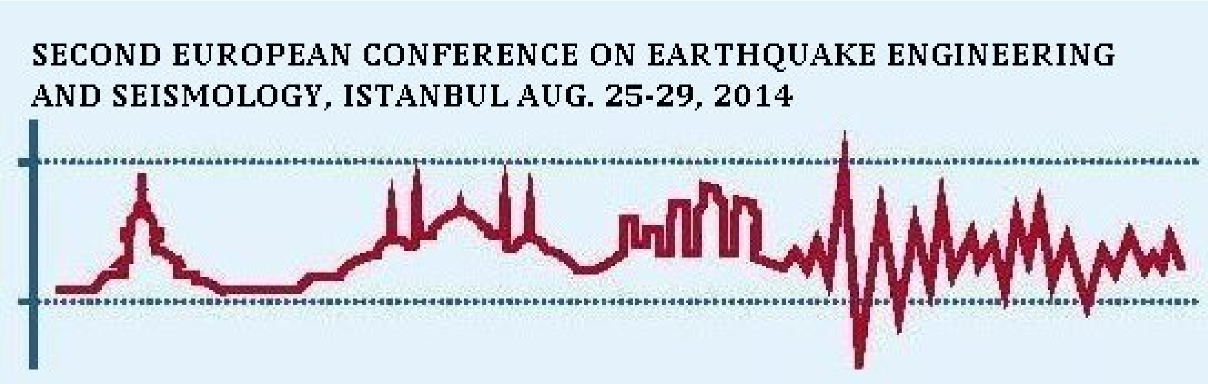

RESERVOIR INDUCED SEISMICITY (RIS) POTENTIAL OF ARTIFICIAL WATER RESERVOIRS

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INTRODUCTION

For the last eighty years, there have been recorded a number of cases where human activity has unintentionally led to earthquakes. Such a seismicity is the least scientifically known type of seismicity and it is related to human activities that unintentionally cause earthquakes: construction of dams and formation of large water reservoirs, exploitation of thermal waters, injection of fluids into rock masses, exploitation of mines as well as big underground explositions. RIS occurrence is very complicated and with insufficiently known triggering mechanisms, varying very much from case to case. These earthquakes cover a very wide range of magnitudes, from micro-earthquakes to the strongest earthquakes with magnitudes of up to M = 6.5.

Seismic activity caused by filling of a water reservoir (RIS) was for the first time identified in the early 1940-ties: 1938 Marathon dam, Greece, 1939 Mead lake, behind Hoover dam over Colorado river. It was then that the causal connection between the filling of a reservoir and occurrence of seismic activity was established. Since then, a number of cases of induced seismicity have been observed worldwide. These earthquakes happened in areas of dams of different heights, structure and different maximum reservoir depths. The strongest earthquake caused by reservoir effects leading to the greatest losses took place at the Koyna dam, India, in 1967. This earthquake was with a magntiude of 6.3.

RESERVOIR INDUCED SEISMICITY

Throughout the world there is a considerable number of earthquake associated with water resevoirs. Usually RIS is present when the reservoir is placed in seismic active region, if there is an active fault in the region of the reservoir ot fault structures characterized with high seismic stress are present. Filling of the water reservoir in a seismic active region is only the triger of the earthquakes, that would eventually happened in some later time. Usuually RIS is associated with reservoirs that have 100m or higher dams (Table 1).

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Table 1 Basic data onsome cases of RIS in the world

Damreservoir	Country	Hight (m)	Volume ($x10^6m^3$)	Year of filling	Strongest Earthq.	M_{max}
Koyna	India	103	2.780	1964	1967	6,3
Kremasta	Greece	165	4.750	1965	1969	4,4
Xingfengjiang	PR China	105	10.500	1959	1962	6,1
Kariba	Zimbabue	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	Egypt	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-Bašta	Serbija	89	240	1965	1967	4,7-5,0
Nurek	Iran	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

There are seven events with earthquakes with magnitude M>5.7 on Richter scale. The strongest registered earthqukes were the one on Koyna Dam (gravity dam), Indija M=6.3 and the Xiengfengijang Dam (batress dam) in PR China, earthquke with M=6.1. Since, in both cases there were no information on the seismic activity of the region prior to dams construction, wether the earthqukes were result of reservoir influence or not is still an open question.

Also, RIS was mentioned in connection to Wenchuan earthquake (PR China, 2008, M=7.9), because Zipingpu reservoir is located close to the activated part of the Longmenshan failt. The156 metara high dam was competed in 2006. At the moment of the earthquake the reservoir was half filled (320,000,000 tons of water). Yetm there is no solid proof that this earthquake was initiated by the fillin of the reservoir.

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.

Despite several well documented cases, there is further a strongly expressed resistance to acceptance of the importance and even the very existence of induced saeismicity among the engineering community at global level.

The investigations of this phenomenon that have been performed so far have pointed to the existence of a number of categories of factors that control such seismicity and that it is necessary to obtain a large number of data particularly by installation of instruments for recording of the seismic activity of the terrain as early as prior to the beginning of construction of a dam in order to find a solution to this problem. In absence of instrumental data, it is very difficult to develop and combine a mathematical-physical model that would be able to describe such a complicated process.

The RIS mechanism is very complicated and varies from reservoir to reservoir. The main reason for this are the different geological, tectonic, seismotectonic and seismological conditions of the region below and around the reservoirs. The RIS occurrence in the region of a reservoir complexly depends on the lithogeological composition, the hydrogeological characteristics of the geological media and the tectonic characteristics of the terrains in the region.

In order that conditions be created for the occurrence of induced seismicity, it is necessary that hydrogeological conditions be also satisfied. This refers to infiltration of the water from the reservoir into the deep zones of the earthquake hypocentres or into the cavern structures in the carbonate rocks in the surrounding of the reservoir.

CASE STUDIES: GRANCAREVO DAM AND KOZJAK DAM

Common characteristic of both case studies is that the seismic activity of the locations was monitored before the construction of the dams was started. The close monitoring was continued during the filling of the reservoirs and continues to present.

Grancarevo Dam, Bosnia & Herzegovina was built in 1968. It is 123 m high arch RC dam that creates the Bileca reservoir (stavi volumen na voda ako mozes da najdes). This is one of the highest dams in Karst region. At least two years before its construction the seismicity of the region was monitored with one three component seismological station. Later it was instrumented with 5 SMA-1 accelerographs as part of the Yugoslav strong motion network. Ftrom 1991 on the strong motion netfor is composed of 6 digital instruments (SYSCOM MS-2002), 5 of them on the dam's body and one in the ooscultacion center plus an analog Kinemetriks SMA-1 instrument installed on the dam's crest as a backup.

In order to investigate the influnce of water level changes in the reservoir on seismic activity, the recorded seismic activity in the period 1999 to 2009 was thoroughly analized.

To obtain spatial distribution of earthquakes' hypocenters, the location of the seismological station „Grancarevo“ (TREBS) was taken as a central point, and on the axes (22.5 degrees apart) on every 10km the hypocenters of the earthqukes were projected (Fig 1). Regarding the direction of the main tectonic features (Dinarides) and fault systems, the most important of all are S(45)W➔N(45)E and perpendiculat to it S(135)W➔N(135)E.

For Grancarevo dam the long term (10 years) of corelation between reservoir water level and eathquake incidence was analysed. Intersting fact is that in 2009 when the precitipation during autmn-spring period was intense, the seismic activity was increased (Fig. 2) with earthquakes with higher magnitudes than usual.

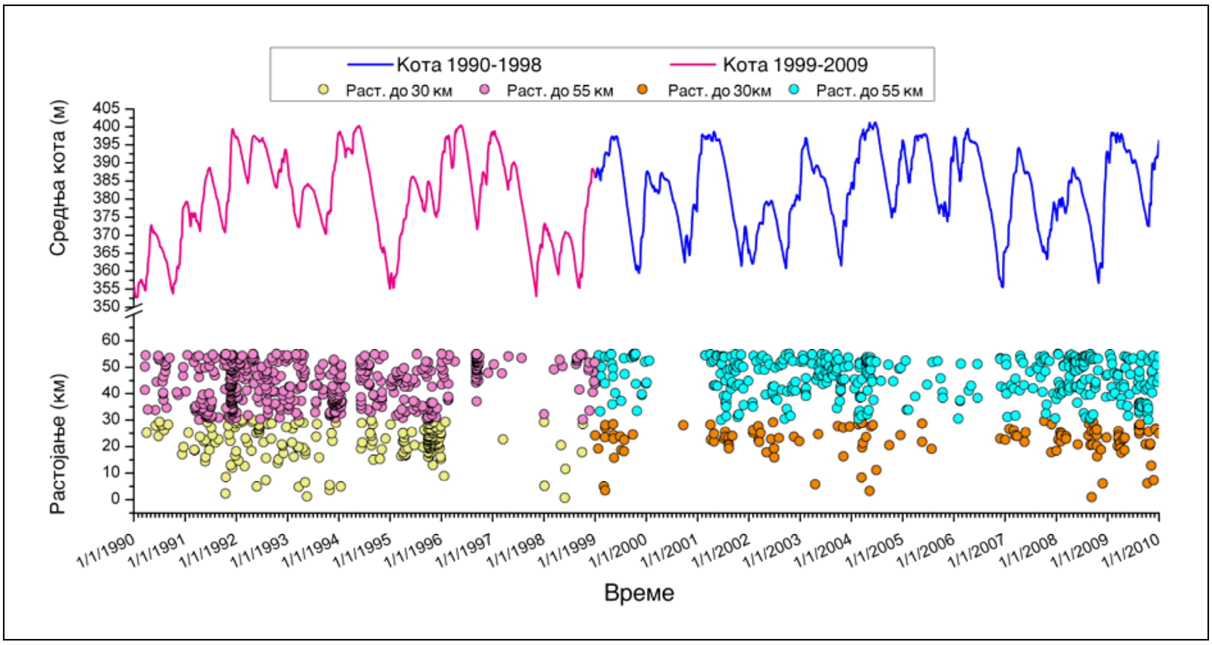

Figure 2. Seismic activity in the period 1990-2009

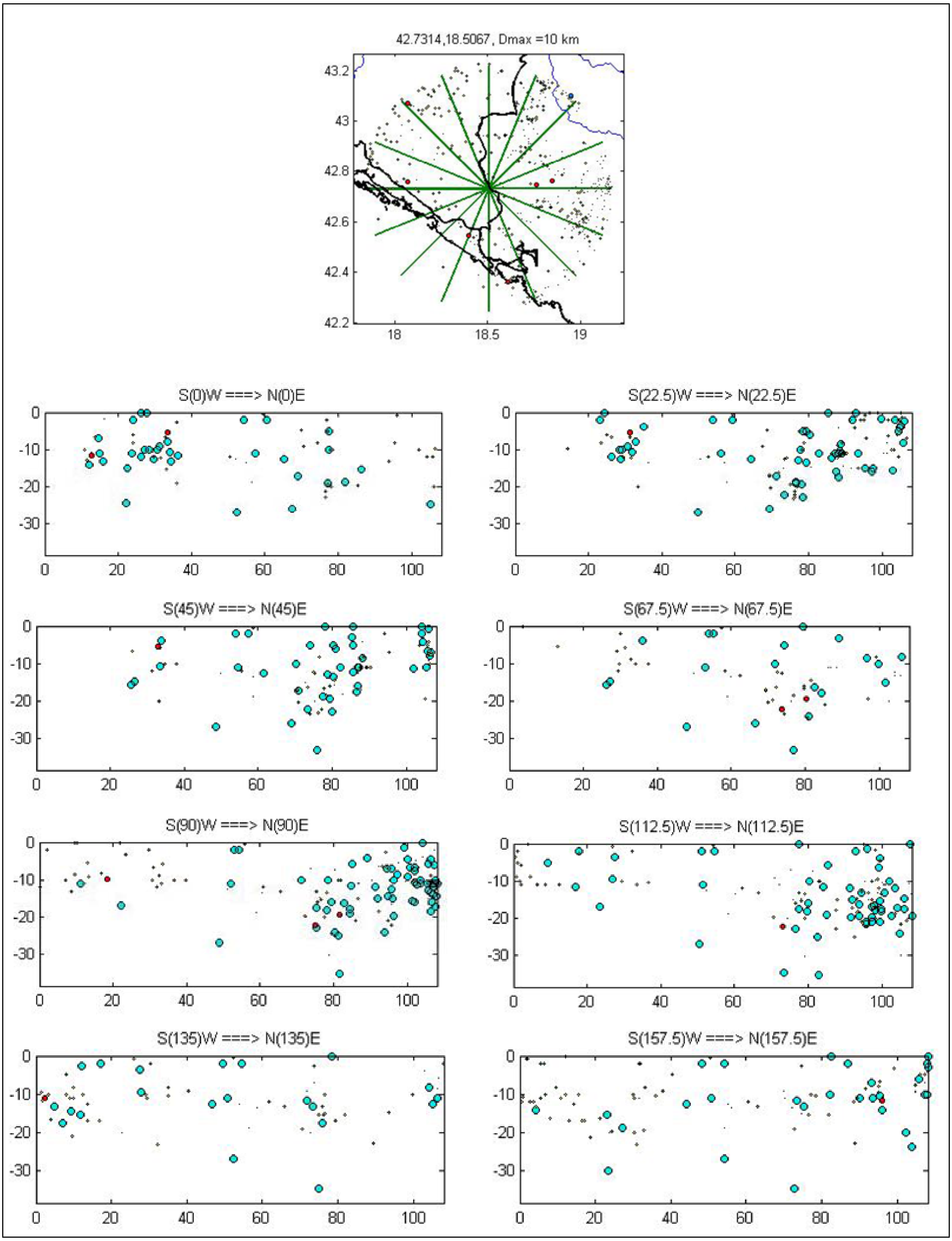

Figure 1 Spatial distribution of hypocenters around Grancarevo Dam at distance less than 55km, (program KATALOG-Matlab, Herak M., 2009)

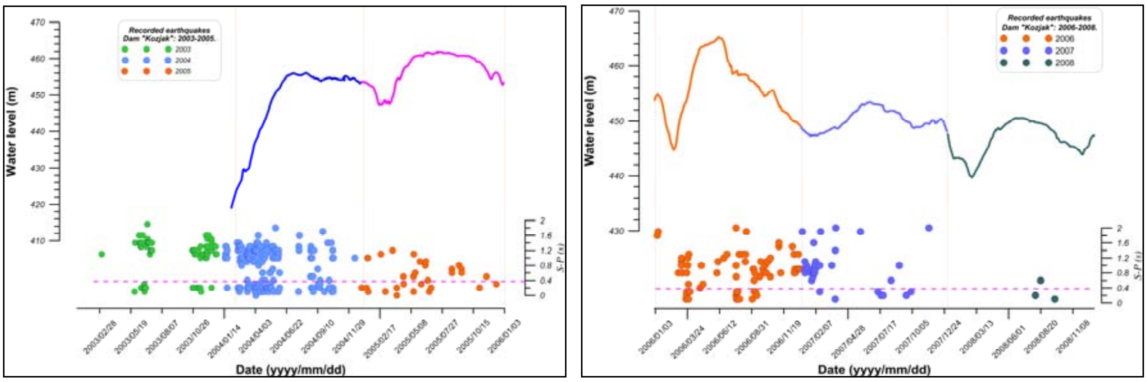

Figure 3. Seismic activity in the period a) 2003-2005 and b) 2006-2008

Kozjak Dam, Republic of Macedonia, built in 2004, 125m high embankment dam. As for Kozjak Dam, seismic activity was closely monitored starting several years befor the construction begin and lasted to 2008. Today, there is seismic monitoring network installed on the dam, It is evident that the seismic activity was altered during the filling of the reservoir. 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 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.

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