Seismic Hazard Assessment for Çetin Dam

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SUMMARY:
The seismic hazard study performed for Çetin Dam, Turkey is presented. For maximum design earthquake (MDE), both deterministic and probabilistic approaches have been utilized. The deterministic evaluation has considered detailed fault investigation and the peak ground acceleration (PGA) is obtained by three recent ground motion prediction equations (GMPEs). A probabilistic analysis has also been performed where Crisis2007 program is utilized. The operating basis earthquake (OBE) is obtained for a return period of 145 years according to ICOLD(1989). For MDE, both the results by probabilistic approach for 2475 and 10000 year return periods and by deterministic approach are considered. The standard error in GMPEs is taken into consideration somehow differently in deterministic and probabilistic approaches. In the deterministic approach, the uncertainty is generally bounded by adding one or two standard error terms, but log-normal distribution and full uncertainty of ground motion variability can be considered in the probabilistic calculations. Related comparisons are discussed. Considering all results, it is concluded to designate the MDE deterministically.

Keywords: Seismic hazard, dam

1. INTRODUCTION

The seismic hazard analysis can be simply defined as a study in order to ascertain the earthquake hazard data in a quantitative way, devoted to the design or seismic risk evaluations. This study should include the uncertainties related to the location and time variations. For the seismic hazard evaluation, there are two main approaches, occasionally regarded as seperate, but should be considered as complementary in authors' opinion. These are referred as the deterministic seismic hazard analysis (DSHA) and probabilistic seismic hazard analysis (PSHA).

This paper presents a general review on seismic hazard study concerning the misunderstandings and discussions about the subject approaches, and a summary of the seismic hazard evaluation performed for Çetin Dam location in Turkey.

2. REVIEW ON SEISMIC HAZARD ANALYSES

2.1. Deterministic Seismic Hazard Analysis (DSHA)

In DSHA, the maximum magnitudes (maximum credible earthquake, MCE) for the earthquake sources (point, line or area) related to the site are determined considering geological and seismotectonic characteristics. In the determination of the maximum level of ground motion at site, the MCE's are assumed to occur at the closest locations of the seismic sources to the site. The ground motion parameters for the site such as peak ground acceleration (PGA) are obtained by utilizing GMPEs for each seismic source and corresponding MCE. The MCE for the seismic source that leads to the maximum level of the ground motion at the site is defined as the controlling maximum credible earthquake, CMCE, which is taken into account for the design parameters. The return period of the deterministic ground motion is out of concern due to its definition with maximum magnitude and minimum distance.

2.2. Probabilistic Seismic Hazard Analysis (PSHA)

PSHA involves the evaluation of the ground motion level and its probability at a site for a specified time interval. In this method, the seismic hazard at a site due to a single source is obtained by addition of the probability functions as: probability of an earthquake with a particular magnitude to occur during a specified time interval, probability that the described earthquake will occur at a specified distance from the site, and the probability that the ground motion resulted by the described magnitude and distance will exceed a specified level at the site (USCOLD, 1999). A specified level of ground motion for a specified period of time can be determined by combining these three probability functions for each source; so the ground motion parameters can be obtained for a desired risk level.

As stated in ICOLD (1989) or USCOLD (1999), the same seismic sources are taken into account in the deterministic or probabilistic approaches. The difference is, only the earthquake source resulting in the maximum ground motion level is considered in DSHA, whereas all of the earthquake sources greater than a specified magnitude are taken into account in PSHA. In this regard, the MCE's are indispensably the same for the common sources used in both deterministic and probabilistic analyses.

2.3. Ground Motion Prediction Equations and Uncertainties in Seismic Hazard Evaluation

The ground motion characteristics in a specified area are estimated by using GMPEs derived by statistical evaluation of earthquake and site records, considering the parameters such as magnitude, distance to the seismic source, fault type, local soil conditions ..etc. Most of the GMPEs are intended to estimate the peak ground acceleration that plays the most significant role in seismic design.

Ground motion prediction equations are in a range of simple equations with a few parameters to very advanced ones involving many parameters because of the complexity of the phenomena. These relationships are given with their variance and standard deviation parameters to account for the uncertainties involved in the statistical evaluation. Some other uncertainties are of concern in the inputs of the seismic hazard study such as the expected earthquake magnitudes, seismic source locations, fault characteristics and site conditions.

It is clear that these substantial uncertainties in the ground motion prediction functions and other seismic parameters should be taken into consideration in the analyses. The variability in the seismic hazard may be groupped into two, namely as aleatory variability and epistemic variability. The aleatory variability is due to uncertainties of the data such as geology, seismotectonics ..etc, assuming the prediction model is correct. Epistemic variability, on the other hand, include the uncertainties in the algorithms of the analysis methods. The aleatory variability is included directly in the PSHA by means of mathematical integration, such as controlling the number of standard errors in ground motion prediction functions. Epistemic variability can be taken into account by including alternative prediction models (Thenhaus & Campbell, 2003) such as using different seismotectonic models and/or GMPEs.

The uncertainties are taken into account in both methods of DSHA and PSHA. According to the authors, the ongoing discussion about the preference or superiority of either method is mainly resulted from the point how these uncertainties should be reflected in these approaches. In the authors' opinion, the uncertainties should be involved similarly in these two methods of analysis, as the effective inputs and prediction models are identical. It is also worthy to note that, a superposition of the extremes should be avoided in the consideration of these uncertainties in different stages of the evaluation and parametric studies should be preferred.

3. DESIGN EARTHQUAKE CONCEPT

There are two different earthquake levels suggested by international agencies (ICOLD,1989 ; USACE, 2007) to be considered in the seismic design of dams. The first one, named as the operating basis earthquake, OBE, is defined as the earthquake with a return period of 144 years by ICOLD. Based on its definiton, it is assessed by probabilistic analysis. The maximum design earthquake, MDE (or safety evaluation earthquake, SEE, defined by ICOLD, 2010) is defined as the earthquake that generates the maximum ground motion level according to the assumed tectonics. MDE can be obtained deterministically by considering MCE, or by probabilistic approach assuming a high return period such as 2500, 5000, 10000 years based on factors like specified tectonics, seismic activity, dam importance and risks related to downstream.

The performance criteria are different for these two earthquake levels. After OBE the dam, appurtenant structures and equipment need to remain functional and damage need to be easily repairable. After an earthquake of MDE level, damage to the dam and appurtenant structures are considered as acceptable, but a catastrophic failure which may lead to an uncontrolled release of reservoir water and life loss should not occur.

There is an ongoing significant discussion about which approach to be used and the incorparation of the variability for determination of MDE. The authors suggest that, because of the inherent characteristics of the seismic hazard evaluation, it is not possible and reasonable to bring strict criteria about the method, return periods or the way to be followed in inclusion of the uncertainties; but seismic hazard for each site should be evaluated by a complementary and parametric study considering different approaches. It is noted that, the results of hazard evaluation are very sensitive to the inputs and assumptions, terms may vary from place to place. Therefore, the analyst should also consider the local site and design conditions in the final decision, with no concessions on safety.

4. SEISMICITY OF THE AREA AND EARTHQUAKE SOURCES

4.1. Layout of the Seismic Sources

The planned location for Çetin Dam with the coordinates of 37.97(Lat.) and 42.39(Long.) is in the East Anatolian Contractional Province. As it can be seen from Figure 4.1, the fault zones affecting the project area are the Bitlis-Zagros Suture Zone in the south, East Anatolian Fault Zone (EAFZ) and North Anatolian Fault Zone (NAFZ) in the north-west of the area.

A detailed study involving the active faults affecting the project area has been conducted (Perinçek, 2009) and the active faults in the immediate vicinity of the dam are defined with their locations and estimated maximum magnitudes. According to the subject study, the controlling seismic source corresponding to MCE for the dam site is Damlı-Beşan Fault with an estimated maximum magnitude of M_w=6.80 and closest distance of 12.5 km to the dam site. Southeast Anatolian Fault Zone, defined as a probable active fault in the Active Fault Map of Turkey, is interpreted as inactive for the region relevant to dam site between Siirt and Hakkari by the corresponding author. The mechanism of Damlı-Beşan Fault has been given as strike-slip.

Earthquakes with a magnitude of gretaer than four, occurred surrounding the project area is shown in Figure 4.2 on which the dam location and the faults are also shown. In the evaluation, the list of the earthquakes with magnitudes larger than M_w>4 occurred in the years between 1900 – 2005 in the vicinity of the project area is obtained from “Boğaziçi University Kandilli Observatory and Earthquake Research Institute” and used for the calculations.

The seismic sources to be considered in the seismic hazard calculations are determined according to the earthquake occurrences, fault zones and active fault map by detailed investigation. In this sense, 5 area and 1 line sources are taken into account for the project location and surrounding area. The layout of these sources are shown in Figure 4.2.

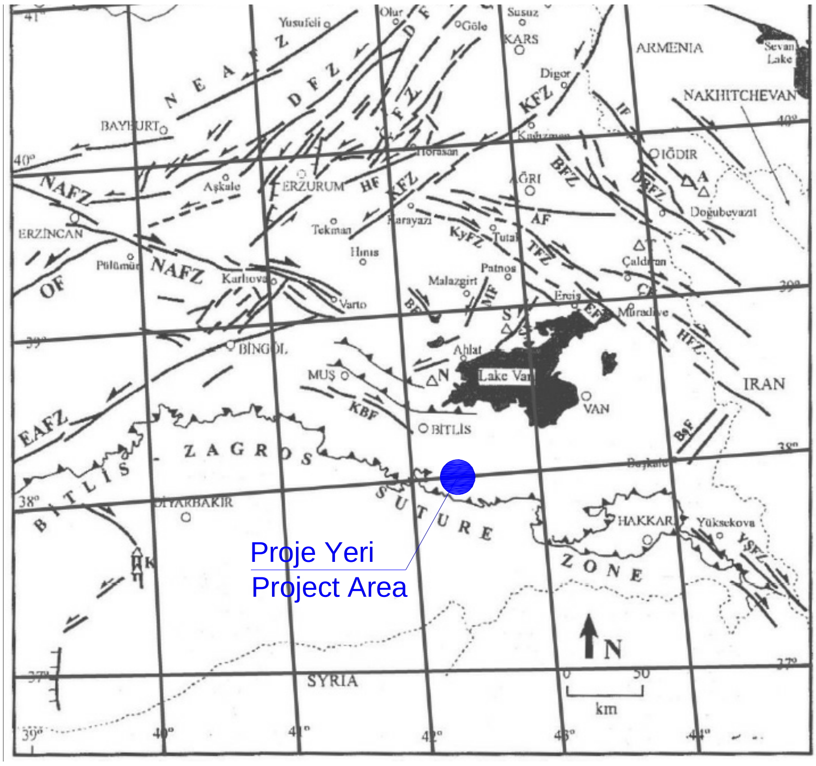

Figure 4.1. Fault Zones Surrounding the Project Area (Bozkurt,2001)

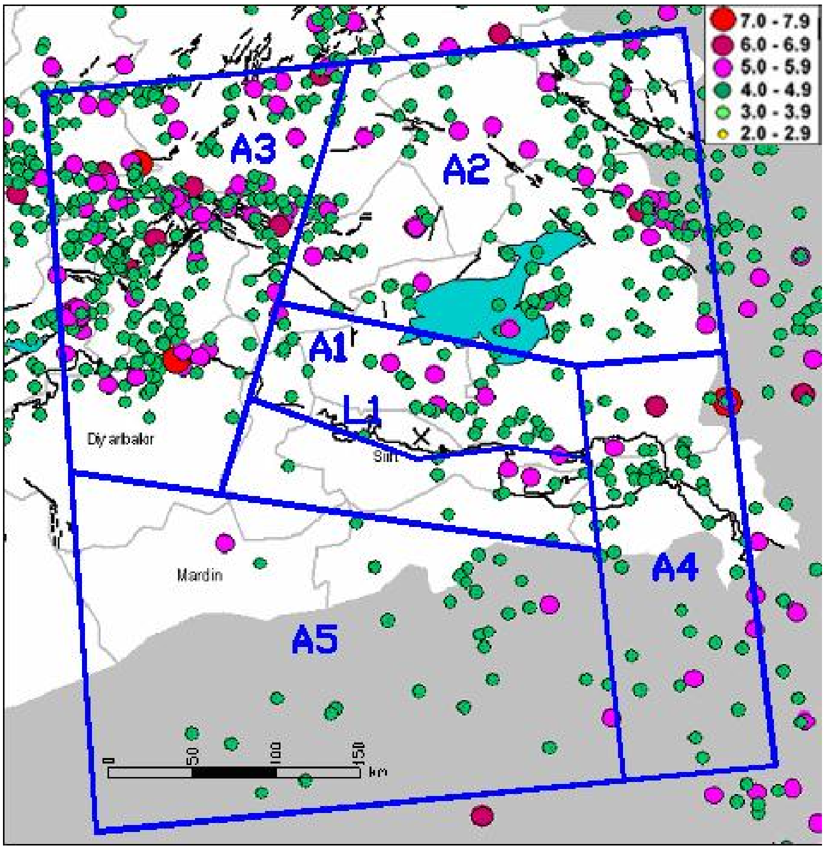

Figure 4.2. Earthquake Map and Seismic Sources Used in Evaluation (Dam Location is marked with “X”)

The earthquakes occurred in the closest seismotetonic zone to the project location, is considered as A1 area source and L1 line source composed of three line segments. The L1 line source layout is based on the active fault map given in detailed investigation mentioned previously.

The earthquakes to the south and north of this zone are taken into account as A2 and A5 area sources respectively. Moreover, the area which is a part of NAFZ, to the west of the project location, is considered as A3 area source; and the earthquakes with relatively large magnitudes to the east of the project location is taken into account as A4 area source.

4.2. Magnitude – Frequency Relationship

The conventional Gutenberg-Richter recurrence law is used to determine magnitude-frequency relationship of the seismic sources to be used in the analysis. The reader is referred to Kramer (1996) for detailed information on magnitude-frequency relationships and Gutenberg-Richter law. The respective parameters of the sources are determined according to the earthquake magnitudes and occurrences and summarized in Table 4.1. The magnitude-frequency curve for Area 3 is given as an example in Figure 4.3.

Table 4.1. Parameters of Seismic Sources

Sources	a	b	M_{maks}	M_{min}
A1	3.59	0.91	6.0	4.0
L1	3.59	0.91	6.8	6.0
A2	4.24	0.94	6.8	4.0
A3	4.14	0.88	7.0	4.0
A4	2.48	0.67	7.6	4.0
A5	2.74	0.79	6.0	4.0

In the report by Erdik et al. (2006), prepared to DLH (General Directorate of Railways, Harbours and Airfields), line sources are considered for main fault zones and the earthquakes with magnitudes M_w>6.5 are assumed to occur on these line sources. The epicenters of the earthquakes with smaller magnitudes are considered to spread over a wider area for each source zone. The same approach is utilized for A1 and L1 sources.

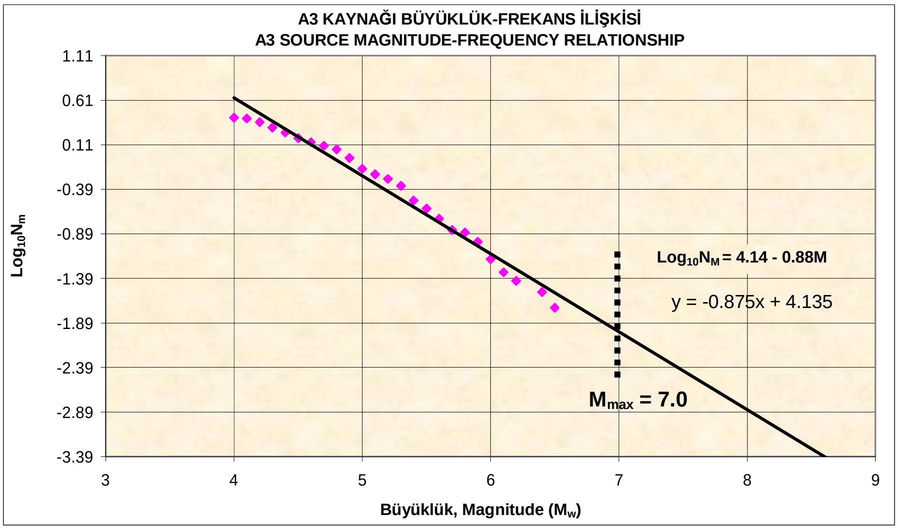

Figure 4.3. Magnitude – Frequency Relationship for Area Source 3

In the same report, Bitlis-Zagros Suture Zone is defined as the Z43 fault zone where the maximum magnitude for the outer area is suggested as M_{max} = 5.0 – 6.6, and the maximum magnitude for the inner fault line is considered to be M_{max} = 6.7 – 7.0. The L1 line source used in this evaluation considers the Damlı-Beşan Fault presented in the active fault study. The subject study suggests the maximum magnitude of M_s=6.95, that corresponds to a M_w of 6.8. In this sense, the maximum magnitude for L1 line source is assumed as M_{max} = 6.8, while the maximum magnitude of M_{max} = 6.0 is taken for the outer area as A1. The minimum magnitude is assumed as M_0 = 4.0. The maximum magnitudes for the other area sources are determined by a simple approach as adding 0.5 units to the maximum recorded magnitudes.

5. SEISMIC HAZARD ANALYSES

5.1. Ground Motion Prediction Equations

In the seismic hazard analyses for the dam location, the peak horizontal ground acceleration has been determined by taking the average of the results obtained by using three different GMPEs which have been developed for PEER Next Generation Attenuation of Ground Motion (NGA) Project as: Campbell and Bozorgnia (2008), Chiou and Youngs (2008) and Boore and Atkinson (2007). In this way,it was intended to consider the epistemic uncertainty, discussed in Section 2.

The shear wave velocity of the foundation rock has been taken as V_s = 1200 m/s, which is used to reflect local soil conditions in all three prediction functions. Boore and Atkinson (2007) relationship is rather simple compared to the other two, as it requires less number of parameters. The PGA can be obtained by the inputs of moment magnitude, the Joyner-Boore distance (r_{jb}), shear wave velocity of the site and fault type. The other prediction functions used in the evaluation require some other parameters such as the closest distance to the rupture plane.

5.2. Deterministic Evaluation

The evaluation of the seismic hazard by deterministic approach has been supported by the active fault study in the vicinity of the project area. According to this study, the controlling source for MCE is Damlı-Beşan Fault with a maximum magnitude of M_w=6.8 at a Joyner-Boore distance of r_{jb}=12.5 km to the dam site. The abovementioned GMPEs have been used to estimate the peak ground acceleration with these parameters, and the obtained results are given in Table 5.1.

In order to include the aleatory variability in deterministic evaluation, it has been found reasonable to consider 84'th percentile values by adding one standard error to the median for the design PGA. The median and 84'th percentile results are summarized in the following table. It can be seen that, very similar results have been obtained by three different relationships.

Table 5.1. Summary of DSHA Results

	Campbell and Bozorgnia, 2008	Chiou and Youngs, 2008	Boore and Atkinson, 2007	Average
PGA (g) [median]	0.18	0.19	0.17	0.18
PGA (g) [median + σ]	0.30	0.32	0.31	0.31

5.3. Probabilistic Evaluation

The probabilistic seismic hazard analyses have been conducted by the computer program Crisis2007 written by Ordaz et al. The seismic sources with layouts and parameters given in Section 4 have been used in the respective calculations.

The GMPEs have been implicated in the program by the externally prepared attenuation tables where the PGA variation is given according to the magnitude and Joyner-Boore distance, r_{jb}. The program allows the use of unbounded or truncated lognormal distribution of the ground motion in the calculations. An unbounded log-normal distribution has been considered in the analyses and the obtained results are summarized for different return periods in Table 5.2. The results for median values are also given in the same table.

Table 5.2. Summary of PSHA Results

	Camp. & Boz, 2008	Chi. & You., 2008	Bo. & Atk., 2007	Average	Return Period (years)
PGA (g) [median]	0.099	0.079	0.079	**0.09**	145
PGA(unbound. with σ)	0.121	0.091	0.097	**0.10**	
PGA (g) [median]	0.194	0.163	0.156	**0.17**	2475
PGA(unbound. with σ)	0.316	0.270	0.277	**0.29**	
PGA (g) [median]	0.239	0.204	0.225	**0.22**	10000
PGA(unbound. with σ)	0.444	0.388	0.405	**0.41**	

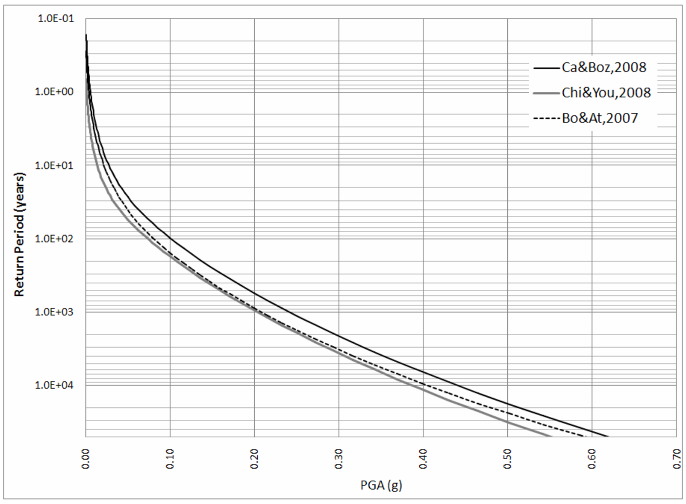

Figure 5.1. PGA Curves for Different GMPEs by PSHA

The obtained hazard curves are shown in Figure 5.1 for unbounded distribution of the ground motion. As the distribution is not truncated to a specified acceleration or number of standart errors, the PGA significantly increases with increasing return period.

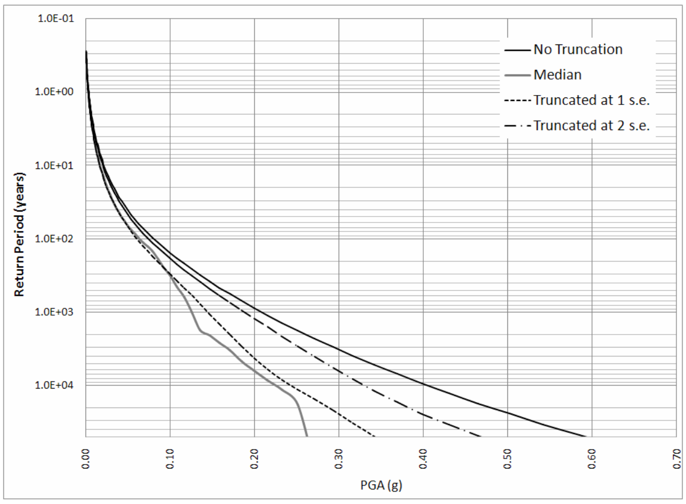

Figure 5.2. PGA Curves for Different Truncation Levels by Boore & Atkinson (2007) Relationship

Here it is worthy to mention that the small differences between the results of different GMPEs might also be affected by the conversion of closest distance to rupture to Joyner-Boore distance for Campbell and Bozorgnia (2008) and Chiou and Youngs (2008) GMPEs.

Incorporating directly the aleatory variability of the ground motion has become a mandatory practice in any hazard analysis. Besides, it is a widely accepted approach to truncate the distribution of the ground motion at a specified number of standard errors to prevent unrealistic predictions (Campbell, 2003). Figure 5.2 shows the results for different truncation levels using the Boore and Atkinson (2007) ground motion prediction equation. The substantial effect of the variability on the predicted PGA's are clearly observed in the subject figure. It is also seen that the difference in predicted PGA due to truncation gets larger with increasing return periods. Here, a careful and reasonable assessment is clearly necessary for the contribution of the aleatory variability of ground motion. As stated by Thenhaus and Campbell (2003), large contribution of the variability should be avoided to prevent the GMPE be overly dominated by the variability itself.

In the hazard curve by probabilistic analysis, the combined effect of all magnitudes and distances on the probability of exceeding a specified ground motion level is considered. A process, called as disaggreagation (also called as deaggregation) is a common method to break the hazard back down into its contributions from various magnitude-distance pairs (Abrahamson, 2000). In this way, the relative contribution of different events is computed and the most important events for the hazard can be determined. The results of disaggregation are different for different return periods.

A disaggregation analysis has been conducted for the site, using the same program, to determine the controlling magnitude-distance pairs on the seismic hazard. Figure 5.3 shows the disaggregation plots for 145, 2475 and 10000 year return periods, by using Boore and Atkinson (2007) relationship to provide insight to the contribution and importance of the specified seismic sources. It can be observed that most of the contribution is from the earthquakes with magnitudes around 6.5 and with a distance around 18 km, indicating that L1 line source is the controlling seismic source for 145 year return period. The contribution of A1 area source, with earthquakes of magnitudes around 5.5 at the immediate vicinity of the dam reaches the contribution of the line source for 2475 years. As the return period increases, the relatively small magnitude earthquakes just at the dam location prevail and control the hazard, as indicated in the plot for 10000 years. As the A1 area source is defined that any earthquake with a magnitude up to 6.0 can occur within the specified area including the dam location, the variability in the ground motion prediction functions corresponding to small magnitudes with a distance of $r_{jb}=0$ dominates the seismic hazard.

5.3. Design Ground Motion Parameters

PGA for OBE has been estimated as 0.10 g for a return period of 145 years, according to the definition of ICOLD.

To determine the PGA for MDE, the results of both deterministic and probabilistic analyses have been considered. As given in Section 5.2, the PGA has been obtained as 0.31 g for the controlling seismic source of Damlı-Beşan Fault. Here, it is found reasonable to include the variability of the ground motion by adding one σ to the median value in the GMPE. It is worthy to note that, this level of ground motion is not the precise or real maximum level, since uncertainties are of concern in the location and specified maximum magnitude for the fault, and there is a 16% probability that this level may be exceeded according to the ground motion prediction functions. Nevertheless, this has been considered a reasonable maximum ground motion level by means of deterministic approach to be considered in the design, with complementary data from probabilistic analyses.

A PGA with a high return period (2500 years or more) is generally suggested for MDE by probabilistic approach. In the probabilistic analyses where the unbounded lognormal distribution of the ground motion has been considered by taking full uncertainty of the prediction equation, for 2500 years the PGA has been obtained as 0.29 g as slightly lower than the one obtained deterministically. A significantly high PGA of 0.41 g has been estimated for a return period of 10000 years. It is shown in Section 5.2 that this high PGA is mainly induced from the variability of the ground motion prediction functions for small magnitude earthquakes just at the dam location; and a truncation in the distribution of ground motion significantly reduces the results at these high return periods.

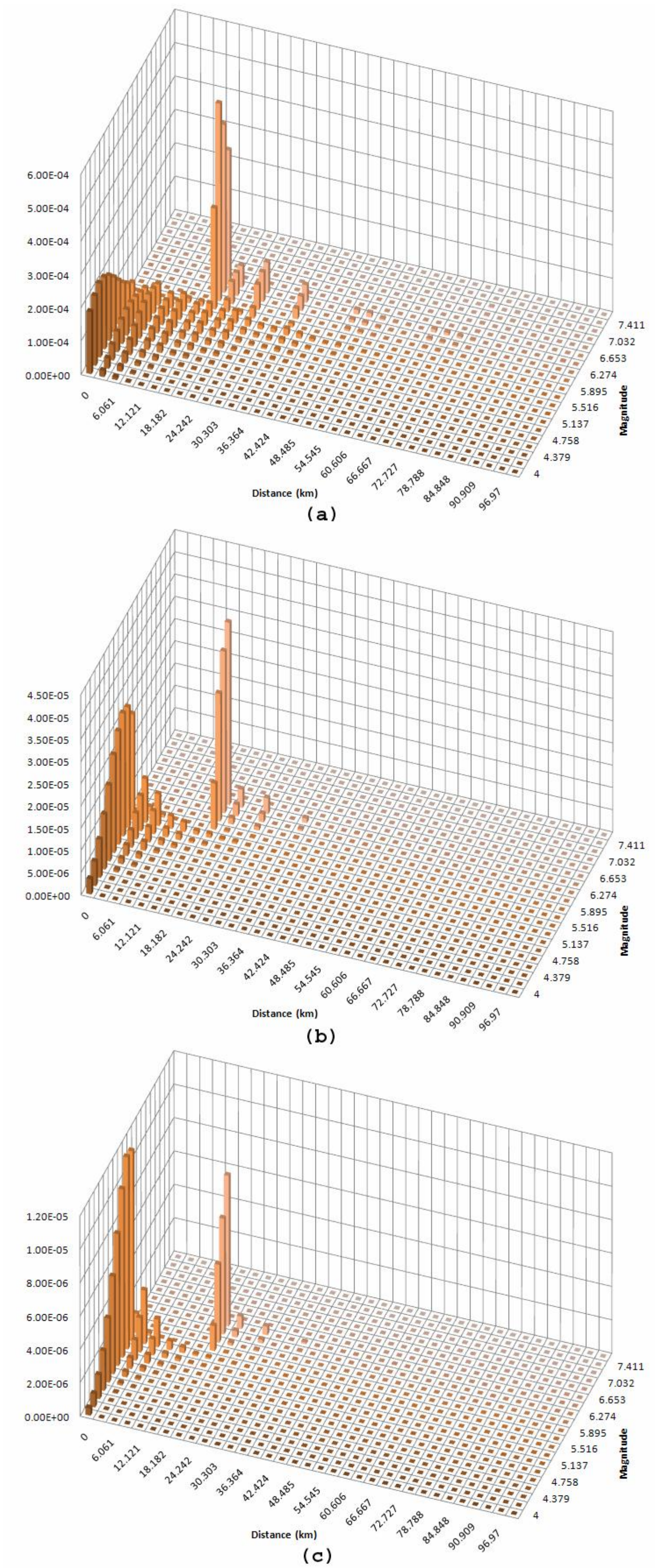

Figure 5.3. Disaggregation Plots for 145 (a), 2475 (b) and 10 000 (c) years

In the light of these data, the MDE to be used in the design has been suggested as PGA = 0.31 g considering the deterministic analysis based on the detailed fault investigation. This PGA is greater than the one obtained for 2475 years return period with full uncertainty, and similar to the one obtained for 10000 years return period by truncating the variability at two σ.

6. CONCLUSIONS

The deterministic and probabilistic approaches, that occasionally regarded as separate, are two methods that should be used as complementary in the seismic hazard evaluation. The seismic hazard assessment for Çetin Dam, Turkey has been presented where both methods are utilized with this principle. The results of the deterministic, and probabilistic analyses with various return periods have been discussed; by also concerning different truncations in the variability of the GMPEs. It has been concluded to designate the MDE by deterministic approach, supported by the detailed fault investigation, for this specific site. The results of probabilistic analyses including disaggregation for different return periods have also been taken into account and necessary comparisons have been made in order to reach this conclusion.

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