Recent seismicity close to the Jirau reservoir in Rondonia State – Brazil

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Abstract

The seismicity observed in the first two weeks of November 2014, near the Jirau reservoir was studied with a local seismic network. Seven seismic events were detected and located close to the dam axis. The two largest events with a magnitude of 2.8 m_R were felt with intensity IV-V (MM). They were the first earthquakes ever recorded in this location. In a search radius of 300 km, there are records of three events, the closest, 180 km away, with magnitude 4.7, in November 25 of 2012. According to preliminary investigation, the events are related neither to blasting at the construction site nor to a fall of large electromechanical equipment near or inside the dam axis. Vibrations generated during the turbines entries tests did not cause the events. The events may not be happened naturally, but they were most likely triggered by the reservoir, which is the only new fact in the area, with a potential to trigger seismicity. Moreover, it happened in the most influential area of lake and few time later after the reservoir impoundment. The great flood of the Jirau reservoir, between January and April 2014, coupled with the rising of the neighbor Santo Antonio reservoir water level, may also have contributed to the Reservoir Induced Seismicity (RIS).

Introduction

Jirau Hydroelectric Power Plant, belong to Energia Sustentável do Brasil (ESBR), is located in the Madeira River, more precisely in an island called Ilha do Padre, about 120 km from the capital Porto Velho. The power plant lake has a flooded area ranging from 31 up to 108 km^2 and a maximum volume of 2.74 km^3. The maximum height of the water surface occurs near the dam axis (62 m) and total length of 1,150 m. The reservoir is the type wire Moorhen with filling started in April 2013 and reached the maximum level of 90 m (sea level), in February 2014. 50 generating machines type bulb produces, when under full load, a power of 3750 MW.

The Jirau Reservoir Seismological Monitoring Programme has been developed by University of Brasilia, started three years before the initial impoundment of the lake, according to the requirements determined by the Seismological Program of the Basic Environmental Plan (PBA). On November 7 of 2014, at 20:34 (UTC) and 16h34min (local time), strong vibrations were felt at the Jirau dam structure, causing a sudden fear in the people working at the offices located at the dam axis, in the reservoir right margin.

According to the reports from these people, two strong consecutive crashes vibrations were perceived in various parts of the concrete structure and in the administrative offices located approximately four kilometers far from the dam axis. Analyses by the engineering staff of the Jirau Power Plant ruled out the possibility of the vibrations being related to testing of the machines at 120% of the capacity. After investigations in the various places where there was heavy machinery working, found that these vibrations were not caused by any fall of a large electromechanical equipment.. Preliminary analysis of the seismograms generated by local seismographic stations was found to be effectively earthquakes with epicenters close to the dam axis.

The biggest magnitude event was the first to be felt, occurred in November 7, 2014, at 16h34m (local time), with a magnitude of 2.8 on the Richter scale and was felt with intensity IV-V in the Modified Mercalli Scale (MM). Another followed this event, with a magnitude of 2.0 m_R occurred 38 minutes later. On November 13 at 10h39min (local time), other 2.8 m_R magnitude event occurred and also was felt with similar intensity.

Residents of Nova Mutum Paraná (RO) town and surrounding areas also felt the two largest earthquakes. They were recorded by two seismographic stations that monitor seismic activity in the area of influence of the Jirau reservoir (JIR1 and JIR2), the seismographic station SAMU (owned by Eletronorte) and station SAML (belong to the consortium of US universities IRIS - International Research Institutions for Seismology), installed near the Samuel reservoir Power Plant and by the ETMB station (owned by Brazilian Seismographic Network - RSBR), installed in the border between Brazil and Bolivia, about 180 km from the epicentral area (Figure 1).

This paper investigates the causes and nature of these events, based on the possible relationship between the seismicity and the Jirau lake formation.

Data analysis

Among the days of November 7 - 13, 2014 were recorded seven events (Table 1). The first was the strongest (2.8 mR) and was recorded by the five three-component stations, indicated by the yellow triangles of the Figure 1. The closest station to the epicenter is JIR2 (~12 km) and the farthest is EIMB (~180 km). Figure 2 shows the waveforms register from the 11/7/2014 event recorded by five stations of Figure 1.

***Table 1** – Source seismic parameters of the seven events detected in the area of Jirau reservoir in the period of November 7 – 13, 2014.*

ID	Date	Time	Origin	Lat	Long	Depth	Mag	No	Gap	Rms
1	141107	2034	57.46	-9.27	-64.64	1.0*	2.8	4	284	0.04
2	141107	2112	55.54	-9.26	-64.65	1.0*	2.0	4	284	0.05
3	141113	1439	20.54	-9.27	-64.64	1.0*	1.8	4	284	0.04
4	141113	1439	39.95	-9.27	-64.65	1.0*	0.8	4	285	0.04
5	141113	1439	57.33	-9.27	-64.65	1.0*	2.8	4	283	0.05
6	141113	1922	19.69	-9.27	-64.65	1.0*	2.1	4	284	0.04
7	141113	2028	9.67	-9.27	-64.65	1.0*	1.3	4	283	0.04

**** Depths set at 1km.***

The second event, also occurred on November seven, happened 38 minutes later, with slightly smaller magnitude (2.0 mR), meaning less intense. On November 13, five events occurred (Table 1). The first at 10h39m (local time), was followed by four others events, the first two happened within one minute lapse time. The largest magnitude observed was 2.8 mR at 10h39m (local time).

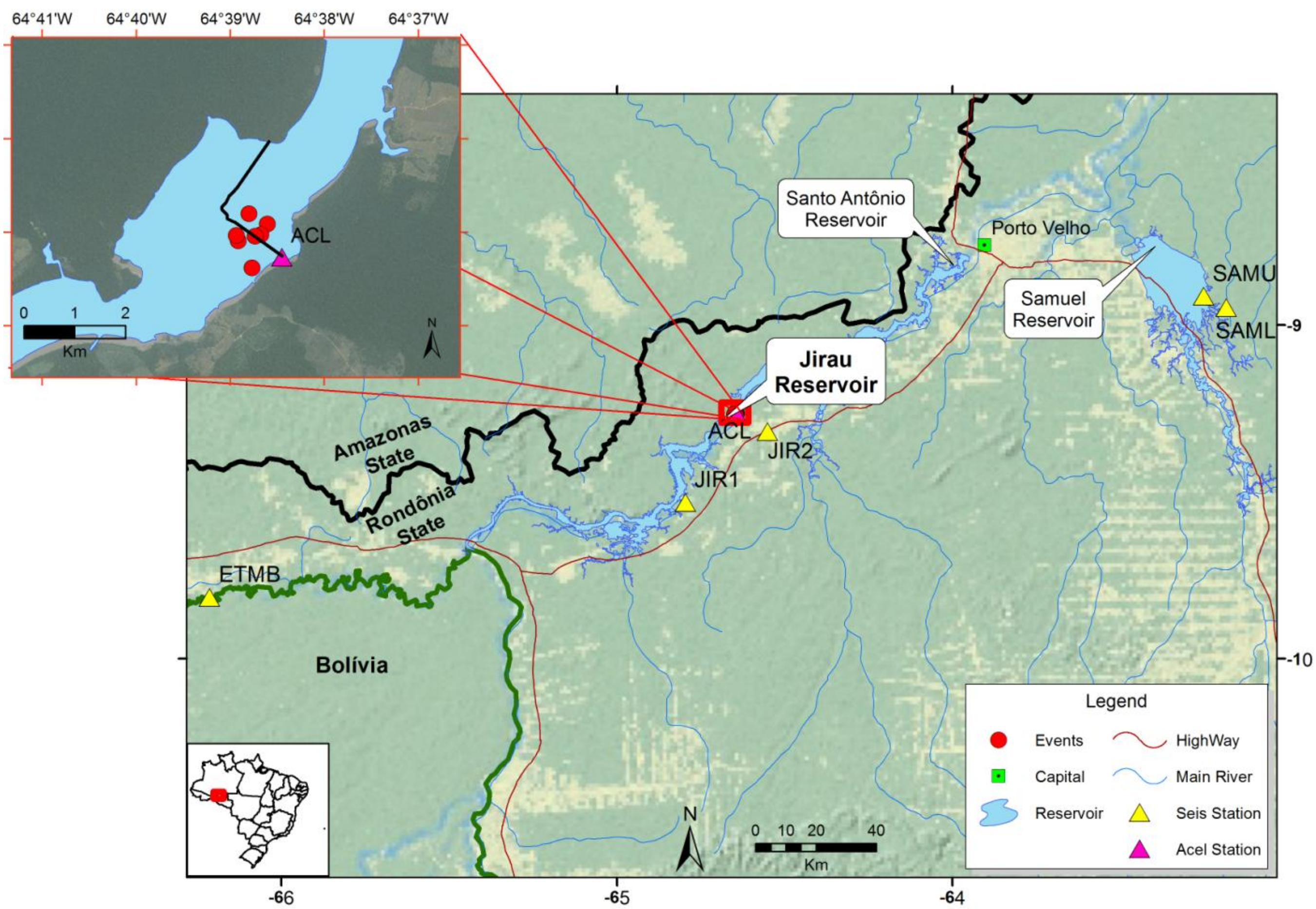

***Figure 1** - Epicentral distribution of the events being detected in the area of Jirau reservoir between November 7 and November 13 of 2014. The Figure also shows the locations of the seismographic stations (yellow triangles) which recorded the two strongest events. The acelerográfica station, installed in the dam axis, is indicated by the red triangle. The black line in the small picture indicates the dam axis.*

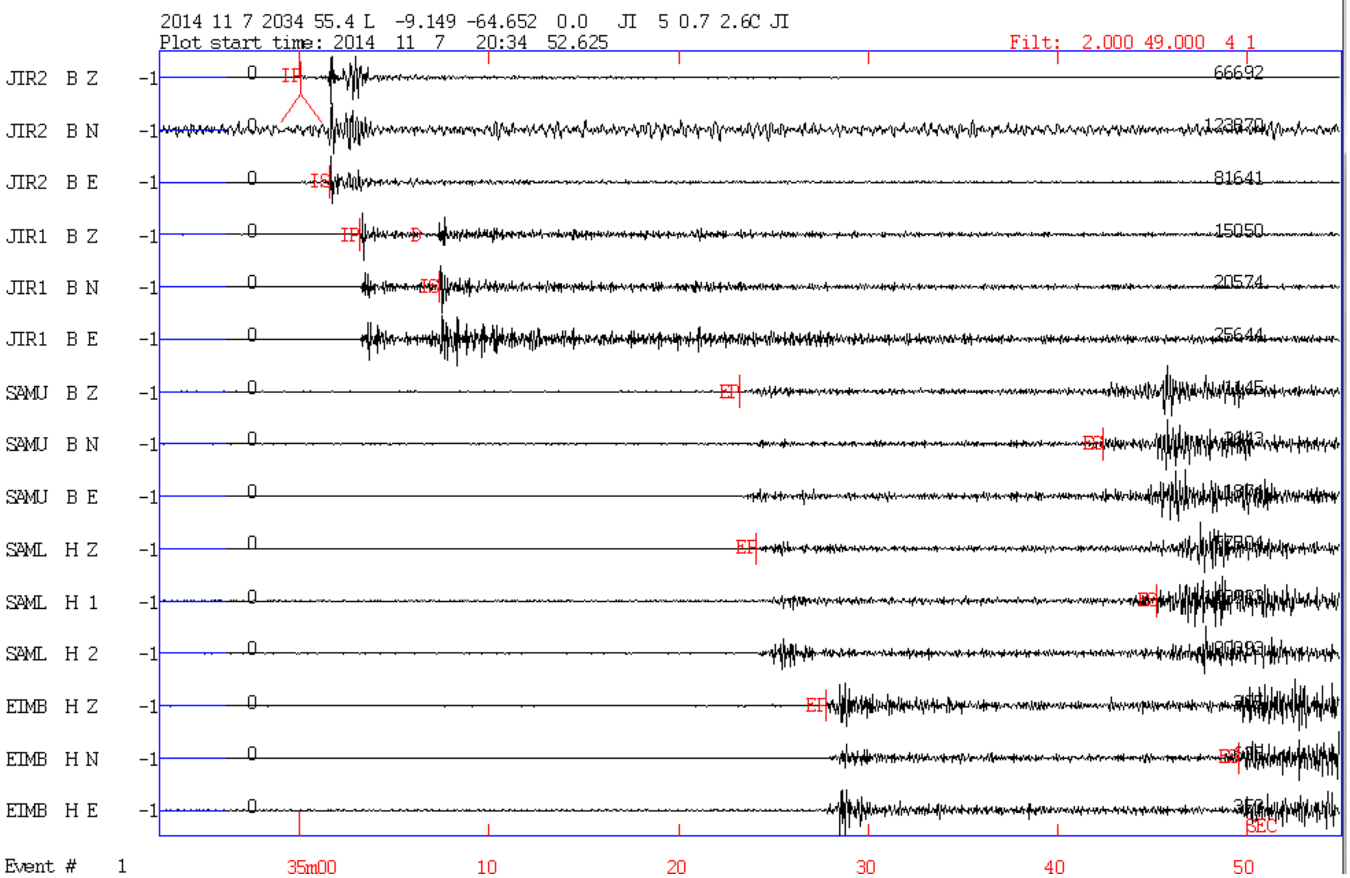

Figure 2 – Digital seismograms of the strongest November 7 earthquake, at 16h34m (local time) recorded by five three-components stations (top-down - JIR2, JIR1, SMAU, SMAL and EIMB. The traces of all stations appear in the order of, vertical component (Z), north-south (HN) and east-west (HE). About 60 seconds of data are shown.

The Figure 3 shows the seismograms of the two closest stations. Clearly one can observe impulsive arrivals of P and S phases, and that earthquake waves arriving first in JIR2 station, suggesting that it is closer to the hypocenter, and the hypocenter is closest to the reservoir.

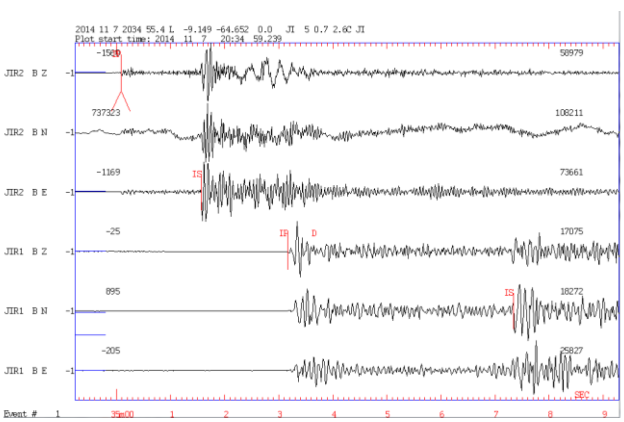

***Figure 3** - seismograms of only the two closest stations (JIR2 and JIR1). Clearly one can observe impulsive arrivals of P and S phases.*

Waveforms correlations

The cross correlation technique between two signals allowed us to establish the degree of similarity between them. Considering that, the GPS clocks of JIR1 and JIR2 stations did not appear well adjusted we have not used the P and S-waves arrival times for the events locations. We used only the times differences between S and P phases arrivals (TS - TP) in both stations together with the backazimute in JIR1 station. Before that, in order to get information about the sources of the seven events locations, we performed the correlation using signal from the vertical components of the seven events registered in JIR1 station to establish the degree of similarity between them, and thus verify if they have common source or close locations. Hence, the T1 peak was found common to all signals (Figure 4). Adjusting this peak (T1) of all waveforms is obtained the Figure 5, which clearly it can be seen that all signals are very well correlated, presenting the same time differences of S- and P-phases arrival times (TS - TP) , allowing us to conclude that sources locations are either common or very close.

As the events have different magnitudes the corresponding waveforms of all signals were first filtered out in the same frequency band, 1 Hz - 12 Hz, to unify the frequency content of each signal and thus to compare them.

Hipocentral locations

The hypocentral locations were made with the hypocenter program (Lienert, 1994) running on Seisan environment (Havskov and Ottomöller, 2010).

Although the events had been detected by up to five stations (figures 1 and 2), we used data of only the two nearest stations (JIR1 and JIR2), and with the possibility of inconsistencies in the time information in JIR1 and JIR2 stations, we chose to use only the travel time differences between P and S phases of the two stations and the azimuth of JIR1 station. The hypocenters were all set at 1km depth. The localization results are shown in Figure 1. The earthquakes occurred in the dam axis very close to the locations where they were felt more strongly. This explains why an earthquake of magnitude 2.8 mR was felt with relatively high intensity (IV-V).

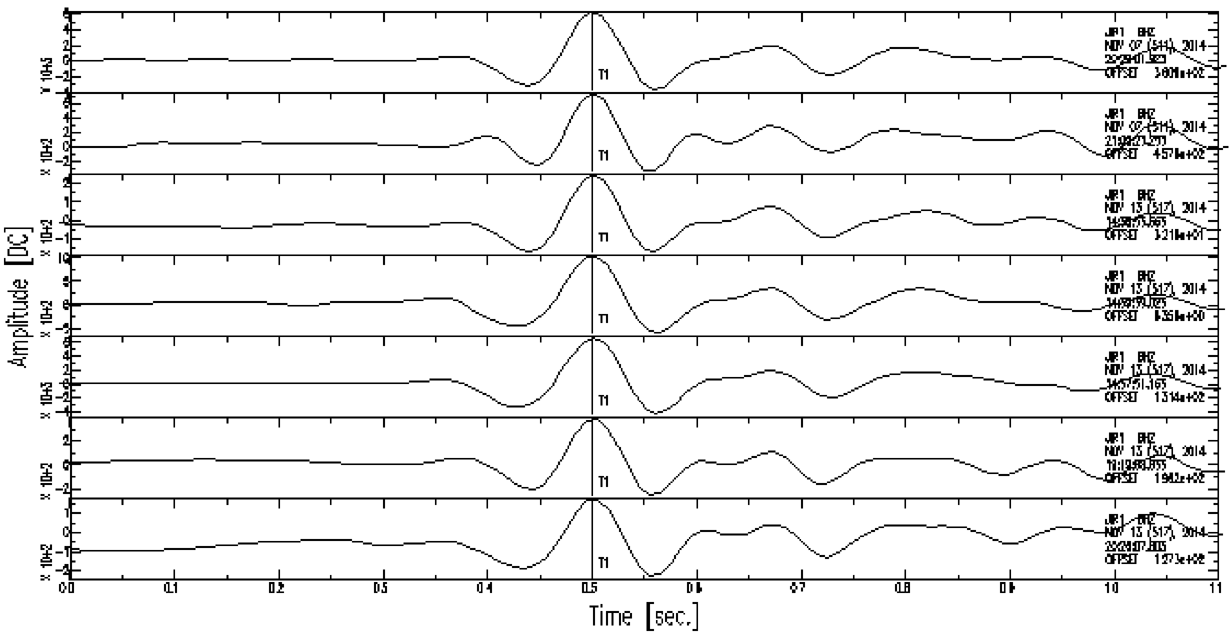

Figure 4 - Correlation of the primary phases (P) of the seven events vertical components, using as a reference the largest event. In the correlation study, it was a band-pass filter in the band of 1 Hz - 12 Hz.

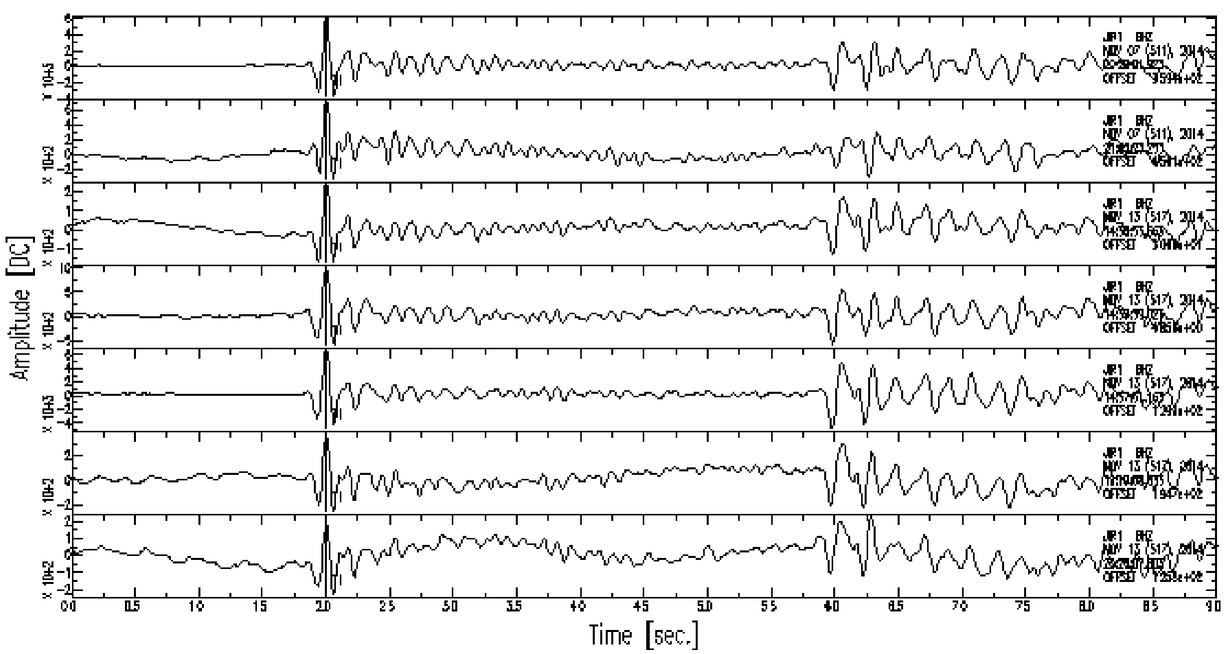

Figure 5 – The pulse T1 showed in the Figure 4 was adjusted to all vertical components. As can be seen the P and S-phases arrivals in all stations are very well correlated. The events have the same phase difference of arrivals time S and P. It was used a band pass filter of 1 Hz - 12 Hz.

Results of the vibrations measures in the dam axis

Given the perception of that not normal vibrations would be happening in the dam axis, it were made 31 manual measurements at various points of the dam axis, using an engineering seismograph Instantel branch, MinimatePlus model with 60 seconds recording time, and at a sampling rate of 1024 sps. The results showed that during the survey no significant vibrations were observed in the dam axis area. It was observed only a small increase in the level of vibrations near the central office (CPD), on the reservoir right margin.

Discussion and conclusions.

Seismicity observed on the first two weeks of November 2014, near the Jirau reservoir was studied with a local network of two 3-components digital seismic stations, both installed on the right margin of the lake. Seven events were detected and located; the largest with a magnitude of 2.8 mR was felt with intensity IV-V in the Modified Mercalli Scale (MM). The hypocenters locations were determined with the hypocenter program (Lienert, 1994), with all depths fixed at 1.0 km. We used the time differences between S and P (TS-Tp) waves, arrivals as well as the backazimute of JIR1 station.

These were the first earthquakes ever recorded in the area of Jirau reservoir. Up to then, in a circular area of 150 km radius (Figure 6), from the dam axis, seismic events were never recorded, unless artificial events caused by detonations in the project construction site. The nearest event so far, with 4.7 magnitude, 180 km away from the dam occurred in 11/25/2012 (event 3 in Figure 7). The largest, 4.9 on the Richter Scale, occurred in 1957, more than 250 km away from the dam axis (see Figure 7).

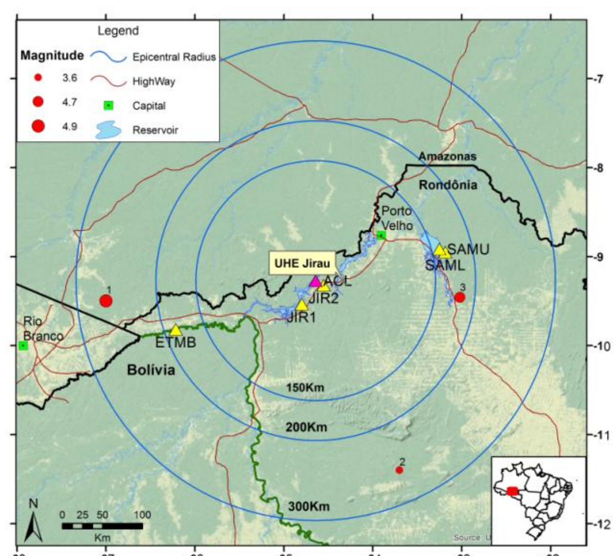

***Figure 6** - Epicentral distribution of earthquakes observed in a circular area of 300 km away from the dam axis.*

It is well known that some engineering works can have significant influence on how the crustal stresses are released in the form of earthquakes. It was found that the hydroelectric reservoirs impoundment might cause a special category of earthquakes called reservoir induced earthquakes or reservoirs triggered earthquakes. The lake acts on the geological environment in two ways: mechanically, under their own weight of water mass; and hydrogeologically due to increasing in the water pressure on the rock pores and fractures. The factors may affect the state of existing stresses in the reservoir area and trigger seismicity. However, seismic activity will only occur if the reservoir area is sufficiently near the breaking point failures due to natural tectonic processes, and therefore a small variation in stress and/or pore pressure can trigger earthquakes. Hence the name of triggered seismicity (Barros and Fontenele, 2012).

In Brazil it was observed 23 cases of Reservoir Triggered Seismicity (RTS) (Berrocal et al, 1984 Veloso, 1992, Veloso et al, 1995; Marza et al, 1995; Assumption et al, 2002; Barros. 2001; Assumption, 2014 and Barros et al, 2015). The biggest observed magnitude earthquake triggered by reservoir in Brazil was 4.2 mR and intensity VI-VII (MM), occurred in 1974 between the two neighboring reservoirs of Porto Colombia and Volta Grande (Veloso, 1992).

For the design of the Jirau structures it was suggested (Themag Engineering, 2009) the adoption of acceleration of 0.10 g – 0.15 g. According to Themag Engineering, in the same report, this value should be considered as a preliminary approach and subject to further verification with additional studies.

The maximum vibration caused by the biggest event was the order of intensity V (MM), which is equivalent roughly to an acceleration of 0.03g, about, or 0.3 m/s^2. Therefore, five times smaller than the maximum acceleration produced by the earthquake design, which corresponds to intensity VII or slightly larger scale.

The evidence that a reservoir induced seismicity or not is given indirectly by comparing the seismic activity level before, during and after the reservoir impoundment, then assessing changes in this level of seismicity due to the lake filling. This can only be done efficiently if there is local seismic monitoring with seismographic stations installed in its area of influence, such as it is the case for the Jirau reservoir. The Seismological Monitoring Programmer of Jirau reservoir began in February 2011, with the JIR1 station (complemented with SMAL Station), three years before the filling of the lake, completed in February 2014. Therefore, the seismicity appeared nine months after the complete filling of the lake.

Worldwide, the vast majority of the SDR cases were observed in the first three years after the initial filling of the reservoir (Simpson, 1986 and Talwani, 1995). In Brazil, about 80% of cases occur in this lapse time, most of which occurred in the deepest part of the lake up to one year after the initial filling (Barros et al. 2015). An important factor in the occurrence of RIS is seasonal variations in water level (filling and/or emptying the lake). A small variation in water level of the Miranda reservoir /MG was enough to trigger an earthquake of magnitude 3.3 mR and intensity VI (MM) (Barros and Caixeta, 2003).

Conclusions

Based on the presented, the results are as follows:

1. The events are neither related to blasting at the construction site nor related to large electromechanical equipment fall near or inside the dam axis;
2. The events were not caused by vibrations generated during the turbines entries tests;
3. The events may not be happened naturally, considering that this was the first time that earthquakes occurred at this location because, as shown in Figure 6 it was never observed seismicity within an area of radius of 180 km from the events epicenters;
4. The earthquakes were most likely triggered by the reservoir, which is the only new fact in the area, with a potential to trigger seismicity. Moreover, happened in the most influential area of lake shortly after its formation;
5. The great flood of the Jirau reservoir, between January and April 2014 coupled with the rising of neighbor Santo Antonio reservoir water level, may also have contributed to the RIS in Jirau;
6. The dispersion to the events epicentral locations is due to the high resolution of the highlight map, because based on the waveforms correlations of the seven events (Figure 5), we concluded that all events are located very close;
7. We conclude, therefore, the need to better monitoring this seismicity, including the installation of new stations on the left margin of the reservoir and closer to the epicentral area.

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