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Earthquake Safety Evaluation of Large Dams in Lower Seyhan Basin, Turkey

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Abstract: The seismic hazard of a dam site based on the peak ground acceleration and risk rating of the dam based on the capacity of the reservoir, the height of the dam, the evacuation requirements, and the potential downstream damages are the dominant factors acting on the general stability of dams. This paper summarizes the methods considered for earthquake safety evaluation and introduces the results of a study, which was performed for the large dams, namely Berdan, Catalan, Seyhan, Sanibey and Nergizlik dams in Lower Seyhan basin. The investigation area is structurally cut by numerous faults, which are resulted by East Anatolia Fault System. The seismic hazard analyses have indicated that peak ground acceleration changes within a wide range for the five dam sites of this area. The total risk analyses depending on the seismic hazard rating of dam site and risk rating of the structure have concluded that most of these large dams have high-risk class for the metropolitan area.

Keywords: dam, earthquake, seismic stability, total risk

1. Introduction

There are mainly two important factors acting on total risk for dam structures: (1) the seismic hazard rating of dam site and (2) the risk rating of the dam and appurtenant structures. The seismic hazard of a dam site can be based on the peak ground acceleration. This value derived from the defined design earthquake produces the main seismic loads. For a preliminary study, the existing map of seismic zones can be used to estimate the seismic hazard of a dam site. The risk rating of the dam should be based on the capacity of the reservoir, the height of the dam, the evacuation requirements, and the potential downstream damages. In general, the seismic and risk ratings are evaluated separately. However, in Bureau method these two factors were combined to define the total risk factor for dam structure in a basin. The type of dam is also an important parameter impacting the total risk rating (Tosun,2006; 2007; 2008, Seyrek and Tosun, 2011; 2012).

Dam designers stated that safety concerns for embankment dams subjected to earthquakes involve either the loss of stability due to a loss of strength of the embankment and foundation materials or excessive deformations such as slumping, settlement, cracking and planer or rotational slope failures. Safety requirements for concrete dams subjected to dynamic loadings should involve evaluation of the overall stability of the structure, such as verifying its ability to resist induced lateral forces and moments and preventing excessive cracking of the concrete (Jansen,1988)

Tosun and co-workers studied on many large dams to relieve their earthquake safety in Turkey (Tosun, 2011; 2012; 2018, Tosun and Oguz, 2017; Tosun and Tosun, 2017a, 2017b; Tosun et al, 2007a; 2007b; 2007c; 2019; 2020). In the study five dams in Lower Seyhan Basin, namely Berdan, Catalan, Mentes and Sanibey, Seyhan were considered. These dams are mainly utilized for producing electricity and providing water for irrigable lands. They have also function for flood control. Totally they have an installation capacity of 584 MW and a reservoir capacity of more than 190 cu.hm in the lower of the basin. This paper deals with an evaluation of earthquake safety of six dams, which have a height from river bed between 41.5 m and 105.0 m from river bed in the lower part of Seyhan Basin (Table 1). The Mentes dam was not considered in this study because of being no exact data for analyses even if it is located in Lower Seyhan Basin.

Table 1. Physical properties of dams considered for this study.

#	Dam	Height from river bed (m)	Function (*)	Type (**)	Completed Year	Volume of embankment (hm^3)	Volume of reservoir (hm^3)
1	Berdan	41.6	I+IU+D+E	EF	1984	2.16	192
2	Catalan	70.0	I+F+D+E	EF	1996	14.50	2 120
3	Nergizlik	50.0	I+F	EF	1995	1.47	22
4	Sanibey	105.0	I+E	CFR	2011	3.94	642
5	Seyhan	53.2	I+F+E	EF	1956	7.50	865

(*) D: Domestic Water E: Energy F: flood control I: Irrigation and IU: Industrial use

(**) CFR: Concrete Faced Rockfill EF: Earthfill

2. Materials and Methods

For this study seismic study has been carried out by deterministic and probabilistic seismic hazard analyses. The deterministic seismic hazard analysis (DSHA) considers a seismic scenario that includes a four-step process. It is a very simple procedure and gives rational solutions for large dams because it provides a straightforward framework for the evaluation of the worst ground motions. The probabilistic seismic hazard analysis (PSHA), which is widely used for dam sites, considers uncertainties in size, location and recurrence rate of earthquakes. For the seismic hazard analysis of each dam site, all possible seismic sources were identified and their potential was evaluated in detail, as based on the guidelines given by Fraser and Howard (2002) and the unified seismic hazard modeling for Mediterranean region introduced by (Jiminez et al, 2001). Five separate predictive relationships for horizontal peak ground acceleration were used for this study (Campbell,1981; Boore et al, 1993; Boore et al, 1997; Gulkan and Kalkan, 2002; Kalkan and Gulkan, 2002).

Some institutions have defined some earthquake levels for dynamic analysis of dam structures. In this study, earthquake definitions given by FEMA (2005) were considered for seismic hazard analyses. The Operating Basis Earthquake (OBE), which was defined by means of the probabilistic methods mentioned above, is the earthquake that produces the ground motions at the site that can reasonably be expected to occur within the service life of the project. MDE is normally characterized by a level of motion equal to that expected at the dam site from the occurrence of deterministically evaluated MCE. Safety Evaluation Earthquake (SEE) is the level of shaking for which damage can be accepted but for which there should be no uncontrolled release of water from the reservoir. Authors state that most of large dams in Turkey were analyzed by using these definitions in past. ICOLD (2016) also some earthquake definitions for dynamic analysis of dams.

Some methods are used to quantify the total risk factor of a dam. One of them considers the seismic hazard of the dam site and the risk rating of the structure separately (ICOLD, 1989). According to this method, the seismic hazard of the dam site regardless of type of dam, can be classified into four groups from low to extreme. This is a quick way for rating the seismic hazard. The hazard class of a dam site obtained from this method provides a preliminary indication of seismic evaluation requirements. Other one is Bureau method (2003), which considers various risk factors and weighting points to quantify the total risk factor (TRF) of any dam. In this methods the TRF depends on the dam type, age, size, downstream risk and vulnerability, which depends on the seismic hazard of the site.

3. Analyses and Results

Embankment dams, which are well compacted according to the specification, are suitable type for regions having high seismic activity according to general decision of dam designers in Turkey. Whereas it is a well-known fact that strong ground shaking can result to instability on embankment and loss of strength at the foundations. Additionally, active faults, which are very close to the foundation of dams, have the potential to cause damaging displacement of the structure.

A detailed study was performed to identify all possible seismic sources for the seismic hazard analyses of the dam sites, as based on the macro seismo-tectonic model of Turkey. The National Disaster Organization and other Institutes prepared the map for general use. However it was modified by the author and his co-workers to use for dam projects at the Earthquake Research Center in Osmangazi University. Local geological features and seismic history were also taken into account to quantify the rate of seismic activity in dam sites. As a result of detailed evaluation, total area covering all basins was separated into four seismic zones. These seismic zones and historical earthquakes are given in Fig. 1. These zones including faults and earthquakes occurred in the basin along last 100 years. The number of earthquakes having a moment magnitude (M_w), which is greater than 4.0, is 254. The numbers of earthquakes with M_w that are greater than 6.0 are 3 for dam sites. There is no earthquake having a magnitude greater than 7.0 in the basin.

Most of the existing dams considered for this study are not under near source effect (MTA, 2013). ICOLD (2016) defined the near-field motion, which is ground motion recorded in the vicinity of a fault. Authors established limits of near-field motion for the investigation area. According to this model, the maximum magnitude of the earthquakes ranges from 5.7 to 5.9 and the minimal distance to fault segment is between 0.4 and 24.3 km for six dams (Table 2). Only one dam, namely Nergizlik dam, can be categorized as “a dam under near source effect” when considered possible fault zone passing through near dam site. The 20 percent of dams considered for this study has a minimal distance, which is less than 10 km to an active fault. In other word, all dams with exception of Nergizlik dam, are not close to10 km to active faults.

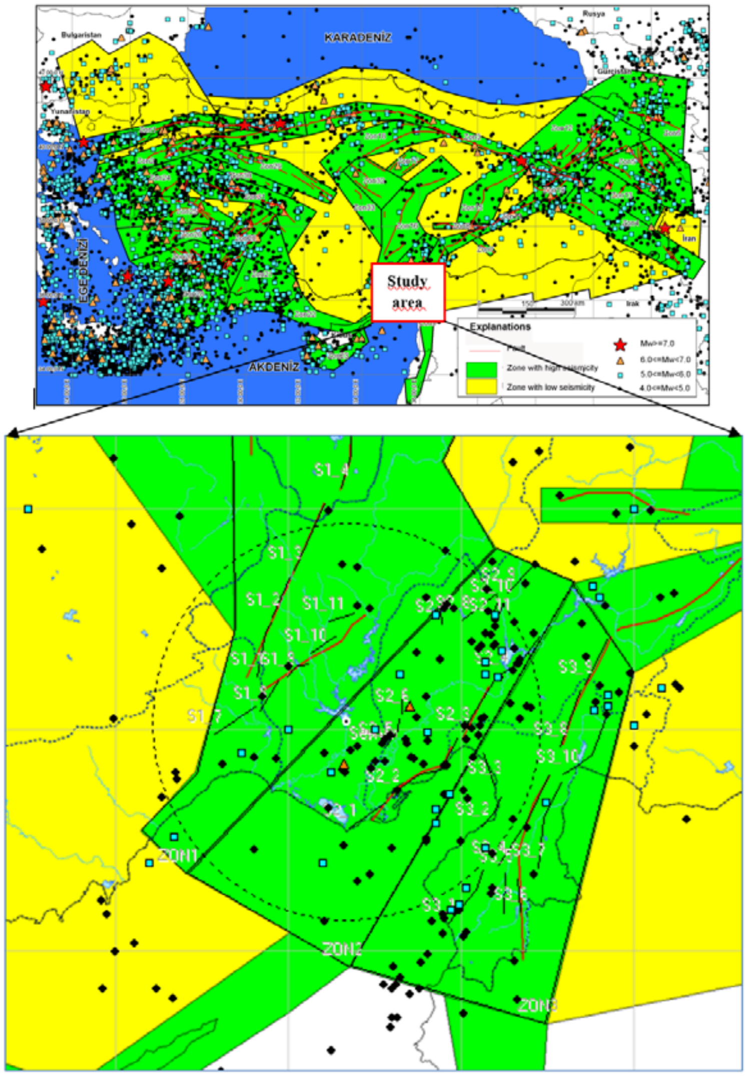

Figure 1. Energy sources and earthquakes in west Anatolia region of Turkey.

The results of the DSHA and PSHA are given in table 2. In this table, M_{max} is the maximum earthquake magnitude in M_w and R_{min} is the minimum distance to fault segment. For deterministic method, mean PGA + 50% and mean PGA + 84% are mean peak ground acceleration at the 50th percentile and Mean Peak Ground Acceleration at the 84th percentile, respectively. The OBE, MDE and SEE are respectively the Operation Based Earthquake, Maximum Design Earthquake and Safety Evaluation Earthquake for probabilistic method.

Table 2. Physical properties of dams considered for this study.

#	Dam	Deterministic Method *				Probabilistic Method **		
		M_{max}	R_{min} (km)	Mean PGA + 50 %	Mean PGA + 84 %	OBE in g	MDE in g	SEE in g
1	Berdan	5.9	21.6	0.129	0.215	0.173	0.233	0.323
2	Catalan	5.7	24.1	0.102	0.170	0.179	0.231	0.305
3	Nergizlik	5.7	0.4	0.310	0.505	0.375	0.530	0.750
4	Sanibey	5.8	23.4	0.123	0.205	0.190	0.247	0.333
5	Seyhan	5.8	24.3	0.090	0.150	0.182	0.234	0.307

The deterministic analyses indicate that peak ground acceleration (PGA) changes within a narrow range with expection of Nergizlik dam. The PGA values ranges from 0.090g to 0.129g for the mean Peak Ground Acceleration at the 50^{th} percentile and from 0.150g to 0.215g for the mean Peak Ground Acceleration at the 84^{th} percentile given in table 2. According to the updated DSI guidelines, the PGA values at the 84^{th} percentile should be taken into account for five dams analyzed throughout the study, when considered deterministic approach (DSI, 2012). For all dams with exception of Nergizlik dam, the PGA values at the 50^{th} percentile should be considered. Table 3 shows the summary of DSI seismic guidelines for dynamic analyses.

Table 3. Selection of Design Earthquake as based on risk classification (DSI, 2012)

Hazard Analysis			
Class	Hazard Ratio	Deterministic Method	Probabilistic Method
I	Low	50 %	T_R = 224 years (*)
II	Moderate	50 %	T_R = 475 years
III	High	84 %	T_R = 975 years
IV	Very high	84 %	T_R = 2475 years

(*) Tr = Return time

The seismic hazard analyses were performed for six dams throughout this study. The results with total risk of each dam are given table 4. All dams with exception of Nergizlik dam are identified in class of II with moderate hazard rating. One dam site has very high hazard rating and are identified as hazard class of IV. ICOLD (1989) state that if the PGA value is greater than 0.25 g and the energy source is closer than 10 km from the dam site, it is classified as hazard class IV with hazard rating of extreme. For five dams, the distance from dam site to active faults, which are given on updated seismic maps, ranges from 20.7 km to 24.3 km.

Throughout this study, two methods have been considered to quantify the total risk for dam structures. In DSI guidelines, total risk factor depends to reservoir capacity, height, evacuation requirement and potential hazard (DSİ, 2012). According to DSI Guidelines all dams are categorized in III and IV risk classes with high and very high risk rating. Following Bureau's method, all large dams with exception of Nergizlik dam are classified in risk class IV, a very high-risk rating. In Bureau method, the values of the TRF range from 165.4 to 191.6. This means that there is no dam having a risk classes of I and II for all dams considered for this study.

Table 4. Total risk of dams considered for this study.

#	Dam	Hazard Analysis		Total Risk (ICOLD,1989)			Total Risk (Bureau, 2003)		
		Class	Hazard Ratio	Risk factor	Risk class	Risk ratio	Risk factor	Risk class	Risk ratio
1	Berdan	II	Moderate	34	IV	Very high	188.6	III	High
2	Catalan	II	Moderate	36	IV	Very high	183.6	III	High
3	Nergizlik	IV	Very high	30	III	Very high	165.4	III	High
4	Sanibey	II	Moderate	36	IV	Very high	182.6	III	High
5	Seyhan	II	Moderate	36	IV	Very high	191.6	III	High

4. Discussions

There are five large dams, which are located in Lower Seyhan basin, for multi-purposes. Three of them are located on the main river of Seyhan basin while other two were constructed on the tributaries of Seyhan river. The earthquake safety and total risk of these dams are evaluated more detail below.

Berdan Dam is a earthfill dam having 66.6 m high from foundation with a total embankment volume of 2 160 000 m^3. It is located on Berdan river in the basin. Its construction was completed in 1984. When the reservoir is at operation stage with maximum water level, the facility approximately will impound 192.0 hm^3 of water with a reservoir surface area of 10.75 km^2. It was designed to provide water for irrigation of land of 24 940 ha and domestic and industrial use with annual capacity of 286 hm^3. It was also designed to produce electricity with install capacity of 10.2 MW. The side slopes of main embankment is 3.25H:1V for upstream and 3.0H:1V for downstream (H=horizontal and V=vertical). On the section there is a impervious zone at center, which is composed of impervious clay. Transition sections of natural granular soil on both side and small-sized crushed rock were designed over rockfill materials (Figure 2). The shell fill in downstream and upstream parts is composed of mixture of earth and rockfill materials obtained from spillway excavation. The alluvium on river bed was removed before beginning the construction of the main embankment. The seismic hazard analyses performed throughout this study indicates that this dam is not critical dam within the basin. It will be subjected to a peak ground acceleration of 0.129 g by an earthquake of 5.9 magnitude and it is 21.6 km far away from an active fault given in new seismo-tectonic map of Turkey in 2013. Its TRF value is 188.6 and it is classified as risk class of III. The 35-years old embankment is in excellent condition.

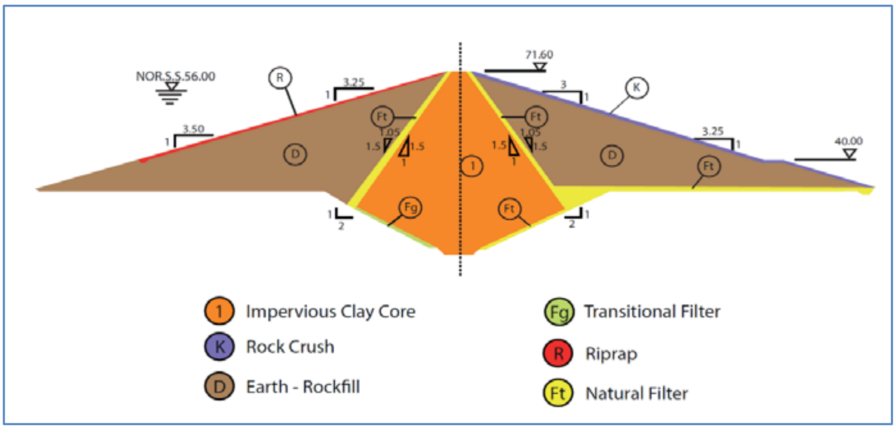

Figure 2. Cross-section of Berdan dam (DSI, 2016)

Catalan dam is a earthfill dam on main river in the Seyhan basin. It has a 82.0 m height from foundation. When the reservoir is at maximum capacity, the facility impounds 2120 hm^3 of water with a reservoir surface area of 84.5 km^2. Its construction was finished in 1996. It is a multi-purpose project to provide domestic water with annual capacity of 236 hm^3, to irrigate land of 3686 ha and to produce electricity with an installed capacity of 168.9 MW. The crest length is 834 m and the side slopes of main embankment is 4.0H:1V for upstream and 3.0H:1V for downstream (H=horizontal and V=vertical) (Figure 3). On the section there is a central impervious core, which is composed of compacted impervious clay and transition sections of sandy and gravelly aggregates was used between the core and semi-pervious soils for both sides. The alluvium on river bed, which is composed of different size of river bed material, was removed before beginning the construction of the main embankment. According to the seismic hazard analyses of this study, it will be subjected to a peak ground acceleration of 0.102g by an earthquake of 5.7 magnitude and its embankment is only 2.4 km far away from an active fault given in new seismo-tectonic map of Turkey in 2014. Its TRF value is 183.6, and it is identified as risk class of III. This 23-year old earthfill embankment is in excellent condition. However, it is most critical structure of the Lower Seyhan basin for downstream life and properties. Therefore, its seismic upgrade should be provided in detail soon.

Nergizlik dam is a earthfill dam having 50-m height with an embankment volume of 1.42 hm^3. It is located on the Nergizlik river in Seyhan basin. Its construction was finished in 1995. When the reservoir is at operation stage with maximum water level, the facility approximately will impound 1.08 hm^3 of water. It was mainly designed to provide irrigation water for lands of Karaisali county. On the section there is a central impervious core, which is composed of compacted clay and a transition section of sand and gravel was designed between the core and shell materials. The seismic hazard analyses performed throughout this study indicates that Nergizlik dam is one of the safe dams within the basin. It will be subjected to a peak ground acceleration of 0.310g by an earthquake of 5.7 magnitude it is very close to the fault segment (0.4 km). It is the most critical structure of Lower Seyhan Basin when considered its hazard rating. However, its total risk is low for downstream life.

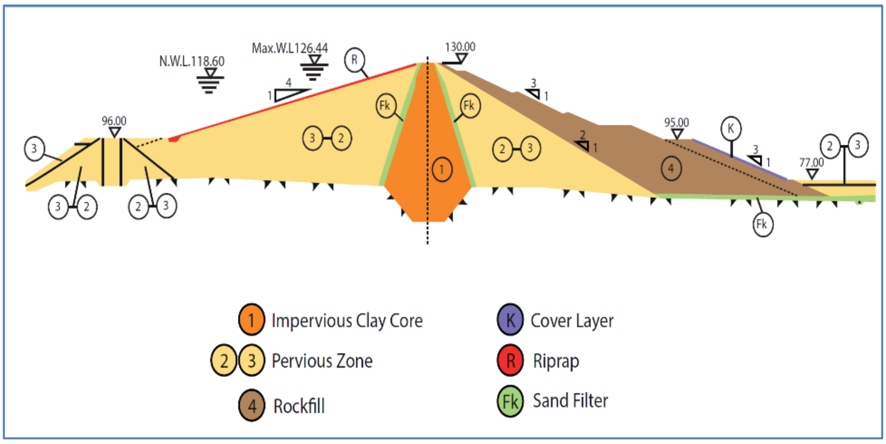

Figure 3. The maximum cross-section of embankment of Catalan dam (DSI, 2016)

The Sanibey dam is a concrete-faced rockfill dam on the Seyhan River near Imamoglu county in the Seyhan basin. It has a 105-m height from river bed and the facility impounds 14.3 hm^3 of water when the reservoir is at maximum capacity. Its construction was finished in 2011. Its system was designed to produce electricity with an install capacity of 310.66 MW and to irrigate land in Imamoglu plain. According to the seismic hazard analyses of this study, it will be subjected to a peak ground acceleration of 0.123g by an earthquake of 5.8 magnitude. Dam site is located 23.4 km for away from an active fault. Its TRF value is 182.6 and it is classified as risk class of III. The Sanibey dam, which is the youngest structure of Lower Seyhan Basin, is now in excellent condition. However, it can be more critical structure than other embankment dams on the view of earthquake safety because of designing on concrete faced type.

Seyhan dam is a earthfill dam having 77-m high from foundation with a total embankment volume of 7 500 000 m^3. It is located on the main river of Seyhan basin. Its construction was finished in 1954. When the reservoir is at operation stage with maximum water level, the facility approximately will impound 865.42 hm^3 of water with a reservoir surface area of 79 km^2. It was mainly designed to provide water for irrigating a land of 148616 ha and producing electricity with installed capacity of 54 MW. The crest length is 1955 m and the side slopes of main embankment is 3.0H:1V for upstream and 2.0H:1V for downstream (H=horizontal and V=vertical) (Figure 4). On the section there are an inclined impervious core, which is composed of compacted clay and a semi-pervious material on downstream and upstream parts. The alluvium on river bed, which is composed of mixtures of fine to large size grains, was removed before beginning the construction of the main embankment. Its TRF value is 191.6 and it is classified as risk class of III. The 63-years old embankment is in excellent condition. However, the seismic hazard analyses performed throughout this study indicates that Seyhan dam is critical dam within the basin. It is one of oldest dams in Turkey and now is surrounded by residential areas of Adana city (Figure 4). Therefore, detail studies about its earthquake safety, total risk and stability should be executed soon as based on the new seismic data introduced after 2013 under the view of a national safety program.

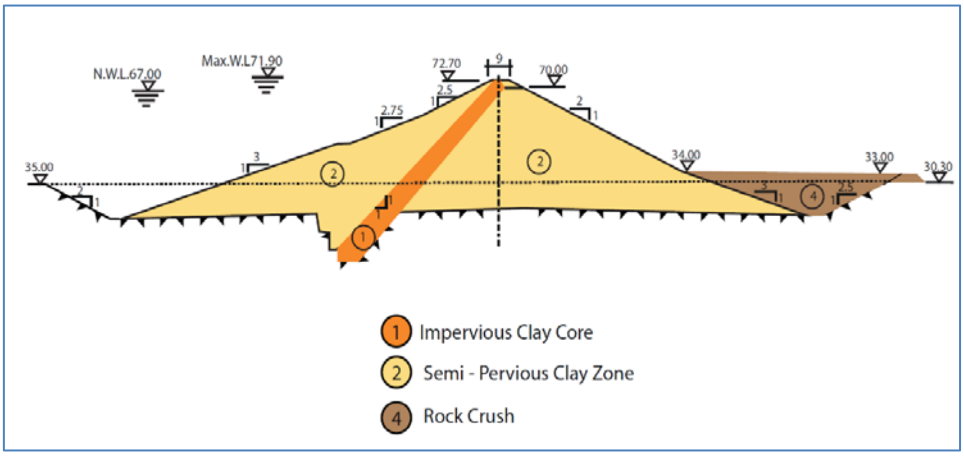

Figure 4. The maximum cross-section of embankment of Seyhan dam (DSI, 2016)

5. Conclusions

In this study, the seismic hazard rating of the dam site and the risk rating of the complete structures were determined for the large dams within the Lower Seyhan basin. The study identified that four of them are not under near source effect. Only one dam is under near motion effect. As a result of this study, 20 percent of dams has very high ratio while other is classified in moderate ratio when considered hazard classification. However, their risk is high and they are members of cascade dam system located in metropolitan area. Especially, the Catalan and Seyhan dams, which have huge volume of water in their own reservoirs. are more critical structures for public safety in Lower Seyhan basin. Therefore, detail seismic hazard analyses should be performed for these structures as based on the updated seismic data and design code under circumstances of the study of a national safety program for dams. In other words, these dams should be re-analyzed by selecting appropriate seismic parameters. Design and construction measures, if necessary, may follow after in cases where the dams are found deficient seismically.

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