Technical Note

Reservoir-Triggered Seismicity in Armenian Large Dams

L.S. Sargsyan

Head of Seismology Division, Armenian National Survey for Seismic Protection, Yerevan, Armenia, email: lilit_geo@yahoo.com

ABSTRACT

Reservoir-triggered seismicity (RTS) is a phenomenon, which has been observed in several large dam projects all over the world, especially for the reservoirs which are constructed in seismically active regions. Practically all the territory of the Republic of Armenia is characterized as the high seismic active area. A review of reservoir triggered seismicity in Armenia shows that it mainly occurs in large dams which are located near active faults. In this paper it has been shown that the number of microearthquakes increase after Tolors reservoir operation, cause changes of seismic regime in the observed regions. The correlation of seismicity and water level in Tolors reservoir allows assuming the influence of long-term harmonious changes of water level on the seismic activity in the region.

Keywords:
Reservoir triggered seismicity;
Microearthquakes;
Tolors dam

1. Introduction

The first registered case of reservoir-triggered seismicity (*RTS*) was observed in the 1930*s* at Lake Mead, which was created by the 220*m* high Hoover arch dam [1]. By the end of 1960*s*, strong earthquakes, which are thought to be reservoir-triggered, occurred in the reservoirs formed by the Koyna (India), Hsinfengkiang (China), Kremasta dam (Greece), and Kariba (Zambia). Therefore, the general interest in this phenomenon (RTS) has sharply increased [2-4].

The main difference between a reservoir-triggered earthquake and a natural earthquake is that the reservoir-triggered earthquake has a relatively high likelihood of occurring within the first few years after impounding of the reservoir or when the reservoir level has reached its maximum elevation. These earthquakes have often a shallow focus and their epicenters are relatively close to the dam sites or the reservoir [5-6]. After dam construction the filling of the reservoir creates a gravity stress field, which is immediately added to the pre-existing tectonic stresses. The field of pore pressures follows, propagating in depth, gradually decreases the initial effective stresses due to the action of the primary tectonic stress field and of the added weight of water in the reservoir [4, 7].

Today it is generally accepted that significant reservoir-triggered earthquakes can only occur in regions with high tectonic stresses in the earth crust, i.e. the causative fault that can produce an earthquake already in near failure conditions, so that added gravity stresses and pore pressure propagation due to reservoir impounding can trigger the seismic energy release [7].

Most of 83 dams (large and small) in Armenia are situated in highland areas of 1500-3000*m* altitude. The majority of dams are embankment ones. Armenian dams are mostly situated in an area with high litologic, tectonic and geomorphologic heterogeneities [8-9].

Armenian Upland is one of the most active segments of Alpine-Himalayan seismic belt, which is related to the collision zone of Arabian-Eurasian plateaus. This region is seismically very active [10]. According to the new seismic zonation map of the territory of Armenia the level of seismic hazard is evaluated with expected ground accelerations up to 0.5*g* which is corresponding to 9-10 seismic impacts on *MSK*-64 scale [11]. However, almost all dams were mostly designed corresponding to seismic hazard level of 7-8 on the *MSK*-64 scale [8].

The Tolors dam is situated in southern part of Armenia (the seismic hazard is evaluated with 0.4*g*) in Syuniq region, near to the border of Iran. According to ICOLD Bulletin-72, for sites in hazard class *IV* (*PGA* > 0.25*g* and active fault closer than 10 km from site) separate consideration of *MDE* (Maximum Design Earthquake) *OBE* (Operating Basis Earthquake) and *RIE* (Reservoir Induced Earthquake) are required [12]. In this paper, Tolors dam seismic conditions after the impounding of the dam is represented.

2. Characteristics of the Tolors Dam

The Tolors reservoir is built on the Sisian River. It is situated in Syuniq region in the southern part of Armenia. The reservoir surface is 381.2 square kilometers and storage capacity is 96 million cubic meters respectively. Tolors is a rock fill dam with a central clay core. Dam height is 69*m*. The reservoir impounding started in 1974.

The foundations of the dam lye in Sisian stratum group (400*m*): tuff and sandstones, diatomite, clays, sands, lapilli's sands, breccias, see Figure (1) [13]. The study area is characterized by several structural units. The main faults in this area are the following: Tashtun, Khustup-Giratax and Vayk faults. Khustup-Giratagh fault's total length is about $135 \pm 10km$, azimuth of propagation is *NW-SE*, sense of slip-reverse, right-lateral, strike-slip, fault dip is 70°-80° *SW*, and dept is $45 \pm 5km$. The mean slip rate is 2.17*mm/yr*. The major earthquake in this fault was the Syuniq earthquake (1407, $M = 6.5$). $M_{max} = 7.0 \pm 0.2$. Tashtun fault's total length is about $120 \pm 5km$, azimuth of propagation is *NW-SE*, sense of slip-normal, left-lateral strike-slip, fault dip is 60°-90°*NE*, and dept is $15 \pm 2km$. The mean slip rate is 1.3*mm/yr*, with this fault which connected the Zangezur *I* earthquake (1931, $M = 6.3$) and the Zangezur *II* earthquake (1968, $M = 4.9$). $M_{max} = 6.5 \pm 0.2$. Vayq fault's total length is about $55 \pm 5.0km$, azimuth of propagation is *SW-NE*, sense of slip-normal slip, fault dip is 80°-90°, and $M_{max} = 6.5 \pm 0.2$ [11, 13].

3. Seismic Activity Around Reservoir Area

Comparison of the pre-impounding and the post-impounding seismic activity is necessary in order to resolve the reservoir-triggered seismicity from back-ground activity.

The first seismic station in this area was installed in 1951 in Goris, which is three-component short-period station by 1974 near the reservoir area with five regional stations already operated, see Figure

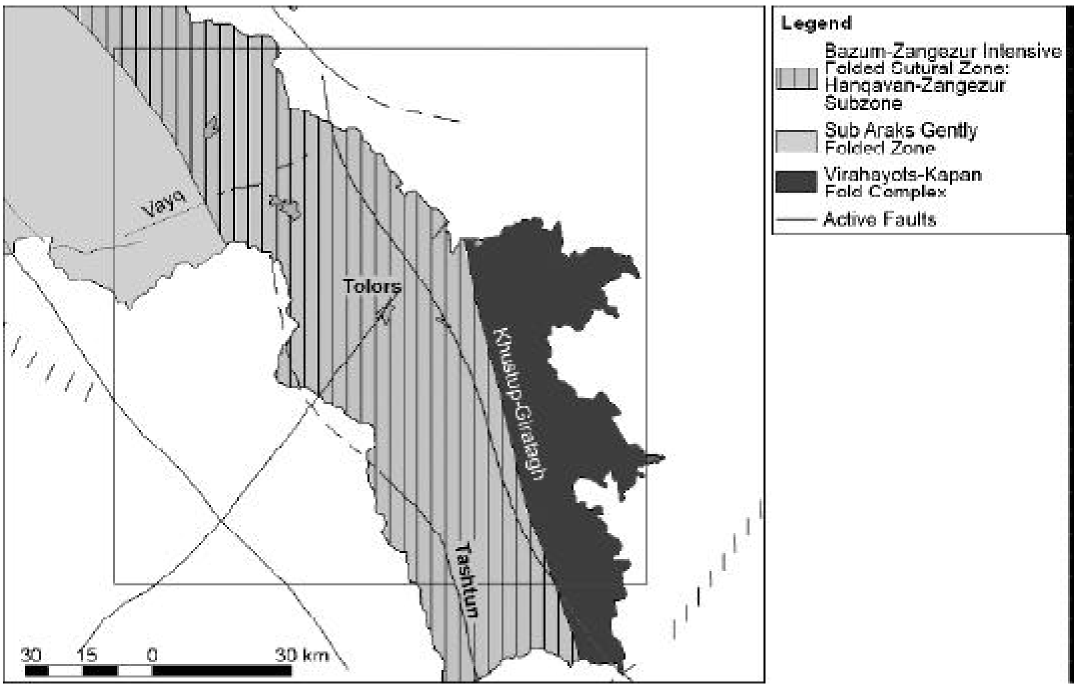

Figure 1. Seismotectonic settings around the Tolors dam showing the main seismotectonic units and features [13].

(2). In our studies we observed data which had been recorded 20*km* and 50*km* regions around the reservoir site during instrumental period (since 1962) using the National Earthquake Catalogue created in National Survey for Seismic Protection (*NSSP*).

Tolors dam is located in the area where two historical strong earthquakes have occurred: the Syuniq earthquake in 1407, $M = 6.5$ and the Zangezur earthquake in 1931, $M = 6.3$. The largest earthquake recorded in the instrumental period was Zangezur *II* earthquake in 1968 with magnitude $M = 4.9$. After this earthquake, a number of aftershocks followed which were declastered from catalogue for this study. For the pre-impounding period the mean number of earthquakes per year occurring inside a 50*km* radial zone is two events. The yearly average number of earthquakes that take place during the post-impounding period is fourteen events.

During only one decade after the impounding of the reservoir several events with $M > 3.5$ have occurred. The largest one occurred in 1982 with $M = 4.2$. After impounding of reservoir in the study area, the number of micro-earthquakes have extremely increased, see Figure (3), but with four years delay after impounding the seismicity in this area is mainly associated with pore pressure diffusion.

The statistical analysis of the distribution of earthquakes that occurred within the 50*km* radial zone with the center on the reservoir shows that earthquakes with magnitude >3 are not randomly distributed, but are mainly associated with the active faults in the investigated site and with the diffusion

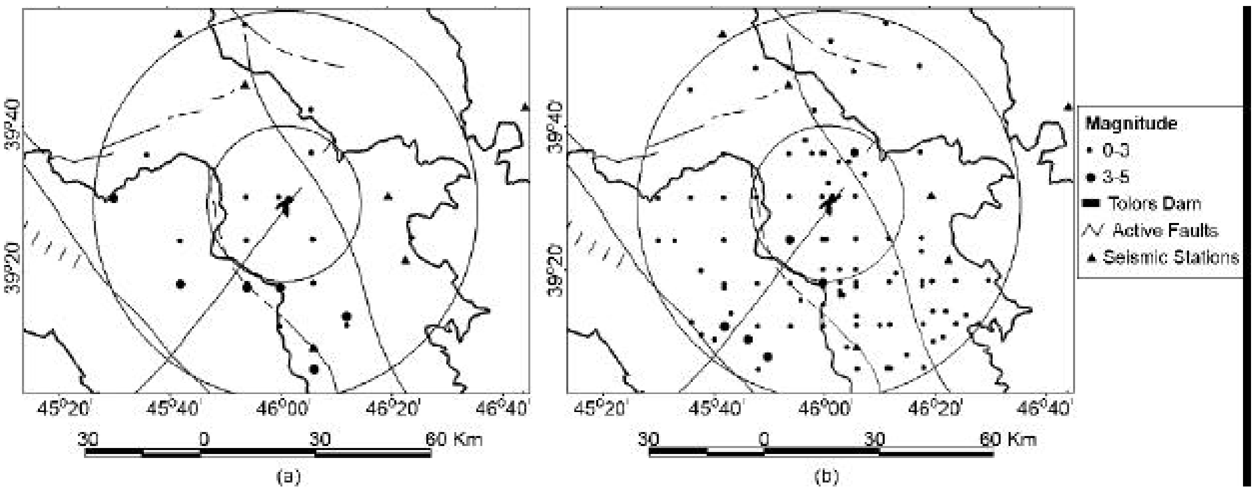

Figure 2. Seismicity around Tolors reservoir area from 1964-1974 pre-impounding time (a) and from 1974-1984 post-impounding time (b).

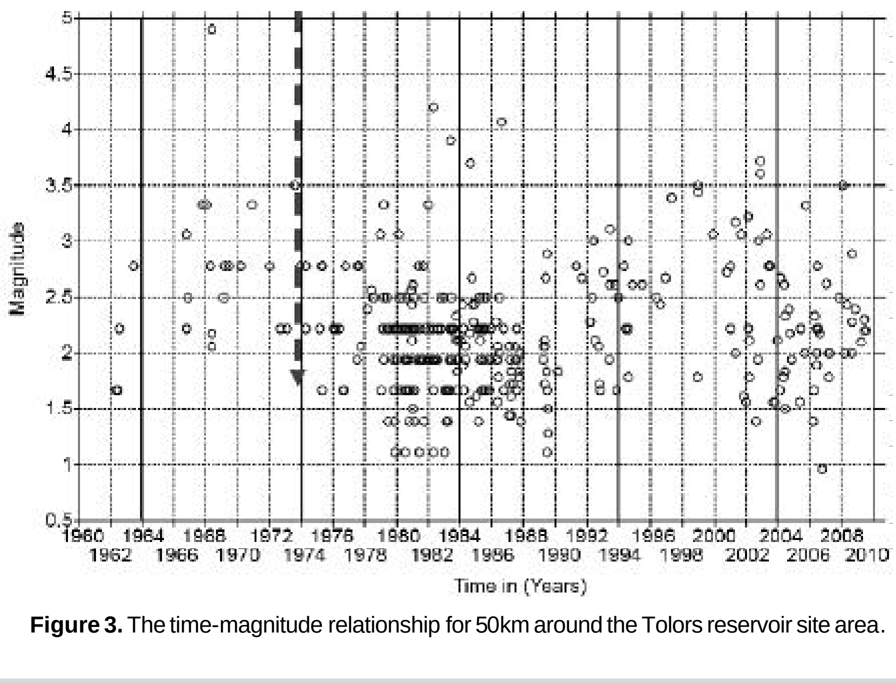

Figure 3. The time-magnitude relationship for 50km around the Tolors reservoir site area.

distributed microearthquakes near the reservoir area. This is explained also with the mosaic-unit structure characteristics of Armenian upland.

The change of seismic regime was observed in the study area. The very important characteristic for *RTS* is the b-value, which is relatively higher than normally found for normal earthquakes, see Figure (4) [14-15]. Table (1) and Figure (4) provide the overview of the *RTS* activity in Tolors dam, recorded from 1962-2008.

4. Water Level and Seismicity

In order to present some speculation on the causative mechanisms of the microearthquakes, it is very important to correlate changes of reservoir water level, reservoir volume and the occurrence of triggered seismic activity [2, 16]. One way is to compare the rate of the earthquake occurrences in the study area with the reservoir water level and its rate change. The analysis of Tolors reservoir water level was done for the rate of change in the water level (*dH/dt*) and the average number of earthquakes per year in the 50*km* radial zone versus time, see Figure (5).

The positive correlation between the frequency of earthquakes and the reservoir water level can be explained mostly by the elastic effects of reservoir unloading. After the first impoundment of the reservoir the water level was not realized to maximum at once. During the first years the level of water was low enough. Seismicity has noticeably increased 3-4 years after the water level had been changed in the reservoir, see Figure (3).

Table 1. The main parameters of seismic regime (calculations are based on maximum likelihood solution).

	62/74	74/84	84/94	94/08
N	25	158	110	89
Mcomp	2.7	2.2	2.2	2.2
Mmax	4.5	4.0	4.0	4.0
b	0.57	1.30	0.97	0.8
Impounding				

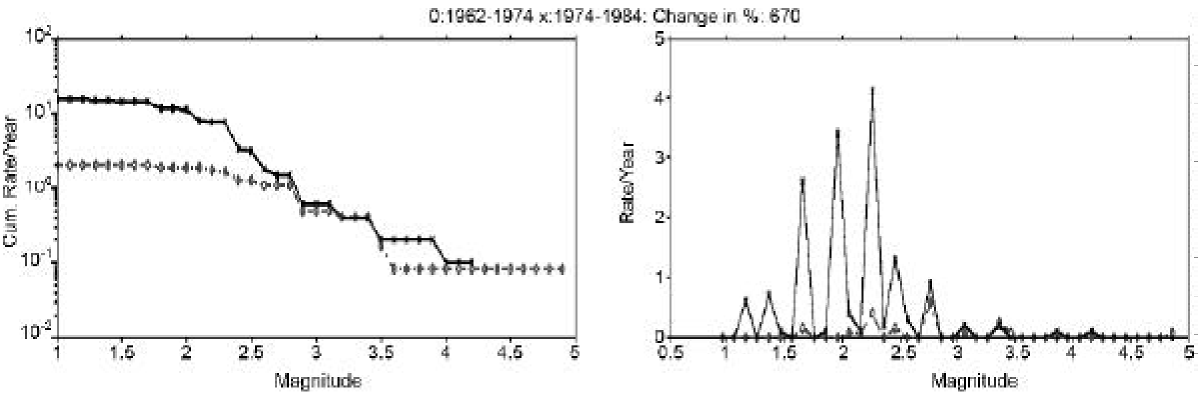

Figure 4. B-value and year/rate changes in Tolors dam area for pre-impounding (o) and post-impounding (x) periods.

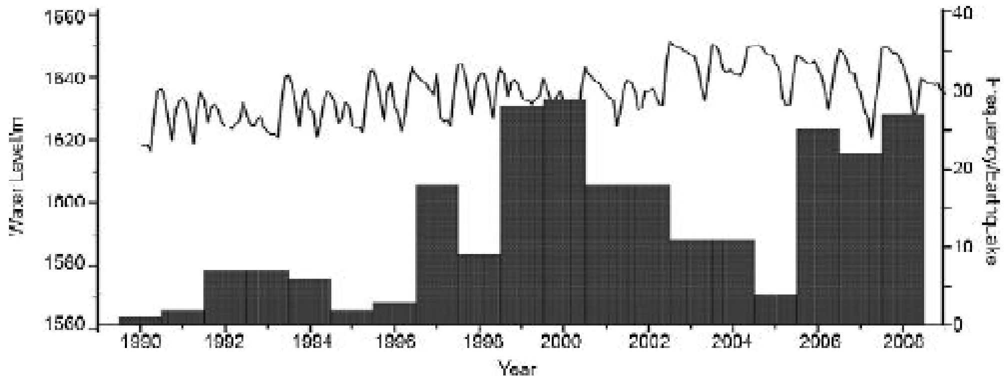

Figure 5. Water level in the reservoir and seismic activity observed in Tolors reservoir area.

5. Conclusions

The observation has shown that the number of microearthquakes has increased after the impounding of Tolors reservoir causing changes of seismic regime in the observed region. Therefore, it seems that the increase in seismicity is closely associated with the impounding of reservoir and can be considered as seismicity triggered by changes in the lake level of the Tolors dam.

The correlation of seismicity and water level in Tolors reservoir allows assuming that the long-term harmonious changes of water level influence the seismic activity in the region. Seismicity is mainly associated with pore pressure diffusion. It is clear that a relationship exists between seismicity and reservoir water level, which probably modifies the pre-exiting tectonic stress field and pore pressures, however, no specific mechanism for the induced seismicity has yet been identified.

Acknowledgments

I am very grateful to all staff of the Vorotan Cascade of Hydroelectric Power Plants Closed Joint-Stock Company, who operate the Tolors dam, for providing data on water level changes for this study. I am grateful to my supervisor Prof. R. Minasyan for his enormous help and support, and Dr. V. Khondkaryan and Dr. S. Margaryan for their valuable editorial comments in preparing this paper.

References

1. Rogers, A. and Lee, W. (1976). "Seismic Study of Earthquakes in Lake Mead, Nevada-Arizon Region", Bull. Seis. Soc. Am., **66**, 1657-1681.

2. Gupta, H. (1992). "Reservoir-Induced Earthquakes", Elsevier, Amsterdam.

3. Gupta, H., Rastogi, B., Chadha, K., Mandal, P., and Sarma, S. (1997). "Enhanced Reservoir-Induced Earthquakes in Koyna Region, India, during 1993-95", *Journal of Seismology*, 47p.

4. Simpson, D., Leith, W., and Scholtz, C. (1988). "Two Types of Reservoir-induced Seismicity", Bull. Seism. Soc. Am., **78**, 2025-2040.

5. Ibenbrahim, A., Ni J., Salyards, S., and Ali, I. (1989). "Induced Seismicity of the Tarbela Reservoir, Pakistan", Seism. Res. Letters, **60**(4), 185-197.

6. Torcal, F., Serrano, In., Havskov, J., Utrillas, J., and Valero, J. (2005). "Induced Seismicity Around the Tous New Dam (Spain)", *Geophys Journal International*, **160**, 144-160.

7. ICOLD Bulletin 72 (1989). "Selecting Seismic Parameters for Large Dams, Guidelines", Committee on Seismic Aspects of Dam Design, ICOLD, Paris.

8. Khondkaryan, V. (1998). "Monitoring of Dams of Armenia and Assessment of Operation Risk", Conseil de L'Europe Cahiers du Centre European, **16**, 193-200.

9. Sargsyan, L., Ballasanyan, V., Minasyan, R., and Ghonyan, A. (2008). "Changes in Seismic Activity in Connection with Varying Water Level of the Azat Reservoir, Armenia", The Sciences about Earth; The Izvestia of the National Academy of Sciences of the RA, Gitutjun, Yerevan, LXI, N 2, 50-53.

10. Balassanian, S., Nazaretians, S., and Amirbekian, V. (2004). "Seismic Protection and Organization", Eldorado, Gumri.

11. Balassanian, S., Nazaretians, S., Avanessian, A., Arakelian, A., Igoumnov, V., Badalian, M., Martirossian, A., and Ambartsumian, V. (1995). "The New Seismic Zonation Map for the Territory of Armenia", *Proceedings of the 21th General Assembly of the International Union of Geodesy and Geophysics*, Boulder, Colorado, USA, 347p.

12. ICOLD Bulletin 137 (2009). "Reservoirs and Seismicity-State of Knowledge", Committee on Seismic Aspects of Dam Design, ICOLD, Paris.

13. Gabrielyan, A. (1981). "Seismotectonics of Armenian SRR", Yerevan.

14. Gupta, H. and Rastogi, B. (1976). "Dams and Earthquakes", Elsevier, Amsterdam.

15. Muco, S. (1998). "Twenty Years Seismic Monitoring of Induced Seismicity in Northern Albania", *Pure Appl. Geophys.*, **153**, 151-162.

16. Talwani, P. (1997). "On the Nature of Reservoir-Induced Seismicity", *Pure Appl. Geophys.*, **150**, 473-492.