Note on Earthquake Safety for Bisri Dam

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In the meeting that was held on April 4, 2019 in the Lebanese Parliament, by the parliamentarian committee for public works – transportation – energy and water, issues and allegations regarding the earthquake safety of the Bisri Dam has been discussed.

This note is prepared to elaborate the following issues and to respond to the allegations raised, including the ones addressed by the committee recommendations on earthquake safety.

1. Conclusive Statement
2. Earthquake Safety of the Bisri Dam
3. Faults Under the Bisri Dam
4. Seismic Activity of the Roum Fault
5. Reservoir Induced / Triggered Earthquakes and Bisri Dam
6. Landslides triggered by earthquakes or after the reservoir filling

1. Conclusive Statement

It is scientifically unsound in total to consider that: "the water impoundment above a "fault" (?), (assumed to be in Bisri lake), *with the weight of this water, under the phenomena called reservoir-triggered seismicity, making it eventually seeping into the subsurface, creating a lubricating effect, which – combined with the weight from above – will change the stresses over the fault line (assumed connected with Roum fault), making the rocks shift below the surface, and creating an earthquake",* for the reasons summarized below:

1- The fracture underneath the Bisri Dam Reservoir is a geological fracture, that can exist anywhere, and cannot be associated with a known neo-tectonic feature or seismologically active fault, e.g. Roum Fault.

2- For this fracture to displace and cause offset on the Roum Fault, it has to be considered initially as an active fault, under a high tectonic stress, which is not the case.

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3- A large magnitude earthquake on Roum fault can possibly originate at a depth of at least 15-20km. It is unsound to believe that a reservoir of about 60-70m head can generate enough pressure to cause seepage to such depths and "lubricate" cracks (assuming the existence of an active fault under the dam).

4- The Awali river is passing through the area and the conducted boreholes proves the existence of underground water at constant shallow levels, as such, with the irrational reasoning the alleged fault is already “lubricated”, and it does not need any additional water height (of meters) to be lubricated.

5- Even if the alleged lubrication process is feasible (which is not), it would be rational to lubricate the central portion of the Roum Fault (which is about 25km to the south of the Bisri Dam) to create an RTS, rather than the north terminus allegedly under the Bisri dam.

6- In the ICOLD Bulletin on Reservoirs and Seismicity – State of Knowledge (Bulletin 137, 2009), the ICOLD’s Committee on Seismic Aspects of Dam Design states that RTS earthquakes may only be considered in the case of the reservoir water depth exceeds 100 m, which is not the case for Bisri dam, as its maximum water height is only 61m.

7- Throughout the world, several thousands of dams have been constructed and are impounding reservoirs which are operating without any observed RTS. We gave the examples of Qaroun Dam in Lebanon, close to the Yammouneh fault, i.e. the largest active fault in the country, and other much larger dams in Turkey built within the close vicinity of major active faults, such as: Almus Dam (fault name: Almus fault), Golova Dam (North Anatolian Fault), Tahtaköprü Dam (Dead Sea fault), and, one of the largest, Ataturk Dam (Bozova Fault).

2. Earthquake Safety of the Bisri Dam

Rockfill dams are generally considered to be inherently stable under extreme earthquake loading, and represent desirable types of dams in highly seismic areas (USCOLD, 2000);

Bisri Dam is designed as a rockfill type embankment dam with very gentle upstream and downstream slopes, wide stabilizing berms and a large freeboard to provide a very safe conceptual design as well as to prevent overtopping even during extreme floods and extreme earthquakes.

The dam foundation material is not really prone to liquefaction during earthquake shaking due to high fines- and clay content. However, as a precautionary measure, the liquefaction resistance will be further increased by installing gravel and stone columns, and deep drains in the foundation.

Bisri Dam was designed per state-of-the-art seismic design regulations of ICOLD. Two of the Bisri Dam Review Board (DRB) members are members of ICOLD's special technical committee on Seismic Aspects of Dam Design.

The seismotectonic framework and the earthquake hazard assessment needed for the determination of the earthquake resistant design of the Bisri Dam are provided in the following documents (attached separately).

- Elias (2014), Report on the Neo-Tectonic Setting and Seismic Sources for the Seismic Hazard Assessment of the Bisri Dam Site
- Erdik et al. (2014), Assessment of Site-Specific Earthquake Hazard for Bisri Dam, Lebanon

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Elias (2014) concluded that the Roum Fault does not appear to continue in the Marj and that there is no evidence for fault offset associated with any known fault under the dam site. Some minor and small faults with very low tectonic deformation rate accommodating syn- or post-depositional deformation in the thick sedimentary infill or stress within the Jezzine anticline or at the tip of the Roum Fault may exist in the subsurface of the Marj. Their surface expression are leveled by the much more active geomorphic surface processes. If so these faults are very likely of small extent and should not represent a serious tectonic hazard to the region.

Erdik et al. (2014) study provided for the earthquake resistant design basis ground motion based on an analysis of the probabilistic and deterministic earthquake hazard at the Bisri Dam site. As per ICOLD Bulletin 148: Selecting Seismic Parameters for Large Dams (2016), the following earthquake ground motion levels were considered.

- The Operating Basis Earthquake (OBE) is determined as the probabilistically assessed earthquake ground motion for an average return period of 144 years.
- The Safety Evaluation Earthquake (SEE) is determined to correspond to the 84-percentile deterministic Maximum Credible Earthquake (MCE). MCE stands for the largest reasonably conceivable earthquake magnitude that is considered possible along a recognized fault or within a geographically defined tectonic province, under the presently known or presumed tectonic framework.

For the earthquake-resistant design of the Bisri Dam, the SEE level earthquake, defined as the Median+1 Standard Deviation (84-Percentile) ground motion due to a Maximum Credible Earthquake (MCE) earthquake scenario was considered. SEE is selected as the maximum ground motion that would result from the following deterministic MCE scenarios:

- Mw7.9 strike-slip earthquake on the Yammouneh Fault
- Mw7.8 thrust (reverse) earthquake on the MLT Ramp
- Mw7 strike-slip earthquake on the Roum Fault

Among those, the Mw7 strike-slip earthquake on the Roum Fault controlled the SEE ground motion and governed the design of the Bisri Dam.

Under the exposure to the SEE ground motion the stability of the dam and life safety was fully ensured with no uncontrolled release of water from the reservoir.

3. Faults Under the Bisri Dam Site

3a- Definition of a fault:

Faults are fractures of the rocks that have accommodated a visible amount of rupture and displacement of the layers and geological entities occurring on both sides of the fractures. Faults are created when the accumulation of stresses inside the rock volume locally exceeds the strength of the rock, resulting in shear or faulting along certain direction, thus forming a fault plane. Faults can be of different dimensions and there are relatively well known physical relationships relating faults and their dimensions to the amount of displacement. Major faults result from the accumulation of important stresses happening at global or regional scales and related essentially to tectonic forces, i.e. forces generated by the large scale elastic loading of the Earth's upper layers, 100-200km thick, called the Lithosphere. Smaller faults can also result from local stresses of various origins such as from subsidence in a basin or from differences in the compaction rates or from fluid migration inside sediments many meters to tens of meters thick.

3b- Faults and stresses:

Under the effect of their causative stress faults generated in a rock volume keep growing with time, accumulating increasing amounts of differential movement, visible on both sides of the fault plane. Since stresses from tectonic origin usually last long (in millions of years) they are associated with larger faults showing large amounts of displacements (meters to km scale). Whereas faults of local origins, usually exhibit smaller ranges of dimensions and offsets (millimeter to meter scale). With time faults may stop moving if their causative stress stopped acting. They become inactive faults.

3c- Fault rupture and rock deformation:

The rupture on a fault affects all layers of rocks overlying it. In the case of near-surface faults the rupture is observed over the ground. In other cases, if the fault is very deep under the surface the movement of the fault-blocks is seen as broad warping or folding of the surface. Thus the careful analysis of the surface morphology and topography can be used to assess the presence of buried active faults.

During their long exposure lasting for many millions of years at or near the surface of the Earth, the rocks are subject to large changes in stress conditions leading to the formation of different groups of faults each according to the prevailing stresses at a given time. These faults are not necessarily active anymore. Therefore, for the same given geological conditions, the chance of having faults in a rock unit increases with the age of the rock.

3d- Faults in the Bisri Dam area:

1- Roum Fault:

The Roum Fault is the main fault accommodating tectonic stress in the Jezzine and Marj Bisri area. It is a prominent fault studied and mapped on geological documents since long. It extends from the western tip of the Hula basin south, to the Bisri River in the north for about 35Km.

Its mapped trace and extent:

As it shows in the geology and morphology of the area the Roum Fault appears to be made of two distinct parts. A first southern segment from Beaufort Castle to Jbaa with a clear and continuous fault trace and a total horizontal offset decreasing northward. A second, northern segment is between Jbaa and Aazour where the fault is more compressive, with a less continuous trace on the surface. Despite many dedicated studies, no trace of the Roum Fault north of the Awali River has ever been found or documented. Nemer 1999 summarizes and presents these studies and also acknowledges the absence of any trace of the Roum Fault in the surface or sub-surface north of the Awali Valley, where its trace is subdued in the topography and replaced by the NE-SW striking Jabal el Mazraa flexure also known as the Chouf Monocline. This is a view shared by many authors (Heybroek, 1942 to Nemer & Meghraoui, 2006 and recently Hajj Chehadeh 2015).

Roum Fault and Marj Bisri:

Elias 2014 reported results from the geological survey of the Marj Bisri area, complementing on the previous geological and geophysical studies executed for the Bisri Dam project since 1983.

The results of all these surveys proved the absence of any active fault that can be associated with the extension of the Roum Fault under Marj Bisri. The recent deposits filling the Marj, and the geomorphology of the area show no evidence for the presence of any such active fault cutting through the modern fill or affecting the course of the River. The topography of the Marj, the morphology of the river and its floodplain, the sedimentary deposits filling the basin, the structural and geophysical data measured and interpreted from the area all concur to the absence of a major tectonic fault extending the Roum Fault under the Bisri Dam and Marj area. It is widely acknowledged and accepted that the Roum Fault stops south of the Awali River as it shows from different scientific publications dedicated for the geology and seismic hazard of Lebanon (Gomez et al 2007, Elias et al 2007, Carton et al 2009, Huijer et al 2015, Goren et al 2015, Brax et al 2016, etc).
The surface trace of the Roum Fault ends south of the Bisri Dam area by around 2km. Like all other terminations of active faults the northern tip of Roum Fault fades away to the north and is replaced by a fractured zone where the tectonic deformation is probably dissipated over many different fractures.

2- Mount Lebanon thrust system:
Recent studies show the connection between the Roum fault and the offshore Mount Lebanon Thrust system or MLT (Elias et al., 2007; Carton et al., 2009). The Roum Fault is the southern onshore segment of the MLT system, a wider fault system responsible for the uplift of Mount Lebanon. The MLT is an eastward dipping fault system with a major ramp connecting at depth with the Yammouneh Fault (the local plate boundary segment) to the east. The Roum Fault under the Jezzine anticline can be considered as a splay of this ramp. It is therefore suggested that the deep ramp is lying under the western slopes of Mt Lebanon (including the Bisri area) at an estimated depth of around 16Km.

3- The buried fault:
Beside these two major faults (Roum and the deep MLT ramp) no other major active tectonic fault exist in the Marj Bisri area. Older studies have detected evidence for the presence of a deep fault buried under the ~120m alluvial fill of the Marj. Elias 2014 discusses the activity of this fault and concludes that, if present, this fault is inactive for different reasons in particular because it does not seem to offset the "recent" 120m of fill above it according to the geophysical results, and subsequently it has no effect or expression on the surface and morphology of the Marj. It is very likely associated to the group of inactive tectonic faults present in the geology of Lebanon and the Chouf area in particular (Homberg et al 2010, Hajj Chehadeh 2015).

4- Non-tectonic faults:
Small faults affecting the sedimentary fill of the Marj were observed at few places around the edge of the plain. Given their peripheral location and their orientation parallel to the basin they are very likely associated with the sedimentary processes and not related to tectonic stresses.

It is reasonable to conclude that no active, major tectonic faults exist in the subsurface of the Bisri Dam area. Minor faults and fractures related to the termination zone of the Roum Fault south of the Dam site

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or to the sedimentary processes within the basin exist but have little impact on the overall geology of the area.

4. Seismic Activity of the Roum Fault

4a- Seismicity of Lebanon between instrumental and historical sources:

The seismic activity of Lebanon during the past decades is characterized by frequent, almost daily on average, small magnitude events that are mostly unnoticeable, contrasting with the large disastrous earthquakes happening over long observation times (centuries to millennia) and well related in historical texts. Therefore the instrumental seismicity data, recorded by modern seismometers cannot be taken to represent the exact distribution and level of ongoing tectonic deformation or to identify the important seismogenic zones. This conclusion is also supported by the fact that the network of seismometers in the region has long been poorly developed, making all instrumentally monitored earthquakes of the past century very badly constrained in terms of magnitude and location. Modern instrumental seismicity, however, as recorded by the national seismological network of Lebanon (GRAL network Local Seismicity Map, CNRS 2019) for the period from 2006 onward have greatly improved the quality of the seismic observations and offers a hint onto the seismicity of Lebanon during the past decade, though still too short to be representative of the major seismogenic structures.

4b- Modern instrumental seismicity data for the Roum Fault area:

The seismicity map 2006-2017 (Figure 3) shows low-magnitude-level events distributed in many groups around the country, as well as a sparse seismic activity almost randomly distributed. The region around Bisri Dam area and Roum Fault shows a concentration of events in southern Bekaa mainly east of the Yammouneh Fault, and another group of events in the Nabatiyeh area resulting from the events of summer 2006 and from the seismic crisis that started in February 2008 with the Srifa, M~5 main event. Taken at its face value this seismicity map shows a lower level of seismicity of the Roum Fault compared to its eastern or western counterparts.

4c- Past earthquakes associated with Roum Fault:

Only two significant earthquakes are associated with the Roum Fault.

1- Historically the Roum Fault area is considered as the source of one major earthquake that occurred on 1st January 1837 (Ambraseys 1997, Daeron 2005). The magnitude~7 earthquake heavily destroyed many cities and places in Southern Lebanon and Northern Palestine. Its effects reached a wider zone, with damage and panic in Beirut and Damascus and it was widely felt in the region.

2- In more recent times the 16th of March 1956 earthquake took place in the area between Iklim el Kharroub and Jezzine. Its location is very poorly constrained due to the lack in local monitoring stations at the time. The earthquake was assigned an epicentral location between Mazraat Ed Dahr and Zabboud (Plassard and Kogoj 1981). The uncertainty associated with this location is at least 10km in each direction and the earthquake could have happened on any of the faults in this area. However, many authors suggested it happened over the Roum Fault (example Plassard and Kogoj 1981, Nemer and Meghraoui 2006). Its magnitude was estimated between 5.1 and 5.7. It resulted in heavy destructions in many parts of southern Lebanon and western Bekaa, and was heavily felt and affected wide parts of the country and surrounding areas. Towns inside the Bisri Valley suffered large destruction, very probably because of the important site conditions. However no surface rupture in the area has been reported.

A paleoseismic study (Nemer et Meghraoui 2006) conducted on the southern segment of the Roum Fault in the Jarmak area, showed that the past 10,000 years have witnessed 4 or 5 large earthquakes rupturing this segment all the way to the surface. According to appropriate geophysical scaling laws (Wells and Coppersmith 1994) such earthquakes happening over the entire length of the Roum Fault could have had a maximum possible magnitude of M~7.

4d- Seismicity of the Roum Fault compared to other major faults in Lebanon:
Compared to the other known three active major faults of Lebanon (Yammouneh, MLT, and Rachaya-Serghaya faults) the Roum fault is the shortest and thus produces maximum earthquakes of smaller magnitudes. However the recurrence of major earthquakes along Roum Fault (estimated to be 2000 – 2500 yrs) is consistent with the scale of recurrence intervals of major earthquakes on the other major faults (ranging between 1000 and 2500 yrs) indicative of the low strain rate dominating the area. This is also corroborated by the relatively low to moderate strain rate values obtained for the area from global or local geodetic data (Kreemer et al 2014, GEM 2014).

Finally, given the long recurrence interval of the Roum Fault and the fact that its last major event happened only 182 years ago, followed by a relatively long period of seismic quiescence, one can conclude that this fault is reasonably far from reaching a critical near-rupturing stress level again in the near future.

5. Reservoir Induced / Triggered Earthquakes and Bisri Dam

Large new reservoirs may increase the seismicity by induced and triggered earthquakes.
Two types of earthquakes associated with reservoirs must be distinguished:

- The Reservoir Induced (non-tectonic) Seismicity (RIS) linked to the karst caves and stress readjustment at the shallow surface layer usually with magnitudes less than 3, and
- The Reservoir Triggered (Tectonic) Seismicity (RTS) linked to nearby causative faults with existing stresses close to failure and triggered by the impoundment of the reservoir with magnitudes not exceeding that of spontaneous characteristic earthquakes.

Triggered seismicity (RTS) is the most important type of reservoir associated seismicity, and should not be confused with its stablemate, simply called induced seismicity; the latter is commonly associated with hydro-fracture and generally implies large local stresses, but small earthquakes. The event size in (RIS) is small because these large stresses are spatially concentrated and can only induce fracture on small volumes of rock. On the contrary, triggered seismicity involves large tectonic structures, where the stress has been independently accumulating to a near failure conditions by the internal Earth's dynamics with the human activity providing only the "last straw" (Mulargia and Bizzarri, 2014).

Temporal distribution of reservoir induced seismicity (RIS) following the filling of large reservoirs shows two types of response:

- at some reservoirs, seismicity begins almost immediately after filling of the reservoir;
- at others, increases in seismicity is observed after a number of seasonal filling cycles.

RIS generally covers micro earthquakes and tend to be clustered around the reservoir.

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The reservoir triggered seismicity (RTS) is a very complex phenomenon, a result of complex, not entirely known mechanisms that are very different in various cases.

Several factors are linked to RTS: a seismically active environment, presence of a causative and fully stressed fault, added weight and pore pressure propagation from the reservoir after impoundment.
For triggered earthquakes to occur, it is required that the area is already under considerable tectonic stress. As the energy released in a reservoir triggered earthquake is the normal tectonic strain energy that has been prematurely released because of the reservoir. This condition is statistically possible on a subset of the potentially seismogenic faults and thus seismicity triggered by small stress changes would require many such faults, even in areas where natural seismicity is low (McGarr et al, 2002).

Throughout the world, several thousand dams have been constructed and are impounding reservoirs which are operating without any observed RIS or RTS. Compared to the large number of operating large reservoirs, there are only a very few instances of possible RTS cases. Out of some 11,000 worldwide "large" dams, only a small number have triggered known seismic activity (USCOLD, 1997).
All of these RTS earthquakes were associated with reservoirs with water depths exceeding 100 m. For a deep reservoir one might argue that the statistical chances of an earthquake exceeding magnitude Mw5.7 being triggered are only about 2%.

In the ICOLD Bulletin on Reservoirs and Seismicity – State of Knowledge (Bulletin 137, 2009) prepared by ICOLD's Committee on Seismic Aspects of Dam Design, 39 cases of RTS are presented.
So far, there are four major RTS events with a magnitude over 6.0. They are:

- 103m high Koyna gravity dam in India (M=6.3);
- 120m high Kremasta embankment dam in Greece (M=6.3);
- 105m high Hsinfengkiang buttress dam in China(M=6.1);
- 122m high Kariba arch dam in Zambia (M=6.25).

The highest observed earthquake magnitude was 6.3.

Although being claimed as an RTS case, it is highly disputed whether the May 12, 2008 Mw 7.9 Wenchuan earthquake in China was influenced by the impoundment of nearby Zipingpu Dam. Zipingu reservoir, in Sichuan, China has a volume of 1 x 109 m3 and lies within a seismically very active, compressive tectonic environment. The Mw 7.9 earthquake occurred 2½ years after initial impoundment on a previously identified fault. The epicenter was 20 km from the reservoir. The rupture initiation depth was 20 km, deeper than that usually attributed to RTS. Power Magazine (2010) states that there is no observational evidence or factual investigations that the Wenchuan earthquake was triggered by the Zipingpu reservoir. As such, the impounding of the Zipingpu and Three Gorges reservoirs did not create any conditions to trigger the devastating Wenchuan earthquake and, this earthquake also has no characteristic features of reservoir-triggered earthquakes.

Based on the review of the mechanisms for RTS and the worldwide experience with dams experiencing RTS, the following conclusions can be drawn:

- The cases of RTS are very few compared to the total number of large reservoirs in the world (only 1% of all the large-deeper than 100m- reservoirs).

- The RTS are associated with tectonic earthquakes linked to nearby fully stressed causative faults with existing stresses close to failure. The upper bound magnitude for RTS events observed so far is 6.3.
- It is well known that for triggered earthquakes to occur, the area must be already under very high tectonic stress and that the reservoir impoundment will not cause damaging earthquakes where they would not otherwise occur.

Regarding the construction of Bisri Dam, it is understandable for the public opinion to express concern for RTS. In this connection it is worthwhile to note the following facts:

1. Reservoir-triggered seismicity appears to occur on dams with heights larger than 100 m (Bisri is 70m tall)
2. The maximum reservoir-triggered earthquake magnitude is only Mw6.3 (Koyna gravity dam (India), 103 m high, 2,78 Billion m3 reservoir capacity, in 1967). The Zipingpu (China) reservoir, alleged to be associated with the RTS event (2008 Wenchuan earthquake) has a height of 156m, a volume of 1,12 Billion m3 and lies within a seismically very active, compressive tectonic environment. Whereas, Bisri Dam has a reservoir volume of only 125 Million m3 and is located in a rather low seismicity area.
3. The Roum Fault has produced the two most recent destructive earthquakes onshore Lebanon the M~7, 1837 and the M~5.7, 1956 events. Its horizontal slip rate is ~1mm/yr. This very low slip rate is further evidenced by the almost identical and parallel slip velocity vectors in the Roum Fault region (Figure 1), which indicate almost no relative motion on both sides of the fault.
4. Assuming that an M5.7 and M7 earthquake on the strike-slip Roum Fault produces respectively about 10cm and 100cm lateral offset at the source, at the strain rate of 1mm/yr, the return period of these earthquakes will be respectively about 100 and 1000 years.
5. The past experience indicate that the Bisri Dam Reservoir is not large enough to possibly trigger and earthquake. But, even it does, one would need, on the average, 900 years to develop adequate seismic strain to trigger a M7 earthquake on the Roum Fault by the impoundment of the Bisri Dam reservoir.

In fact, as it can be assessed from Figure 2, the return period for a large earthquake (Mw7.5) in the region is about 5,000-6,000 years.

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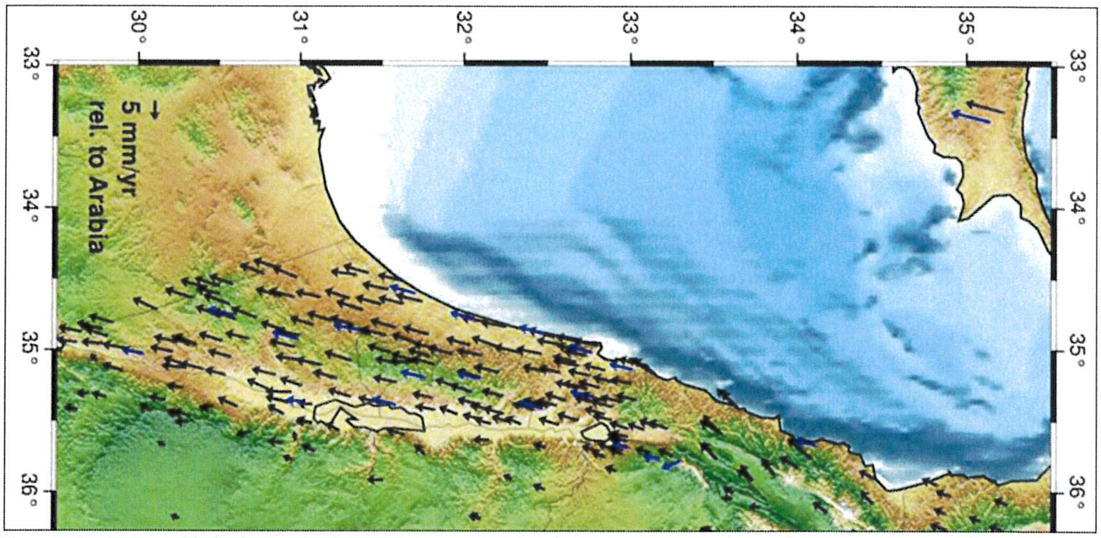

Figure 1. 1- Global geodetic strain rate model (After, GEM Technical Report 2014-07)

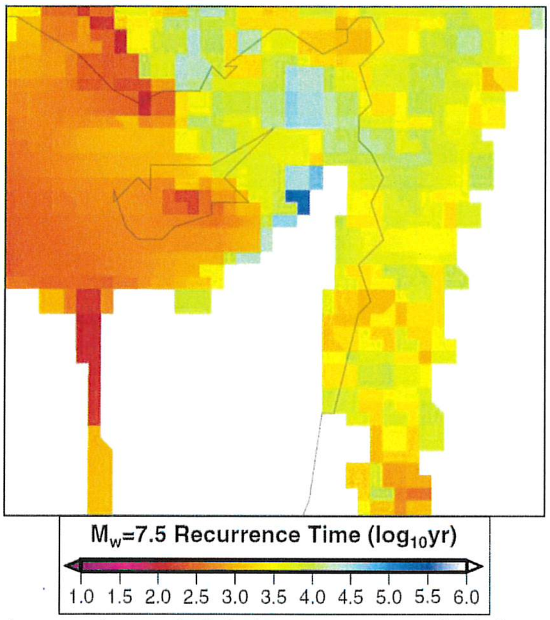

Figure 2. A geodetic plate motion and Global Strain Rate Model (After, Kreemer et al., 2014)

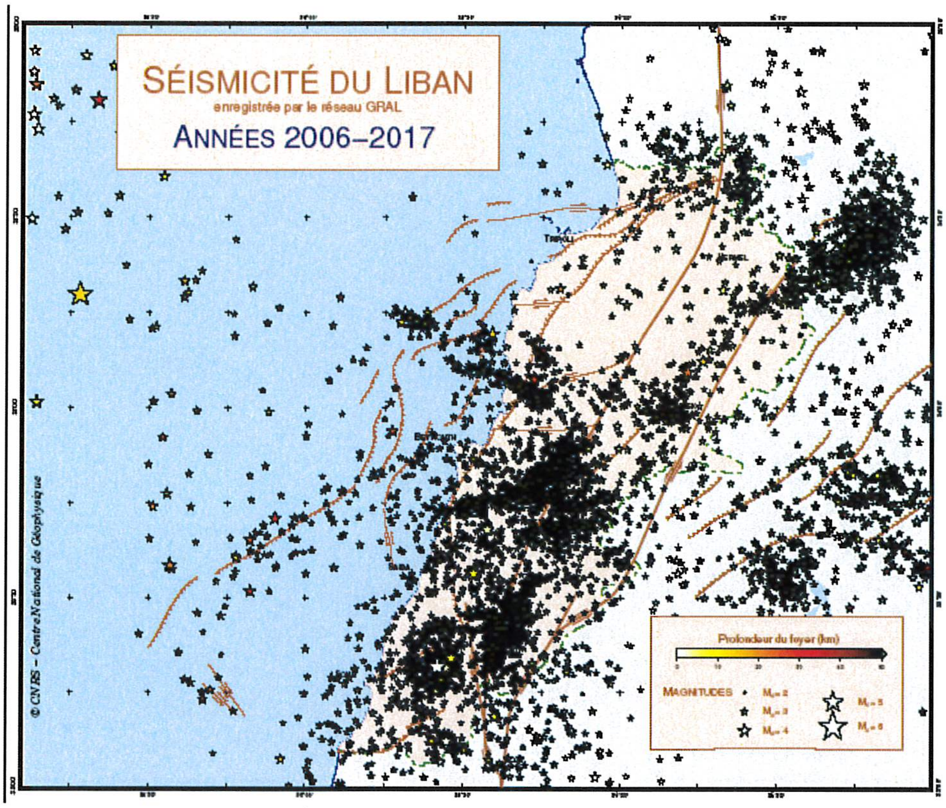

Figure 3. Seismicity map of Lebanon 2006-2017 as observed by the Lebanese seismic network (GRAL) of the National Center for Geophysical Research.

6. Landslides triggered by earthquakes or after the reservoir filling

As per the conducted surveys and studies, landslides that could be triggered by earthquakes or after the reservoir filling are at no risk or at maximum very restricted locally, and not to influence the dam at all. The limestone rocks and their rock masses, mainly occurring in the right side of dam and reservoir are of high strength and with not disturbed structure exhibiting high global strength. Continuous weak planes to provide sliding surfaces are absent. In the other parts of the reservoir, where sandstone formations are present, besides an acceptable overall strength there is a lack of such a structure in the formation in order to form critically unstable slopes. These slopes are not anyhow high enough to create stability issues.

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