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THE PROSPECT OF SEISMIC MONITORING OF THE DARBANDIKHAN DAM IN KURDISTAN, IRAQ, AND THE SURROUNDING REGION

Rami Ibrahim[1], Hemin Ahmed[2*], Hafidh A.A. Ghalib[3], Abdulrahman Khani[4], Saman Esmail[5], and Rahand Majeed[6]

[1] EMR Solutions & Technology, USA; rami.ibrahim@emrsolutionsit.com
[2] Directorate of Darbandikhan Dam, Kurdistan, Iraq; hemingeology@gmail.com
[3] EMR Solutions & Technology, USA; hafidh.ghalib@emrsolutionsit.com
[4] General Directorate of Dams and Reservoirs, Kurdistan, Iraq; rahmankhany@googlemail.com
[5] Directorate of Darbandikhan Dam, Kurdistan, Iraq; samankirkuk@yahoo.com
[6] Directorate of Darbandikhan Dam, Kurdistan, Iraq; shekhany1999@gmail.com
***** Correspondence: hemingeology@gmail.com

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Abstract

Darbandikhan Dam is an embankment dam located in Kurdistan, Iraq, a seismically active region. The Zagros Fold and Thrust Fault belt is known for generating significant earthquakes, including the devastating magnitude 7.3 Ezgeleh-Sarpolzahab earthquake that struck the region on 12 November 2017. The purpose of this study is to examine the seismic activity in the region over the period 1917 to 2023 and its recent impact on the Darbandikhan dam structure. A total number of 6138 events are found in national and international catalogs within the geographical region 44.9°- 46.9° E and 34.4°- 35.6° N with magnitudes between 1.0 and 7.3 and focal depth ≤ 20 km. We also examined the induced seismic activity in the area by comparing it with the water level of the dam's reservoir. A poor correlation between the occurrence of earthquakes and the loading and unloading of the Darbandikhan reservoir due to the lack of a comprehensive seismic observation system in the region. Considering that Kurdistan Iraq Seismological Network (KISN) stations are sparsely distributed, we propose deploying a dense local network of seismic and strong motion stations in and around the dam. The proposed network would consist of (1) a network of strong motion stations on and inside the body of the dam to analyze its response to earthquake shaking, (2) a network of broadband seismic stations distributed throughout the vicinity of the dam region to monitor the local seismic activity, and (3) a network of Global Navigation Satellite Systems (GNSS) that offer a precise, continuous, and automated approach for measuring and identifying even minor structural deformations on the dam. Note, these proposed networks should also be considered for the other dams in Iraq, *e.g.*, Dokan and Duhok, as well as Mosul Dam, because they are all subject to seismic activity in the north and northeast of the country.

Keywords: Darbandikhan Dam; 2017 Ezgeleh-Sarpolzahab earthquake; seismic monitoring; GNSS stations.

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1. Introduction

Darbandikhan Dam is in an area known for its varied geological formations and tectonic activity. The foundation of the dam is primarily composed of sedimentary rocks, including limestone, marl, and shale, which are part of the Sinjar formation. The surrounding area is influenced by the tectonic forces associated with the ongoing collision between the Arabian Plate and the Eurasian Plate. This tectonic activity has resulted in the formation of the Zagros fold and thrust belt, making it prone to earthquakes and associated ground motions (Abdulnaby, 2019; Abdulnaby et al., 2014; Jassim & Goff, 2007).

Darbandikhan Dam is an embankment dam located in the most seismically active Kurdistan region of Iraq, in the contact of the High and low folded Zone, approximately 67 km southeast of the city of Sulaymaniyah and 230 km northeast of Baghdad. The dam’s construction began in 1956 and was completed in 1961, creating a vast reservoir that stretches across an undulating landscape. During that period, earthquakes might have been considered as a general load, but not with the detailed analysis and ground motion parameters required by modern codes. If any seismic analysis was performed, it was likely based on a simple equivalent static force, not a dynamic analysis. The design might have relied more on conservative empirical rules and overall safety factors for stability than explicit seismic performance criteria. The examination of the unpublished document produced by Harza Engineering Company, the American firm responsible for designing the dam, reveals that the stability evaluation employed the sliding wedge and slip-circle approaches, revealing that the safety factors varied from 2.21 to 1.22 under different loads. The analysis also indicated that the most severe scenario occurs when the reservoir is at an elevation of 485 meters and subjected to an earthquake acceleration of 0.1 g, during which the downstream slope, evaluated using the sliding-wedge method, exhibited a minimum factor of safety of 1.22.

The tectonic setting of the Darbandikhan dam is intrinsically associated with its position in the Zagros Fold-Thrust Belt, a significant geological formation arising from the continuous convergence of the Arabian and Eurasian tectonic plates. This collision is the principal cause of seismic activity and structural deformation in the area. The Darbandikhan dam is situated within this belt, a zone of intense deformation where sedimentary rock layers have been folded into anticlines and synclines and displaced along numerous thrust faults. The folds and faults generally align in a northwest-southeast direction, reflecting the direction of the principal compressional stress. Thrust faulting is the dominant style of faulting in the region and plays a significant role in earthquake generation. The ongoing tectonic activity makes the Zagros region, including the area around Darbandikhan, prone to frequent earthquakes of varying magnitudes. The dam is located at the end of a gorge cut through the Bammo Anticline by the Diyala (Sirwan) River (Figure 1). The Anticline consists of Tertiary rocks, ranging from older to newer, including (1) the Kolosh formation consists of dark grey sequence of claystone, shale, siltstones and sandstones with rare conglomerate, (2) the Sinjar formation consists of well thickly bedded – massive limestone, (3) the Gercus formation, characterized by a mixture of red claystone, sandstone, and infrequent conglomerates, (4) the Pila Spi formation, the upper part is composed of well bedded, white and grey limestone and chalky marl with chert nodules, toward the top, while the lower part shows well bedded, hard, porous, poorly fossiliferous limestone with algal or shell sections, with dolomitic limestone, chert intercalations and rare concentrations of gastropod debris (Sissakian & Fouad, 2016)

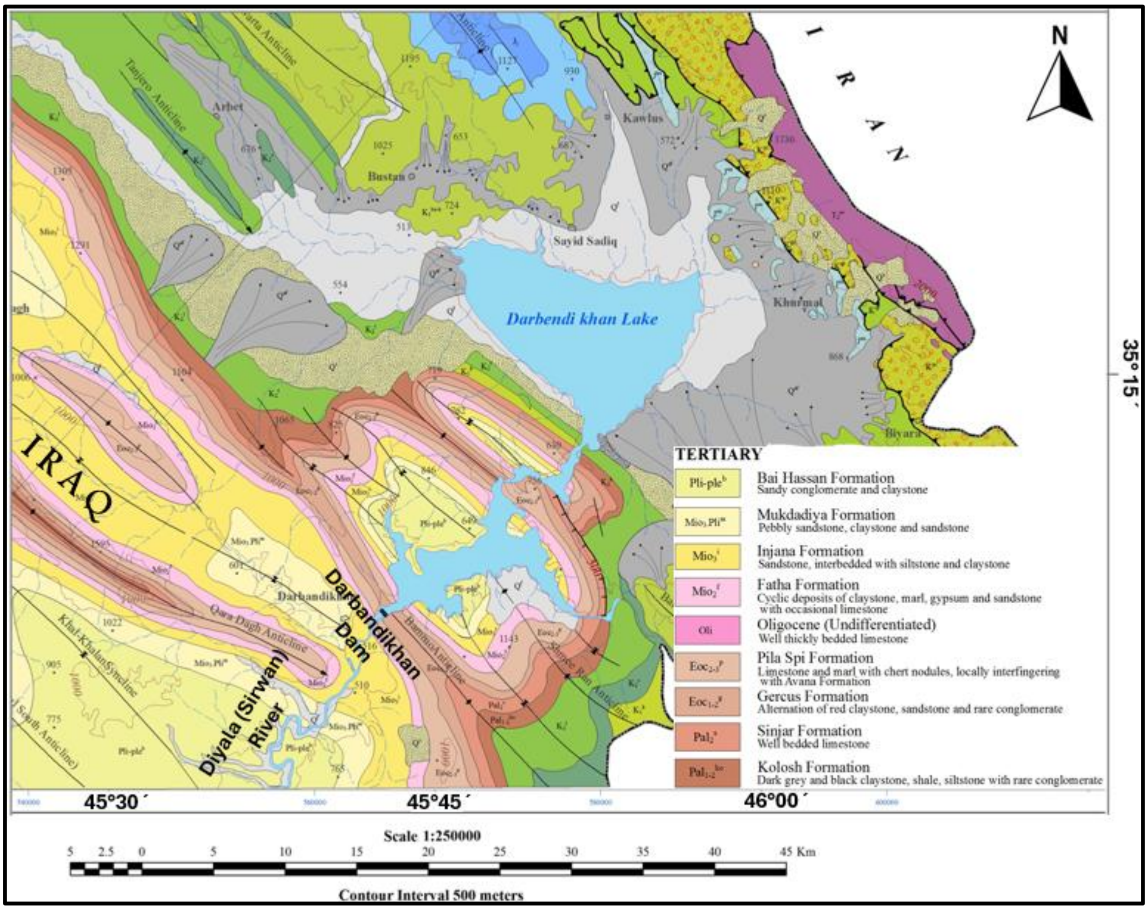

Figure 1. A map showing the geological settings surrounding the Darbandikhan dam and its lake after (Sissakian & Fouad, 2016).

The purpose of the dam is to regulate the flow of the Diyala (Sirwan) River, i.e., flood control, irrigation, and hydroelectric power generation. The dam is 128 m high with a central clay core and rockfill shoulders. The length of the dam at the crest is 445 m (535 m including its chute spillway). The reservoir design capacity at normal operating level (485.00 m above sea level) is 3 billion m^3, of which 2.5 billion m^3 is live storage and 0.5 billion m^3 is dead storage capacity. In 1974, the dam reservoir exceeded its storage capacity, and in the 1980s, its power plants were upgraded.

Over the past decades, the dam has also faced many difficulties of geological origin, *i.e.*, the recurrence of earthquakes of all magnitudes in its vicinity. The latest devastating earthquake is the magnitude M_w 7.3 Ezgeleh-Sarpolzahab earthquake that struck the region on 12 November 2017 at 18:18 UTC. Its epicenter is located at 34.957° N and 45.792° E, and the focal depth ranges from 15 to 25 km, likely to place it in the upper crust. Its epicenter is situated near the Iranian town of Ezgeleh, around 40 kilometers east of Darbandikhan Dam, behind the Iraq border in the western Lorestan arc. More than 600 victims died, primarily in Sarpolzahab, a significant Iranian municipality with a population of over 90,000, located about 50 kilometers south of Ezgeleh. The towns on the Zahab plain, situated north of Sarpolzahab, suffered substantial damage (Barnhart et al., 2018; Nissen et al., 2019). Consequently, the dam structure experienced significant deformation due to the earthquake. Numerous minor and major cracks, encompassing both transverse and longitudinal varieties, have developed in the crest pavement at the abutments and the dam's center, as well as along the dam axis on both the upstream and downstream sides of the crest. Figure 2 illustrates instances of enduring damage to the dam and its infrastructure. Figure 2a illustrates the spillway wall displaced lower by 40 cm relative to the dam's structure. Figures 2b and 2c illustrate the development of transverse and longitudinal cracks on the dam's crest, while Figure 2d depicts the complete collapse of one of the dam's administrative buildings. The geodetic study completed immediately following the earthquake indicates that the dam has sustained permanent earthquake-induced deformations: about 22 cm horizontally in the upstream/downstream direction and 13 cm horizontally from the right abutment to the left abutment. The largest vertical movement was approximately 48 cm. Despite being impaired, the dam managed to withstand the seismic forces and prevent catastrophic flooding downstream (Abdullah et al., 2020; Al-Husseinawi et al., 2018; Yousif et al., 2019) examined the dam displacement rate before and after the earthquake using InSAR time series analysis from October 2014 to March 2018. Their results suggested that the dam was relatively stable before the event, with a maximum line of sight (LOS) velocity of 4 mm/year; nevertheless, after the event, the dam's crest continued to experience creep at a rate of up to 70 mm/year until at least March 2018.

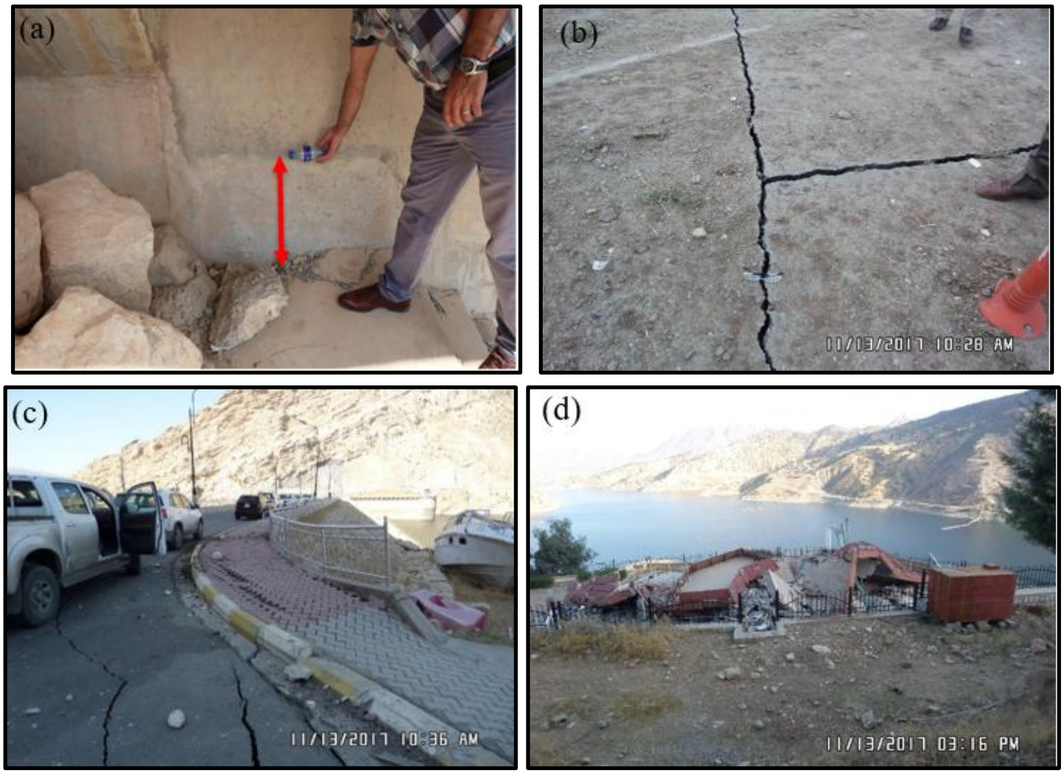

Figure 2. Photos captured after the 2017 Ezgeleh-Sarpolzahab earthquake showing (a) displacement between the spillway and the dam body, (b and c) cracks on the dam’s crest, and (d) damage to the Darbandikhan dam directorate guest house.

The purpose of this study is to analyze the seismic activity surrounding the dam region and to better understand the tectonic activity and induced seismicity that may impact the dam infrastructure. The latter will require further in-depth study once a local seismic network is established.

2. Data and Analysis

The seismic activity in the Darbandikhan region and adjacent areas was obtained from the unified earthquake catalog of Iraq (Ahmed et al., 2024). Their catalog is an integrated catalog of the Kurdistan Iraq Seismological Center (KISC). It is noteworthy that KISC operates the KISN, a sparse seismic network of eight three-component broadband seismic stations, and the five-element three-component broadband KSIRS array. The data from these stations are telemetered to KISC in real-time and automatically processed using the SeisComPro software system. KISC analysts review the detected events and issue monthly and yearly bulletins. In addition to the KISC catalogs, the Iranian Seismological Center (IRSC), the International Seismological Center (ISC), and the USGS National Earthquake Information Center (NIEC) catalogs were used for the unified earthquake catalog of Iraq. It resulted in identifying 6138 earthquakes that occurred over the period 1917 – 2023 in the geographical area bound by 34.4° to 35.6° N latitude and 44.9° to 46.9° E longitude (Figure 3). Figure 4 illustrates the annual frequency distribution of earthquakes between 2006 and 2023. Prior to 2006, the year the KISN started operations, only 63 events were cataloged by international organizations. The seismic activity significantly escalated in and after 2017, attributed to the 2017 Ezgeleh-Sarpolzahab earthquake and its aftershocks, culminating in the highest record in 2018. The moment magnitude (M_w) of these earthquakes ranges from 1.0 to 7.3, where most earthquakes have a magnitude less than 4 (Figure 5). Most of these earthquakes are located in the upper crust, with focal depths of less than 20 km, as illustrated in the three-dimensional image shown in Figure 6. The seismic activity surrounding the Darbandikhan dam is linked to adjacent fault systems, notably the Diyala (Sirwan) fault and the Zagros folded and thrust belt regions. Furthermore, the focal mechanism solutions for earthquakes occurring near the dam were examined and illustrated in Figure 7. The focal mechanism solutions are derived from the Global Centroid Moment Tensor (GCMT) project at Harvard University and the Iranian Seismological Center (IRSC) at the University of Tehran, encompassing the period from 2003 to 2023. The fault source zone of the 2017 Ezgeleh-Sarpolzahab earthquake, as delineated by Barnhart et al. (2018), is also illustrated in the same figure for comparative analysis. Analysis reveals that most earthquakes in both catalogs are situated inside the structural fault source zone, indicating that the principal focal mechanisms are of reverse and strike-slip varieties. The western edge of the source area indicated that the primary mechanisms are reverse-type faults with magnitudes of 7.3, 5.1, 5.8, 5.0, 4.5, and 5.0, possibly linked to the Khanaqin fault in the vicinity. Furthermore, strike-slip faults with magnitudes of 5.8, 4.7, 4.7, and 4.9 are recognized along the right margin, presumably associated with transverse faults; for further details, refer to Sissakian et al. (2025). The northern edge of the source region indicates that earthquakes reveal strike-slip faults aligned with the Diyala (Sirwan) fault. The northern area of the Darbandikhan dam reservoir shows a reverse fault with a magnitude of 5.2.

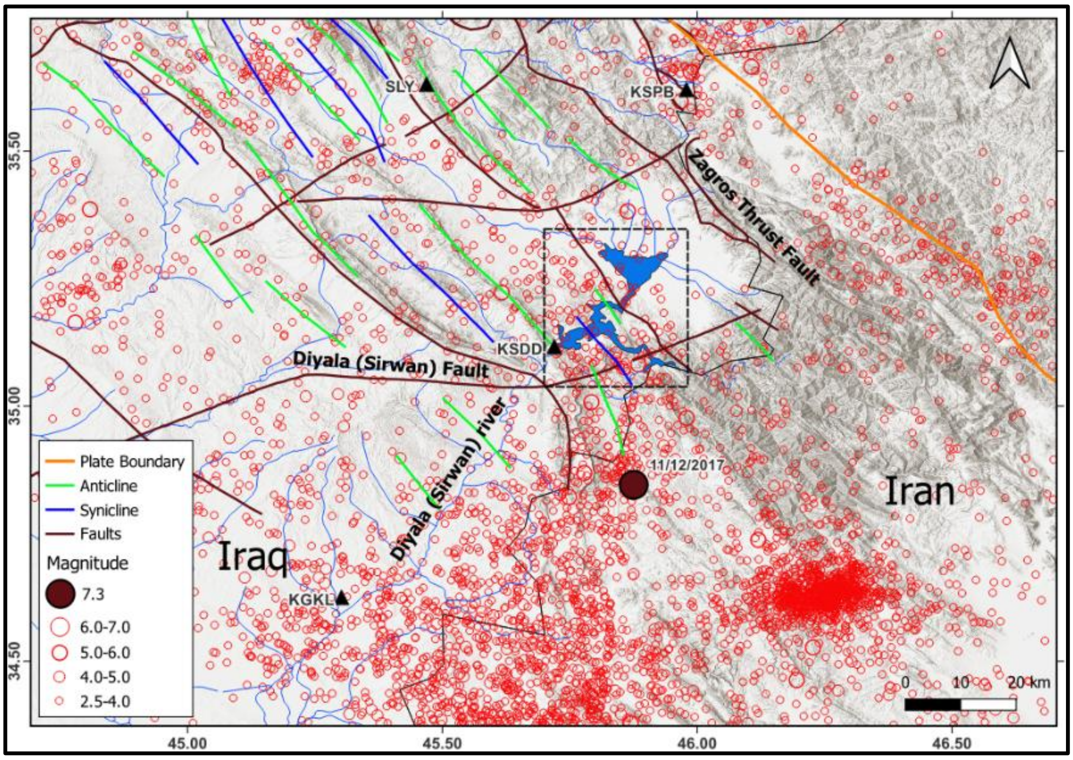

Figure 3. The earthquakes occurred at the study site and surrounding areas, for the period 1917-2023. Brown circle refers to the epicenter of the 2017 Ezgeleh-Sarpolzahab earthquake (M_w 7.3). Black triangles refer to seismic stations run by the Kurdistan Iraq Seismic Network (KISN). Fault, anticline, and syncline traces on the ground surface were digitized from the tectonic map of Northern Iraq, scale of 1:500,000, produced by the Food and Agriculture Organization (FAO) coordination office of Northern Iraq.

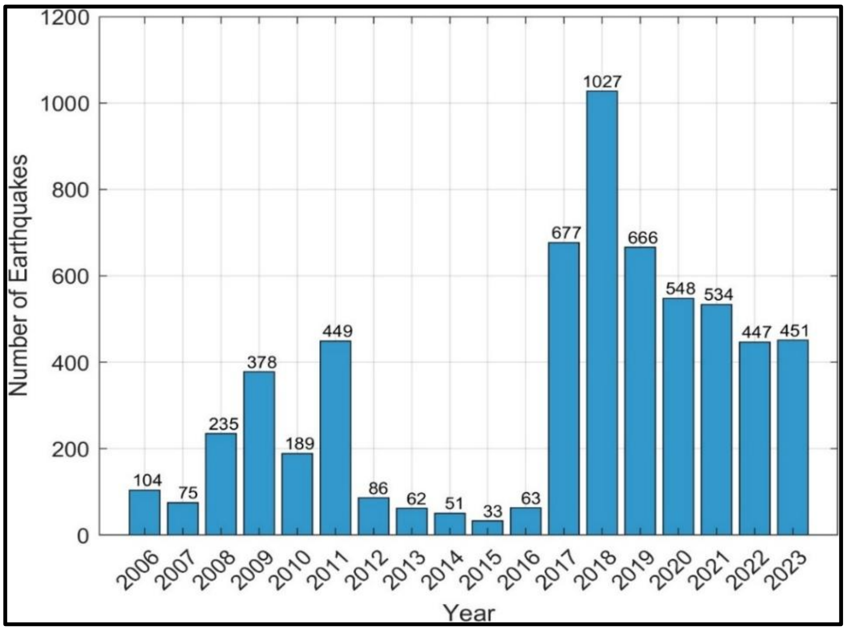

Figure 4. The histogram illustrates the annual frequency of earthquakes in the studied area from 2006 to 2023. It illustrates the rise of earthquakes following the 2017 Ezgeleh-Sarpolzahab earthquake.

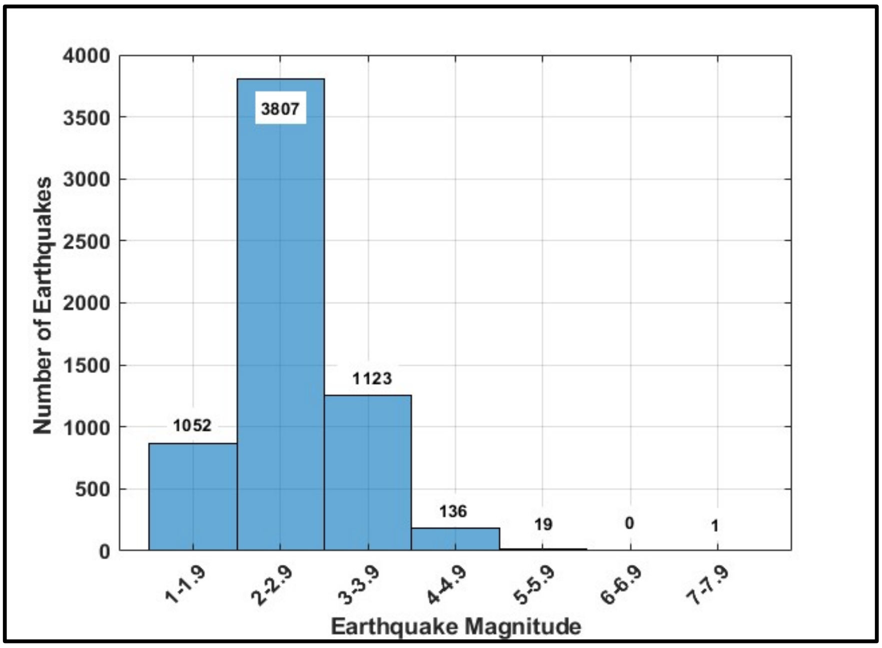

Figure 5. The histogram shows the number of earthquakes versus magnitude.

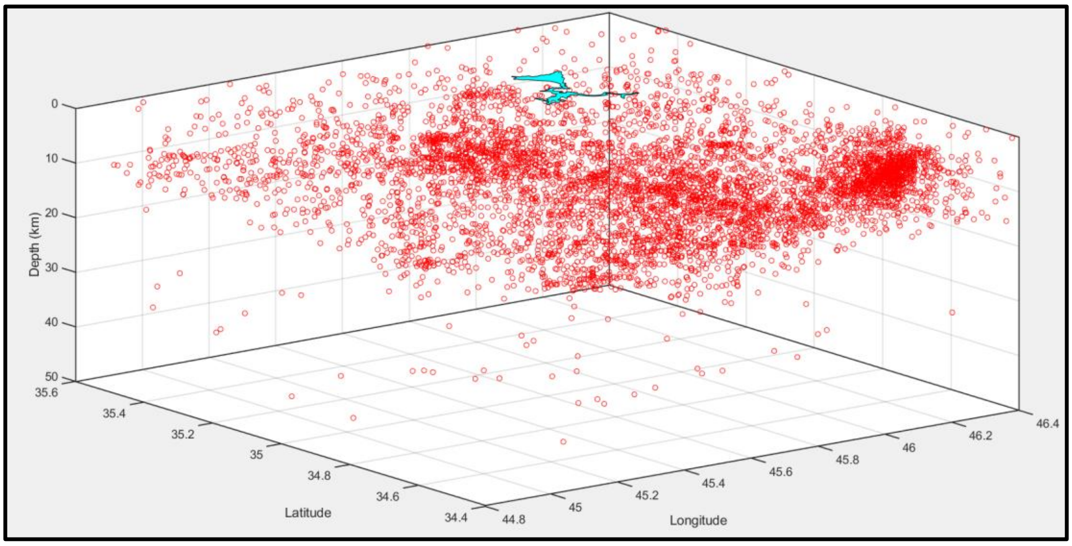

Figure 6. Three-dimensional view of the earthquake distribution at the Darbandikhan Dam and surrounding regions.

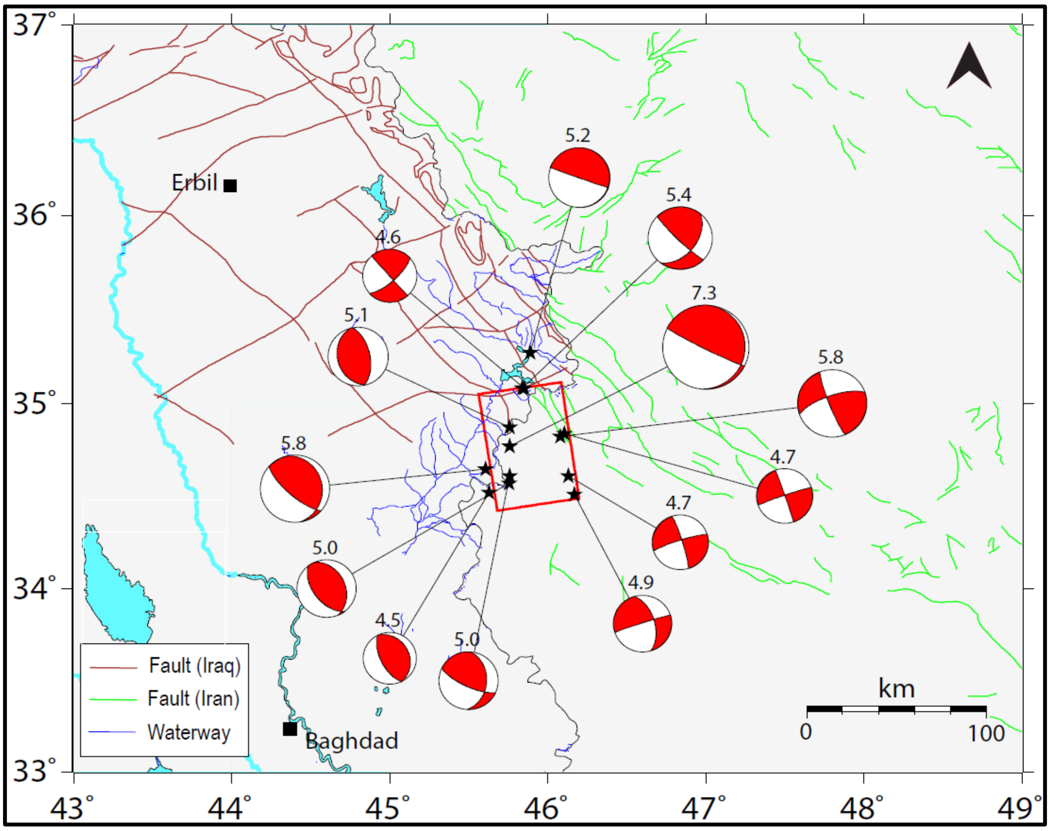

Figure 7. The focal mechanism solutions from 2003 to 2023 around the Darbandikhan dam, as shown in beach balls, the value over each beach ball refers to the earthquake moment magnitude, and the black star refers to the earthquake epicenter. The red rectangle refers to the fault source area that generated the 2017 Ezgeleh-Sarpolzahab earthquake according to Barnhart et al. (2018). Brown lines denote faults derived from the tectonic map of Northern Iraq, scaled at 1:500,000, produced by the FAO Coordination Office of Northern Iraq. The green lines denote faults in Iran, as per Mahsuli et al. (2019).

3. Reservoir Induced Seismicity

The Reservoir Induced Seismicity (RIS) refers to the earthquakes caused by the physical changes that occur when massive reservoirs are filled with water. The mechanism of such seismicity may either be immediate due to changes in the elastic stress or delayed due to changes in pore pressure and fluid diffusion. The weight of water changes the tectonic stress conditions by either increasing the vertical stress due to loading or increasing the pore pressure, reducing the effective normal stress. The net effect of stress changes can increase or decrease the stresses applied on the existing faults, depending on the orientation and the geometry of the reservoir and the fault system (Kangi & Heidari, 2008; Roeloffs, 1988; Simpson et al., 1988; Zhang et al., 2017).

The Darbandikhan dam region is characterized by hot, dry summers and cool, wet winters. The rainy season is usually in the winter and spring months, starting in October and continuing through March, with occasional extensions into May. The reservoir's water level has been regularly monitored over the years. To examine the seismicity's temporal pattern, we compared its development with the reservoir's monthly water level fluctuations for the period 2019-2022. The seismicity region was confined to events situated beneath the dam's reservoir and its adjacent area, as seen by the dashed rectangle in Figure 3. Figure 8 illustrates a comparison of the frequency of earthquakes and the water level in the dam reservoir from 2019 to 2022. It showed a reasonable correlation between the loading and unloading of the Darbandikhan reservoir and the frequency of earthquakes in 2022, but indicated a lack of correlation in other years. The observed lack of correlation between these two data sets over time can undoubtedly be attributed to the inadequate capability to monitor the seismicity of the dam region. KISN currently has only one operational broadband three-component station, KSDD, located at 35.1169° N and 45.7202° E, about one kilometer from the dam.

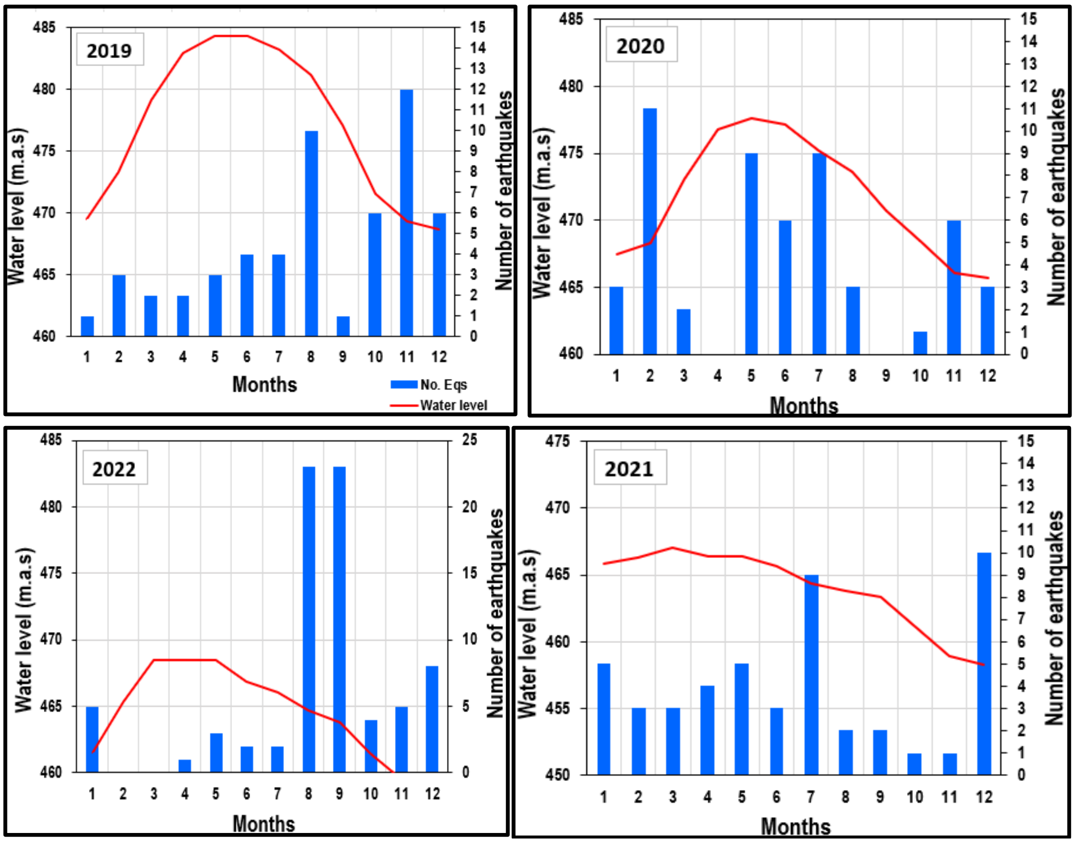

Figure 8. A comparison between the local seismicity (blue) and the Darbandikhan reservoir water level (red) for the period from 2019 to 2022 shows a poor correlation between the two data sets.

4. Proposed Monitoring Systems

Understanding the hazards and history of earthquakes in a region is required to design, construct, and maintain dams to withstand potential ground shaking. Hence, it is crucial to continuously monitor the local as well as the regional seismic activity and tectonic setting. Dams like Darbandikhan, Dokan, Duhok, and Mosul in north and northeast Iraq are subject to continuous seismic activity of various magnitudes. Large earthquakes are devastating, but damage to structures can occur because of the impact of recurring smaller magnitude events and the buildup of stress over time. Seismic observation is also critical for evaluating the integrity and stability of dams during and after an earthquake. It helps in understanding how the dam and its foundation materials will respond to seismic forces and ensures that the dam can withstand the ground shaking without catastrophic failure. Continuous seismic monitoring provides real-time data on how a dam behaves during an earthquake. This includes measuring dam deformation, settlement, and potential structural damage caused by ground shaking. Monitoring allows for early detection of any changes in dam behavior that might compromise its safety and contributes to comprehensive risk assessment and management strategies for dams (Chowdhury et al., 2020; Mendes et al., 2007).

KISC stations are by no means planned to effectively monitor the seismicity at or around the Darbandikhan or any other dam in the region. Therefore, to properly study and understand the potential seismic hazard on the Darbandikhan Dam, we propose a comprehensive but preliminary plan consisting of:

4.1. Strong Motion Stations

Deploy a network of strong motion stations on and inside the body of the dam to analyze its response to earthquake shaking. As shown in Figures 9 and 10, install two strong motion instruments in the dam's abutment, one at the midpoint of the crest and one at the junction between the dam body and concrete spillway structure, the weak part of the dam where vertical displacement was observed during the 2017 Ezgeleh-Sarpolzahab earthquake. Additionally, it is recommended to position two instruments within the grouting galleries and another instrument at the foundation. Furthermore, it is advisable to position one instrument at the free field downstream at a distance of 3 – 4 times the height of the dam to avoid any structural interference caused by the dam.

4.2. Broadband Stations

Deploy a network of broadband stations distributed throughout the vicinity of the dam region to monitor the local seismic activity. As shown in Figure 11, install five stations to cover the area of the dam and its surroundings to monitor the earthquakes associated with the faults and the induced seismicity in the region.

4.3. Global Navigation Satellite System (GNSS)

GNSS offers accurate, continuous, and real-time or near real-time measurements of three-dimensional displacements (horizontal and vertical) of points on the dam structure and its surrounding foundation. This enables engineers to identify minor movements, settlement, or lateral displacement that may signify structural distress, foundation instability, or reactions to external forces such as seismic activities or the filling/emptying of reservoirs. We recommend the installation of two receivers on the crest, one on the abutment, one downstream, and one on the dam's flank, outside of the dam body, considered as reference points (Figure 12). For instance, GPS stations placed on the dam's abutment (the side where the dam connects to the natural ground) and foundation areas can detect movements in the surrounding rock or soil, which might affect the dam's overall stability (Ehiorobo & Ehigiator Irughe, 2011; Tsakiri & Stewart, 2001). It's worth mentioning that most large dams in the world are observed by GNSS, and impressive results are obtained. For instance, (Reguzzoni et al., 2022) monitored a dam in Italy with five GNSS sensors, achieving daily millimeter-level precision suitable for a semi-early warning system for deformation detection at the dam.

Figure 9. Deployment of the proposed strong motion stations to monitor the activity at the dam's body.

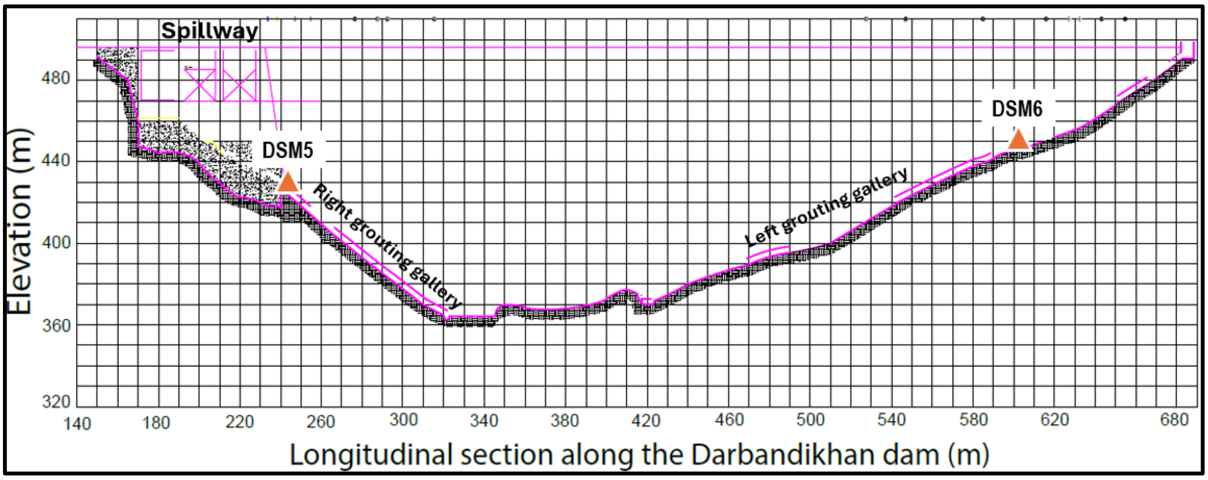

Figure 10. Longitudinal section through the dam shows the position of stations DSM5 and DSM6 within the grouting galleries located in the dam's body.

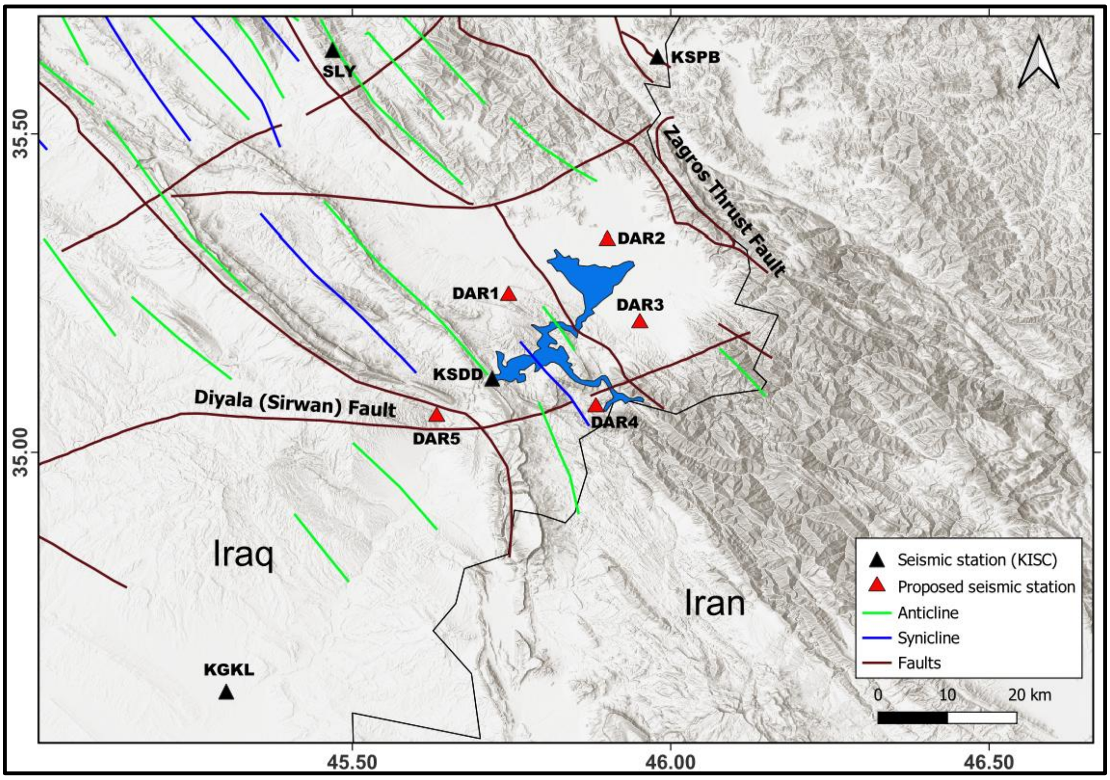

Figure 11. The proposed seismic network is deployed around the dam's reservoir to record seismic activity in the region.

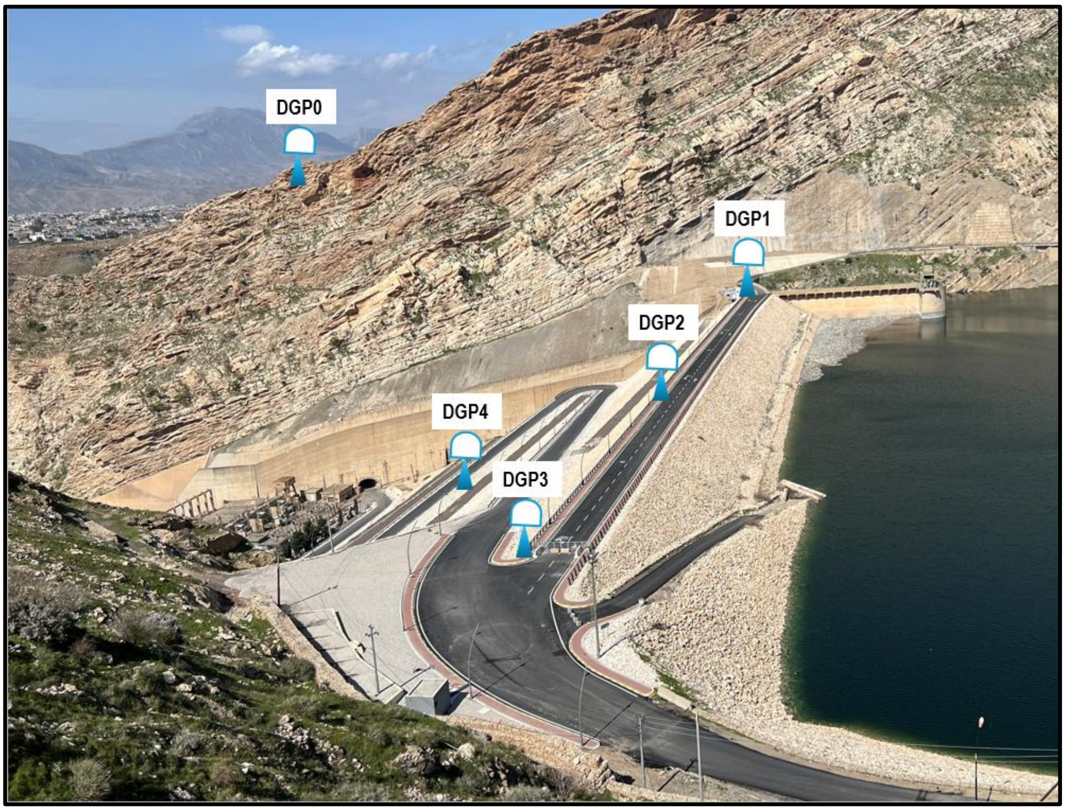

Figure 12. Deployment of the proposed GNSS receivers to monitor the movement within the dam's body.

5. Results and Discussion

Upon analyzing the seismic activity at the Darbandikhan dam and its surrounding areas, which pose a significant hazard to the dam and its infrastructure, we identified over 20 strong motion events from 1917 to 2023 that exceeded a magnitude of 5, including the 2017 Ezgeleh-Sarpolzahab event (M_w 7.3). Most earthquakes in the region occur at shallow depths of less than 20 km (i.e., upper crust), thereby increasing the hazard in the area. Furthermore, focal mechanism solutions for 13 earthquakes were acquired from the GCMT at Harvard University and the IRSC at the University of Tehran, indicating that the predominant fault type mechanisms are reverse and strike-slip. The focal mechanism is essential for comprehending regional tectonics, as it offers clear explanations for the stresses and movements occurring within the Earth's crust, where earthquakes originate. For instance, reverse faulting in the region confirms that the Arabian Plate is pushing northeast into the Eurasian Plate.

As aforementioned, the maximum recorded earthquake in the region was of $M_w = 7.3$; however, Abdulnaby et al. (2020) proposed seismic hazard maps of Iraq to provide valuable insights into the potential earthquake risk in the region. Using local and international seismicity catalogs, they divided Iraq and the surrounding regions into 12 seismic source zones, with the Darbandikhan dam located in zone 1, known as the Bitlis-Zagros Thrust Belt. The potential maximum Gutenberg-Richter magnitude in that zone is $M_{max}=7.8 \pm 0.2$. The Darbandikhan dam is in the region where the Peak Ground Acceleration (PGA) ranges from 0.4 to 0.5 g, with a 2% probability of being exceeded within 50 years or a return period of 2475 years. To eliminate any ambiguity for the reader, the stability assessment would have been performed in accordance with the dam's specific and rigorous design standards, rather than the generic building code applicable to a school or office structure in the vicinity.

In addition to tectonic events, the dam is subject to induced seismicity that may arise from the loading and unloading of water in the dam's reservoir. The water level of the dam's reservoir was analyzed in relation to the frequency of seismic events in the vicinity. A minor correlation has been defined between the frequency of earthquakes and the fluctuations of the Darbandikhan dam’s reservoir. This relationship may indicate induced seismicity taking place in the vicinity of the dam. The absence of a definitive correlation may be ascribed to the lack of a comprehensive seismic monitoring system in the region.

6. Conclusions

Safeguarding a dam like Darbandikhan is not an option. It is a requirement that cannot be ignored or deferred because the impact of another large earthquake on an already weakened dam can be more devastating. The occurrence of the M_w 7.3 Ezgeleh-Sarpolzahab earthquake on 12 November 2017 was not a coincidence. It can happen again at any time because the tectonic setting and abundant fault systems in the region are continuously being stressed by the northeastern and counterclockwise rotational motion of the Arabian plate. In addition, the potential impact of reservoir-induced seismicity cannot be ignored or deferred either, because earthquakes of smaller magnitudes frequently occur throughout the Darbandikhan Dam region. Their cumulative effect on an already weakened dam structure can also be devastating. Therefore, it is imperative to start monitoring the seismicity and tectonic patterns of the region using (1) a network of strong motion stations on and inside the body of the dam to analyze its response to earthquake shaking, (2) a network of broadband stations distributed throughout the vicinity of the dam region to monitor the local seismic activity, and (3) a GNSS monitoring network that offers a robust, non-invasive, and extremely precise technique for the continuous assessment of dam structural integrity, essential for their safe operation and risk mitigation. Failure to start understanding through studies the effect of seismicity on the dam and failure to develop scientific safeguards to mitigate earthquake risk can be very costly in life and property. Given the dam's age and its location in a highly active seismic zone, it is highly probable that the Darbandikhan Dam has undergone or needs to undergo seismic re-evaluation and potentially rehabilitation to meet modern safety standards.

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