Adopted Measures for Evaluation and Remediation of the Damages Occurred in Darbandikhan Dam due toa Major Earthquake

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Abstract

A strong earthquake (Mw=7.3) hit the Darbandikhan dam on November 12, 2017. According to its magnitude and effect classifications, the earthquake was classified as a major earthquake with serious damage effects. Consequently, the earthquake caused deformation (cracks and settlement) in the dam body. The dam could not store water during 2018. Therefore, thorough inspections were carried out by several teams including a team from the University of Sulaimani-Iraq. It was concluded that adequate design and construction of dams can protect dams from even large earthquakes. It was also concluded that the adopted measures used for evaluation and remediation of the earthquake-induced damages in the Darbandikhan dam are reliable in checking dam safety. However, geophysical resultsusing Ground Penetrating Radar (GPR) and the Multichannel Analysis of Surface Waves method (MASW) were notcompatible with the geotechnical results in the Darbandikhandam.

Keywords: Dam Remediation; Earthquake; Rock-fill Dams; Failure; Deformation; Transverse Cracks; Dam Safety; Geophysical Methods.

1. INTRODUCTION

Many dams around the world have been struck by large scale earthquakes (Bardet and Davis 1996; Yamaguchi et al., 2008 & 2012, Singh et al., 2005). Problems such as cracks, settlements, displacements, slope instability, new leakages and increased seepages, erosion and malfunctioning of drains and relief wells may occur due to the earthquake. Any of the aforementioned problems can lead to a catastrophic failure in embankment dams if effective remedial measures are not considered. Accordingly, promptly after the earthquakes, suitable examinations and adequate measurements are required for embankment dams (Paul 2004).

In 2017, the Darbandikhan dam subjected to a strong earthquakenever experienced before. Dam expert teams (Iraqi experts, world bank experts, UNDAC, etc.) visited the dam for inspection purposes.The Iraqi's experts followed the procedure recommended by ICOLD(1988) for the inspection as cited in (Pinto, 2010). The inspections included a primary visual inspection immediately after the earthquake, then a more detailed visual and safety inspection based on data that are recorded and measured by monitoring devices.

This research presents the measures adopted forthe evaluation and remediation of the damages that happened to theDarbandikhan dam due to a major earthquake that occurred on November 12, 2017.

2. DARBANDIKHAN DAM

Darbandikhan dam is a multi-purpose rock-fill dam located on the Diyala (Sirwan) river approximately 65 km south-east of Sulaimaniyah city and 230 km north-east of Baghdad city (Iraq); at Latitude 35.1128° N, and Longitude 45.7053° E as shown in Figure 1. The dams' dimensions are 128 m height, 445 crest length, and 17 m crest width at elevation 495 m. The construction was begun in 1956 and completed in Summer 1961.The total capacity of the Darbandikhan reservoir is 3 km^3 at the normal pool level (El. 485.00 m); 2.5 km^3 live storage and 0.5

km^3 dead storage. The reservoir is controlled by a gated ogee spillway having three 15mx15m Tainter gates. The spillway is located at the right abutment adjacent to the dam embankment. The dam's body composes of a thin vertical clay core with side slopes of 1:0.3, upstream and downstream transition zones (twostages chimney drain upstream consists of a finer-grained filter layer and a coarser-grained drain layer each of width of 3 m, and three stages drain at the d/s), and upstream and downstream dumped rockfill shells with side slopes of 1:1.5 and 1:1.35, respectively. The core and filters were compacted, while the outer rockfill shells were dumped. There is no alluvial layer present under the dam. Figure 2shows the maximum cross-section of the dam.

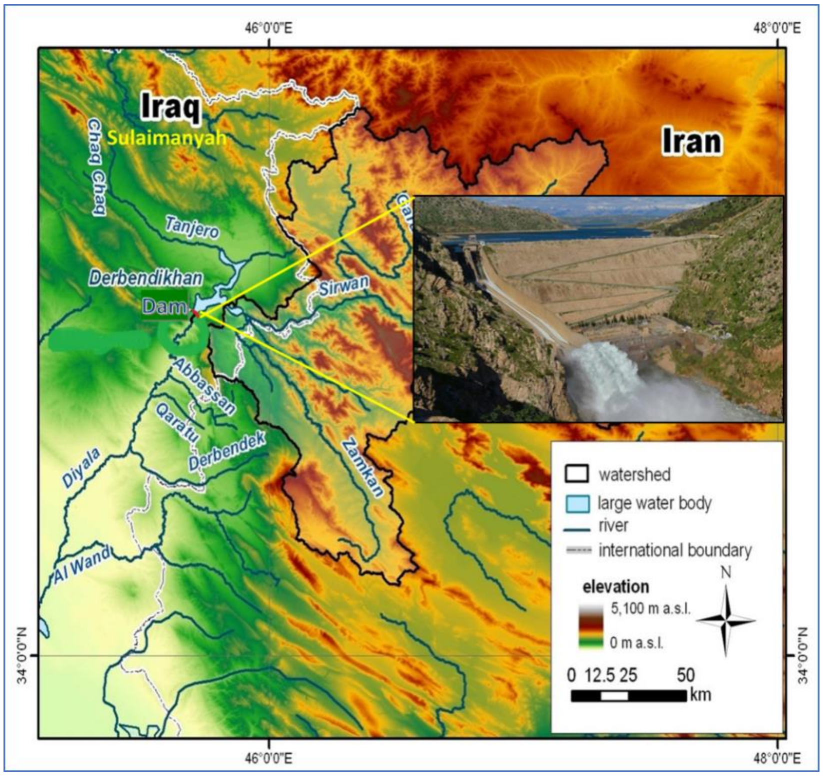

Figure 1 Darbandikhan Dam location/ Iraq (Directorate of Darbandikhan Dam (DDD) 2017)

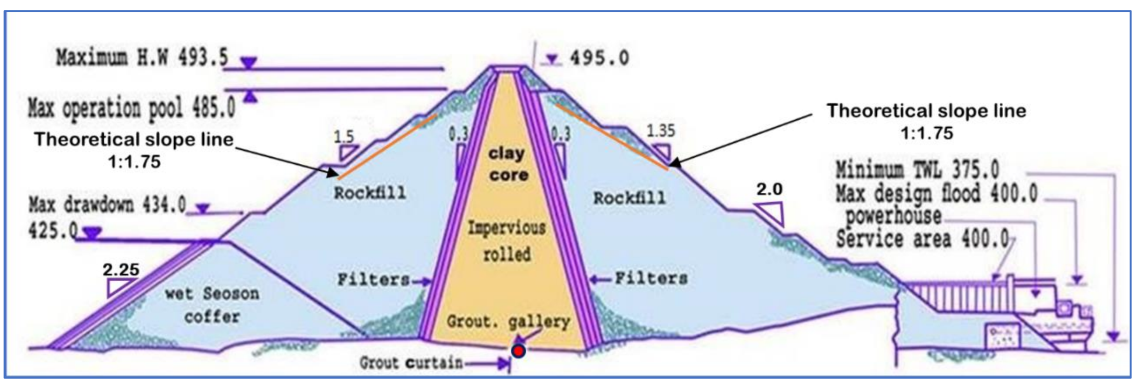

Figure 2 Maximum Cross Section of Darbandikhan Dam (DDD 2017).

3. EARTHQUAKE PROPERTIES

A strong earthquake with a moment magnitude of 7.3 (Mw = 7.3) occurred on November 12, 2017, near the Iran-Iraq border (220 km northeast of Baghdad, Iraq) (USGS, 2017). The focal depth and distance of the earthquake from the Darbandikhan dam were 23.4 km and 32 km respectively. The event commonly referred to as the Ezgeleh Earthquake and resulted in 500 victims and about 12 000 homeless. It was the most disastrous earthquake that has affected the Iraq/Iran border since 1909 (USGS 2017).A major feature of the observed earthquake besides its high magnitude is its duration. Long durations of earthquakes may have more impact on embankment dams than short-period earthquakes having the same peak acceleration or even less peak acceleration (Yamaguchi et al., 2012). The Ezgala earthquake duration was about 30 seconds (Zare et al., 2017).

4. GEOLOGICAL CONDITIONS

Darbandikhan dam is located at the end of a narrow steep-sided canyon cut through an anticline by Diyala/Sirwan River. It lies in a folded nappe zone to the southwest of the plate boundary where the Arabian plate is being subducted beneath the Persian plate. At the dam site, the rocks dip downstream towards the southwest; about 45 degrees. The dam is sited on a series of thick beds of heterogeneous sedimentary rocks (Calvin & Davis 1958).

5. DAM SAFETY INSPECTIONS

The preliminary visual inspection stage commenced immediately after the earthquake on the same night of the incident (see Figure 3). In this stage, the dam was visuallyinspected in order to explore the extent of damagesalong with taking photos and recording videos. On the day after the incident, after checking the safety of the spillway and the bottom outlets,it was decided to lower the water level in the reservoir in order to investigate the lower parts of the dam. The water level in the reservoir was then gradually loweredfrom the elevation 471.9 m to the elevation 464 m, about 8 m, in about two months.

Figure 3 Visual inspection just after the earthquake.

During the visual inspections, many cracks and fallen rocks were observed on the crest of the dam, especially near the abutments. The cracks and fallen rocks were then documented. From the preliminary visual inspections, it was concluded that more inspections (detailedinspections) were necessary in order to identify all the crack patterns in detail.Therefore, the General Directorate of Dams and Reservoirs(GDDR), Iraq,decided to conduct a detailed safety inspection in collaboration with theUniversity of Sulaimani/Engineering Consultation Bureau(SECB). The main purposes of the detailed safety inspections were:

a) Inspecting the state of damage identified in the reports of preliminary visual inspections,

b) Assessing the safety and implement countermeasures as needed.

The detailed safety inspections included the following actions:

1. Geodetic survey
2. Geophysical investigation
3. Test pits (Trenching)
4. Continues Drilling in the clay core
5. Seepage rates and piezometer readings

5.1. GEODETIC SURVEY

In the days following the earthquake, the experts of the GDDR visited the Darbandikhan dam and carefully surveyed the dam body and its appurtenant structures. The objective of the survey was to map the patterns of cracks and the displacements that occurred due to the earthquake. The locations of the visible cracks were precisely located and identified. The width of the cracks was then measured. The movements and settlements of the dam body and its appurtenant structures relative to control points erected on bedrock were also determined. These data were compared to another survey carried out before the earthquake, in March 2017. From the comparison carried out between the two sets of data, it was found that the maximum settlement (ΔH) that occurred at the crest of Darbandikhan dam was 48 cm (ΔH/H=0.38%) which is well within the range of the settlement values occurred in the other dams that subjected to large earthquakes as reported byYamaguchi, etal.,(2012) and Swaisgood (2003), where H is the dam height. Based on their statistical analysis the maximum amount of settlement ($\Delta H/H$) measured at the crest of Rockfill dams after earthquakes is ranging around 0.001% and 1%.

5.2. GEOPHYSICAL INVESTIGATION

In order to detect cracks and weakened zones within the upper part of the dam body especially in the clay core, a geophysical investigation was carried out in 2018 at the transverse crack locations near the spillway.In this geophysical investigation, conducted by AMAK Company, two different methods were used; Ground Penetrating Radar (GPR) and the Multichannel Analysis of Surface Waves method (MASW) (Hijab 2018). From the interpretations of the geophysical data,the geophysical investigators identified three anomalies(deformations)at three locations with three different depths; at 8.0m, 22m, and 22m for D1, D2, and D3 respectively as shown in Figures (4) & (5). Accordingly, they recommended further field investigation in order to check the situation of the deformation in the clay core at zones D1, D2, and D3.

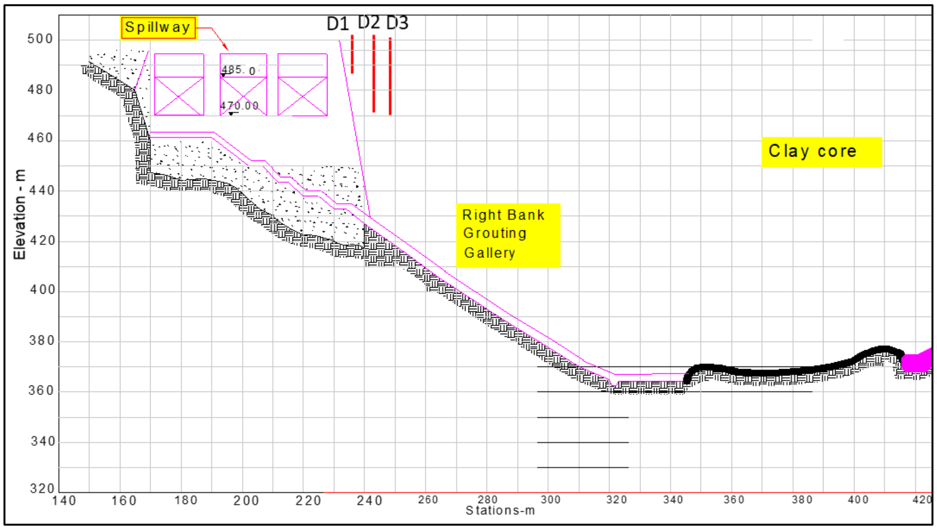

Figure 4shows the locations of the deformation zones (D1, D2, and D3) along the dam body section (Hijab, 2018).

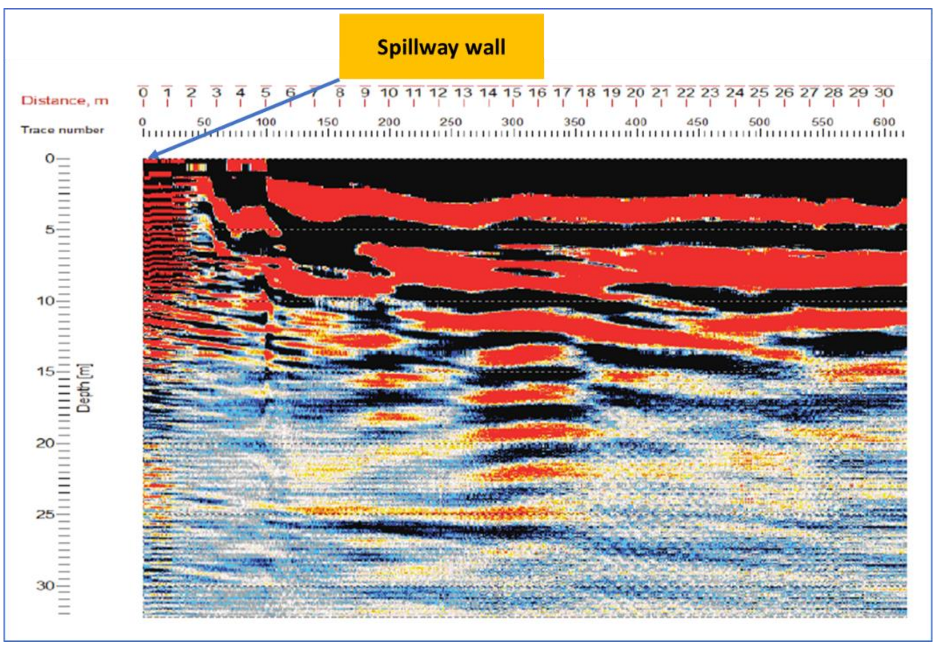

Figure 5 Radargrams of the GPR profile of locations D1, D2, and D3 at distance 3m, 10m, and 17m, respectively, measured from the spillway structure (Hijab, 2018).

5.3. TEST PITS (TRENCHING)

The cracksoccurred due to the earthquake were mostly along the crest of the dam that ran mainly in the longitudinal direction, and some transverse cracks at the abutments. However, there were no differences in elevation between the two sides of the transverse cracks on the crest of the dam except that the one next to the spillway wall. Figure 6shows a detailed mapping of cracks observed after the earthquake. Several test pits were dug at the crack's locations, except the transverse crack next to the spillway, all the cracks on the crest weresuperficial cracks; they were developed just in the protective layer and terminatedat the top of the clay core (their depths were less than two meters).**Error! Reference source not found.**shows the transverse crack next to the spillway. It appeared that the crack formed a wedge at this location. The maximum width of the wedge was 74 cm (Yousif et al., 2019). A tape measure was used for measuring the depth of the crack which was about 1.5 m.

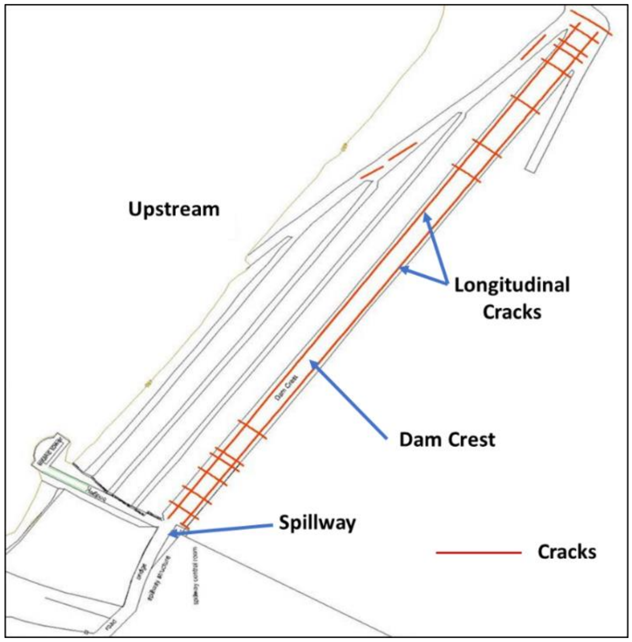

Figure 6*Cracks pattern(Yousif et al. , 2019)*

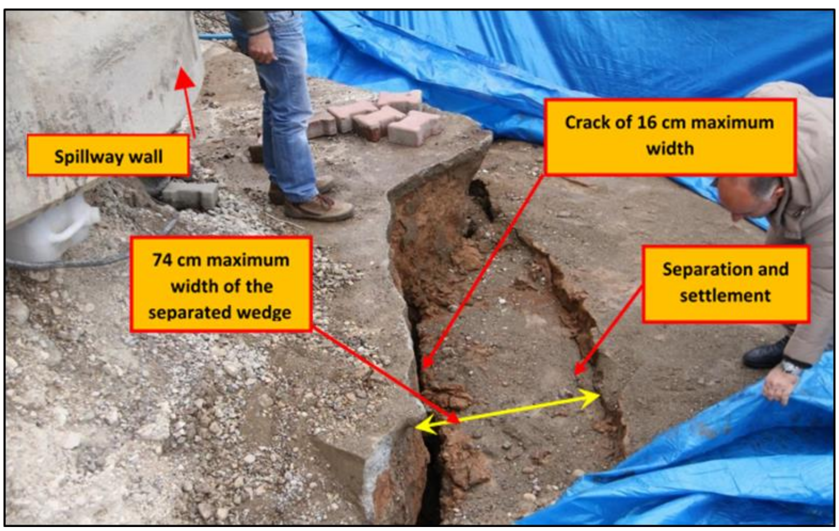

Figure 7: The crack at the contact between the spillway and the embankment (Yousif et al., 2019).

5.4. CONTINUES DRILLING IN THE CLAY CORE

Based on the geophysical recommendations, further field tests werecarried out in order to check the condition of the clay core at the area close to the spillway.Threeboreholesat three locations(D1, D2, and D3 shown in Figure 4) were drilled using a continues method of drilling. Visual inspection was then carried out on the borehole logs. In addition, to check thestrength of the clay core, an in-situ test was carried out on the clay core borehole logs using a pocket penetrometer instrument.Pocket cone-penetrometer is a valuable tool for providing approximate values of the undrained strength quickly (Bowles, 1996). Table (1) shows the results of the pocket penetrometer tests for D2 borehole.It can be seen that the values of (q_u) vary from 1.25 to 4.2 kg/cm^2. This indicates that the consistency of clay for borehole number D2 (as an example) varied from stiff clay to hard clay. The results for the other tests, D1 and D3 boreholes, were similar to the results of D2 borehole.

Furthermore, constant-head tests were carried out for determining the hydraulic conductivity of clay core in which the boreholes D1, D2, and D3 excavated. The hydraulic conductivity tests were conducted using the method recommended by USBR in 1974 (USBR 1974). According to the results, concentrated seepage did not happen. In addition, the hydraulic conductivity of the borehole was very small; between 0.05 and 0.248 m/year. The obtained value of the hydraulic conductivity is close to the original value of the hydraulic conductivity of the material in the dam core; 0.032 m/year (Calvin and Davis, 1958).

From the results of the visual inspections of the borehole logs, strength test results, and constant-head tests, the traces of cracks and softening or weakened zones in the clay core at the three locations were not obtained. The incompatibility between the geotechnical and the geophysical results can be attributed to the existing of different types of materials in the study area (i.e. concrete, clay, sand, gravel, and rock materials).

Figure 8 Clay core log using continuous core method.

Table 1: Unconfined compression test results for borehole D2 usinga pocket penetrometer.

Borehole Depth (m)	Unconfined compressive strength (q_u) (kg/cm^2)
5.5-6.5	1.75
6.5-7.5	1.25
7.5-8.5	1.25
9.5-10.5	1.75
10.5-11.5	1.75
11.5-12.5	4.2

6. SEEPAGE RATES

The seepage rates in most of the dams that experienced major earthquakes exhibited a rapid increase immediately after the earthquake for a small period of time. However, they returned to their original values in a short time (Yamaguchi et al. 2008,Yamaguchi et al. 2012,Pells and Fell, 2002).Regarding the Darbandikhan dam, since the seepage rates through the dam body could not be measured due to the absence of the toe drain (Yousif et al. 2019), the seepage data obtained were belonging to the seepage rates measured in the dam galleriesonly. In general, the seepage rates in the grouting galleriesincreased suddenly just after the earthquake, but even after two years, the seepage rates have not come back to the rates before the earthquake. However, no wet areas have been observed at the downstream slopes of the dam so far. The following subsections demonstrate the seepage behavior in the grouting galleries.

6.1. SEEPAGE RATE IN LEFT BANK GROUTING GALLERY

During 2017, the response of the seepage discharge in the left bank grouting gallery to the changes in the elevation of the reservoir water surface was similar to that during the year 2016 except the time of the major earthquake that hit the dam on November 12, 2017 (see Figure 9). One day after the major earthquake, the seepage in the left bank grouting gallery increased rapidly from 1 *l/min* to about 2.1 *l/min*; about 110% increased. Since then the increase (about 110%) has been persistent. However, after the major earthquake, the pattern of the relationship between the seepage discharges and water elevations in the reservoir returned to the previous shape.

For the year 2018, the pattern of the relationship between the seepage discharges and water elevations in the reservoir was similar to those of the years 2016 and 2017. However, in 2018, the water surface in the reservoir was not allowed to rise more than 10 meters; from the elevation of about 460 m to the elevation of about 470 m.

For the year 2019, the pattern of the relationship between the seepage discharges and water elevations in the reservoir was similar to those of the years 2016 and 2017.

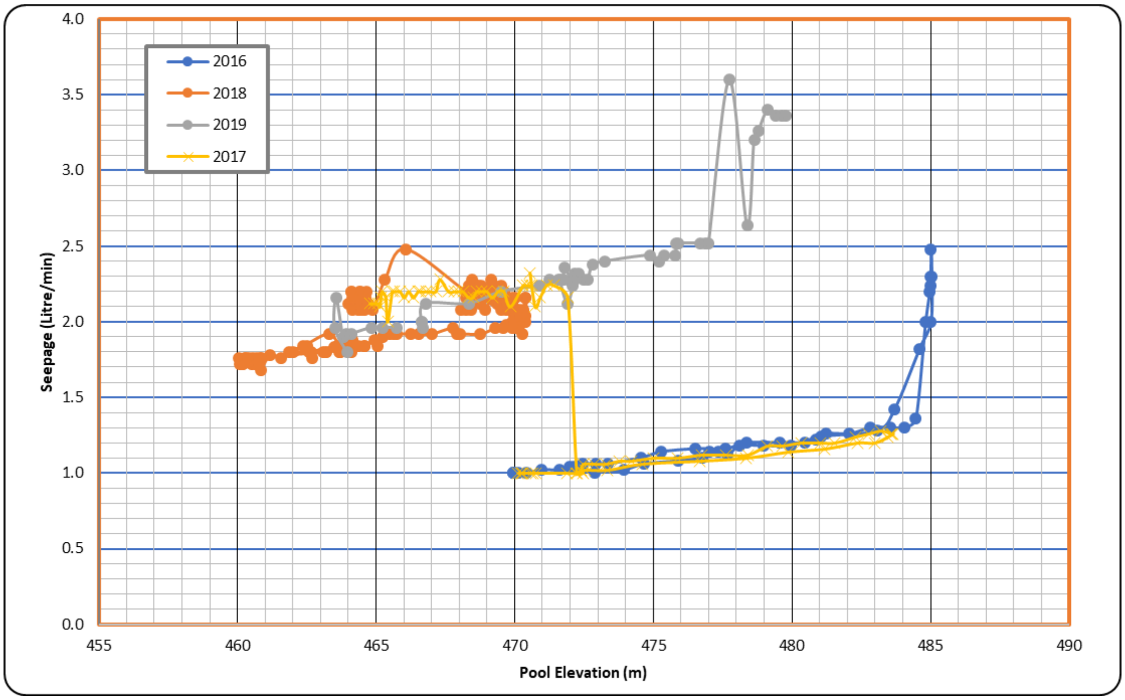

Figure 9: Left abutment grouting gallery seepage vs pool elevation.

6.2. SEEPAGE RATE IN RIGHT BANK GROUTING GALLERY

Figure 10 shows the change of seepage in the left gallery versus water elevation in the reservoir. From the figure, it can be noticed that there are two consecutive sudden increases in the seepage amount in the right bank gallery. The first seepage discharge has increased from 1.8 l/min to more than 5.5 l/min suddenly due to the November 12, 2017 earthquake. The second increasing was from about 5 l/min to more than 9 l/s, which means that the seepage quantity has increased about four times more than the seepage before the major earthquake. However, it is believed that the second increase might be due to another earthquake of Mw of 6.0 on December 11, 2017.The dam will be safe, provided that there is no turbid flow and that these amounts of seepage discharge are still low compared to the size of the dam's reservoir. However; as far as the seepage doesn't contain turbid water, and as far as it does not concentrate to a specified point, it can be concluded that the increased seepage will endanger the safety of the dam.

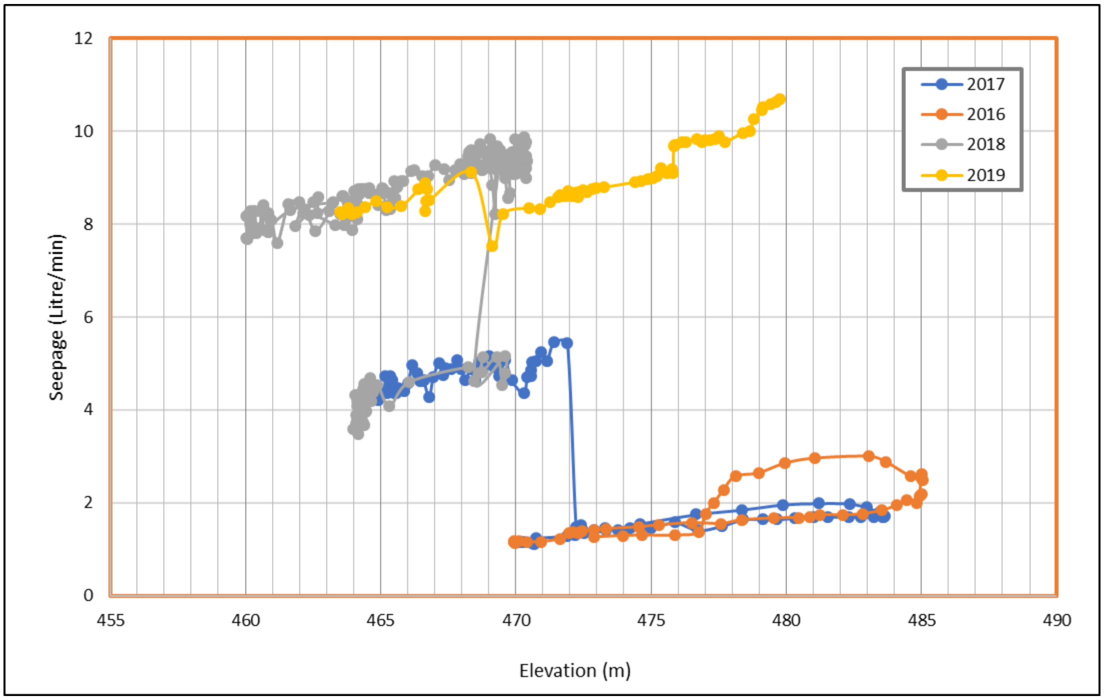

Figure 10: Right abutment gallery seepage versus pool elevation.

7. PIEZOMETERS READING

Regarding the relationship between the piezometer readings and the reservoir elevations; a graphical analysis showed that some piezometers experienced rapid increase in their readings (such as; P420, P440, P280, and P323) immediately after the November 12, 2017 earthquake, while the other piezometers showed no change in their readings after the major earthquake.

8. IS IT SAFE TO STORE WATER ABOVE ELEVATION 471.9 m?

Due to the awareness and cautions about whether there were cracks in the lower parts of the dam or not, the water level was not allowed to rise above elevation 470 m during 2018. However, in 2019, based on the results obtained from the drilled boreholes and on the promised information regarding the behavior of Earth Core Rockfill Dams (ECRD) subjected to major earthquakes, it wasdecided to gradually raise the water level in the reservoir. The decision of rising water level in the reservoir in 2019 was based on the academic findings and observations mentioned in Pells and Fell (2003), Fell et al., (2008), Ali Zomorodian and Jamali Moghadam (2011), Correia Dos Santos et al., (2015), and USBR (2015).

According to a statistical analysis carried out by Pells and Fell (2003), the depth of cracks that occurred in embankment dams due to earthquakes ranges from 15 to 100 times the width of the crack at the crest. For the Darbandikhan dam, the width of the major transverse crack that occurred in the clay core next to the spillways structure was about 16 cm. So, the estimated depth of this major crack should be between 2.4 m and 16 m from the top of the clay core (i.e. it may go down from elevation 490.6 m to elevation 479m).

In addition, Fell et al., (2008)as cited in (Concepts, 2015)stated that erosion in clay cores in embankment dams may not occur until the following two condition fulfilled;

1- The width of the transverse cracks reaches 1 or 2 inches and'
2- The hydraulic gradient approaches 0.5 or more.

In addition, the width of possible cracks in clay cores may be reduced or closed due to swelling by the wetting process.

Regarding the Darbandikhan dam, fulfilling the two conditions simultaneously is very rare; coexisting cracks with widths more than 2 inches and hydraulic gradients equal to or higher than 0.5 whenthe water elevation is 485 m. In

addition, the clay constituted the core is a well compacted high plasticityclay. Furthermore, the upstream and the downstream wide cohesionless filters will contributeto the crack filling or self-healing process should any crackexist in the core (Ali Zomorodian and Jamali Moghadam 2011; Correia Dos Santos et al., 2015;USBR 2015).
From all of the above analyses and the results of the various investigations, the authorities of the Darbandikhan dam concluded that there were no problems severe enough to threaten the safety of the dam and that the dam was safe and could store water to its full capacity.Accordingly, in May 2019, the water level in the Darbandikhan reservoir was raised to the elevation 484.28 m which isonly 0.72 m below the designed normal water level.

9. DAM DAMAGES REPAIR

Based on the results of the detailed inspections, the repair works for the damaged parts of the dam crest was started in June 2019. The asphalt road, sidewalk, and electrical poles (they were old and some of them partially damaged) werefirst demolished and then reconstructed as shown in Figure 11. Regarding the spillway-embankment interface,it was decided to excavate the cracks to depths where the cracks will disappear and reconstruct it again as shown in Figure 10. Since it wasfound that the interface crack between the spillway wall and the embankment part of the dam was a superficial crack, it does not endanger the safety of the dam.

Figure 11: The crest of the dam before and after removing the damaged parts.

Figure 12: Excavation next to the spillway wall.

10. CONCLUSIONS

Darbandikhan dam has experienced several damages and deformations (settlement and cracks) due to a strong earthquake that occurred on November 12, 2017 (Mw = 7.3). Accordingly, in order to check the dam's status after the earthquake, thorough inspections were carried out by several teams. The measures necessary for evaluation and remediation of the earthquake-induced damages were adopted by those teams. Both geophysical and geotechnical investigations were carried out in order to check the dam's status following the major earthquake. Although it suffered damages, the dam performed satisfactorily and survived the earthquake.Accordingly, based on the results of the detailed inspections and investigations, since there was no evidence on existing cracks or weakened zones in the dam core, the water level in the Darbandikhan reservoir was risen to elevation 484.28 m (full reservoir level) by the end of May 2019 and the damaged parts of the dam crest were repaired by August 2019.

From the results of the inspections and the evaluations, the following conclusions can be drawn:

1. Adequate design and construction of dams can help them pass through even large earthquakes.
2. The adoptedmeasures used for evaluation and remediation of the earthquake-induced damages in Darbandikhan dams were dependable for checking dam safety.
3. Geophysical methods such as Ground Penetrating Radar (GPR) and the Multichannel Analysis of Surface Waves method (MASW) were not reliable in identifying cracks and weakened zones in the Darbandikhan dam.

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