Chapter 7

Earthquakes and Dams

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1. Introduction

Earthquake is defined as a sudden and rapid shaking of the earth caused by the breaking and shifting of rock beneath the Earth's surface and it creates seismic waves, which can result in damages and failures on man-made structures constructed on the crust of earth [18]. Dams and large reservoirs constructed on the area with high seismicity, pose a high-risk potential for downstream life and property. It is clear that active faults, which are located close to dam sites, can induce to damaging deformation of the embankment as based on instability of the dam and strength loss of foundation materials. Scientists have realized so many researches for explaining the behavior of earth structures under seismic forces.

Earthquake effects on dams mainly depend on dam types. [28] 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. According to [9], 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.

Earthquakes can result in damages or failures for dam structures, while dams with large reservoirs can induce to earthquakes. Case studies about the seismic performance of dams under large earthquakes are available in the literature. [31] state that earthquake safety of dams is an important phenomenon in dam engineering and requires more comprehensive seismic studies for understanding the seismic behavior of dams subjected to severe earthquakes. It is a well-known phenomenon that earthquakes can result damages and failures for dams and their appurtenant structures. There is another fact that dams with large reservoirs also trigger earthquake.

Ground shaking from earthquakes can collapse dams. There are some important cases, which subjected to damages and failures after earthquake. Lower San Fernando Dam in USA is first example failed as a result of liquefaction phenomenon under the earthquake loading conditions. In case of the May 12, 2008 Wenchuan earthquake in China many dams and reservoirs had been subjected to strong ground shaking. So many dams and hydropower plants were damaged. During the 2001 Bhuj earthquake in Gujarat, India, 245 dams had been affected and rehabilitated or strengthened after the earthquake. Also, in the case of the March 11, 2011 Tohoku earthquake in Japan, damages were observed about 400 dams and the 18 m high embankment dam failed and 8 people lost their live.

Large reservoirs can trigger earthquake. According to recent surveys, Reservoir Triggering Seismicity (RTS) has been observed at over 100 locations worldwide [4, 19, 20]. The largest and most damaging earthquake triggered by a man-made reservoir may be the 7.9-magnitude Sichuan earthquake in May 12, 2008. One of the most serious cases was in 1967 in Koyna, India. The magnitude of this earthquake was 6.3. Also significant effects have been observed Hsingfengkiang dam in China, Kariba dam in Zimbabwe and Kremasta dam in Greece. The effect of reservoir loading on the existing stress field has been investigated by several studies [1, 5, 13, 14, 15, 19, 20, 21, 22, 23]. The field studies indicates that the main factors acting reservoir seismicity are in-situ stress conditions, availability of fractures and faults, geology of the regional area, dimensions of the reservoir and the nature of reservoir level fluctuations.

The paper gives an overview on the dams, which are under the effects of strong ground motions. It investigates the effects of earthquake on dams, also effects of dam on earthquake occurrence. Some cases are given to explain both phenomena and clarify the total risk of large dam structures when considered earthquake effects. The subjects presented in the paper were addressed by the international committees and recent surveys. It mentions main requirements for large dams on view of earthquake engineering to find rational design solutions. The purpose of this paper is to sketch the state of the art in dam engineering, as based on lessons learnt from seismic events.

2. Effects of earthquake on dams

[8] states that damages to dams and their appurtenant facilities may result from (1) direct fault movement across the dam foundation or (2) from ground motion induced at the dam site by an earthquake located at some distance from the dam. The second one is commonly seen, however first one results to more serious problems for dams and their appurtenant structures. A good example to damages resulted by ground shaking vibrations in dams is Sefid buttress dam, which was damaged near crest due to ground shaking the 1990 Manjil earthquake with a magnitude of 7.5 in Iran. In this dam, damages have been observed near crest due to ground vibration. For fault movements in dam site, the Shih-Kang weir can be considered as good case study. In this dam, two openings were failed due to large movements of Chelungpu fault during the magnitude of 7.3 in Chi-Chi earthquake of September 1999 in Tawian. After severe damages observed on this dam, dam engineers more seriously considered active or seismo-

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genic faults on dam sites. Because dams located on active faults pose significant risk for total stability of project and public safety.

Liquefaction is defined as a phenomena in which the strength and stiffness of a saturated soil is reduced earthquake shaking. It generally means the state change from solid to liquid. Lower San Fernando Dam in USA is first known dam failed as a result of liquefaction phenomenon under the earthquake loading conditions. During the 1972 San Fernando Earthquake, Lower San Fernando Dam failed a result of liquefaction phenomena [12, 17, 24]. Its embankment with the structures on crest slid into the reservoir. In other words, approximately 3.0 million cubic meter of dam embankment was displaced into the reservoir. The 1994 Northridge earthquake, some ground movement with minor cracking seems to have occurred at the sites of Los Angeles Dam, which was constructed to replace the San Fernando Reservoir. There was significant differential settlement of the ground of about 5 cm in the northern section, and 20 cm in the southwestern section of the site [24].

During the 2001 Bhuj earthquake in Gujarat, India, 245 dams had been affected and rehabilitated or strengthened after the earthquake [34]. Due to Mid Niigata Prefecture Earthquake in 2004, Japan, several embankment dams and some off-stream impounding facilities for power generation and irrigation system suffered damages such as cracks on dam bodies [10].

In case of the May 12, 2008 Wenchuan earthquake in China many structures about 1803 dams and 403 hydropower plants having a total installed capacity of 3.3 GW were damaged due to strong ground shaking. Most of dams were small earth dams with exception of four large dams having a height greater than 100 m. According to Chinese officials the earthquake occurred along the Longmenshan fault, which is a thrust structure along the border of the Indo-Australian Plate and Eurasian Plate, the rupture lasted 120 sec, the rupture propagated at an average speed of 3.1 km/s toward northeast. The rupture length and focus depth is about 300 km and 10 km, respectively. The maximum displacement was recorded as 9.0 m [6]. As a result of this earthquakes so many elements of dam such as dam body, spillways, powerhouses, penstocks, switchyards, hydro-mechanical and electro-mechanical equipments, temporary structures were damaged, other disasters such as rockfalls, landslides and landslide dams were observed. No dams were failed during this earthquake, although there were so many damaged dams. [8] states that dams must be designed to withstand strong earthquakes, which can seriously result multiple hazards.

In the case of the March 11, 2011 Tohoku earthquake in Japan, damages were observed about 400 dams and the 18 m high embankment dam failed and 8 people lost their live [34].

The dams, which are located on shear zones, have high risk potential when they are subjected to strong ground motion. There are some examples in India for structures located at the northern India. One of the Namada Valley dam, which is built at the triple junction of the fault zones, tectonically and geologically a disturbed area. Terhi dam in India has also similar position under dynamic loading conditions. Researchers states that Terhi dam might release energy along the fault segment between Nepal and Tibet and also trigger an earthquake which has a magnitude close to or greater than 8.0.

In Turkey, there is a sheared zone which is close the triple junction of the famous strike slip faults in east of Turkey. [28] stated that Surgu dam, which damaged on the Dogansehir earthquake with Ms of 5.8 in 1986, Polat dam and Cat dam have the PGA values of 0.256g, 0.170g and 0.211g, respectively. The geology of dam sites are very complicated and frequently jointed, fractured and faulted. The author points out the fact that these dams are under the influence of local near-source zone and have high-risk potential for earthquake conditions. The author's thought was absolutely confirmed by damage on the Dogansehir earthquake with Ms of 5.8 on Surgu dam.

In general, strong ground shaking can result in the instability of the embankment and loss of strength at the foundations [2, 9, 16, 17]. Most of dam engineers have thought that embankment dams are suitable types when well compacted according to the specification, However, it is not an acceptable thought that embankment dams can be induced to damages and failures even if well compacted, while they are under near source effect.

There is no one major problem in seismic safety of embankment dams. Whereas near source effect seems the most serious problem for embankment dams. [28] reveals the fact that active faults, which are very close to the foundation of dams, have the potential to cause damaging displacement of the structure. Especially Concrete Faced Rockfill Dams (CFRD's) have high risk potential when considered near source effect (earthquake epicenter to dam axis is less than 10 km). This phenomenon is dealed with the fact that the transferred energy by rockfill is not absorbed by concrete face during earthquake. Wieland (2010) state that until the Wenchuan earthquake of 12 May 2008 no large concrete face rockfill dam (CFRD) was subjected to strong ground shaking. He questioned that faced concrete of CFRD's can have a behavior as the river embankment which was subjected the 21 September 1999 Chi-Chi earthquake in Taiwan [32 and 33]. Figure 1 shows buckling of river embankment lining after the earthquake.

3. Effects of dams on seismicity of the region

Large reservoirs can trigger earthquake. This phenomenon is defined as Reservoir-induced Seismicity that is mainly depended to excessive water pressure created in the micro-cracks and fissures in the foundation units under and near the reservoir. Water within the rock masses under huge hydrostatic pressure acts to lubricate faults, which are already under tectonic strain, however are prevented from slipping by friction of rock planes. It is clearly known that it mainly depends on nature of structural geology and lithology of surrounding rocks. However, it is very difficult to accurately predict when and where reservoir induced earthquake will occur. ICOLD recommends that Reservoir Triggered Seismicity (RTS) should be considered for reservoirs having a depth more than 100 m. USCOLD has reported that Reservoir Induced Seismicity (RIS) should be taken into account for reservoirs deeper than 80-100m.

It is clear that number of seismic events increases near reservoir areas of large dams after impounding sequence. The earthquake seismicity was firstly observed in 1929 for Marathon

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Figure 1. Buckling of river embankment lining after the 1999 Chi-Chi earthquake [32]

dam having 60 m height, Greece. Increase in seismicity was also seen in 1935 after the impounding of Hoover dam, which is a concrete arch dam with a height of 220 m. Up to now, RTS has been observed on over 100 dams in the world. The earthquake intensity has increased after impounding of Keban Dam, which is the second largest dam of Turkey with a storage capacity of 31000 hm^3.and 207 m height from foundation [30]. Recently scientists believe the fact that the over one percent of reservoirs resulted to earthquake which can damage or fail the main structure. It is not a negligible value that this mechanism should be considered by engineers in design stage.

Damages due to RTS have been in two dams: (1) Koyna dam, which is gravity dam having 103 m height in India. It was subjected to an earthquake with magnitude of 6.3 in 1967. (2) Hsinfengkiang dam, which a buttress dam having a height of 105 m in China. It was subjected to earthquake with magnitude of 6.1 in 1962. Researchers state that earthquakes were caused in their reservoirs by RTS. The substantial longitudial cracks were developed near crest for both dams. Both dams are still in operation after strengthened.

The reservoir capacity is an important factor in triggering earthquakes as well as reservoir depth. Phenomenon about Reservoir Induced Seismicity (RIS) mainly conforms for the reservoir filling periods. It can also be seen for a reservoir after a certain time lag [5].

There are some important cases that strong earthquakes may affect a large area. Recent surveys indicate that there are at least 100 cases of earthquakes, which were triggered by reservoirs. The most serious case may be the 7.9-magnitude Sichuan earthquake in May 12, 2008, which killed an estimated 90,000 people. This earthquake has been related to the construction of the Zipingpu Dam, which is a 156 m high concrete faced rockfill dam with a reservoir of 1 120 hm^3. [7] classified two types of earthquakes associated with reservoirs while explaining the complicated mechanisms of RTS after the 12 May 2008 Wenchuan earthquake in China: (1) The small magnitude earthquakes, which occur immediately after reservoir impounding or following sudden reservoir water level fluctuations are mainly related to stress adjustments in the foundation rock, collapse of karst caves and mining pits and mass movements, (2) Earthquakes, which are caused by seismicgenic faults passing through or adjacent to the reservoir area, are referred to as RTS. [7] states that the initial stress state must already be close to failure so that a minor change in strength properties in a fault plane caused by water in the reservoir could trigger seismic events and the magnitude of RTS events may gradually increase until the main shock occurs. Authors have explained the mechanism of Wenchuan earthquake by the earthquake of tectonic nature.

4. A case study on the reservoir triggered seismicity for an existing dam

Turkey is one of the most seismically active regions in the world. There are so many dams, which are under the effect of near-source zones in Turkey. There are some examples of embankment dam in Turkey, which were damaged during the earthquakes occurred in past. There is no any concrete dam, which was damaged as a result of earthquake in Turkey [25, 26].

Ataturk dam, which is a 169 m height zoned rockfill dam on the Euphrates River in Turkey with an 84 000 hm^3 of water reservoir, poses high risk about triggering phenomena by reservoir. It has the largest reservoir of Turkey with 48 700 hm^3 (Figure 2). Its crest length is 1 670 m and base width is approximately 900 m. It is located 35 km north of the Birecik dam reservoir and 120 km south of Karakaya dam body.

Its main embankment construction was started in 1985 and completed in 1990. The reservoir level has maximally reached to 537 m up to now. Its level fluctuates from 526 to 535 m as based on climate change and energy demand. It was designed a multi-purpose structure for irrigating lands, producing electricity and providing flood control. It generates electricity of 8100 GWh per year with an installed capacity of 2400 MW.

It is a rockfill dam with central core. There is a transition section of sand, gravel and small sized crushed rock between the core and rockfill materials. It has also a coarse grained soil zone obtained from river deposits and a random zone, which is composed of laminated limestone. The upstream and downstream shells are composed of large-sized crushed rocks. The alluvium on river bed, which is composed of sand, gravel, clay and silt mixtures, was removed before beginning the construction of the main embankment. The basement of Ataturk dam is formed by karstic limestone, regarded as problematic rock for dam foundation. An intensive grouting program was applied to prevent water leakage from the reservoir [28].

Author has completed a study from seismic hazard analysis to 2-D finite element analysis to assess its static and dynamic stability for Ataturk dam [31]. For the seismic hazard analyses of

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Figure 2. A general view from Ataturk dam

the dam site, first all possible seismic sources were identified as based on the new seismic zonation map of Turkey by means of a software, which was developed at the Earthquake Research Center in Eskisehir Osmangazi University [29]. As a result of detailed evaluation, the dam site and vicinity were separated into four seismic zones. Figure 3 shows these zones including faults and earthquakes occurred in the basin along last 100 years.

At the first design stage, it was considered only Eastern Anatolian Fault System (DAF) for seismic hazard analysis. As a result of this study, the value of Peak Ground Acceleration (PGA) was low for MDE. Recent study conducted by author indicates that the PGA value is considerable level and Bozova fault has a significant potential for reservoir triggering seismicity for Ataturk dam. It was located 3.0 m far away from the dam body and has a parallel position to the dam crest. This fault can produce an earthquake with a magnitude of 6.5 to 7.0. The seismic hazard analysis was performed for the dam by means of two separate methods. The deterministic seismic hazard analysis shows that the PGA value ranges from 0.284 to 0.536. These PGA values are high. Because the fault is very close to the dam site. The results of probabilistic seismic hazard analysis indicate that peak ground acceleration (PGA) changes within a wide range (0.057g and 0.203g) for OBE. For MDE and SEE, the PGA value averages to 0.197g and 0.408, respectively [31].

The seismic hazard analyses performed throughout this study indicates that Ataturk dam is one of the most critical dams within the basin. As based on the author's recent studies, Total Risk Factor (TRF) value is 146.5 and it is identified as risk class of III. It means that it has high risk potential for downstream life and structures. [31] states that the 25-years old rockfill dam also has some problems in static condition and it cannot meet current seismic design standards. The earthquake intensity in dam site and reservoir area has been increased after reservoir impounding or following sudden reservoir water level fluctuations. The Bozova fault, which is very close to dam body, can be a source of earthquake triggered by the reservoir of Ataturk dam. Also, Terbela dam with a reservoir of 13 690 hm^3 in Pakistan can be classified as high risk dam when considered this phenomena.

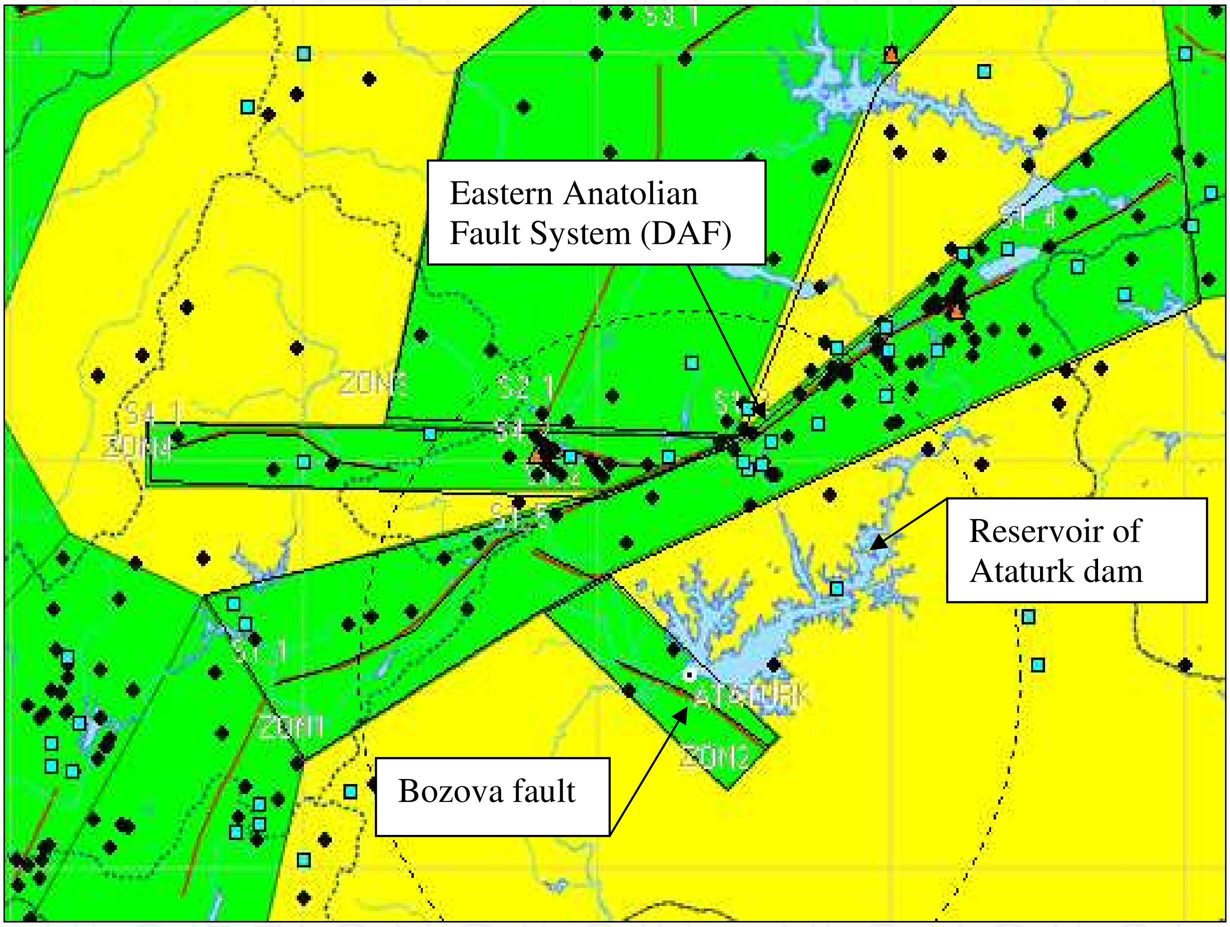

Figure 3. Location of dam site on seismo-tectonic map and earthquakes

5. Main design principles for dams located on active seismic area

The seismic activity of dam sites is generally analyzed by two methods: (1) The deterministic seismic hazard analysis and (2) The probabilistic seismic hazard analysis. The deterministic seismic hazard analysis is a very simple procedure and gives rational solutions for large dams. Due to the unavailability of strong motion records, various attenuation relationships were adopted to calculate the peak ground acceleration (PGA) acting on dam sites. The probabilistic seismic hazard analysis considers uncertainties in size, location and recurrence rate of

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earthquakes. The probabilistic seismic hazard analysis provides a framework in which uncertainties can be identified and combined in a rational manner to provide a more complete picture of the seismic hazard [11].

The computer program used for seismic analysis should be available for the probabilistic and deterministic assessment of seismic hazard. The seismic sources should be identified and the recurrence interval of earthquakes should be estimated. As a result of an extensive survey and a search of available literature [28, 29, 31]. Several sources have been identified to help analyzing the seismic hazard of dams in Turkey and surrounding countries. The earthquakes that occurred within the last 100 years should be used for estimating seismic parameters. Seismic zones and earthquakes within the area having a radius of 100 km around the dam site should be considered.

For beginning to a seismic hazard analysis, primary factors such as regional geological setting, seismic history and local geological setting should be studied, and then earthquake definitions should be executed. Figure 4 summarizes the methods of analysis for a dam site and dam body. After selection of earthquakes, static, pseudo-static and dynamic analyses should be performed and liquefaction phenomenon and near source effect should be evaluated. In Turkey, a design engineer should conform to diagram given in Figure 4.

Earthquake definitions are given below:

The Operating Basis Earthquake (OBE) was defined by means of the probabilistic methods. It is known as the earthquake that produces the ground motions at the site that can reasonably be expected to occur within the service life of the project [3]. It will be appropriate to choose a minimum return period of 145 years. It means a 50 percent probability of not being exceeded in 100 years.

Maximum Credible Earthquake (MCE), which is the largest earthquake magnitude that could occur along a recognized fault or within a particular seismo-tectonic province, was obtained for each zone and the most critical framework for the dam site was selected as Controlling Maximum Credible Earthquake (CMCE). The Maximum Design Earthquake (MDE) was then defined. It generally represents the ground motion with 475 years of return period [28]. It means a 10 percent probability of not being exceeded in 50 years.

According to [3], MDE is normally characterized by a level of motion equal to that expected at the dam site from the occurrence of deterministically evaluated MCE and Safety Evaluation Earthquake (SEE) should be used for critical structures located in very active seismic area. Most of large dams in Turkey were analyzed by using these definitions [28].

Terminology used for seismic analysis of dams varies between countries. In the last publication of [8], new earthquake definitions have been made. In this bulletin the Safety Evaluation Earthquake (SEE) is newly defined as the level of shaking for which damage can be accepted but for which there should be no uncontrolled release of water from the reservoir. In Turkey, it is defined as a level of ground motion having 2 percent probability of not being exceeded in 50 years. [8] states that SEE may be chosen to have a lower return period depending on the consequences of dam failure.

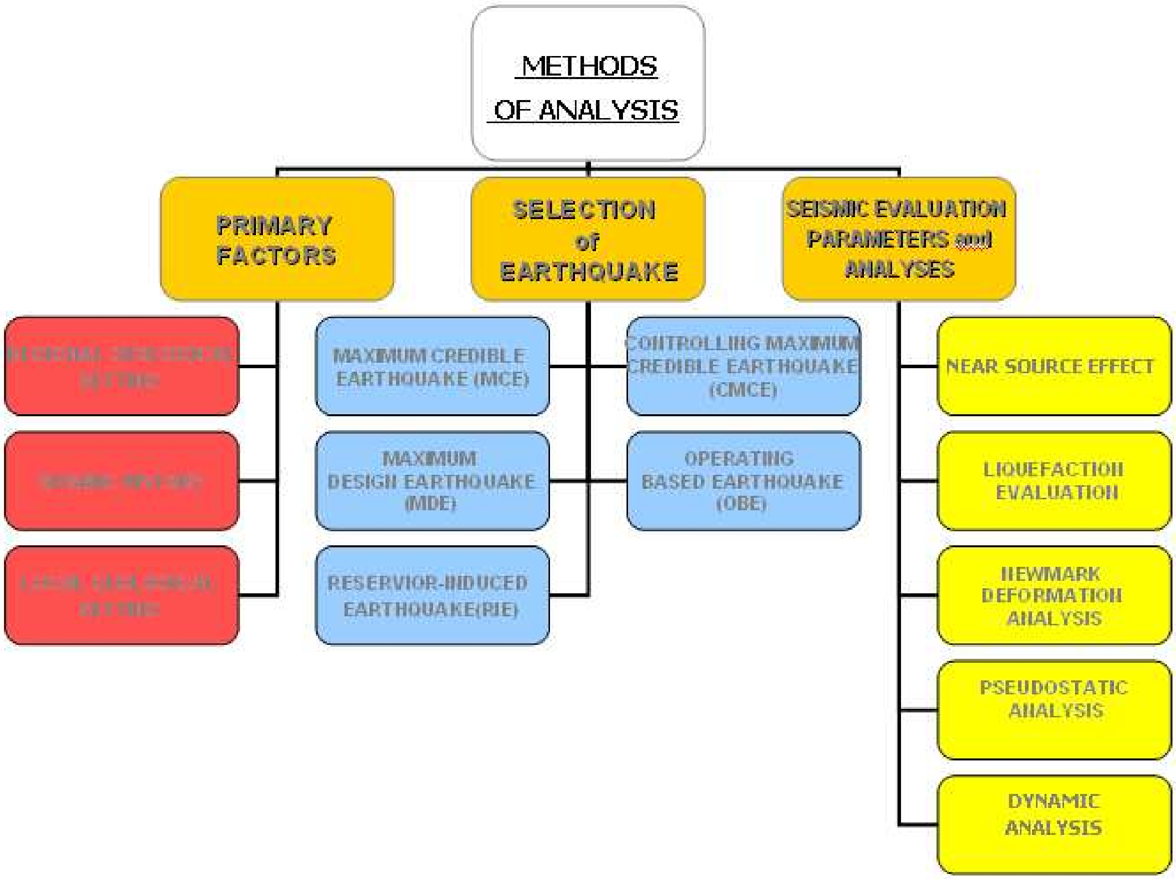

Figure 4. Methods of analysis for a dam located on active seismic area in Turkey

6. Conclusions

The total risk for dam structures mainly depends on the seismic hazard rating of dam site and the risk rating of the completed structure. This paper gives an overview on the effects of earthquake on dams and effects of dam on earthquake occurrence, and points out the necessity of special design and construction measures for the dams, which are under the effects of strong ground motions. It is clear that the main requirement in earthquake-resistant design for dams is to protect public safety, downstream life and property. Therefore, some important factors listed below should be taken into account in design stage:

i. Large dams must be designed with a capability of resisting severe earthquake motion or fault movement at the dam site without uncontrolled release of water stored in reservoir.

ii. For large dams located on non active seismic area, Reservoir Triggering Seismicity (RTS) can be more critical. Therefore, RTS should be defined sensitively as based on local geologic units and tectonic structures by means a detail seismic hazard analysis.

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iii. Damages to dams and their appurtenant facilities may be resulted from (1) direct fault movement across the dam foundation or (2) ground motion induced at the dam site by an earthquake located at some distance from the dam. The second one is commonly seen, however first one results to more serious problems for dams and their appurtenant structures.

iv. Active faults pose the potential to cause damaging displacement of the structure when they are located very close to dam site. There are some examples of dams, which were damaged during the earthquakes that occurred in the past. Especially Concrete Faced Rockfill Dams (CFRD's) have high risk potential when considered near source effect with strong ground motion. This phenomenon is dealed with the fact that the transferred energy by rockfill is not absorbed by concrete face during earthquake. Near source effect should be considered with more attention for large dams in design stage.

v. For the dams, which are under near source effect, embankment type with clay core seems more appropriate type because of being self-repairing properties of clay material when this type is technically and economically feasible for the selected dam site.

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