Study and update of Reservoir-Triggered Seismicity (RTS) in Balbina (AM) and Tucuruí (PA) reservoirs

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Abstract

The studies related to the seismicity caused by damming of watercourses in Brazil, Reservoir-Triggered Seismicity (RTS) or Reservoir-Induced Seismicity (RIS), emerged in the mid-1970s after an earthquake in the small Carmo do Cajuru reservoir (MG) that was felt by the local population. However, a significant milestone in RTS research occurred in 1974 with the largest earthquake of this nature in Brazil, which occurred between the neighboring Porto Colômbia (SP) and Volta Grande (MG) reservoirs, approximately one year after the impoundment, measuring a magnitude of 4.2 mb and intensity VI-VII (MMI). Thus, the latest studies indicate the existence of 26 cases of RTS in Brazil. Among these cases, in the Brazilian Legal Amazon, are the Balbina (AM) and Tucuruí (PA) cases, which have been analyzed until the year 2001. The cases have been updated in this study, analyzing them years after their respective impoundments. Considering the inconsistency of local seismic monitoring, it has been verified the continuity of possible triggered earthquakes has been observed in nearby of both reservoirs, albeit with distinct rates of seismic activity and epicentral distribution.

Introduction

The analyses aimed at understanding earthquakes triggered by the damming of watercourses in Brazil emerged in the mid-1970s after a tremor occurred in the state of Minas Gerais in the Carmo do Cajuru reservoir area. The intensity and magnitude of this earthquake were assessed as VI on the Modified Mercalli Intensity (MMI) scale and 3.7 mR on the regional magnitude scale, respectively (e.g., ASSUMPÇÃO et al., 2002).

The study focused on this area enabled the classification of Brazilian reservoirs with triggered events according to the type of seismicity observed, namely, initial or delayed, as conducted by Assumpção et al. (2002) and Barros et al. (2018). The initial seismicity emphasizes the earthquakes that occur at the beginning of damming when there is a more abrupt and/or significant water level fluctuation (TALWANI, 1997). On the other hand, delayed seismicity refers to seismic activity that occurs over a longer time interval after damming, taking into account various potential water level fluctuations over time (SIMPSON; LEITH; SCHOLZ, 1988). Furthermore, Assumpção et al. (2002) and Barros et al. (2018) analyzed potential factors contributing to reservoir-triggered seismicity in Brazil, including geology, stress regime, dam height, and reservoir volume.

An aspect of great relevance regarding earthquakes generated by anthropogenic actions is the classification in terms of their type, that is, induced or triggered, a categorization proposed by McGarr and Simpson (1997), as cited by Kang, Zhu, and Zhao (2019). According to Dahm et al. (2010), induced earthquakes are those that occur exclusively due to changes in stress caused by human activities. Thus, the occurrence, as well as the entire development of critical stress situations, would be linked to human intervention. On the other hand, triggered earthquakes would be understood as those likely to occur even without any interference, but human action would trigger the release of pre-existing stresses. However, the discrimination between induced and triggered earthquakes is a complex process (e.g., KLOSE, 2013). This is because most cases involve a lack of prior knowledge of stress distribution in a given region, complicating the analysis of stress changes and the subsequent classification of the event's nucleation type (KANG; ZHU; ZHAO, 2019). Therefore, in this study, the term "triggered" was chosen to reflect the possibility of both cases.

Seismicity resulting from human activities has been the subject of numerous studies over the years. According to Klose (2013), there are various occasions that induce subsurface stress changes due to anthropogenic intervention, such as variations in material volume, stress fields generated by temperature changes leading to possible body dimension alterations, material insertion or extraction from a specific area, as well as pressure variations through fluid percolation in fractures and/or pores, affecting the so-called pore pressure of rock. This intervention can occur, for example, through mining activities or damming of water bodies (which form artificial water reservoirs), which is the focus of this article. The Mohr-Coulomb failure criterion is a crucial tool in the analysis and understanding of earthquakes triggered by geotechnical activities (KANG; ZHU; ZHAO, 2019), as it encompasses the necessary conditions for the activation of a failure within an isotropic body (LABUZ; ZANG, 2012). The Mohr-Coulomb failure criterion can be summarized by the following expression (KANG; ZHU; ZHAO, 2019):

$$\tau_{crit} = C + \mu(\sigma_n - P)$$

Thus, the difference between the current normal stress (σn) and the pore pressure (P) multiplied by the friction coefficient (μ), added to the cohesion (C), determines the critical stress required for fault slip ($\tau crit$). Therefore, it can be observed that the higher the pressure generated in the pores, the lower the critical stress required for the nucleation of the event.

Method

Covering a significant portion of the national territory, approximately 58.9%, the Legal Amazon comprises the states in the northern region (Acre, Amazonas, Amapá, Maranhão, Pará, Rondônia, Roraima, and Tocantins), as well as a fraction of the central-west (through the state of Mato Grosso) and northeastern regions (including part of Maranhão) (IBGE, 2020). Furthermore, the territory is responsible for hosting the Amazon river basin and, consequently, watercourses where power plants have been established over time, as shown in **Figure 1**. Thus, we have the Tucuruí (in the state of Pará) and Balbina (Amazonas) reservoirs, where the hydroelectric power plants owned by the Northern Electric Power Company (ELETRONORTE) in the Brazilian Amazon are located, with their respective positions also depicted in **Figure 1**. The damming of the Balbina water body occurred in October 1987, while that of Tucuruí took place in September 1984 (ASSUMPÇÃO et al., 2002).

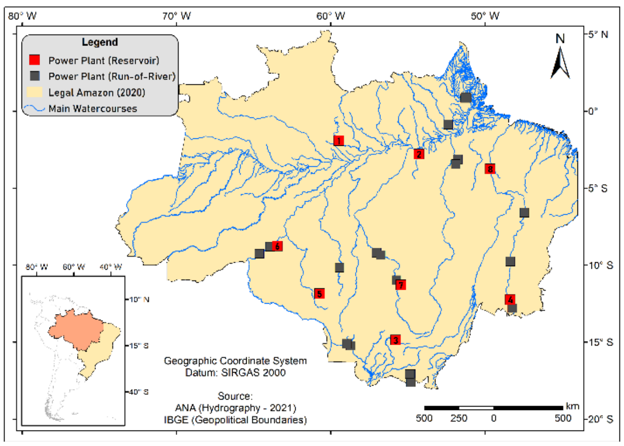

Figure 1 - *Map of distribution of hydroelectric power plants (HPP) present in the Legal Amazon, classified according to their type, including the main watercourses of the territory. The main reservoirs linked to the installation of power plants are numbered from 1 to 8, as follows: 1-Balbina; 2-Curuá-Una; 3-Manso; 4-Peixe Angical; 5-Rondon II; 6-Sanuel; 7-Sinop; and 8-Tucuruí.*

The methodology was based on a review study of reservoir-triggered seismicity in the Brazilian territory, relying on key bibliographic sources on the subject developed by Assumpção et al. (2002) and Barros et al. (2018). Additionally, an investigation of earthquakes occurring in the vicinity of the Tucuruí and Balbina reservoirs in the Brazilian Amazon was conducted, updating the cases regarding the observed seismicity in recent years, specifically between 2001 and 2018. The study made use of the database from the Seismological Observatory of the University of Brasília (SIS-UnB) and seismic catalogs available through the Brazilian Seismographic Network (RSBR). Earthquakes within a radius of 150 km from the dam axis were considered, as this area represents the primary influence zone of the reservoir and potentially triggered earthquakes. The ArcGIS software (Esri) was utilized for data mapping, along with graphical analyses to obtain the results.

Results

Seismicity in Balbina

Considering the collection of earthquakes between 2001 and 2018, a selection was made of those located within a radius of up to 150 km from the dam axis, which is responsible for the impoundment of the water body. This would be the primary area of influence of the reservoir, where the potential triggered earthquakes are expected to occur. Regarding the Balbina dam axis, a total of 72 tremors were identified in the considered period, but only 35 of them could be located due to insufficient data to determine the epicenter of all events. **Figure 2** presents the result through the mapping of the epicenters, showing their respective positions in relation to the reservoir, as well as the magnitudes of these events. It was observed the occurrence of two new proposed main magnitudes in the region, 3.7 mR on May 27, 2001, and on May 30, 2014. Previously, the magnitude of the main event was assessed as 3.4 mb (Assumpção et al., 2002; Barros et al., 2018).

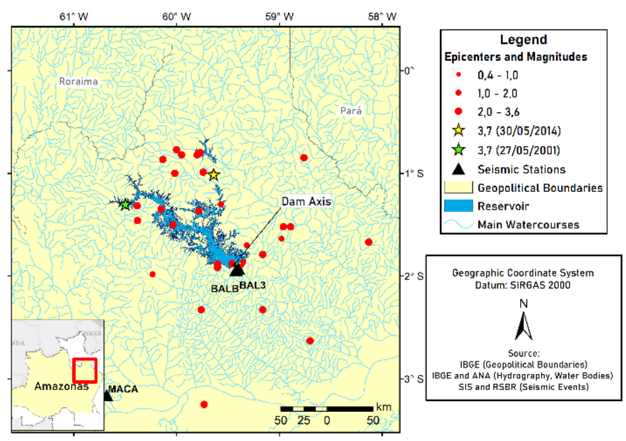

Figure 2 - *Epicentral distribution of the probably triggered earthquakes around the Balbina reservoir, considering a radius of up to 150 km from the dam axis. The triangles indicate the locations of the seismographic stations, where BAL3 refers to the station that assumed operation after BALB stopped. The stars denote the highest magnitudes observed in the analysis period.*

Figure 3 presents the seismic activity rate for the Balbina reservoir according to the study period, along with the new proposed higher magnitudes.

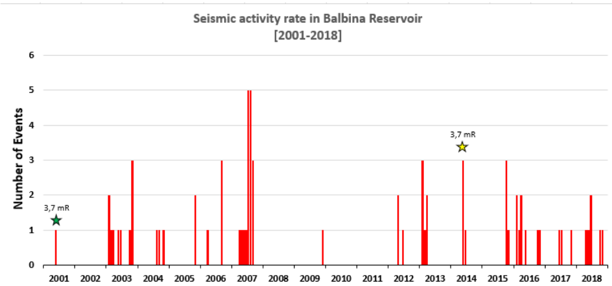

Figure 3 - *Number of monthly events representing the seismic activity rate for the Balbina reservoir in the period from 2001 to 2018.*

Seismicity in Tucuruí

The Tucuruí reservoir was also analyzed for seismicity between the years 2001 and 2018, considering both the available data from the Seismological Observatory and the seismic catalogs of RSBR. Thus, 39 events were identified within a distance of up to 150 km from the dam axis. It is worth noting that this number also results from an analysis of waveform doubtful events (such as those with high location error), excluding them from the update and directly affecting the respective count. Furthermore, only 14 of these events could be located due to insufficient data. The epicentral distribution in relation to the Tucuruí reservoir is shown on the map in **Figure 4**, as well as the location of its main event: 3.6 mR, which occurred on March 2, 1998 (BARROS et al., 2011), and no new proposals for higher magnitudes were identified.

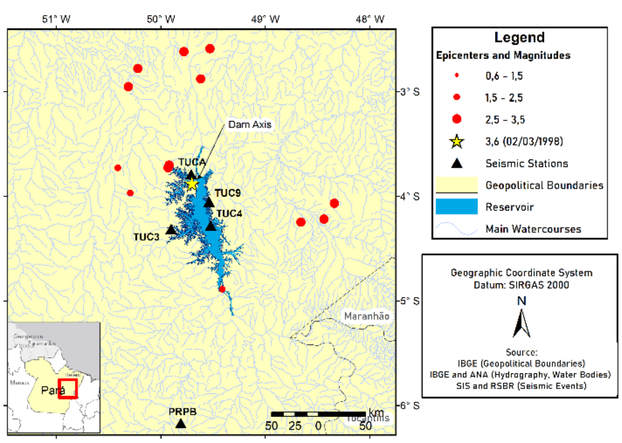

Figure 4 - *Map of the epicentral distribution of probable triggered earthquakes around the Tucuruí reservoir, considering a radius of up to 150 km from the dam axis.*

Just like the Balbina reservoir, the total events observed in Tucuruí were also evaluated in terms of temporal distribution, as shown in **Figure 5**.

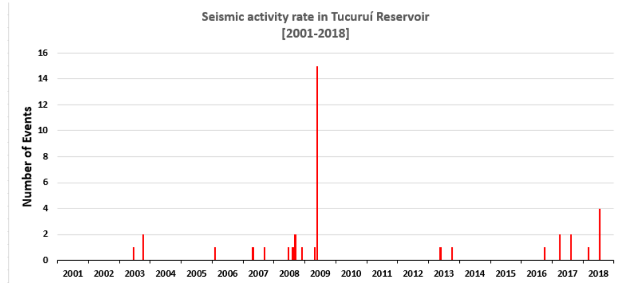

Figure 5 - *Number of monthly events representing the seismic activity rate for the Tucuruí reservoir in the period from 2001 to 2018.*

Conclusions

Given the aforementioned, the update of the RTS for the Balbina and Tucuruí reservoirs demonstrates that seismic activity in the area has persisted despite several years having passed since their respective impoundments in October 1987 and September 1984. During these periods, the water level fluctuations occurred more abruptly and exerted a more significant influence on triggering mechanisms. Regarding Balbina, a clear local seismic activity was observed, which continued until the year 2018, reaching a maximum of 5 monthly events in July and August 2007.

Regarding seismicity in Tucuruí, there was a lower indication of seismic events. However, the constant inactivity of the stations may have contributed to this fact, as they did not record possible earthquakes during the analyzed period. For instance, between late 2009 and 2011, the local stations operated irregularly or exhibited consistent data gaps, which hindered a satisfactory reading of the seismic trace. Thus, the maximum number of events was recorded in May 2009, totaling 15 events. Despite this, the analysis of the seismicity histogram of Tucuruí (**Figure 5**) reveals that its main activity cycles are still represented by the after impoundment period (initial seismicity), as well as the one that occurred between the 1997 and 1998 decades according to Assumpção et al. (2002).

Thus, this study allowed, as intended, an update of the cases regarding the observed seismicity in recent years, following the publication of the latest references on the subject (ASSUMPÇÃO et al., 2002; BARROS et al., 2011; BARROS et al., 2018). It is demonstrated, therefore, that both reservoirs maintain a propensity for seismic activity, contributing to the number of earthquakes with epicenters in the Brazilian Amazon and highlighting the need for continued monitoring of these regions.

Furthermore, the epicenters of Tucuruí mapped between 2001 and 2018 were compared to the previously proposed and available in the literature. In this way, radii were drawn from the epicenter of the main event that occurred on March 2, 1998, as can be seen in **Figure 6**.

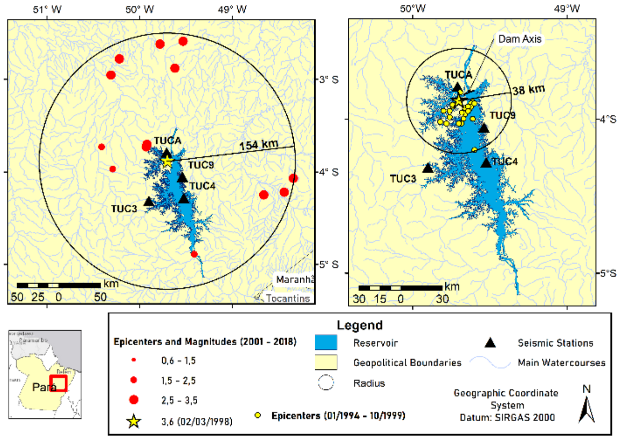

***Figure 6** - Radius of the main area affected by seismicity in Tucuruí, from the epicenter of the earthquake on March 2, 1998, according to the update from 2001 to 2018 presented in this work versus the period from January 1994 to October 1999. The epicenters from the latter were taken from Barros et al. (2011).*

It is noticeable that until the year 2001, the events are closer to the dam axis compared to those in the subsequent years. For instance, between the decades of 1994 and 1999, the earthquakes are within a radius of up to 38 km from the main event and, consequently, from the dam axis. Whereas in the period of this study, the tremors were concentrated within a radius of up to approximately 154 km, thus further from the dam axis. Considering the location uncertainty, the farther the epicenters are from the dam axis, the lower the probability of being classified as triggered events.

Regarding Balbina, the most recent events do not reflect such a pattern, since there is no loss of evidence of possible triggered earthquakes in the vicinity of the dam axis, as can be seen in **Figure 2**.

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