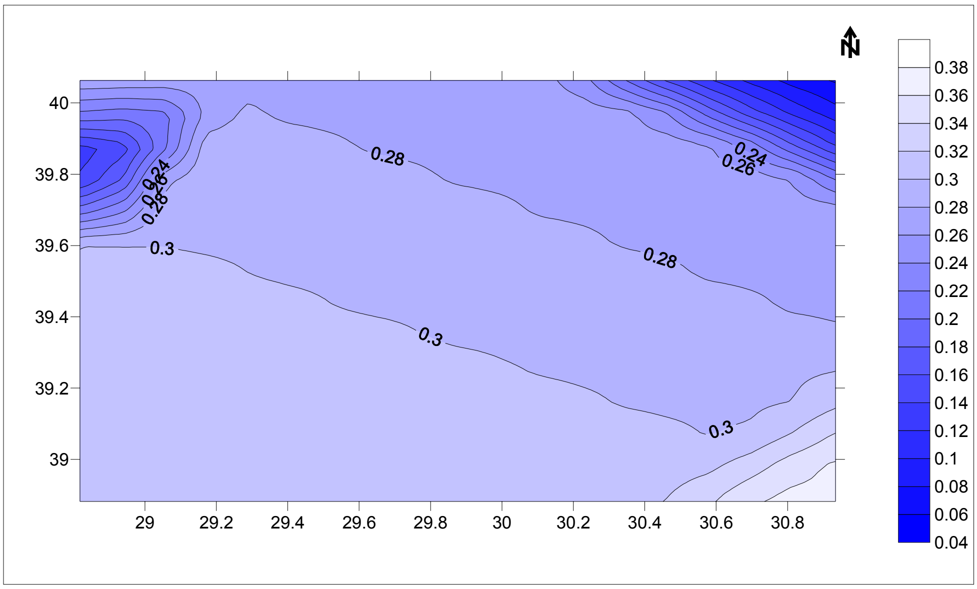


**Figure 8.28.** PSH map for ‘soft’ site class based on Ambraseys et al. attenuation relationship (1996) (1000-year return period)

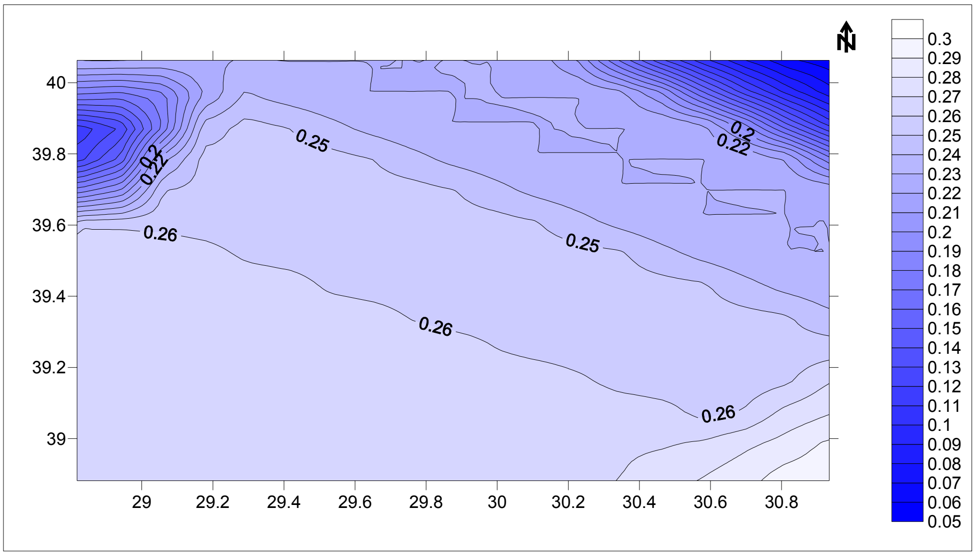


**Figure 8.29.** PSH map for 'stiff' site class based on Ambraseys et al. attenuation relationship (1996) (475-year return period)

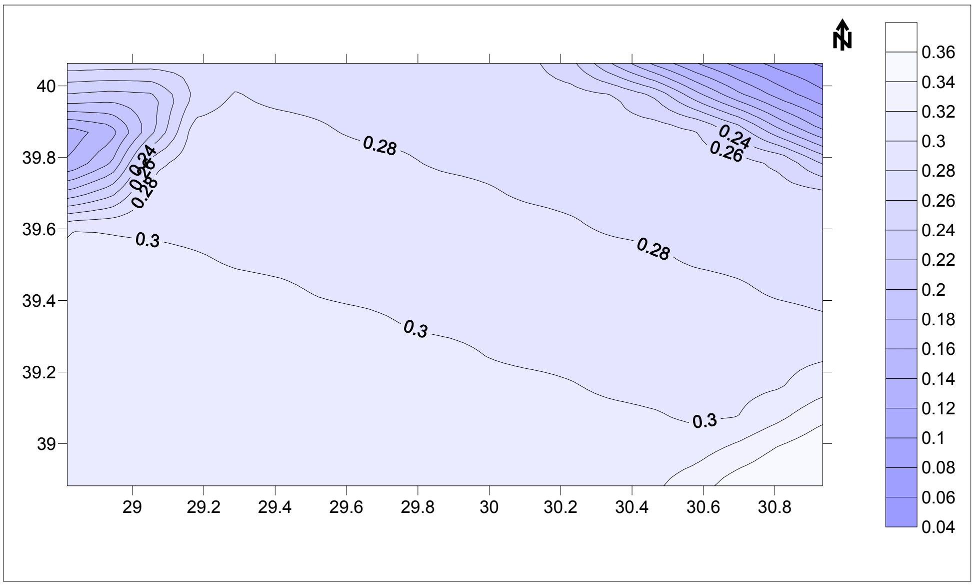


**Figure 8.30.** PSH map for 'stiff' site class based on Ambraseys et al. attenuation relationship (1996) (1000-year return period)

So for the downtown area of Eskişehir, the probabilistic seismic hazard maps or iso-PGA contours developed by one single predictive relationship of Boore et al. (1997) could be suggested for a 10% probability of exceedance in 50-year and 100-year return period for three different site conditions: 'rock', Class C' and

‘Class D’ instead of proposing an equally weighted map (by logic tree method) or utilizing a map developed by an attenuation relationship which is thought to overestimate the hazard values for even ‘rock’ sites( Abrahamson and Silva, 1997)

### 8.2. Deterministic Approach

Although the main purpose of this study is to develop a probabilistic sesmic hazard assessment, a deterministic analysis has been also performed in order to visualize the differences between them. Like in a typical deterministic analysis ,this part of this study has comprised four main steps:

a) The first stage is common for both of the analyses either deterministic or probabilistic. It consists of the definition of earthquake source or sources (Reiter, 1990). For the deterministic analysis which has been developed for this study, the configuration of individual source or sources have been selected to be mainly 5 ‘line (linear) sources’:

1) North Anatolian Fault Zone (Geyve-İznik segment)
2) Eskişehir Fault Zone (EFZ)
3) Kütahya Fault Zone (KFZ)
4) Gediz Fault
5) Akşehir Fault Zone (AFZ) (Akşehir Master Fault)

b) The second stage is the selection of controlling earthquake (Reiter, 1990) and the closest distances between downtown area of Eskişehir and the specified fault ot fault zones thought to affect the study area. For this part of the analysis (deterministic approach), the maximum magnitude values assigned to each source prior to this part in the probabilistic analysis have remained same but in addition to that the closest distances between Eskişehir downtown area and the points (coordinates) on the faults were measured and given in Table 8.4. below.

**Table 8.4.** The closest distances between Eskişehir downtown area and the specified linear seismic sources

| SEISMIC SOURCES | DISTANCE (d, km) |
|---|---|
| NAFZ (Geyve-İznik segment) | **78** |
| Eskişehir Fault Zone (segment) | **2.5** |
| Kütahya Fault Zone | **59** |
| Gediz Fault | **105** |
| Akşehir Fault Zone (segment) | **135** |

c) The third step is the determination of earthquake effect at the site of interest by means of an earthquake ground motion attenuation relationship (Reiter, 1990). For this determination, three different predictive attenuation relationships have been selected as in the case of probabilistic analysis except the local predictive attenuation relationship developed by Gülkan and Kalkan (2002).

d) The last step comprises the definition of the hazard at the site which means the direct oıtput of third step (Reiter, 1990). Peak ground acceleration values at the downtown area of Eskişehir calculated by means of these three attenuation relationships and their averages for each seismic source have been given in Table 8.5. below.

**Table 8.5**. Peak ground acceleration values calculated at the downtown area of Eskişehir based on three different attenuation relationships

| Seismic Source | d(km) | Mmax | 1 | 2 | 3 | Average |
|---|---|---|---|---|---|---|
| NAFZ(Geyve-İznik segment | 78 | 7.5 | **0.068** | **0.073** | **0.059** | **0.067** |
| EFZ | 2.5 | 6.8 | **0.56** | **0.37** | **0.55** | **0.49** |
| KFZ | 59 | 6.4 | **0.048** | **0.051** | **0.039** | **0.046** |
| Gediz Fault | 105 | 7.3 | **0.062** | **0.052** | **0.040** | **0.051** |
| AFZ | 135 | 6.8 | **0.025** | **0.033** | **0.023** | **0.027** |

1 Abrahamson and Silva (1997)

2 Boore et al. (1997)

3 Ambraseys et al. (1996)

# CHAPTER IX

## DISCUSSIONS

Although the probabilistic seismic hazard (PSH) maps representing the levels of peak ground acceleration with a probability of 10% in 50-year and 100-year period for rock sites have shown different values of peak ground acceleration for different types of attenuation relationships, the distributions of the levels of hazard such as high hazard levels, medium hazard levels, low hazard levels within these maps have been similar. However, the situation is a little bit complicated and different for the PSH maps prepared by the regional attenuation relationship of Gülkan and Kalkan (2002) because they do not resemble very much to the other ones developed by the relations not specifically regressed from the recordings of Turkey. In their regional relationship (Gülkan and Kalkan, 2002) a limited number of records, especially from the two recent 1999 earthquakes have been used and they have been naturally observed to dominate the strong-motion data base and so the regression equations. Apart from this factor, the difference could also be originated from the rather different division of site classes according to average shear wave velocities when compared to the site classes considered by the relationships of Boore et al. (1997); and Ambraseys et al. (1996). On the other hand the fact that the estimated values of peak ground acceleration vary between the regional attenuation relationships of Abrahamson and Silva (1997), Boore et al. (1997) and Ambraseys et al. (1996) would not be a very surprising observation. These predictive relations have different distance and magnitude limitations, different data bases of strong-motion records, different source distance definition, different magnitude scaling, different regression methods and models possessing several dummy variables showing distinct parameters of the attenuation, different site classifications and of course different standard error definitions for the uncertainty.

It is evident that the values of peak ground acceleration obtained for a grid of different sites or for a specifically defined site at the downtown area of Eskişehir for distinct attenuation relationships are different when compared with the previous studies carried out for Turkey (Erdik et al., 1999 and Gülkan et al., 1993) and especially for this region (Ayday et al., 2001). Rather than the appropriate selection of the attenuation relationship, this differentiation could originate both from the handicaps, lacks or deficiencies of the software (besides its advantages) used in this study or from the lack of data for proper earthquake source characterization, especially in the definition of earthquake source.

On the other side, the program used within the scope of this thesis does not allow either the usage of different attenuation relationships or even the usage of different forms of the same attenuation relationship for different seismic sources. This is a very important issue in seismic hazard analysis studies since every attenuation relationship has a significant advantage over the others to be considered specifically; for example a relationship could take into consideration far-field effects whereas the other one could not or the one with a strict distance limitation could not posses any factor for the style of faulting or any other more important parameter which is vital for a specific earthquake source. So the necessity of using one attenuation relationship is thought to be very questionable for a sophisticated, well-engineered analysis. In addition to that the default selection of the same type of a recurrence relationship in the program may or may not represent the individual behaviors of single faults when compared with more sophisticated laws. But in the absence of a sufficient available data, it would not be correct to claim that the other improved models would have better figured out the distribution of the earthquake magnitudes. On the other hand, there may be another problem coming from the definition of each seismic source. In this study, the earthquake sources have only been defined as areal sources in order to visualize the situation from a more conservative perspective. The first question is whether the approximation of areal zonation will still provide an optimistic conservatism under the circumstances of conscious ignorance of the effect of some seismic activities already recorded since they are not included within one of these defined sources or whether the jargon of conservatism will be a little shifted from its principal definition or not. Unfortunately the second question whether modeling some well defined sources like finite fault lines could be more realistic or not will remain unanswered because of the lack of various parameters defining the fault characteristics in Turkey or even because of their suspicious reliabilities. There are various contrary opinions about the exact location of the faults or fault zones, their lengths or their rupture areas between the earth scientists. So the confusion lies under the fact that modeling an earthquake source as an areal seismic source zone would still be conservative when leading to some future major overdesigns.

On the other hand, by this study or by most of the probabilistic seismic hazard studies throughout the world the concept of the logic tree could be judged whether it is logical or not. Because a logic tree approximation tries to combine different predictive models which were formed by distinct regression methods developed by different databases on a straight platform. So this approximation of logic tree could not have led very realistic results.

When coming to the issue of 'Memoryless Poissonian Process', of course the importance of the statement that dependent events should be culled from the available seismicity data bases has to be taken into consideration. But when the results calculated with accordingly differentiated minimum magnitude values for different sources and the ones by a minimum magnitude value of 4.0 as stated initially are compared, a drastic difference could not be observed at all.

Finally after the representation and evaluation of the iso-PGA contours for different soil classes ('stiff' and 'soft' soil sites), the variations in acceleration levels developed by Ambraseys et al. (1996) could not be seen as satisfactory or as significant as in the case of Boore et al. (1997) which had classified the different site conditions according to their ranges of shear wave velocities. It is sure that as the predictive relationships get more well-developed and improved soil conditions or classifications, within their models, the inclusion of site conditions in the relationships and their effects on them will be more valuably considered for a site.

Although a deterministic analysis was also performed in order to compare the results from a broader perspective within the scope of this study, its results were not considered very valuable for this study, just because of the nature of the deterministic approach but still it was figured out that Eskişehir Fault Zone is the dominant seismic source controlling the great amont of hazard in the city of Eskişehir; just as stated also by probabilistic approach.

# CHAPTER X

# CONCLUSION

In the scope of this study, probabilistic seismic hazard maps and curves have been developed for the city of Eskişehir. For this development, after the preparation of a seismotectonic map and the identification of the selected seismic sources with their characteristics, four attenuation models taking the uncertainties into consideration (Abrahamson and Silva, 1997; Boore et al., 1997; Ambraseys et al. 1996 ; Gülkan and Kalkan, 2002), one being site-specific (Gülkan and Kalkan) have been selected to be used in a probabilistic seismic hazard model implemented by a computer program which is named as SEISRISK III (Bender and Perkins, 1987). As a strong ground motion parameter, peak ground acceleration value has been utilized. The probabilistic seismic hazard maps were constructed on a two-dimensional grid, by the calculation of the hazard at each of a set of sites spaced uniformly on this grid. First the probabilistic seismic hazard maps which were constructed by the selected above mentioned predictive attenuation models and which show the expected levels of peak ground acceleration at different sites (rock, stiff soil and soft soil) with a probability of exceedance of 10% in 50 and 100-year periods were developed. Then the approximation of 'logic tree' was applied in order to form the maps having equal contribution from each of the three selected attenuation relationships (Abrahamson and Silva, 1997; Boore et ai., 1997; Ambraseys et al., 1996) with the same return periods. In addition to these maps seismic, hazard curves were figured out with the contribution of these four attenuation regression models at the downtown area of Eskişehir and it has been observed that the attenuation relationship intended to give the highest levels of hazard was the one of Abrahamson and Silva (1997) whereas the one giving the lowest hazard levels was the model of Boore et al. (1997) for 'rock' sites. In addition to these implementations, the hazard maps for two different soil classes were developed based on two selected attenuation relationships

(Boore et al. (1997) and Ambraseys et al. (1996)) then for these two tpes of ‘soil’; ‘stiff’ and ‘soft’ soil sites rather than the predictive relationship of Ambraseys et al. (1996), the attenuation relationship of Boore et al. (1997) has been thought to give more reliable and logical results. Finally, since Eskişehir is a city situated over a great amont of alluvium type of soils, in probabilistic analysis, it has been suggested to utilize the attenuation predictive relationship of Boore et al. (1997) which was observed to give more reasonable results for ‘soi’l sites.

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