Tucuruí reservoir new seismic network

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Abstract

The seismic monitoring of Tucuruí reservoir began in 1978, five years before the lake impoundment. Initially, with a single uniaxial analog station and, subsequently came to have four telemetric stations with a central recording facility with four MEQ-800 smoked papers recorders synchronized with the same time base. ELETRONORTE purchased recently twenty two digital three-components stations (eighteen seismic and four acelerographic) to modernize and expand its seismic monitoring network installed in the Amazonian reservoirs of Tucuruí/PA, Balbina/AM and Samuel/RO and the new reservoirs of Belo Monte/PA and Dardanelos/MT, as well as to reactivate the seismic monitoring of the Coaracy Nunes/AP reservoir. In Tucuruí reservoir are to be installed eight permanent stations, four seismic and four acelerographic and, two more temporary seismic stations are planned. This paper describes the Tucuruí reservoir seismic network, stations characteristics, instrumentation and real time data transmission system. Before to do that, we present a brief review of induced seismicity observed in Tucuruí Reservoir.

1. Introduction

The Tucuruí Reservoir, for its size and importance, with a length of 240 km, a flooded area of 3200 km^2, volume of 56.1 km^3 and a height of 77 m, generating 8300 MW, 8% of all energy consumed in the country, besides being a seismic reservoir, justifies the need for a comprehensive and modern seismic network. This network will be composed by eight permanent stations, four seismic and four acelerographic stations (figures 1 and 2) and, additionally, two more temporary seismic stations are planned, in the case of reappearance of Reservoir Induced Seismicity (RIS) in the Tucuruí reservoir. Of the eight permanent stations, five have already been installed; two seismic and three acelerographic; four of them are already sending their data in real time to the Seismological Observatory (SIS) of the University of Brasília (UnB) (see figures 1 and 2). With this network, it will be possible to locate earthquakes, determine magnitudes and measure ground motion accelerations caused by possible Tucuruí reservoir induced earthquakes, besides allowing studies of crustal structure, seismic sources and attenuation of seismic waves, a very important data for the evaluation of seismic hazard and, therefore, to mitigate the seismic risk in the region.

The RIS is a subject well accepted and it has been studied for more than six decades (Carder, 1945). Results of the constructive iteration between the reservoir and geological environment present in its influence area. The reservoir mechanical (due to the weight of the water) and hydraulic affects (due to increased pressure in the pores of rocks) can reduce the required stresses to break the existing faults within or very close to the lake. However, this will only be possible if the faults are in critical conditions of rupture and that the action of the lake will be enough to break them, triggering earthquakes. Therefore, the occurrence of RIS will depend on the manner in which the additional effects caused by the reservoir will interact with the tectonic and geological environments present in the lake influence area (Simpson, 1976).

The RIS observed in Tucuruí reservoir is one of the twenty-two cases that have already been observed in Brazil; which maximum magnitude was 4.2 m_b and intensity VI-VII in the Modified Mercalli (MM) Scale (Barros and Fontenele, 2011). The biggest magnitude observed in Tucuruí was 3.6 m_b on March 02 of 1998, which was felt by the local population with intensity IV-V (MM) (Barros and Marza, 1998).

The proof of the RIS is made in indirect way, comparing the level of seismicity observed before and after the lake impoundment. What is possible only with the seismic monitoring of the lake influence area before, during and after its impoundment. Hence, the importance of the seismic monitoring of a reservoir.

The seismographic monitoring of Tucuruí reservoir began five years before the start of the lake impoundment, in 1985, and during all subsequent time it has never been discontinued, except for some periods of time, due to stations operational problems. The first reservoir-induced earthquakes appeared six months after the lake start filling (Fig. 3), which at that time was monitored by a single analog station. Since then the reservoir began to be monitored by a four-station seismic network and later by two, and at least one station, most of the time a digital three components station. But, unfortunately, it was not possible to have precise hypocentral location and neither focal mechanism studies. The current network is intended to be a permanent network, considering the fact it has been observed seismicity in the Tucuruí reservoir (Fig. 1) and in this case, it will be possible to make confident studies on the possible future seismic activity in the area.

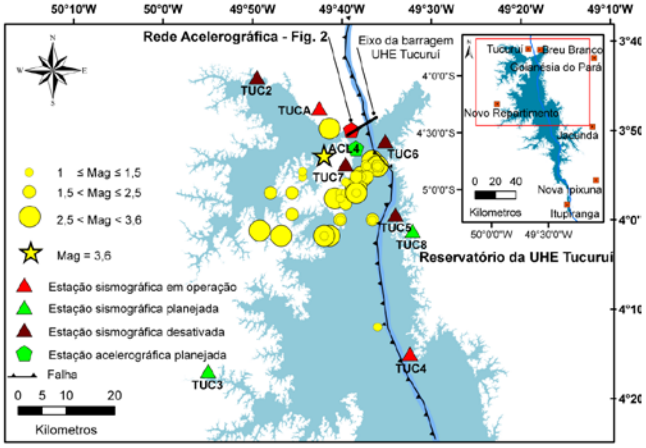


Figure 1 - *Map of Tucuruí Reservoir, with the epicentral distribution of the induced earthquakes and location of seismic and acelerographic stations. Installed (in red), disabled (brown) and planned (green). The seismic stations TUC3 and TUC8 and the acelerographic ACL4 are planned to be installed later this semester. The installation points of the acelerographic network stations installed on the dam axis are shown in Figure 2.*

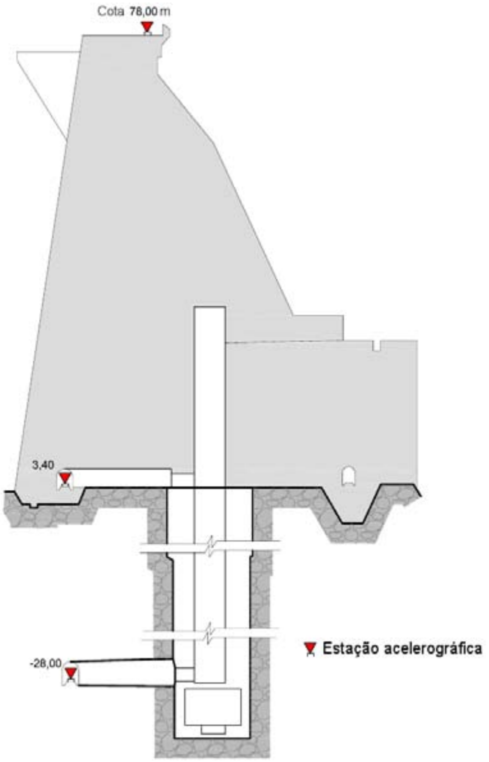


Figure 2 - *Positions of acelerographic stations (red triangles) installed on the dam axis, block BG1. acelerographic station 3 (ACL3), on the dam top, at quota of 78 m, station acelerographic station 2 (ACL2) at the dam base, at quota of 3.4 m, acelerographic station 1 (ACL1) in the drainage tunnel in quota -28 m*

2. The RIS in Tucuruí reservoir

In the lake pre-filling phase, the natural seismicity observed occurred at distances beyond 100 km of the future dam. The nearest event of greater magnitude (4.5 m_b) occurred 300 km from the dam, on January 12 of 1970 (Veloso, 1992). So, there was not natural seismicity in the area of the future reservoir. Six months after the start of the filling, low-magnitude events began to be observed, with epicenters within the lake or in its periphery (Fig. 1). These characteristics associated the Tucuruí Reservoir to the phenomenon of RIS, and the pattern of seismicity observed is a typical case of RIS with initial response (Simpson, 1976 and 1986), i.e., the earthquakes occur from the beginning of the lake filling up to three years after the complete reservoir impoundment. Earlier this activity, the SIS/UnB installed a network with four analogue stations, operating by radio-telemetry with a recording central station (MEQ-800 recorders), whose clocks were synchronized at the same time base.

2.1. Characteristics of the RIS in Tucuruí

Tucuruí RIS presented two distinct phases. The first occurred between March 1985 (six months after the beginning of the lake filling) and December of 1986, with events located within the Lake in a trending SW-NE (figures 1 and 3), continued in March 1987 until 1989, with the epicenters migrating to the lake periphery. The second phase began in January of 1994 and continued until 1999, with epicenters distributed in the same region of the first phase. During this last sequence occurred the biggest induced earthquake in Tucuruí reservoir, magnitude 3.6 m_R, in March 02 of 1998 (Barros and Marza, 1998).

The first phase was characterized by initial lake response, fast response, according to Simpson (1976), because the earthquakes occur almost simultaneously to the reservoir filling, as demonstrated by the emergence of micro-activity in the same month in which the lake reached the maximum filling level (72 meters). Just three months after the first induced earthquake, occurred the most significant event, reaching magnitude 2.8 m_D. The events that followed showed an alignment with NE-SW trending (Fig. 1). This alignment should be related to a fault in the region, although unknown. In the first phase occurred seven main events, with magnitudes ranging between 2.8 m_D and 3.2 m_D.

In 1987, two years after the reservoir reaches its maximum elevation, occurred seven events, located near the existing residential village, downstream of the reservoir, about two km from the dam axis. The main event reached magnitude 3.4 m_D. This activity may be related mainly with the effects of increased interstitial pressure caused by the diffusion of liquid through the pores and fractures of rocks, reducing the effective stress, took the rock to rupture after the water has traveled the marginal areas of the Reservoir. This phase has a gap between 1987 and 1988, revived in July, 1988, and ended in July of 1989 (see Fig. 3).

The second phase began in January of 1994 and finish in October of 1999. In this phase, it were detected 93 events. The maximum magnitude ever observed in Tucuruí occurred in this phase (3.6 m_R, in March 2, 1998). This phase seismicity may be related to the accumulation of regional stresses in conjunction with a cumulative effect of reservoir loading and the increase of interstitial pressure of water in pores and fractures of rocks. Another important factor in explaining this phase is that after 1996 there was an unusual variation in the reservoir water level. The specific variation in 1996 (10 meters) was caused by the filling of the Serra da Mesa/GO reservoir, which is upstream of the Tucuruí dam, located in the same Tocantins river. Two years later, when Tucuruí reservoir was at its maximum height, occurred the biggest induced earthquake by Tucuruí reservoir.

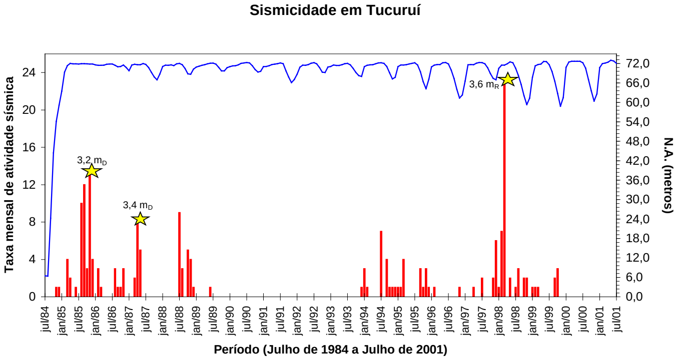


Figure 3 *– Temporal evolution of the induced seismicity observed in the Tucuruí Reservoir from 1984 to 2001. After 2001 only few micro events were detect.*

3. Seismic network at Tucuruí Reservoir

It comprises of eight stations, four seismic and four acelerographic, and, additionally, is planned to install two more seismic stations in case of recurrence of RIS in Tucuruí reservoir. All data will be transmitted in real time to Brasilia.

3.1. Seismographic network

The permanent Tucuruí reservoir seismographic network consists of four three components seismic station, in the band of 30 s to 100 Hz and data, acquired at each remote station (Fig. 4), at a rate of 100 samples per second. Data are sent initially via digital radio to a central station, located at the dam structure, and then to the ELETRONORTE office in Brasilia, via optical fibers installed in the ground wire cable (inside of the lightning cable protection of the transmission power line). In Brasilia, the ELETRONORTE server computer's data is accomplished the translation of the local IP address for the public IP address, allowing access to data by SIS/UnB computer, where data are received in real time.

Figure 4 - *View of the instruments and seismometer shelters of TUCA station (pictured above, on the left). Seismometer shelter internally lined by styrofoam plates (picture above, on the right) and seismometer pit covered with fine sand (bottom photo). The latter was covered with tile.*

3.2. Accelerograph Network

Three of the four network accelerograph stations are installed in the structure of the dam, one on the crest (elevation 78 m), one at the base (elevation 3.4 m) and the other one at the bottom of the sump, block BG1, at elevation -28 m (see Fig. 2). These three stations are already sending their data to the Seismological Observatory by the ELETRONORTE intranet. The fourth station, reference station, will be located about 2 km from the dam structure on the island named Gemoplasma (see Figure 1).

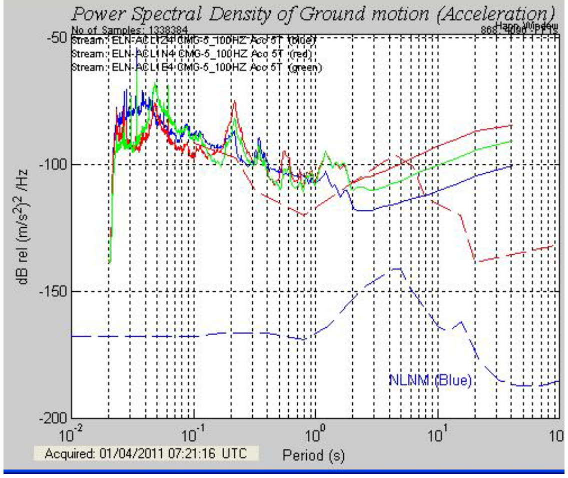
The accelerometers are Guralp mark, model CMG-5T, with Low gain output of 2 g (g = 10m/s^2) and frequency response ranging from DC to 200Hz. The digitalize is the same used in seismographic stations - Guralp mark, model-CMG DM24S3EAM with a resolution of 24 bits and dynamic range of 137 dB. The data are recorded continuously at a rate of 100 samples per second. Since the only station installed at the dam crest (ACL3) receives GPS signal, the other two stations are synchronized by the GPS signal received at station ACL3. Figure 5 shows details of installation of the instruments of ACL2 station, at an quota of 3.4 m.

Figure 5 - *View of the acelerographic station ACL2, located in the drainage gallery of block BG1 (elevation -28 m), showing the digitizer (left foreground), the uninterruptible power supply (behind of the digitizer), the switch (above of the digitizer) and the accelerometer (on the right).*

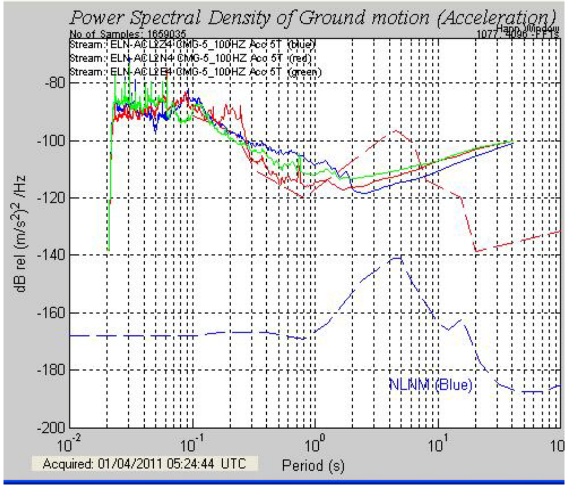
4. Sites Survey and site selection

In the site survey it was used a complete seismograph system: seismometer Guralp mark, model CMG-40T, with frequency response from 0.03 Hz to 50 Hz, and digitiser Guralp too, model DM-24 with 24-bit resolution and 130 dB of dynamic range. Noise tests were conducted at various points, for about 30 minutes, at different times of day. The results are in the report “Deployment of the seismic network of Eletrobrás Eletronorte in the Tucuruí reservoir, by Fontenele et. al. (2011) (in Portuguese).

The sites selected for the stations, unfortunately, are not the best, due to the following problems: i) Tucuruí reservoir is located in the Amazon basin, a very difficult place to find outcrops; ii) The choice of the points for stations was conditioned to the existence of radio-visibility for the signals transmission; iii) Problem of land expropriation; and iv) Problem of safety equipment. For example, the stations TUC5, TUC6 and TUC7 have been disabled for security issue and all set of TUC2 station equipment was stolen. Figure 6 shows the spectral density of ground acceleration for all the chosen points and Table 1 summarizes the characteristics of each point.



(A)



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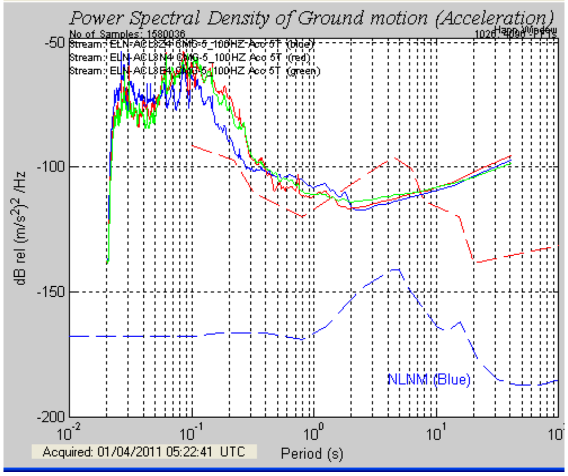

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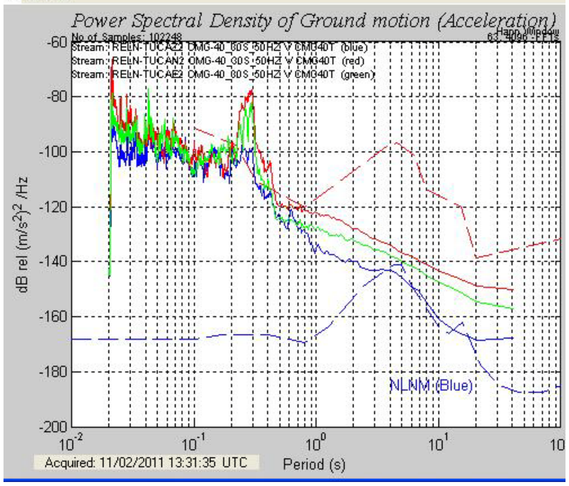

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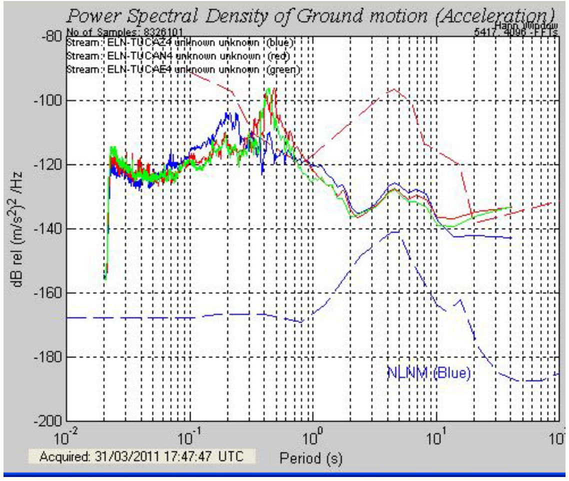

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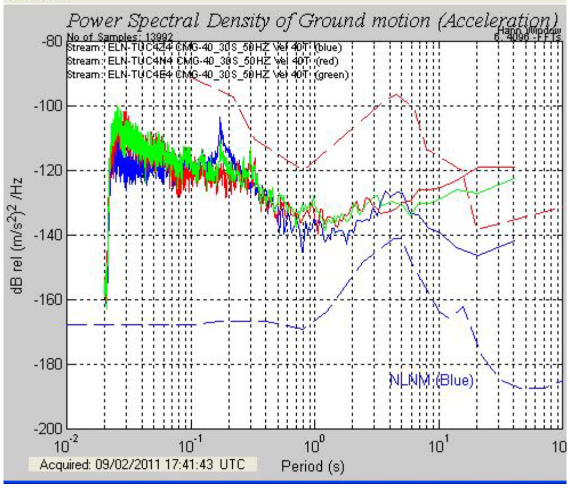

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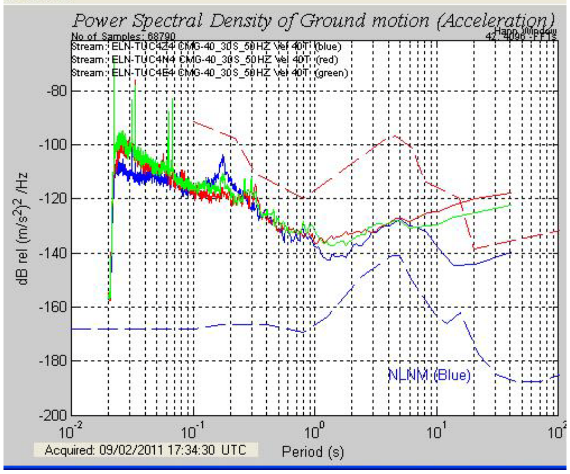
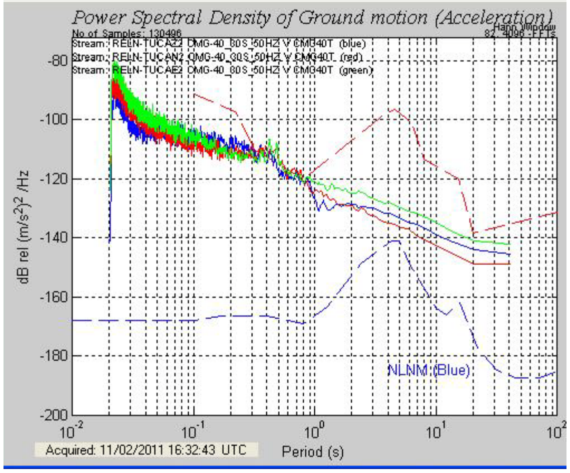


(G)



(H)

***Figure 6** - Acceleration power density spectra [(dB rel(m/s^2)^2/Hz x period (s)] determined for the sites of accelerographic stations ACL1 (dam top, A), ACL2 (dam base, B), ACL3 (dam bottom, – 28 m, C), reference station ACL4 (D) and seismic stations TUCA (E), TUC3 (F), TUC4 (G) and TUC 8 (H). Observe that the sample noise was collected for different lapse time and in different period of the day. The blue and red lines are Peterson (1993) references model for the New Low Noise Model (NLNM) and New High Noise Model (NHNM), respectively. Green, red and blue lines are the traces for the movements in the Vertical, East-West and North -South directions, respectively.*

***Table 1.** Characteristics of the site selected for the stations.*

Station	Lat.	Long.	Elevation	Site characteristic
ACL1	-3.833	-49.650	-29 m	Dam structure
ACL2	-3.833	-49.650	3,6 m	Dam structure
ACL3	-3.833	-49.650	78 m	Dam structure
ACL4	-3.867	-49.641	70 m	Soil
TUCA	-3.792	-49.709	225 m	Lateritic crust
TUC3	-4.282	-49.916	126 m	Outcrop
TUC4	-4.250	-49.540	125 m	Soil
TUC8	-4.015	-49.601	107 m	Lateritic crust

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