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APPLICATION OF DETERMINISTIC SEISMIC HAZARD ANALYSIS ON THE AREA OF 1970 GEDIZ EARTHQUAKE

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Abstract

Deterministic seismic hazard analysis is used to evaluate the effects of potential earthquakes. By using this approach, approximate peak ground acceleration (PGA) values can be estimated for the area of interest. In this research, the area which was severely affected by the 1970 Gediz earthquake has been studied to assess the PGA distribution. Detailed geological characteristics and scientific parameters (unit distribution, fault locations and attenuation relationships) are the main input for the results. Four main fault zones are used for modeling and according to marks, peak earthquake magnitude generated from the fault zones and type of geological units are the main interest for the location of the settlements.

Keywords: Deterministic seismic hazard, 1970 Gediz earthquake, PGA, scenario earthquakes.

1. Introduction

Seismic hazard studies have become increasingly more important for earthquake engineering applications all around the world. It is possible to mitigate the damages of earthquake for the constructions by using engineering techniques. Seismic hazard assessment is commonly used to define and classify the susceptible areas and in the preparation of seismic zonation maps. The main purpose of the seismic hazard mapping is to obtain ground motion distribution in any place. The ground motion parameters include peak ground acceleration, peak velocity, peak displacement, and response spectral values or histories of acceleration, velocity and displacement gained from past earthquakes.

As it is known that Turkey is one of the susceptible countries for the earthquake damages. There are a lot of active faults, faults zones and fault systems creating large magnitude earthquakes. For that reason, seismic hazard assessment approaches are very important. The map given in Figure 1 was prepared based on peak ground acceleration (PGA) methodology estimated by means of probabilistic seismic hazard approach considered for a return period of 475 years. Furthermore, Turkey is categorized into five different seismic zones: I to V, each of which has specific PGA (peak ground acceleration) values of >0.4 g, 0.3-0.4 g, 0.2-0.3 g, 0.1-0.2 g and <0.1 g, respectively. 43 % of cities are located in zone I., whereas 28 % of them in zone II. These settlements are highly populated and industrialized; therefore they play important roles in country's economy.

In this research, deterministic seismic hazard approach has been applied for the determination of PGA values. According to Figure 1, study area is located on the I. degree earthquake zone. Historical and recent earthquakes similarly prove that the area is very vulnerable for future earthquakes. For the reason, this area has been chosen to apply deterministic approach. This research aims to show the importance of geological units, distance between source faults and settlements.

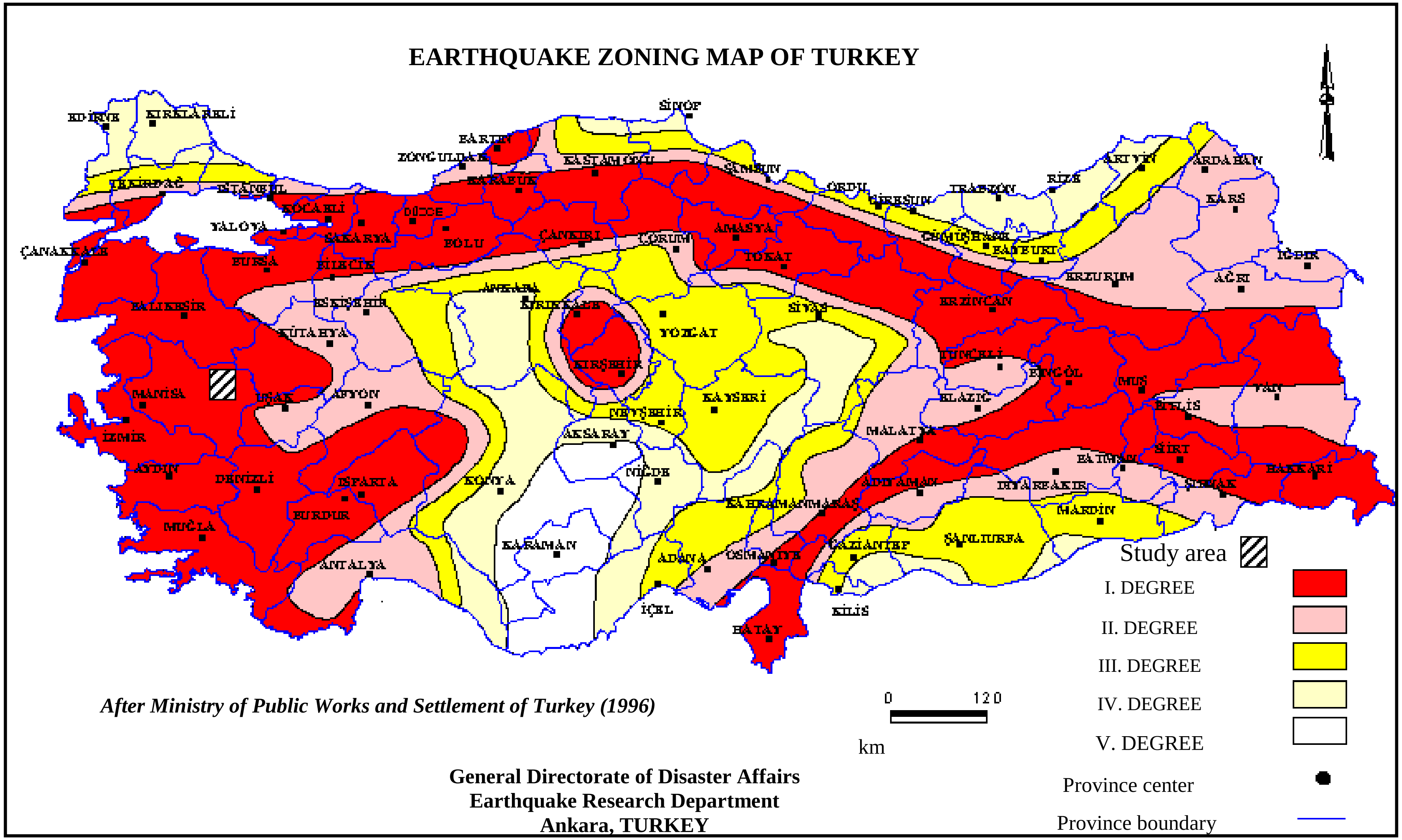


Figure 1. Earthquake zoning map of Turkey. Rectangle shows the study area (after Ministry of Public Works and Settlement of Turkey, 1996).

2. Background on Deterministic and Probabilistic Approaches

Seismic hazard mapping are done by two different approaches; a) deterministic and b) probabilistic. In deterministic seismic hazard analysis (DSHA), earthquake scenarios are evaluated separately. For each sources (single faults or fault zones), a scenario earthquake is defined by magnitude, distance between source and area, style of faulting and in some cases rupture direction. The ground motion for the scenario earthquake is usually estimated by using attenuation relationship, but is sometimes estimated using seismological simulations of the ground motion [1]. DSHA is based on geology and is attenuated to physical reality in nature.

A typical DSHA can be described in four-step process [2]

1. Identification and characterization of all earthquake sources capable of producing significant ground motion at the site. Source characterization includes definition of each source’s geometry and earthquake potential (Figure 2).

2. Selection of a source-to-site distance parameter for each source zone. In most DSHAs, the shortest distance between the source zone or point and the site of interest is selected. The distance may be expressed as an epicentral distance or hypocentral distance, depending on the measure of distance of the predictive relationship(s) used in the following step.

3. Selection of the controlling earthquake (i.e, the earthquake that is expected to produce the strongest level of shaking), generally expressed in terms of some ground motion parameter. The selection is made by comparing the level of shaking produced by earthquakes (identified in step 1) assumed to occur at the distances identified in step 2. The controlling earthquake is described in terms of its size (usually expressed as magnitude) and distance from the site (Figure 2).

4. The characteristics of hazard are usually described by one or more ground motion parameters obtained from predictive relationships. Peak ground acceleration, peak velocity and response spectrum ordinates are commonly used to characterize the seismic hazard (Figure 2).

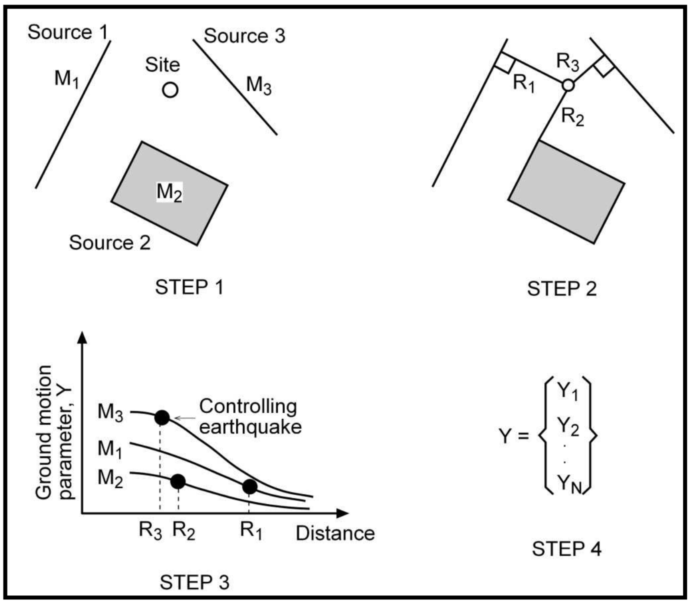


Figure 1. Diagrams showing four steps of deterministic seismic hazard analysis [3].

Probabilistic seismic hazard analysis (PSHA) is more complicated than deterministic analysis and is often seen as a “black box” by practicing engineers. For this reason, PSHA seems to be less reliable than DSHA. In the past 20 to 30 years, the use of probabilistic concepts has allowed uncertainties in the size, location and rate of recurrence of earthquakes and in the variation of ground motion characteristics with earthquake size and location to be explicitly considered in the evaluation of seismic hazards. PSHA provides a framework in which these uncertainties can be identified, quantified and combined in a rational manner to provide a more complete picture of the seismic hazard. The PSHA can be described as a procedure of four steps [2].

1. The first step, identification and characterization of earthquakes sources, is identical to the first step of DSHA, except that the probability distribution of potential rupture locations within the source must also be characterized (Figure 3).

2. Next, the seismicity or temporal distribution of earthquake recurrence must be characterized. A recurrence relationship, which specifies the average rate at which an earthquake of some size can be exceeded, is used to characterize the seismicity of each source zone. The recurrence relationship may accommodate the maximum size earthquake, but it does not limit consideration to that earthquake, as DSHA often do (Figure 3).

3. The ground motion produced by earthquakes of any possible size occurring at any possible point in each source zone must be determined with the use of predictive relationships. The uncertainty inherent in the predictive relationship is also considered in a PSHA (Figure 3).

4. Finally, the uncertainties in earthquake location, earthquake size, and ground motion parameter prediction are combined to obtain the probability that the ground motion parameter can be exceeded during a particular time period (Figure 3).

The proper performance of a PSHA requires careful attention to the problems of source characterization and ground motion parameter prediction and to the mechanics of the probability computations. But in the application of probabilistic approach, there are many uncertainties. So, probabilistic method should never be used for (1) multiple expert opinion, (2) logic tree, and (3) deaggregation. On the other hand, it can be used for (1) preliminary evaluation, (2) for an operating basis earthquake, (3) for risk analysis, and (4) for design of non-critical construction [4].

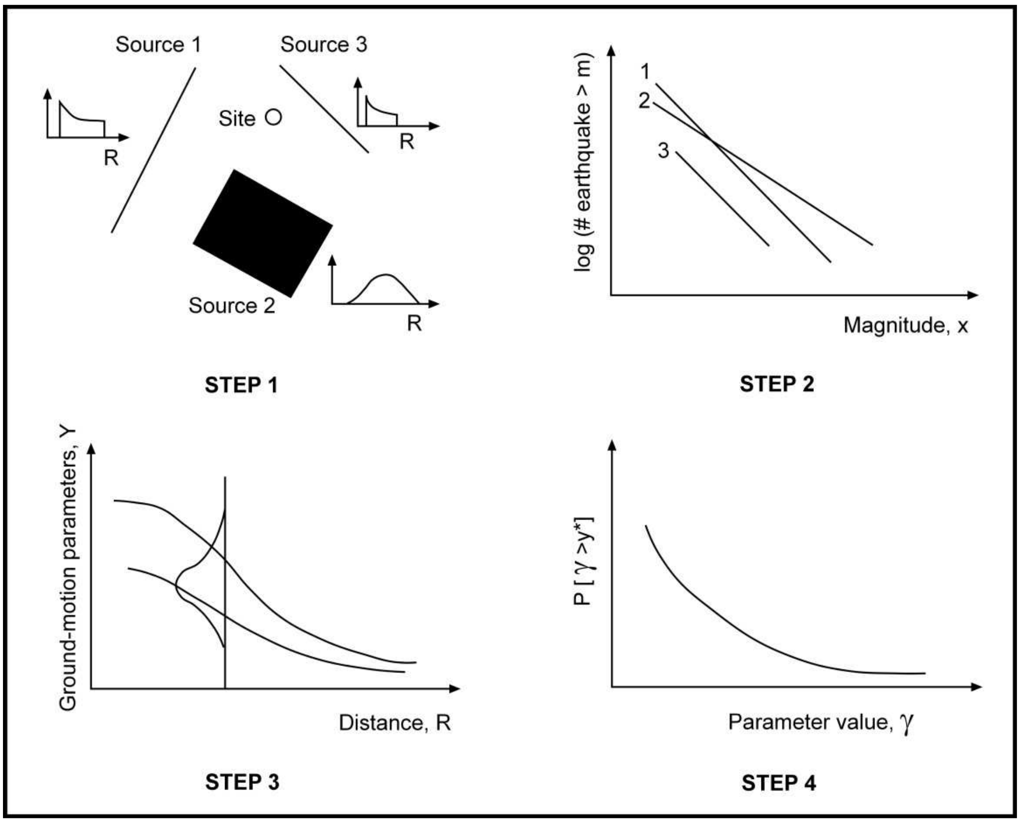


Figure 3. Diagrams showing four steps of probabilistic seismic hazard analysis [3].

In the 1960s and 1970s, the DSHA was used as the main type of seismic hazard analysis, but it has been gradually replaced by the PSHA. For the past two decades, the discussions are based mainly deciding which method can predict hazard of future earthquakes more accurately. The probabilities of occurrence for the “worst-case” in DSHA can be very low. This means that the construction of facilities designed for the worst hazard can be very expensive. On the other hand, the PSHA has been discussed in different aspects such as used algorithm and damage of historical earthquake. But they cannot succeed properly to imitate the earthquake generation, damage of historical earthquake and the accurate ground motion [5].

Therefore, probabilistic approach needs more information; moreover, some assumptions have many inputs. In the case of many assumptions, the amounts of uncertainties might be increased. PSHA is just a large number of deterministic analyses with added feature such as recurrence interval, computer applications, standard deviation and definite attenuation relationship. Simpler decisions and well-understood seismicity and tectonics point to deterministic representations [6]. There are more discussions about the probabilistic and deterministic approaches, but they are beyond the scope of this study. Additionally, DSHA is based on the geological features of the site [7 and 4] whereas PSHA is focused on earthquake statistics and numerical calculations [8, 9 10, and 11]. Because of the reasons and substantial input data, deterministic approach has been chosen to apply preparation of seismic hazard map in this study.

DSHA is used to calculate distribution of PGA in this work because, geological characteristics of the area collected from field work is much more than needed data to apply PSHA. Deterministic approach is aimed to find maximum possible ground motion at the site of interest, and then the size of the largest possible earthquake is estimated for each of the previously defined seismic sources. The underlying philosophy behind, also termed as the "scenario" ground motions procedure [12] is: (i) "scenario earthquake" is both scientifically reasonable and estimated to produce most severe strong ground motion at the site, (ii) the public can be informed about the possible earthquake hazards and (iii) a wide audience can fully be assured to the safety of important structures and critical facilities even for the largest possible seismic events [13].

4. Input data

The results of all analysis to prepare the map in the concept of deterministic seismic hazard analysis are extremely dependent on our knowledge about the source (faults), units and attenuation relationship. Data defining the structural models and seismic sources must be properly defined and assigned to the area [14].

In the first step of seismic hazard map analysis, earthquake sources have to be described based on their characteristics such as line, point and area and lengths. The main inputs for this application are the earthquake sources. In the study area, there are four line sources as fault zone named as Muratdağı, Simav, Şaphane and Yeşilova fault zones and one point source which is epicenter of previous earthquake information (1970.03.28 Gediz earthquake). Detailed geological mapping have been done by Gürboğa [15]. Lastly, formula of attenuation relationship proposed by Ulusay et. al. [18] for Turkey is used for calculations.

4.1. Fault zones and epicenter of 1970 Gediz earthquake

Two types of DSHA have been performed in this study. They are the line sources (fault zones) and point source (1970 Gediz earthquake). Four maps for line sources and one map for point source have been produced. Although, 2 large earthquakes occurred in the 1944 and 1970, there is no reliable epicentral information about the 1944 earthquake. Due to this restriction, the epicenter of the 1970 Gediz earthquake could only be used for PGA distribution.

To analyze the seismic hazard of the study area and its vicinity, earthquake sources (fault zones) that may affect the area have been defined regarding the main tectonic structures. There are four main fault zones in this part of Akşehir-Simav Fault System (ASFS) that may create big earthquakes and hit the study area sternly. These fault zones include a number of single faults; however, they are being represented and evaluated separately as a single line. The demonstration of fault zones has also very important variable for the estimation of magnitude. In this point of view, fault segmentation has to be done properly. For example, it was common to use 1/3 to 1/2 of the total fault length for the estimation of earthquake magnitude [19]. Later on, fault segmentation studies on well-studied faults have replaced [1]. But in this study, all single faults in each fault zones were connected to get as single line (Figure 4). The main reason of this assumption is that the study area is not very large, so, in case of an earthquake they may move together within each fault zone at once. Briefly, these four fault zones are not limited with the study area. During the calculation of peak earthquake total length of them are considered.

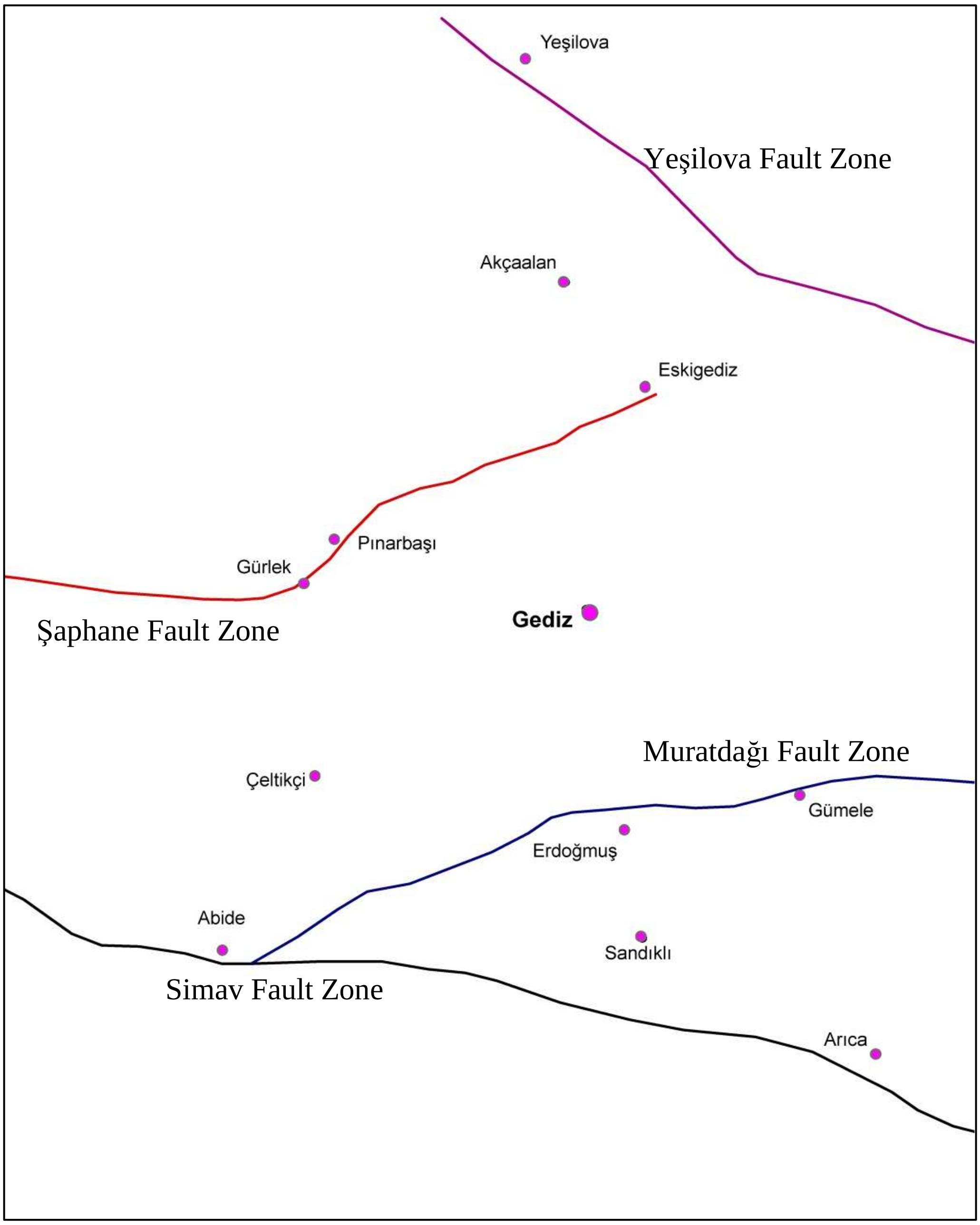


Figure 4. Locations of the four fault zones around study area.

4.2. Estimation in magnitudes of scenario earthquakes

The next step after the description of sources for large earthquakes is to define the magnitude of the scenario earthquake. For these sources, estimated peak earthquakes so called "scenario earthquake" here are clarified by using the surface rupture length. Wells and Coppersmith [20] proposed a relationship between rupture length and various magnitude values such as M_s, M_b, M_d, M_L and M_w. For the calculation of earthquake magnitudes for Turkish earthquakes, the relation proposed by [21] was chosen. According to this research, fault rupture length versus M_s [21] and fault rupture length in logarithmic scale versus M_s relations were described [22].

Before going to explain the determination of M_s and M_w by using the surface rupture length of the faults, the explanations and relationships of the various types of magnitudes are briefly clarified below:

There are different magnitude types to determine the size of an earthquake. They can be done by using the seismogram rather than on the amount of damage. To obtain different magnitudes of an earthquake, different parts of the radiation pattern of earthquake waves (body or surface waves) are used. The concept of earthquake magnitude, a relative size scale based on measurements of seismic phase amplitudes, was developed by K. Wadati and C. Richter in the 1930s, over 30 yrs before the first seismic moment was calculated in 1964 [23]. The general form of all magnitude scales is given by

$$M = \log (A/T) + f(\Delta, h) + C_s + C_r \qquad (1)$$

where A is the ground displacement of the phase on which the amplitude scale is based, T is the period of the signal, *f* is a correction for epicentral distance (Δ) and focal depth (h), C_s is a correction for the siting of a station (e.g., variability in amplification due to rock type), and C_r is a source region correction. Magnitudes are obtained from multiple stations to overcome amplitude biases caused by radiation pattern, directivity, and anomalous path properties. Four basic magnitude scales are in use today: M_L, m_b, M_s and M_w. M_L local magnitude known as Richter magnitude was suggested by Richter [24]. Richter observed that the logarithm of maximum ground motion decayed with distance along parallel curves for many earthquakes.

$$M_L = \log A - 2.48 + 2.76 \log \Delta \qquad (2)$$

where A is the displacement, and Δ is epicentral distance. M_L is also very useful scale for engineering applications. Many structures have natural periods close to Wood-Anderson that is a seismometer for the observation of seismic waves. Furthermore, this magnitude type can be used for an earthquake that has magnitude bigger than 6.0 and distance smaller than 700 km. m_b is the body wave magnitude which is based on the few first cycles of P-wave arrival and given by

$$m_b = \log (A/T) + Q(h, \Delta) \qquad (3)$$

where A is the actual ground-motion amplitude in micrometers and T is the corresponding period in seconds, Q (h, Δ) is the correction for depth and distance. When m_b is measured, it is usually for the largest body wave (P, PP, etc.). M_s is surface-wave magnitude that is measured beyond the 600-km-long-period and used on M>6.0 earthquakes. This is proper for the magnitudes of shallow earthquakes, because deep earthquakes cannot generate the surface-waves. The equation for surface-wave magnitude is given by

$$M_s = \log A_{20} + 1.66 \log \Delta + 2.0 \qquad (4)$$

where A_{20} is the amplitude of the 20-s-period surface wave in micrometers.

M_w called as moment magnitude was derived by Kanamori [25]. The equation of moment magnitude is given by

$$M_w = (\log M_0 / 1.5) - 10.73 \qquad (5)$$

where M_0 is seismic moment that is a better measure of the size of a large earthquake [23]. Moment magnitude (M_w) is being increasingly used for moderate and large earthquakes all around the world.

The reasons for this result are (1) it is very quick process to calculate the M_w by using the modern instruments and analytical techniques; (2) it is tied directly to physical parameters such as fault area, fault slip and energy, rather than to amplitudes of particular seismographic records in particular frequency bands; (3) geodetic, field-geology and seismographic methods are used to estimation of it; (4) this magnitude is adequately suitable for the estimation of size of large earthquakes [26]. In addition, the best scale for scientific and engineering purposes is the moment magnitude (M_w) scale since it is related to the rupture parameters.

Because of the appropriate scientific and engineering usage for magnitudes, moment magnitude (M_w) was selected in this study for the construction of seismic hazard map. Moment magnitudes of scenario earthquakes sourced from different fault zones in an interested area can be calculated by using equations of Wells and Coppersmith [20], Aydan [21] and Ulusay et al [18]. To provide a uniform and reliable scale for attenuation relationship, the database from the Turkish strong motion stations, developed by Ulusay *et al*. (2004) have been used to determine the M_w from M_s values for Turkish earthquakes. The relationship and conversion equations between M_s – M_w, M_b – M_w, M_d – M_w, and M_L – M_w, which were also derived by Ulusay *et al*. [18] by considering the Turkish database, are given in Figure 5. Before defining the M_w, M_s values have to be found by using the probable surface rupture length of earthquake sources (Figure 6 from [22]). As it is mentioned before, there are four different fault zones. By using the surface length of these faults, possible rupture lengths are estimated and their relations given in Figure 6 are used to find the maximum magnitude (M_s) of an earthquake.

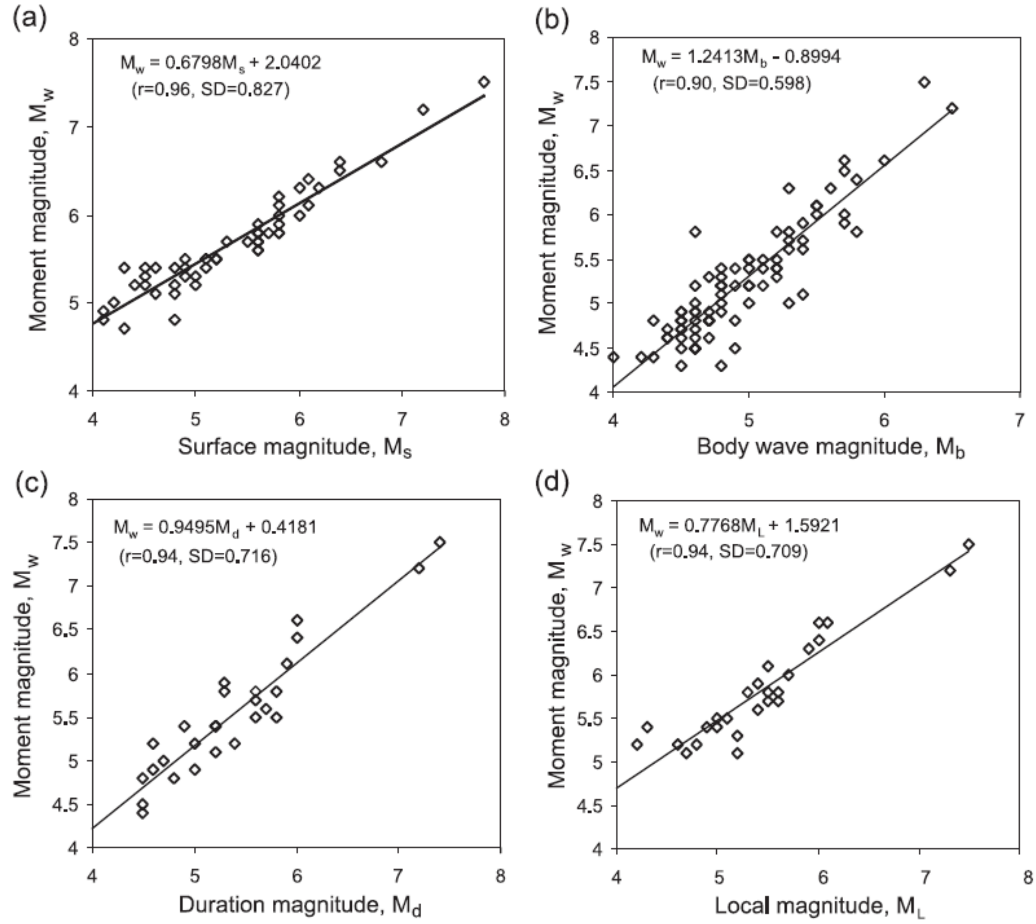


Figure 5. Correlations between M_w and M_s, M_b, M_d and M_L values for Turkish earthquakes (r: correlation coefficient; S.D: standart deviation) [18].

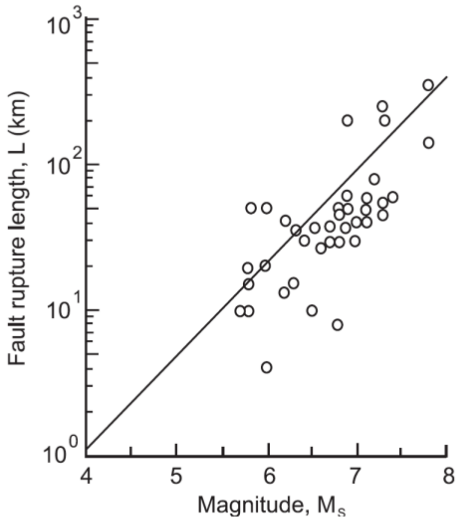


Figure 6. Relation between surface magnitude (Ms) and surface rupture length (L) based on the Turkish earthquakes [22].

Finally, the reference point to determine the maximum magnitudes for each fault zone is their total lengths. The most important issue is to find out their actual lengths. In this study, all earthquake sources cut through of the study area. Although the parts of the faults that are outside of the study area are not considered in the topic of this work geologically, they have to be included in all calculations because of their affects in case of an earthquake. By means of the total lengths, probable M_s and then M_w values and then can be calculated.

4.3. Determination of PGA values

The best way to estimate expected PGA is by investigating instrumental data of past strong earthquakes in interested area. This was not possible for this study, because, last strong earthquake took place in March 28, 1970 and at that time there was no strong motion station. In such cases different approaches are used to estimate.

PGA (peak ground acceleration) values can be calculated by using the M_w, distance between line for faults or epicenters for previous earthquakes and points assigned by the gridding on the map, and attenuation relationship equation. Attenuation relationship is a very controversial issue all around the world. Because of the dissimilar applications (PSHA or DSHA), special site conditions, different countries and authors, a number of attenuation relationships were proposed and each of them were used for different purposes. There are some studies for the calculation of PGA values by using the database of large Turkish earthquake [18, 19 and 20]. The equation suggested by Ulusay *et al.* [18] was used in this research.

We need to know M_w for each fault zones by means of their total length, and S_A and S_B (site conditions) values. $S_A = S_B = 0$ for rock (basement and volcanic rocks) (Figure 7), $S_A = 1$ and $S_B = 0$ for soil (Miocene sediments) (Figure 8), and $S_A = 0$ and $S_B = 1$ for soft soil (Plio-Quaternary and alluvial deposits) (Figure 9) are used [18]). All these input data have been evaluated by ArcGIS 9.3 computer programme. The calculated values are M_w= 6.7 for Şaphane Fault Zone, M_w= 6.6 for Simav Fault Zone, M_w= 6.6 for Muratdağı Fault Zone and M_w= 6.5 for Yeşilova Fault Zone. Then, the study area was separated into equal intervals as vertical and horizontal lines (gridding). This grid system is composed of 2667 points. For each point, firstly, S_A and S_B site conditions were assigned.

Secondly, attenuation relationship suggested for Turkish earthquakes by Ulusay et al., [188] was employed for this analysis.

$$PGA = 2.18\, e^{0.0218(33.3M_w - R_e + 7.8427S_A + 18.9282S_B)} \qquad (6)$$

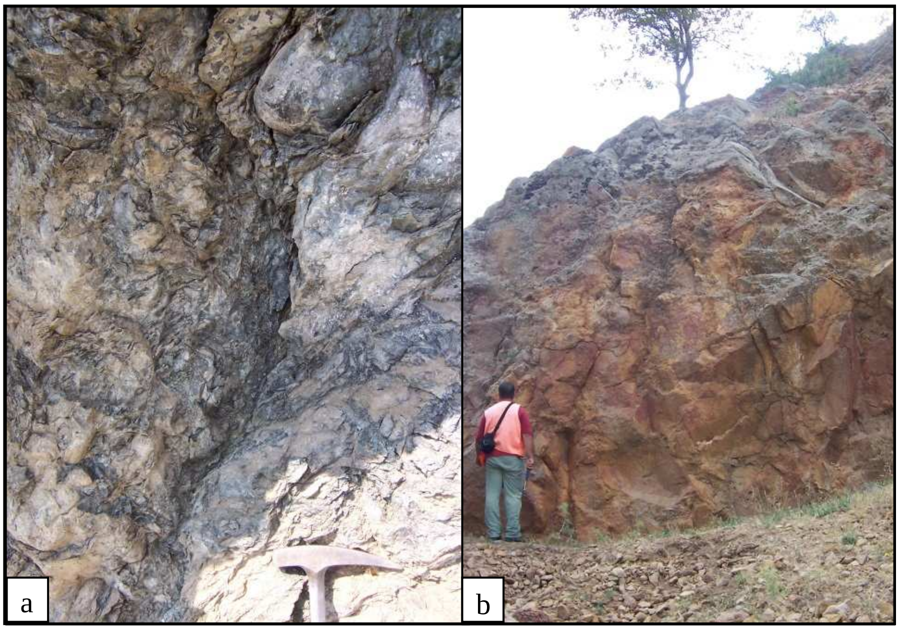


Figure 7. Close up view of the basement (a) and volcanic rocks (b) ($S_A = S_B = 0$).

Figure 8. General view of the tilted Miocene limestone beds ($S_A = 1$ and $S_B = 0$).

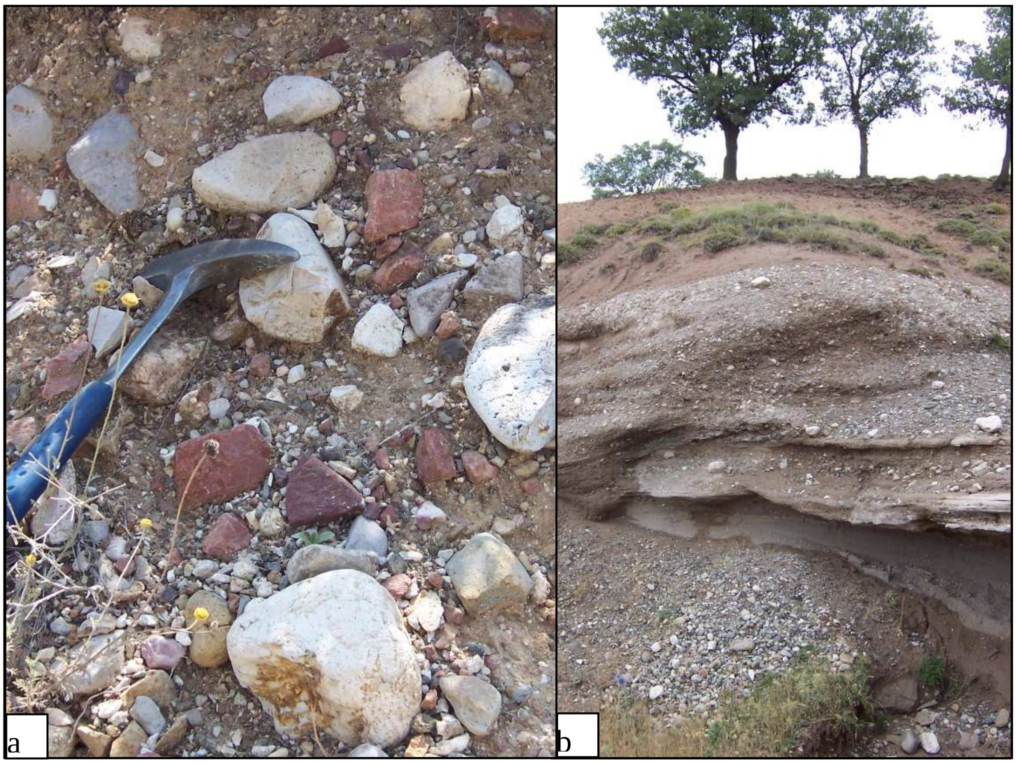


Figure 9. Close up view of the Plio-Quaternary (a) and alluvial deposits (b) (S_A= and S_B = 1).

All unknown parameters have been determined such as total length of faults (earthquake sources) for maximum magnitude, gridding of the study area and the distance between center points of all gridding square and faults, site conditions (S_A and S_B), and attenuation relationship. Later on, the study area can be analyzed by using the computer program for each fault zone. It means that four different maps for four scenario earthquakes have been produced. Additionally, one more map has also been produced by using the epicenter of the 1970 Gediz earthquake as a point source. And then, these five maps have been compared to each other.

5. Flow Chart of the Deterministic Seismic Hazard Mapping

Scenario-based deterministic approach is more appropriate and it allows the user to a realistic definition of PGA in scenario-like format to be accompanied by the determination of advanced hazard indicators. The steps which can be applied in the deterministic approach have been explained before. According to this flow chart, the geological map of study area has been prepared as containing main rock or soil types (Figure 10). Mapping is significant to determine the ground motion (shaking) in case of a scenario earthquake. Two different scenario earthquakes have been arranged for the deterministic approach. First one is the reactivation of fault zones. Second is the previous events which gave huge damages on the study area, taken as a reference earthquake (28.03.1970 M_w= 7.2 Gediz earthquake) to create scenario earthquake. It gives approximately 9 km surface rupture length and can yield ~ 6.6 M_w that is calculated by total length of the fault zone. In this study, type of faulting is not considered in the usage of the attenuation relationship. In some recent studies [27, and 28], the attenuation models have different ground motion from reverse and strike-slip earthquakes.

In summary,

1) Detailed geological mapping (Figure 10) have been prepared during field work,
2) The map have been gridded (Figure 11) for the values of S_A and S_B,
3) S_A and S_B values for each point have been assigned,
4) Shortest distance between fault line and assigned points have been calculated (R_e),
5) M_w values have been determined for each fault line and 1970 Gediz earthquake,
6) Lastly, by using the PGA formula suggested by Ulusay *et al*., [18] have been applied.

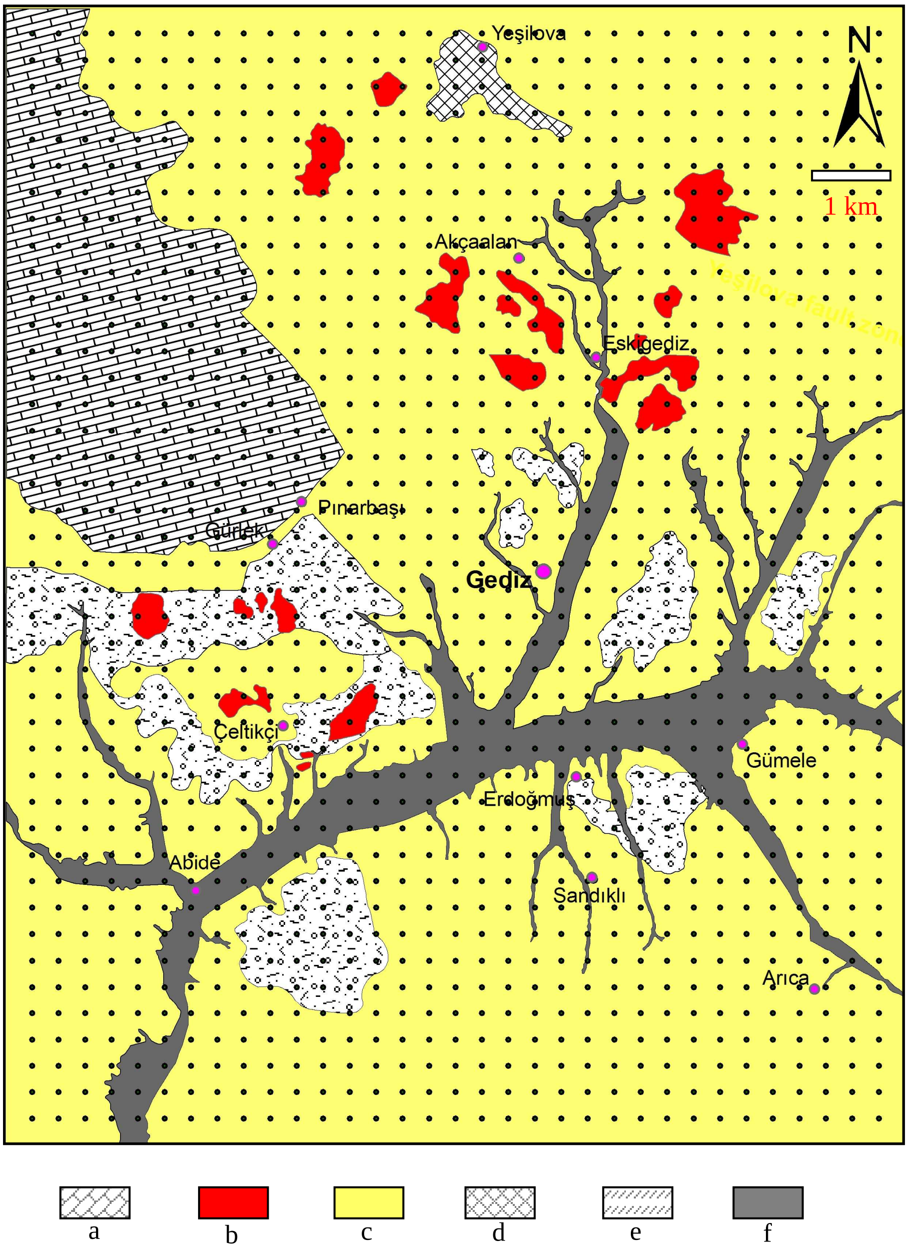


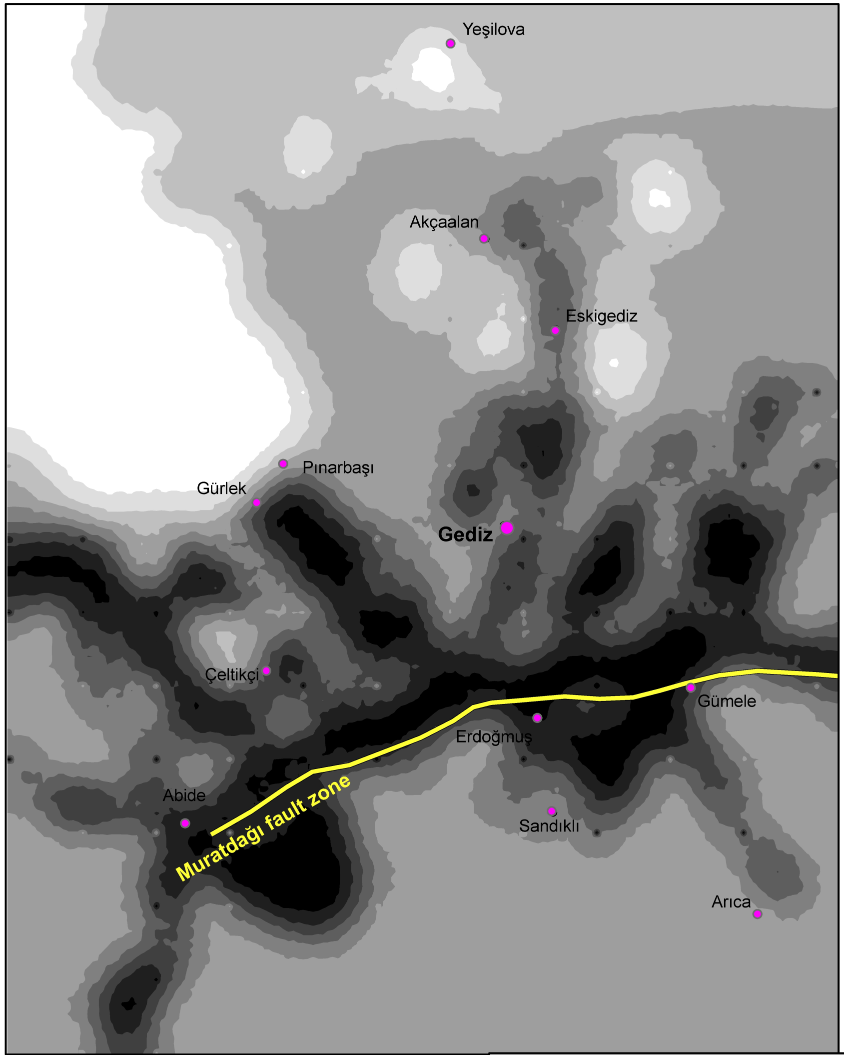
Figure 10. Geological map of the study area. a. recrystalline limestone, b. volcanic rocks, c. limestone-marl intercalation, d. travertine, e. terrace deposits, f. alluvial deposits.

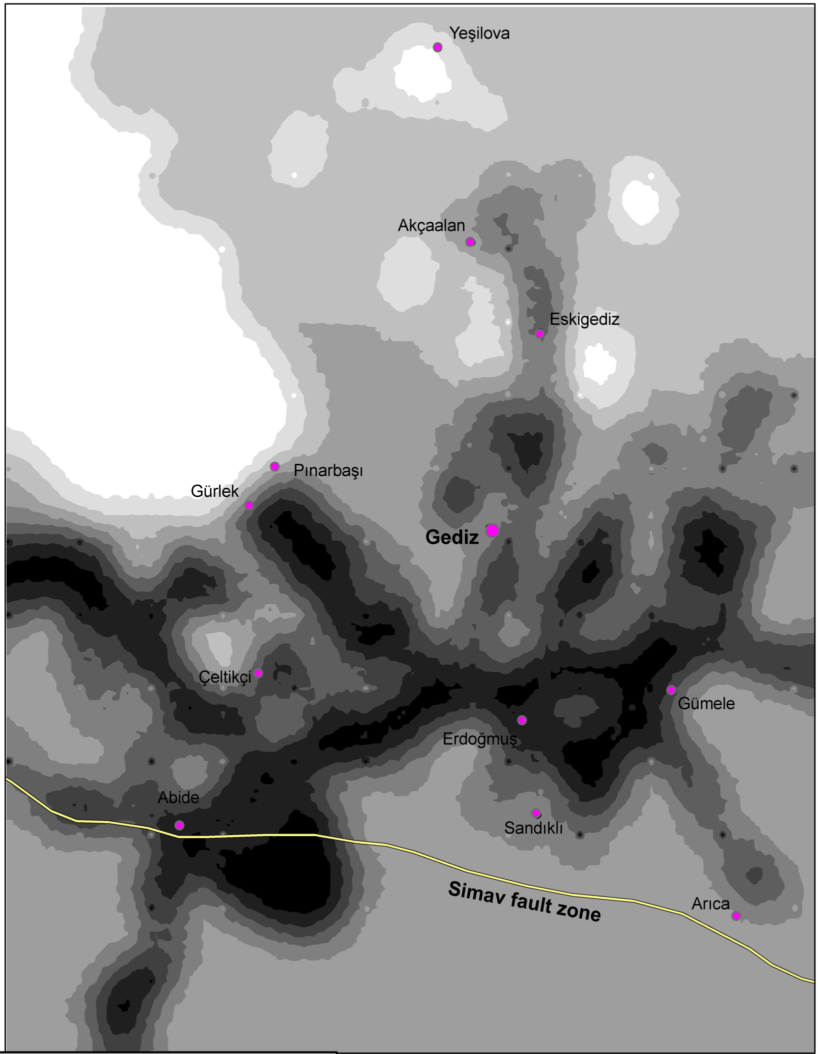
6. Results of the DSHA

According to 2667 point locations (Figure 10), results of the DSHA have been submitted. For each point, S_A and S_B values were described by considering the rock types and the closest distance to the source fault have been calculated. Based on the distance, zonation of PGA values has been performed for four faults. The results for Muratdağı (Figure 11), Simav, (Figure 12), Şaphane (Figure 13) and Yeşilova (Figure 14) fault zone have been presented.

The detailed examination of these results indicates that the PGA values changes in the range of 0.233 – 0.366 g. The peak values are observed in the places where major fault zone and alluvium exist. Oppositely, volcanic and metamorphic rocks yield very low PGA values.

One more deterministic seismic hazard analyses (Figure 15) has been applied for point source as epicenter of 1970 Gediz earthquake (red star in Figure 15). When it was examined in detail, the result is exactly the same as the result of Yeşilova Fault Zone. Because, the epicenter of this earthquake is very close to Yeşilova Fault Zone and their products are coincided.





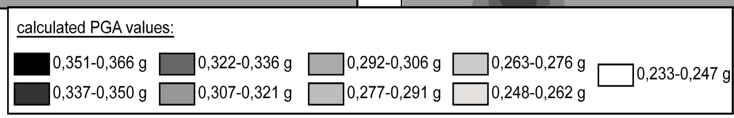
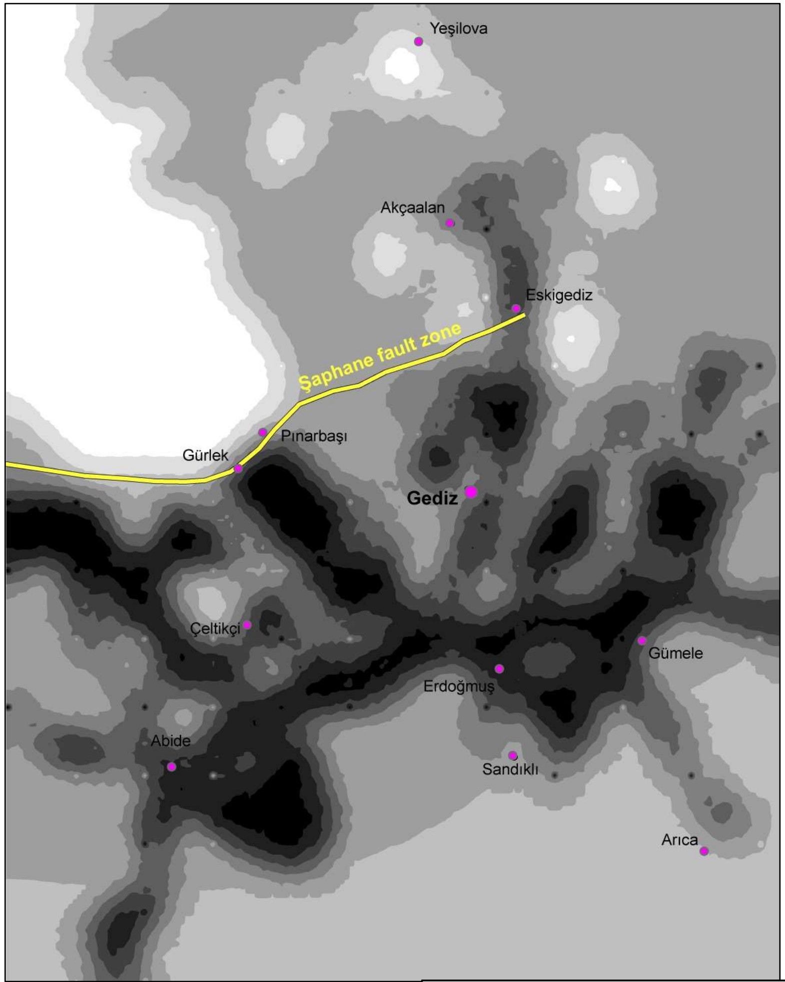
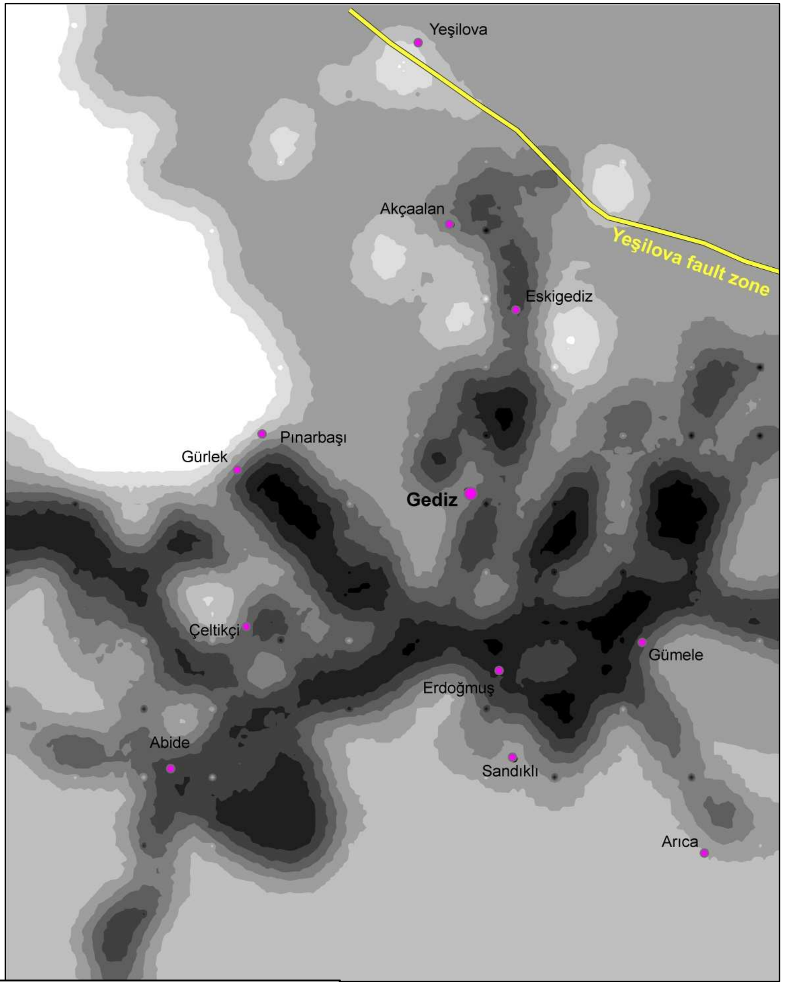


Figure 11. Deterministic seismic hazard map showing ground motions (PGA) expected from M_w 6.7 scenario earthquake sourced from Muratdağı fault zone.

Figure 12. Deterministic seismic hazard map showing ground motions (PGA) expected from M_w 6.6 scenario earthquake sourced from Simav fault zone.





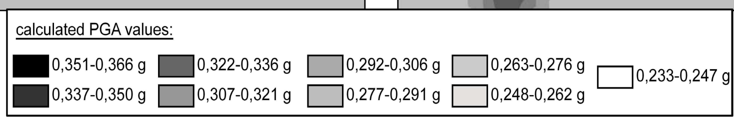


Figure 13. Deterministic seismic hazard map showing ground motions (PGA) expected from M_w 6.6 scenario earthquake sourced from Şaphane fault zone.

Figure 14. Deterministic seismic hazard map showing ground motions (PGA) expected from M_w 6.5 scenario earthquake sourced from Yeşilova fault zone.

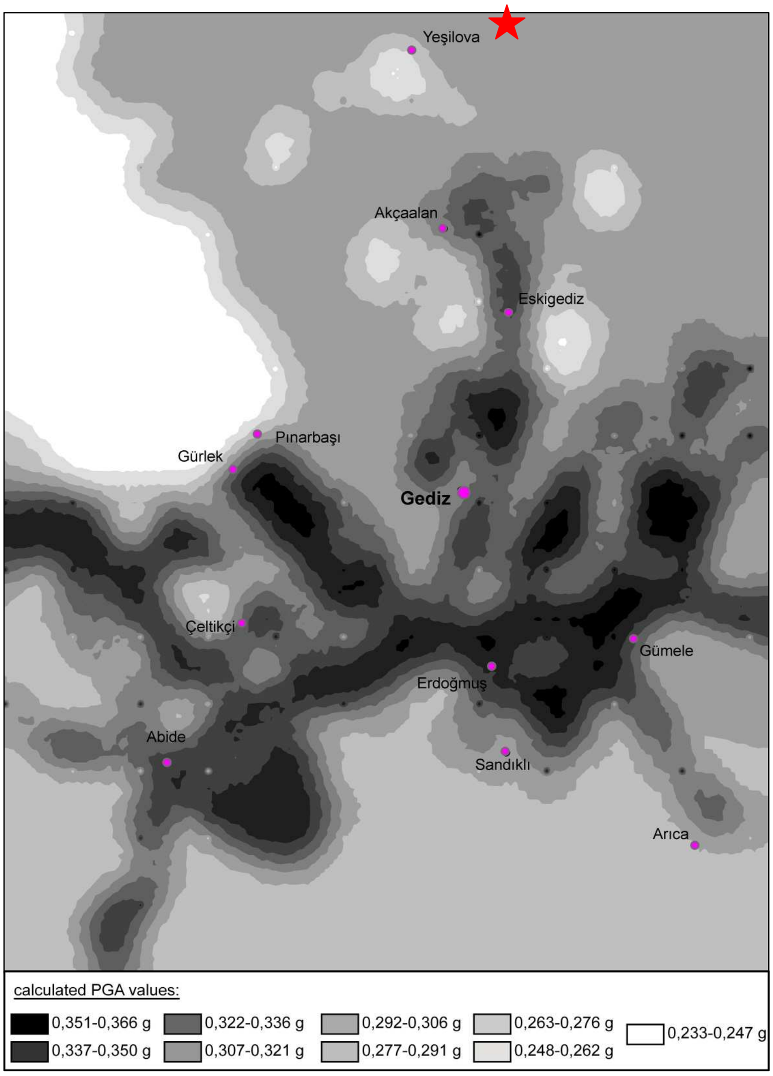


Figure 15. Deterministic seismic hazard map showing ground motions (PGA) expected from M_w 7.2 1970 Gediz earthquake (red star is the epicenter of the earthquake).

Lastly, the comparison between computational result of the 1970 Gediz earthquake (Figure 15) and izoseist distribution (Figure 16) after the earthquake shows some differences because of the scale disparity. But, general trend of the high PGA values between Yenigediz and Akçalan is approximately N-S in trend. In Figure 16, same pattern is observed for intermediate and intermediate to high intensity area.

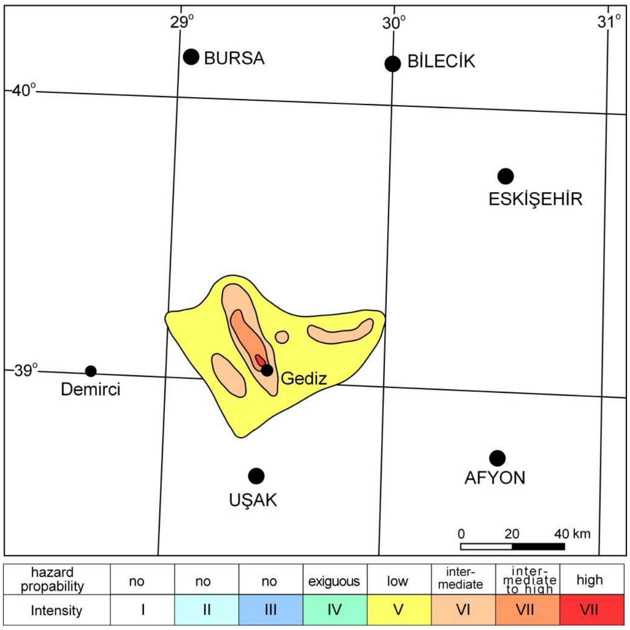


Figure 16. Izoseist map of the 1970 Gediz earthquake [29].

6. Conclusion

Rock and soil type mainly control the damages. PGA distribution of the study area shows that clearly. Figure 15 has been prepared by the Gediz earthquake with M_w 7.2 magnitude. Comparison between Figure 15 and Figure 16 indicates that approximate high PGA values are almost N-S in trend.

The deterministic approach gives a clear and trackable method of computing the distribution of PGA whose assumptions are easily discerned. This is the first step for the preparation of seismic hazard mapping. Addition to this step, site effect and many other input must be included such works. Therefore, the users of these PGA distribution map should be chary. Because, hazard is controlled by many factor. This research includes only geological features and attenuation relationship.

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