Estimating Reservoir Induced Seismicity RIS Potential. Case Study - Kozjak Dam

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SUMMARY:
For the last 70 years, over 80 cases of reservoir induced seismicity (RIS) have been reported, startingin late 30's of last century (Lake Mead, USA, Kremasta, Greece). Induced seismicity has been expressed through earthquakes with magnitudes ranging from 3 to 6.3 on Richter scale. Temporal distribution of induced seismicity following the filling of large reservoirs shows two types of response: (1) at some reservoirs, seismicity begins almost immediately after filling of the reservoir; (2) at others, increases in seismicity is observed after a number of seasonal filling cycles. These differences in response may correspond to two fundamentally different mechanisms of RIS. In order to identify RIS, data on the background seismicity should be provided through seismic monitoring of the area of the future reservoir. Monitoring of the seismic activity on Kozjak Dam (height: 126m, embankment dam, reservoir volume 550x106 m3) started 2 years before beginning of filling and continues ever since. Comparison between the seismic data and reservoir water level indicates that there is a correlation between the changes in the water level and the seismic activity.

Keywords: RIS, earthquake, water level, dam, reservoir, seismicity

1.INTRODUCTION

The reservoir induced seismicity (RIS) is a very complicated phenomenon, a result of complex, not entirely known mechanisms, that are very different in various cases. RIS covers a wide interval of earthquake magnitudes, from micro earthquakes to very strong ones with magnitudes of up to M=6.5.

The investigations of this phenomenon have so far pointed to the existence of a number different factors that control such a seismicity and that it is necessary to provide a large number of data by installing instruments for recording of the seismic activity of the terrain starting with the beginning of the construction of a dam.

In most cases of induced seismicity, the earthquake magnitudes have been small and have not represented a threat for the structural integrity of the dam and the remaining structures in its surrounding.

Dut to its size and depth (height: 126m, embankment dam, reservoir volume 550x10^6 m^3), the dam and the reservoir of the hydroelectric power plant „Kozjak" belong to the category of structures that are considered to have the potential of occurrence of RIS on a world scale. The dam was completed in 2004 when the filling of the reservoir started. Monitoring of seismic activity started in 2003 by the installation of the three-componental seismological station in the vicinity of the dam under construction.

2. INDUCED SEISMICITY (Reservoir induced seismicity –RIS)

In the case of occurrence of induced seismicity, two types of earthquakes can be defined:

- Earthquakes which are not of tectonic nature, have shallow hypocentres and are mainly associated with the adaptation of the stresses in the foundation rock, the collapse of carst holes or mines, landslides. Characterized by relatively small magnitudes, they often occur soon after the filling of the reservoir and follow the abrupt change of the water level in the reservoir.
- Earthquakes of tectonic nature that are caused by displacement of seismically active faults that cut or run through the reservoir region. The initial stress state is usually very close to the failure point so that even small changes of the strength chracteristics at the fault plane which result from the action of the reservoir may induce seismic activity. The epicentres of the foreshocks with small magnitudes are usually located around the faults: the earthquake magnitudes gradually decrease until the major (the strongest) shock occurs. The aftershocks that follow the main shock may last for a certain time. Since the process of infliltration of water into the rock masses lasts for a longer time, there is usually a time interval between the achievement of the maximum water level and the occurrence of the main shock.

These two types of earthquakes are indicated as endogenic and exogenic induced earthquakes.

2.1. Causes of Occurrence of Induced Seismicity

Induced seismicity is mainly mentioned in association with large/high dams. Table 1 shows data on several cases of induced seismicity observed worldwide. For each RIS case, relevant data as is the magnitude of the strongest shock, the dam height, the reservoir volume, etc., are given.

Table 1. Main Data on Selected Cases of Induced Seismicity

Dam/reservoir	Country	Height (m)	Volumen\ ($x10^6m^3$)	Year of filling	Year of the strongest earthquake	M_{max}
Koyna	India	103	2.780	1964	1967	6,3
Kremasta	Greece	165	4.750	1965	1969	4,4
Xingfengjiang	China	105	10.500	1959	1962	6,1
Kariba	Zimbabve	128	160.368	1959	1963	6,2
Hoover	USA	221	36.703	1936	1939	5,0
Marathon	Greece	63	41	1930	1938	5,7
Aswan	Egipat	115	165.000	1978	1981	5,3
Benmore	New Zealand	118	2.100	1965	1966	4,5
Monteynard	France	155	240	1962	1963	4,9
Kurobe	Japan	186	199	1960	1961	4,9
Bajina-Ba{ta	Srbija	89	240	1965	1967	4,7-5,0
Nurek	Tajikistan	317	10.400	1972	1972	4,6
Mangla	Pakistan	116	7.250	1967	1967	4,2
Grandval	France	88	292	1959	1963	4,7
Canalles	Spain	150	678	1960	1962	4,7

The occurrence of induced earthquakes on a reservoir location is conditioned by certain geological conditions. The surrounding of the reservoir must contain either seismogene structures that may generate tectonic earthquakes and, at the same time, such hydrological conditions that enable inflitration of water deep into the rock masses, or fractured rock masses and carst pits which lead to the occurrence of non-tectonic earthquakes.

The RIS cases that have happened worldwide show that the strongest earthquakes occurred after a number of foreshocks and were followed by a series of aftershocks. In certain cases, such an activity lasted for several years. The existence of series of foreshocks shows how necessary and needed is the seismic monitoring of reservoir locations in the period prior and during construction. Another important data is the time interval between the first filling of the reservoir and the strongest earthquake that can be as long as several days (Kremasta,Greece), weeks (Kariba, Zimbabve) or one or several years (Hiengfengijang, Koyna). These differences are essential for definition of the seismic triggering mechanism. The postponed seismic activity points out that the seismic trigger is rather the increase of the water pressure than stresses in hard rock.

2.2. Mechanism of Occurrence of Induced Seismicity

The seismic activity that results from change of conditions regarding the soil and the rock masses caused by the creation of the water reservoir in a given region can be divided into two time categories:

Initial seismicity is the result of the moment effect of loading (or unloading) and the postponed effect of pore pressure diffusion. After this initial activity, there is an increase of frequency and magntiude of earthquakes. The strongest earthquake usually takes place after finishing the filling of the reservoir and achieving the maximum water level. The time span between the beginning of the filling and the strongest earthquake varies from several months to a few years, depending on the characteristics of the water reservoir location. In this period of increased activity, there follows a period of gradual decrease of activities (for months or for years) to the level characteristic for the period prior to the filling of the reservoir, which points out that the elastic response of the rock masses to the filling of the reservoir has stopped.

Prolonged seismicity when the cause of occurrence of RIS is the pore pressure increase, which is in relationship with the fequency and amplitude variations of the water level in the reservoir (Roeloffs, 1988). The peaks of variation of pore pressure happen directly below the lake and are decreased with distance from it. The changes in strength are in delay in respect to the changes in the water level. In the case of this RIS category, the earthquakes are associated with big and/or fast changes of the water level in long time intervals (lower frequency). Seismicity is recorded below the biggest depth and in the surrounding. The seismic activity lasts for decades and seems not to have the tendency to cease.

The review of documented RIS cases shows that the phenomenon takes place in different geological-morphological conditions of the site and that generalization can hardly be done. Still, a single circumstance is common for all cases: the formation of the water reservoir and its filling with water increases the hydraulic pressure in the rock masses.

The filling of any reservoir leads to variation of underground water levels in the wider area whereat the water from the reservoir will fill all the existing cavities and pores and will lead to water saturation of the surrounding soil volume (underground reservoir). After saturation, the variations in the reservoir water level will be the cause of occurrence of a water course with variable pressure in the direction of the underground reservoir. Such a non-uniform water course suggests that a significat increse of pore pressure is possible, depending also on the specific geologial conditions at the very site, i.e., reduction of permeability as a consequence of the changes of the rock masses due to the increased stress. Sufficiently high concentration of such presure in the rock mass may induce rock deterioration.

Significant increase of the pore pressure may develop as a result of the nonstationary water course that occurs due to the difference in stresses that results from the reservoir weight, i.e., stresses generated by the water course. As a result, it is obtained that the variable ultimate strength of the rocks can be exceeded at some points and can lead to failure of the rock mass and consequently, release of potential energy accumulated with the deformations. These points can be considered sources of microseismic activity resulting from failure of the rock masses.

2.3. Induced Tectonic Earthquakes

The energy of the tectonic earthquakes is the result of accumulation of deformation energy at the seismogene sources in the Earth’s crust, irrespective of the existence or nonexistence of a water reservoir. Compared with the huge amount of energy that is released during a strong earthquake, the effect of filling of the reservoir on the stress energy in the seismogene fault is very small and can only trigger earthquakes when the energy acumulated in the fault is close to its critical stress state.

The occurrence of an induced tectonic earthquake is conditioned by the fulfillment of certain seismic and hydrogeological conditions:

(1) existence of seismic structures in/or near the reservoir;
(2) the seismic structure is close to the failure point prior to the beginning of the filling of the reservoir, and
(3) existence of hydrological conditions for infiltration of water from the reservoir in the deep layers of the rock masses.

It is clear that few large reservoirs fulfill these conditions which is the reason why there are only a few cases of tectoic earthquakes of greater magnitudes that happened mainly at reservoirs with high dams (Koyna, Xingengisng, Kariba, Marathon). The area that can be involved in the process of infiltration cannot be extended behind the first mountain range that limits the valley in which the reservoir that defines the spatial distribution of the potential earthquakes is.

As to the type of fault structures, the investigations have shown that normal and strike slip faults are mor susceptible to occurrence of induced seismicity.

2.4. Case study „Kozjak“ Dam

2.4.1. Seismotectonic characteristics of the Region

Between the mountain massifs of Suva Gora and Osoj in the west, and Suva Planina with Rudina and Kozjak in the east, there stretches part of Treska River with very steep slopes. From geological aspects, the terrain is mainly composed of marbles and dolomitic marbles, tectonically folded, cracked and partially carstified. From the location of the dam profile upstream, there is the natural widening of the river bed which is mostly filled with the reservoir lake of Kozjak dam.

In this area, there are rocks of different age ranging from the Precambrian to recent rocks mainly composed of complexes of Precambrian highly metamorphic rocks, Paleozoic phylitic shales and plutons, Mesozoic sediments and magmatites, to Tertiary-Quaternary continental formations.

In the course of the neotectonic stage of development of the wider surrounding of the Kozjak dam, the pre-neogene geotectonic structures were transformed into a system of blocks with uplifting and subsiding tendencies of different intensity.

In southwest, there is a fault, which is very much pronounced in the terrain, particularly below the very top of Kozjak, in the direction of Treska River. In this area, there is carstification developed to the stage of karst holes. A small segment of a regional active fault (maximum expected magnitude of M = 5.8 degrees according to the Richter scale), is situated in the area of the dam and the Kozjak reservoir. Defined near the location are other few regional and local tectonic faults with maximum expected magnitudes within the range of up to M = 5.5.

2.4.2. Location

Kozjak Dam is located on Treska river, in the cental western part of Republic of Macedonia and forms approximately 28km long reservoir. Regarding their physical characterics (height: 126m, embankment dam, reservoir volume $550x10^6$ m^3), the dam and the reservoir can be reagred as having RIS potential.

2.4.3. Seismic Oscultation of Kozjak Dam

In the period 2003-2008, the seismic activity of the region of Kozjak dam has been monitored with three seismological stations equipped with short-period digital seismographs installed near the Kozjak reservoir (codes: KOZJ, SAMO and BELI). The distribution of epicenter of the recorded earthquakes are presented on Fig.1. Seismic activity is characterized with weak earthquakes, magnitudes less than

2.2. The monitoring of the seismic activity of the area of HPP Kozjak (in the during filling of the reservoir and its further exploitation) was intended to confirm the possible effect of the re-distribution of stressses within the Earth as a result of reservoir filling.

The changes of the water level and the variation of the observed seismic activity in the period 2003-2005 near KZJ, i.e. the dam crest, are shown in Fig. 2. Considering that the construction of the dam was still underway in 2003, the recorded earthquakes were due to the natural seismic activity of the dam area. It should be noted that these earthquakes also include records that are due to the activities related to the construction of the dam (mining and similar activities). With the beginning of the filling of the reservoir, it is clear that the seismic activity is increased during the filling and particularly upon water level reaching 426 m above sea level. Series of earthquakes that practically occurred below the seismological station are clearly distinguished. This activity lasted until 22.06.2004 god.

In the period 2003-2008, only weak earthquakes took place in this area (analysis of the seismic activity was performed only for earthquakes that were considered to have hypocenters in the near surrounding of the reservoir according to the arrival time difference of the seismic P and S waves (time Δt_{PS}). Earthquakes with time Δt_{PS} less than 0.5s, are considered to have hypocentres practically below the location of the KOZJ seismological station, i.e., their hypocentre is practically below the dam crest. As to the other two stations, considering the distance of BELI and SAMO stations from the dam (KOZJ), their Δt_{PS} is approximately up to 3.0 seconds. In the beginning of 2007, in the phase of seasonal filling of the reservoir, an increased seismic activity was again recorded. This activity ended in May 2007 (Fig. 3). In the beginning of 2007 until the end of 2008, the activity was considerably reduced and a small number of earthquakes were recorded in the immediate surrounding of the dam. From the analysis of the data from the seismological stations BELI and SAMO, it is clear that a small number of earthquakes took place in the vicinity of these stations during the entire period of osculation (2003 – 2008). Some of the earthquakes with time Δt_{PS} of less than 3s which are of interest for the seismic monitoring of HPP Kozjak belong to the earthquakes from the immediate vicinity of the reservoir. These data are highly useful in investigation of the normal seismic regime in this part of the territory of the Republic of Macedonia.

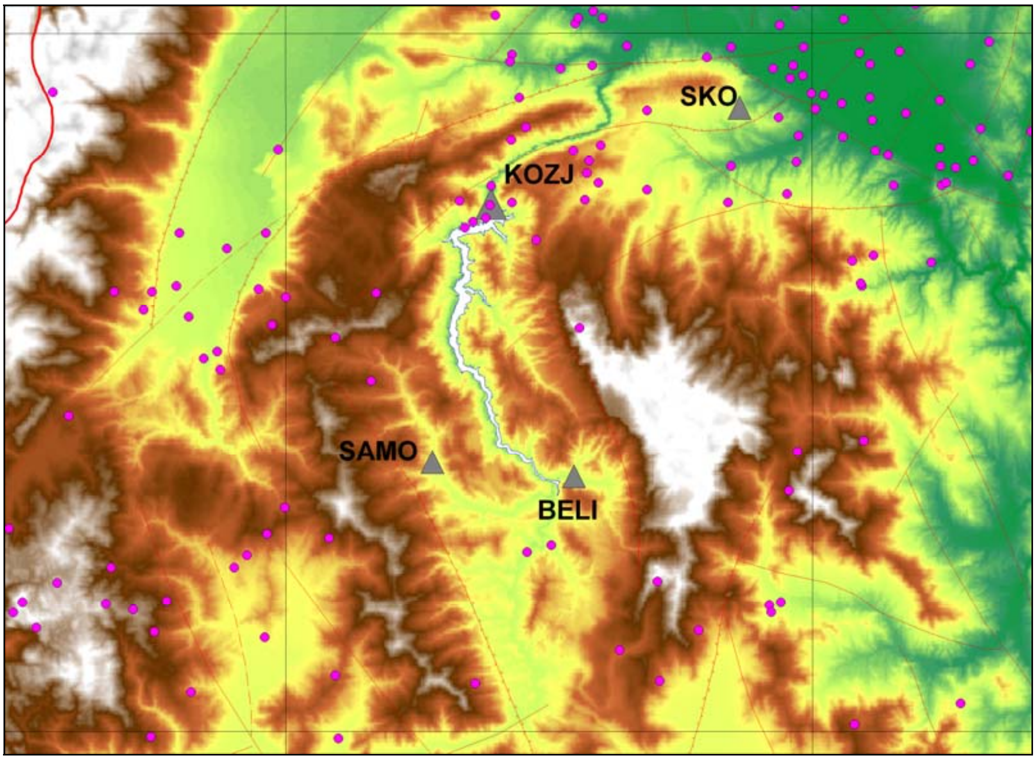

Figure 1. Epicentral map of seismic activity (2003-2008)

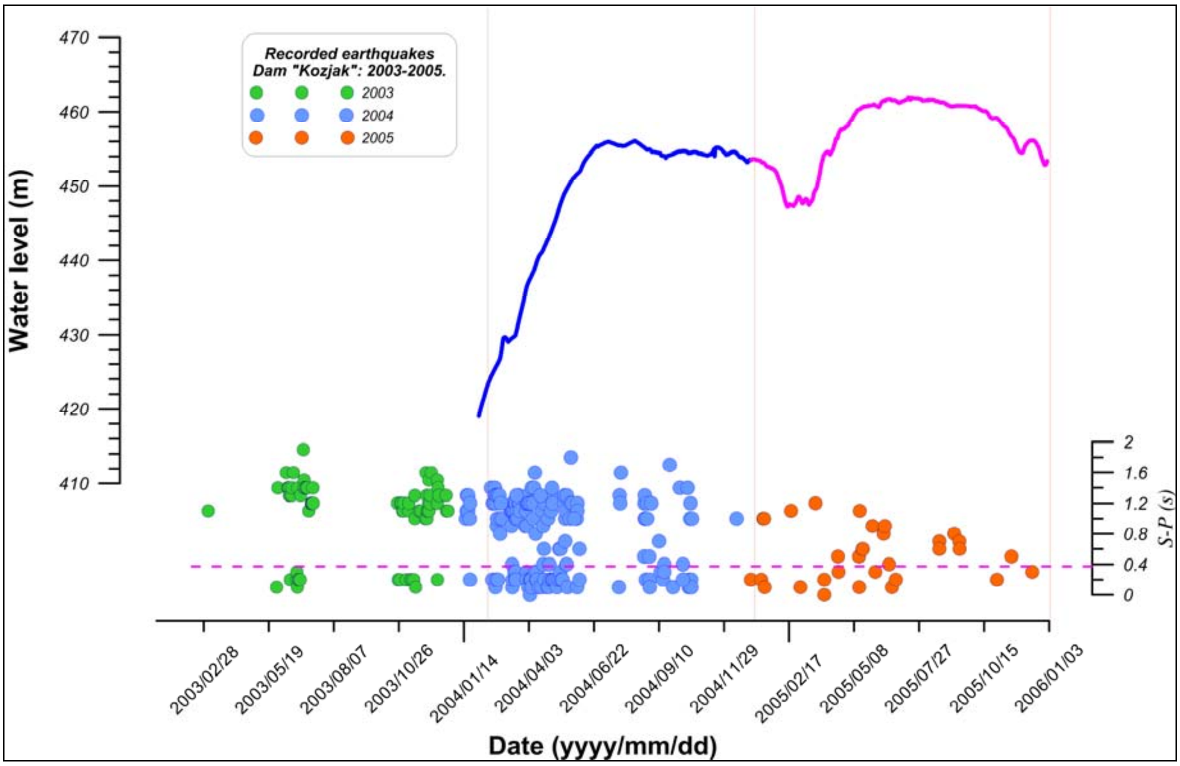

Figure 2. Seismic activity in the period 2003-2005

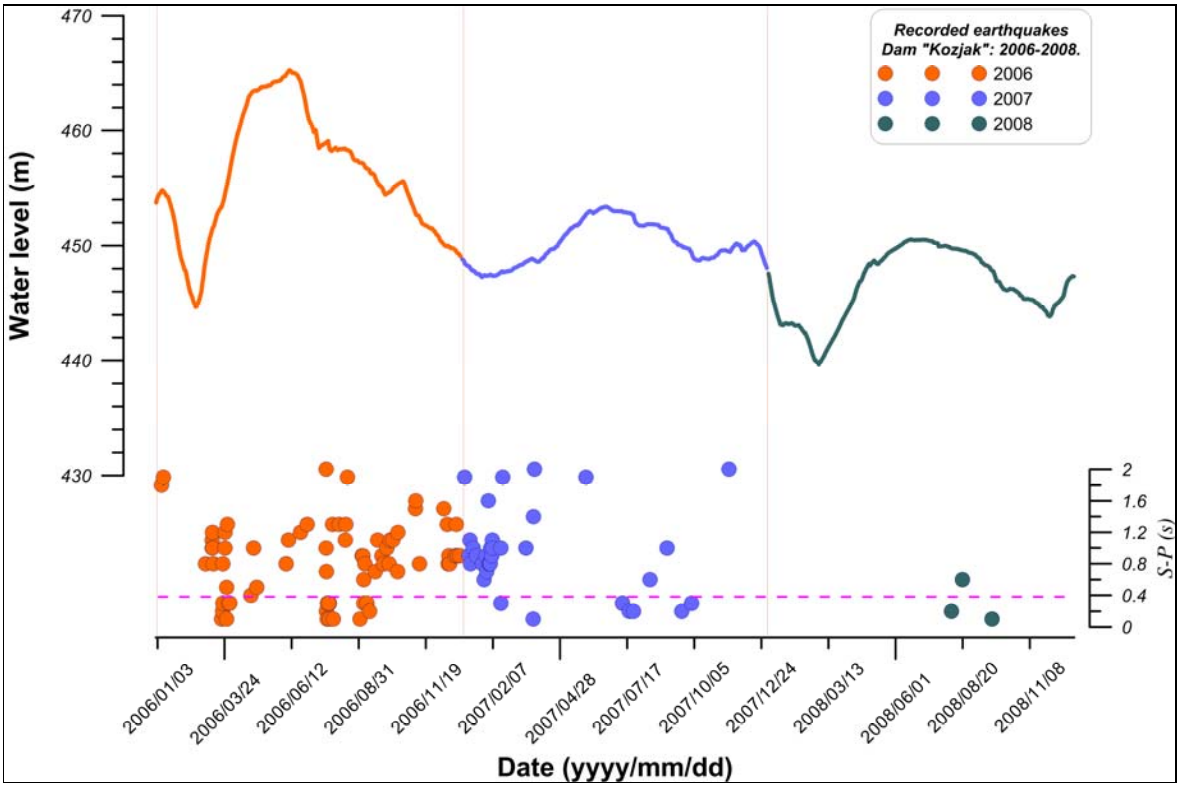

Figure 3. Seismic activity in the period 2006-2008

CONCLUSIONS

There is a limited number of data on occurrence of induced seismicity at individual locations of dams and reservoirs worldwide. Particularly missing are data on the seismotetonic conditions in the terrains in which these induced earthquakes occur. Their mechanisms are very complicated, insufficiently known and understood and frequently vary from case to case.

The seismic activity in the area of HPP Kozjak and beyond was monitored through recording of earthquakes that occurred in the reservoir area in the period 2003-2008.

In the second half of 2007, the reduction of the total quantity of water in the reservoir of HPP Kozjak was accompanied by occurrence of induced seismic activity (local) in the vicinity of the dam crest (station KOZJ).

The increase of the water level and its further variation in the course of 2008 was not accompanied by local seismic activity.

The time of changes in the water level and the occurred seismic activity recorded by the seismological stations SAMO and BELI in Samokov and v. Belitsa shows that the closer local epicentral areas were active during the entire period of monitoring.

From the comparison of the wave shapes of the selected earthquakes recorded at the seismological station KOZJ, it is clear that the mechanism of occurrence of earthquakes at their foci was different. Further profound investigations should show whether such differences are due to the differences in the local tectonic conditions inside the Earth in the vicinity of the dam where earthquakes take place or are due to the local changes of the stress field as a result of the change of the water level in the lake.

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