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Analysis of the state of stress in the characteristic of reservoir-induced earthquakes for a case study of the Irapé HPP in Minas Gerais

Análise do estado de tensão na característica de sismos induzidos por reservatório para um estudo de caso da UHE de Irapé em Minas Gerais

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Abstract: The understanding of the seismic evaluation behavior in structures, in general, is extremely important. For regions with low-intensity earthquakes such as Brazil, this assessment is not as widespread, however, there are risks related to earthquakes caused by the filling of the reservoir, little addressed by designers, which are triggered close to the dam and can cause possible damage to the structure. The Irapé Hydroelectric Power Plant (HPP) is the highest dam in the country, at 208 meters. This dam was monitored by the Seismological Observatory of the University of Brasília (OBSIS-UnB) during the filling of the reservoir in 2006. This work aims to evaluate the influence of the reservoir filling of the Irapé HPP and its correlation with the seismic data captured during this filling process. For this, the region of influence of the additional effort along the local crust was evaluated by means of the finite element method via ANSYS software. The results presented found that the events that occurred during the filling of the dam are within the limits of variation of the state of tension, being characterized as events induced by the reservoir being predominantly shallow, being in a region of influence at distances smaller than 4 km from the surface.

Keywords: Seismic evaluation; HPP; Dam; Induced Earthquake.

Resumo: O entendimento do comportamento da avaliação sísmica nas estruturas, em geral, é extremamente importante. Para regiões com sismos com baixas intensidades como o Brasil essa avaliação não é tão difundida, no entanto, existem riscos relacionados aos sismos originados pelo enchimento do reservatório, pouco abordado pelos projetistas, que são desencadeados próximos ao barramento e podem provocar possíveis danos a estrutura. A Usina Hidrelétrica (UHE) de Irapé é a mais alta barragem do país, com 208 metros. Essa barragem foi monitorada pelo Observatório Sismológico da Universidade de Brasília (OBSIS-UnB) no enchimento do reservatório em 2006. Este trabalho objetiva avaliar a influência do enchimento do reservatório da UHE de Irapé e a sua correlação com os dados sísmicos capturados ao longo desse enchimento. Para isso, avaliou-se por meio do método dos elementos finitos via software ANSYS a região de influência do esforço adicional ao longo da crosta local. Os resultados apresentados constataram que os eventos ocorridos durante o enchimento da barragem estão dentro dos limites de variação do estado de tensão, sendo caracterizados como eventos induzidos pelo reservatório sendo predominantemente rasos, se encontrando em uma região de influência em distâncias menores que 4 km da superfície.

Palavras-chave: Avaliação Sísmica; UHE; Barragem; Sismo Induzido.

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1. Introduction

Induced seismicity is a field of knowledge that involves different areas and is triggered when there is a variation in the natural state of the crust, influenced by human activities such as construction of large dams (Gupta, 1985, 2017; Gupta et al., 1972; Silva, 2014; Silveira, 2018), geothermal exploration (Evans et al., 2012; Majer et al., 2011), gas and oil extraction (Buttinelli et al., 2016; Ruiz-Barajas et al., 2017), nuclear explosions (Arkhipova et al., 2012; Balassanian, 2005), CO2 injection (Nicol et al., 2011; Zoback & Gorelick, 2012) and increased load on specific zones (Henriquet et al., 2019). Also, induced seismicity requires improved studies of the possible natural hazards that may occur (McClure & Horne, 2014a, 2014b).

Reservoir-triggered seismicity (RTS) is a phenomenon with anthropogenic influence recorded concomitantly and/or after the filling of a reservoir (generally a Hydroelectric Power Plant – HPP) and can be classified into two types: initial seismicity and prolonged seismicity. The first is associated with the filling of the reservoir in which there is a variation in the water level, resulting in an increase in load (or discharge) and a late effect due to pore pressure diffusion (Gupta et al., 1972; Simpson, 1986; Talwani, 1995; Valoroso et al., 2009). Prolonged seismicity, on the other hand, is little observed and is related to the amplitude and frequency of the reservoir oscillation and the poroelastic properties of the surface rock (Gupta, 2018).

In the field of dam construction engineering, preliminary knowledge of the geotechnical characteristics of the dam installation site, as well as information about efforts, crust deformation rate and earthquake risks are extremely important for the calculation in the projects of such dams structures (Mendes, 2018; Silveira et al., 2021; Silveira & Pedroso, 2018). However, the evaluation of efforts along the crust is quite complex, as it involves elements of different mechanical characteristics and requires analytical treatment that is often limited to a simplification of reality. And as a way to get around this problem, the use of the Finite Element Method (FEM) is presented as a viable alternative, as it allows discretizing complex geometries and solving problems in media that involve different materials, non-linearities, among others (Duarte & Kim, 2008).

Given the above, this paper presents a discussion on the main aspects related to RTS analyses, involving the influence of additional loading caused by the filling of the reservoir along the local crust, evaluating the region of influence of this effort and its correlation with the incidence of events seismic. For this, a case study of the HPP of Irapé in the state of Minas Gerais was studied, where earthquakes were quantified during the filling of the reservoir, presenting their location and intensity. Regarding numerical modeling, the region of influence along the crust that this additional effort causes was evaluated, allowing the delimitation of the region where induced earthquakes may occur. Thus, the work stands out in terms of pioneering studies focused on induced seismicity correlated with changes in the stress state of the local crust with the filling of the reservoir located in Brazilian territory.

2. Characterization of the study area – HPP of Irapé – MG

To conduct the study, the Hydroelectric Power Plant (HPP) Presidente Juscelino Kubitschek de Oliveira, known as HPP Irapé introduced in Figure 1, was defined as the study area. This HPP has a difference in level of 208 meters, a length of 551 m and a reservoir water mirror with an area of 137 km².

The filling of the Irapé HPP reservoir began in 2005 and was completed in 2006, the date of the project's inauguration. In this time interval, seismological monitoring was carried out through three seismographic stations (Figure 1), whose purpose was to analyze the seismicity induced by the reservoir during the filling stage.

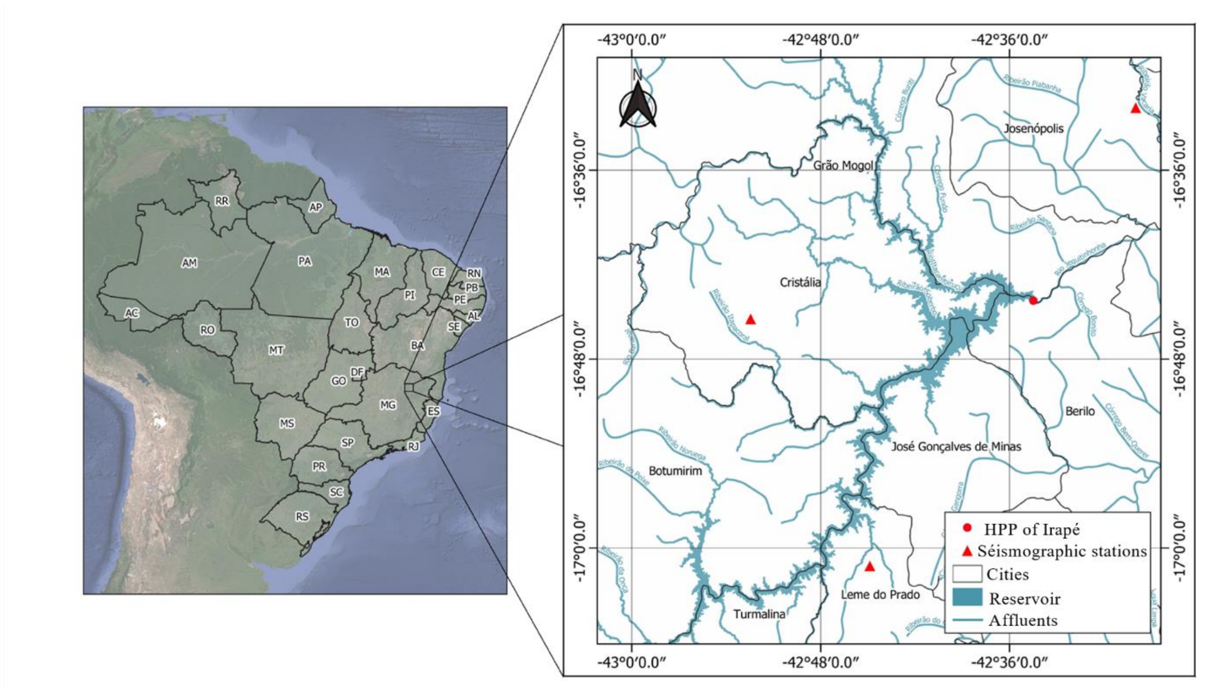

Figure 1 – Location of HPP of Irapé – MG
Source: Authors (2022).

The analyses cited were done by (Chimpliganond et al., 2007; Silva, 2014). Chimpliganond et al. (2007) carried out preliminary studies on the seismicity induced by the reservoir of HPP Irapé and found a direct correlation between the seismic events and the filling of the reservoir, presented in Figure 2, showing that the highest magnitude recorded (3.0 mD) arose in the final phase of the reservoir filling. Silva et al. (2014) studied the same seismicity, characterized the geology around the HPP of Irapé and found that the spatial orientation of seismic events matched those of the relief lineaments, suggesting that the direction of possible fault planes is correlated to the main direction of rupestrian structures in the study area.

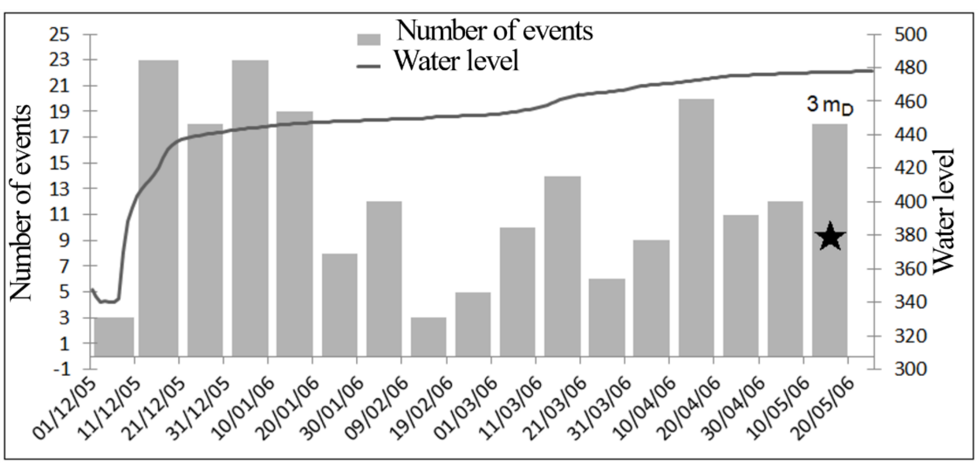

Figura 2 – Histogram of the temporal distribution of the seismic record associated with reservoir level variation (modified from Chimpliganond et al., 2007and Silva et al., 2014). The highest magnitude seismic event (3 mD) is represented by a star.
Source: Authors (2022).

The distribution of seismic events with their respective magnitudes recorded during the filling of the dam is shown near the structural elements of the dam, as observed in Figure 3. It can be seen that the seismicity is interconnected with the filling of the reservoir, showing greater magnitudes along the bed of the dam, where there was increased pressure in the crust.

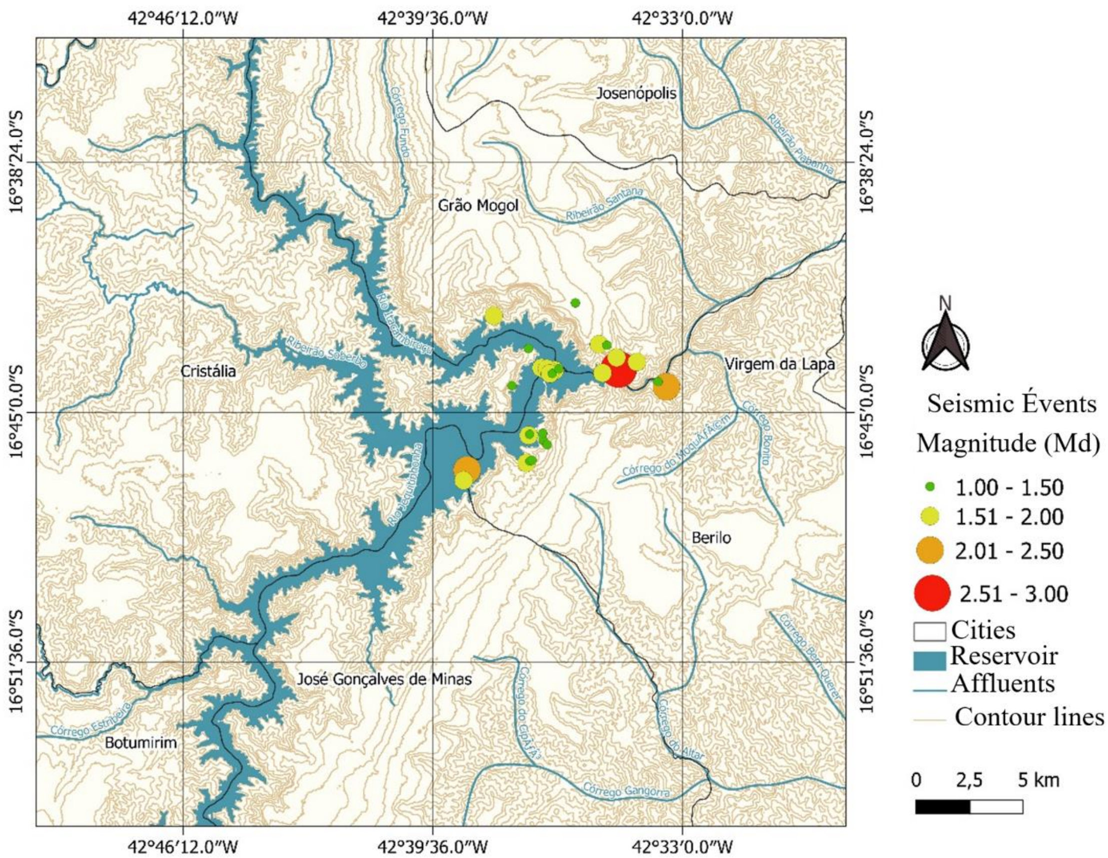

Figure 3 – Distribution of seismic events recorded during the dam filling.
Source: Authors (2022).

3. Analysis of the variation of stress and strain state

The filling of the reservoir caused the variation of stress and deformation state in the local crust of the studied HPP, leading to the appearance of earthquakes as observed in Figure 3. In order to verify the influence of the increase in load through this filling, a profile was used along the reservoir passing through the earthquake of greatest intensity, as seen in Figure 4, and observing the change of stresses in the crust along the depth.

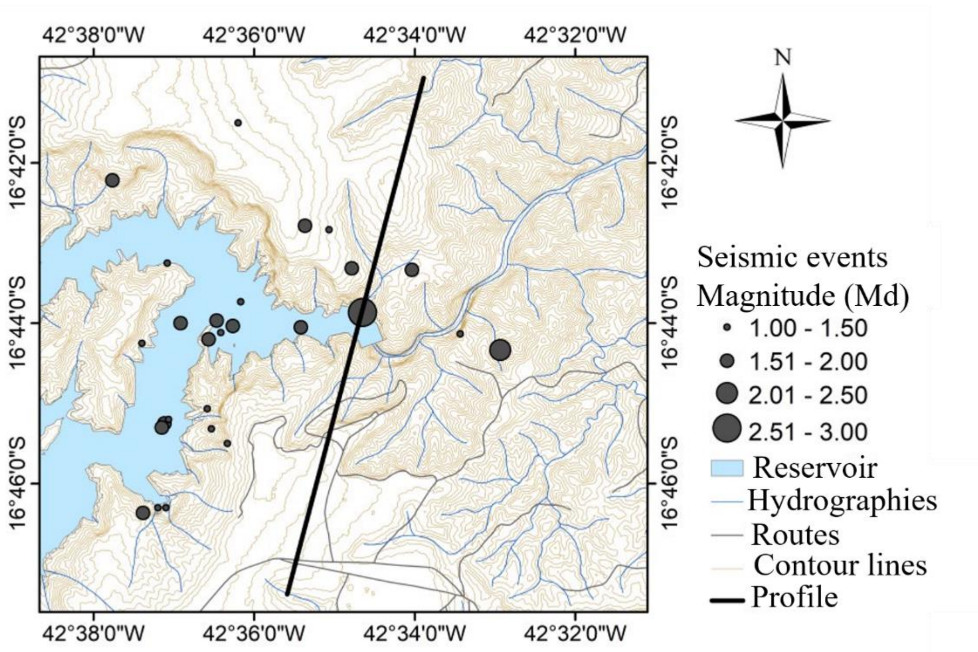

Figure 4 – Profile and distribution of seismic events recorded during the dam filling.
Source: Authors (2022).

For this, two profiles were used to characterize the stresses along the crust. The first one is presented in Figure 5, showing the geometry and positioning of the loading for the validation model. Thus, the physical properties of the crust were assumed considering it homogeneous in a rectangular section, in order to evaluate the convergence of the finite element used in the modeling. A profile with a constant load along the surface of 1000 m length was adopted. The added force refers to the weight of the water at its maximum elevation of 180 m, applied along the surface. The convergence study was carried out along the straight Y_0 - Y_{4000} m in terms of stresses and displacements. It should be noted that in both cases of study the boundary conditions were adopted referring to zero vertical displacements at the base, and horizontal on the sides.

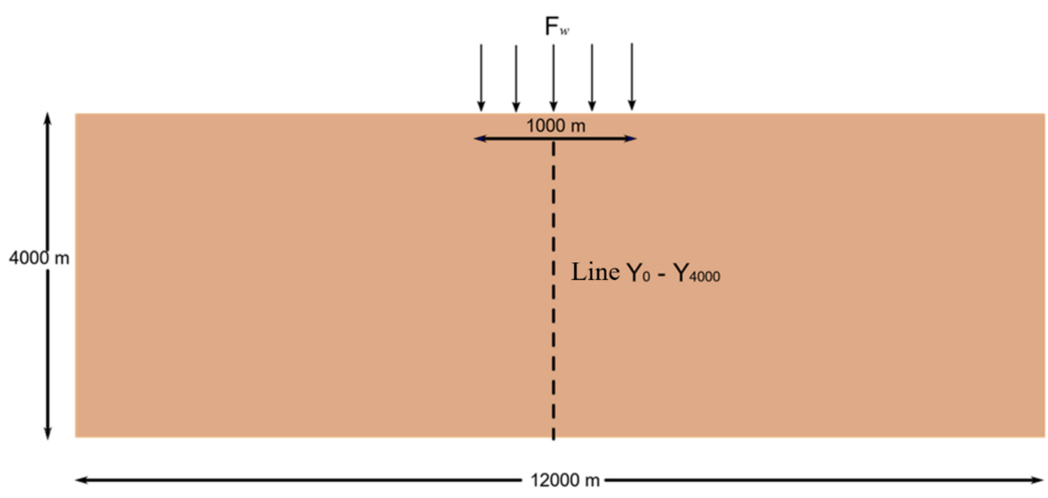

Figure 5 – Homogeneous profile for the validation.
Source: Authors (2022).

The second was considered a profile close to the structural elements of the Irapé HPP shown in Figure 6, passing through the largest seismic event recorded and considering a greater length of water sheet and greater depth of the reservoir.

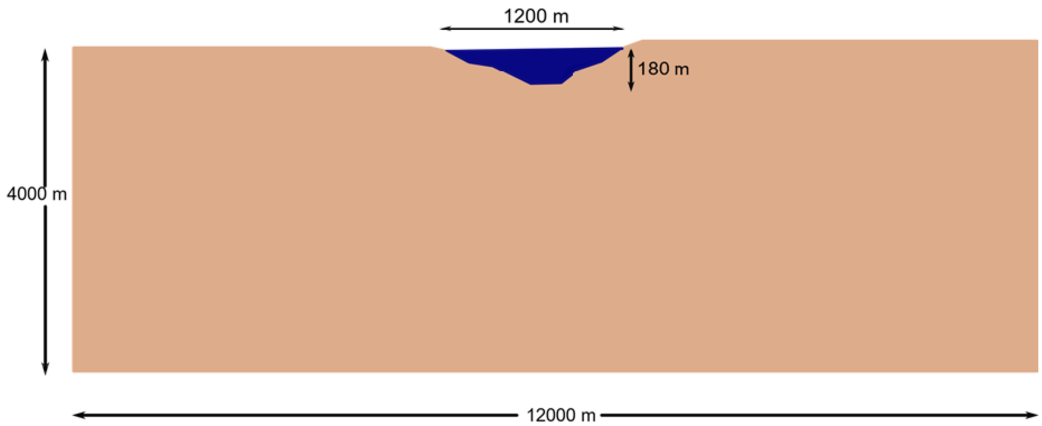

Figure 6 – Study profile of the Irapé HPP region.
Source: Authors (2022).

For this two-dimensional model referring to the Irapé HPP profile, it comprised a crustal section 12 km long and 4 km deep with elastic mechanical behavior. The reservoir region (Figure 6), on the other hand, comprises a 1200 m long section with depth varying along the section, with a maximum at 180 m.

Furthermore, we adopted average elastic properties for the continental crust using Young's modulus 70000 MPa, Poisson's ratio of 0.25 and average crust density of 2670 kg/m^3. To calculate the magnitude of the stress related to the weight of water, Equation 1 was used. The adopted properties were based on the study of which evaluated the local geology of the Irapé HPP as supracrustal rocks.

Equation 1 Water pressure at elevation h:

$$P = \rho g h = \gamma h \tag{1}$$

Where ρ represents the specific mass of the water; g the gravity value; γ the specific weight, and h the water elevation.

In the stress/strain modeling, for a homogeneous, isotropic, linear viscoelastic medium for the local crust the ANSS Library finite element, PLANE 183, was adopted for the plane state of deformation. This element is defined by 8 or 6 nodes with two degrees of freedom at each node: nodal translation in the x and y directions (Figure 7-a) and can be a plane or asymmetric element. To model the failure, one must use contact elements that simulate the discontinuity at a given location. For this, two elements were adopted: Conta 172 (Figure 7-b) and Target 169 (Figure 7-c) that represent, respectively, the contact and slip between "target" and deformable areas.

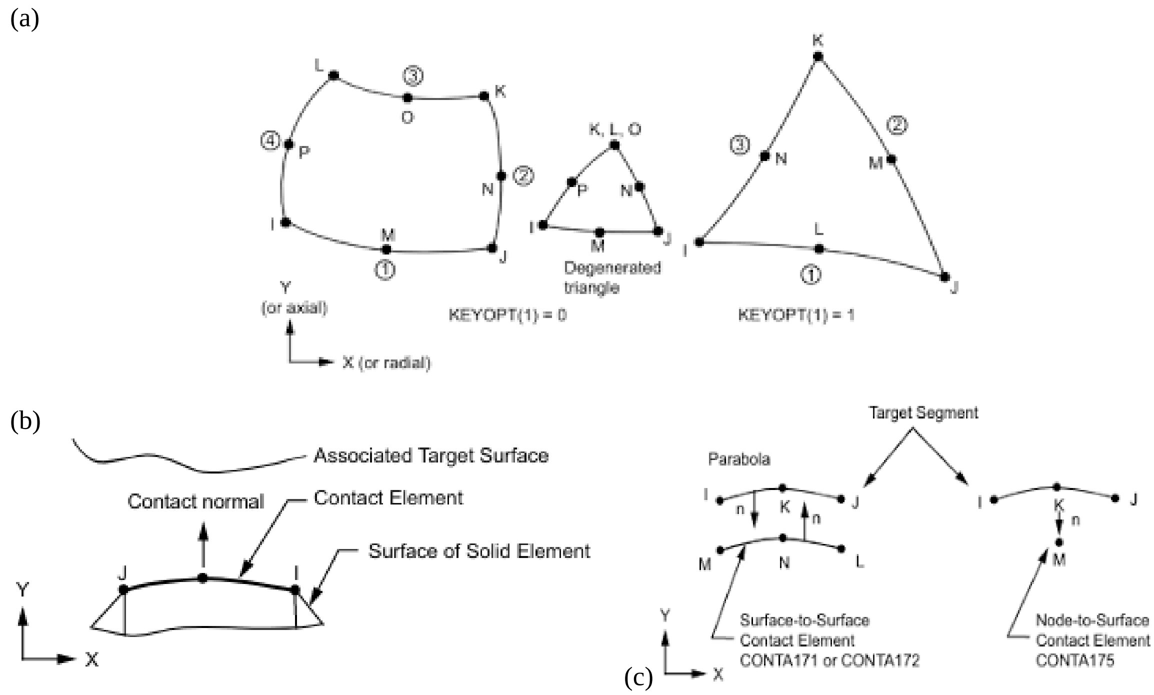

Figure 7 – Elements Plane 183 (a); Conta 172 (b) and Targe 169 (c).
Source: (ANSYS® Multiphysics v.14.5. Ansys Inc., n.d.).

Regarding the modeling of the system, we used a model that has 2595 elements and 8119 nodes, with variable geometry and with boundary conditions presenting vertical displacement at the base and horizontal movement at the side fixed. For the model loads we adopted the force expressed by equation 1 that depends on the specific mass of the water, gravity and reservoir elevation. This model is presented in Figure 8.

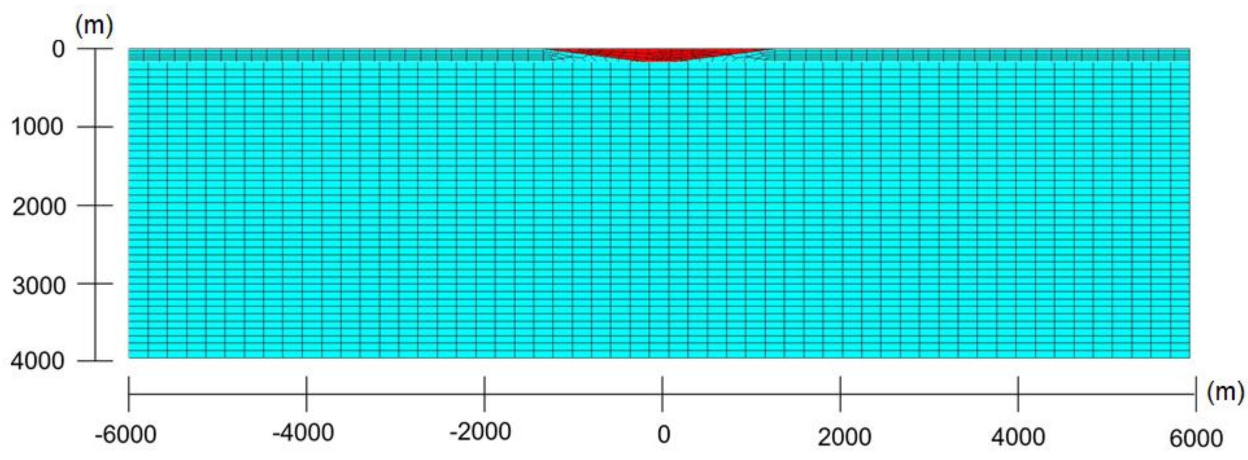

Figure 8 – Crustal profile mesh of the Irapé HPP dam.
Source: Authors (2022).

4. Results and discursion

The analysis of the results corresponded initially to the verification of the convergence study, since it is a numerical study; and by going through preliminary steps, and verifying the simplified models, one acquires the necessary confidence for more complex analyses. In the sequence the case study considering the local region of Irapé was evaluated, where the correlation of the numerical results with the quantification of seismicity during the filling of the reservoir was analyzed.

4.1. Convergence Analysis

The mesh definition is very important for analyses using Numerical Methods, because if the mesh consists of larger elements than necessary, it will lead to large errors. In the opposite situation, it presents waste of time and energy used in the discretization of the problem. Numerical studies for static and dynamic loading in geological and geotechnical problems should be validated with simplified examples because of the greater control in the comparative response with analytical studies (Alves do Nascimento Júnior, 2016; Genikomsou & Polak, 2015; Mikelić et al., 2014; Oliveira França Júnior, 2022)

For the convergence analysis we used the model presented in Figure 5, adopting a control line Y_0 - Y_{4000}, in which we verified the magnitude of the stresses and the displacement along the profile in relation to two types of mesh: 1200 (medium) and 4800 (fine) elements.

The result shows that for a mesh with 1200 quadrilateral elements, with an average size of 200 × 200 m (Figure 9), we already have satisfactory results when compared with the result with 4800 elements of size 100 × 100 m (Figure 10). This is because we used a rich element with 8 degrees of freedom (*ANSYS® Multiphysics v.14.5. Ansys Inc.*, n.d.), enabling faster convergence (Mendes, 2018).

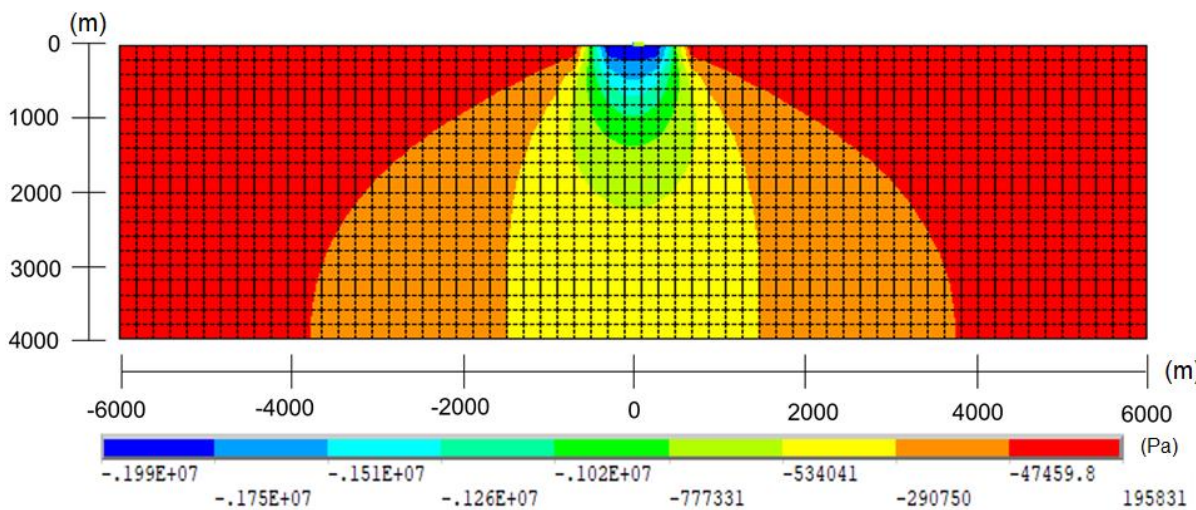

Figure 9 – Vertical stresses in the profile evaluating an average mesh.
Source: Authors (2022).

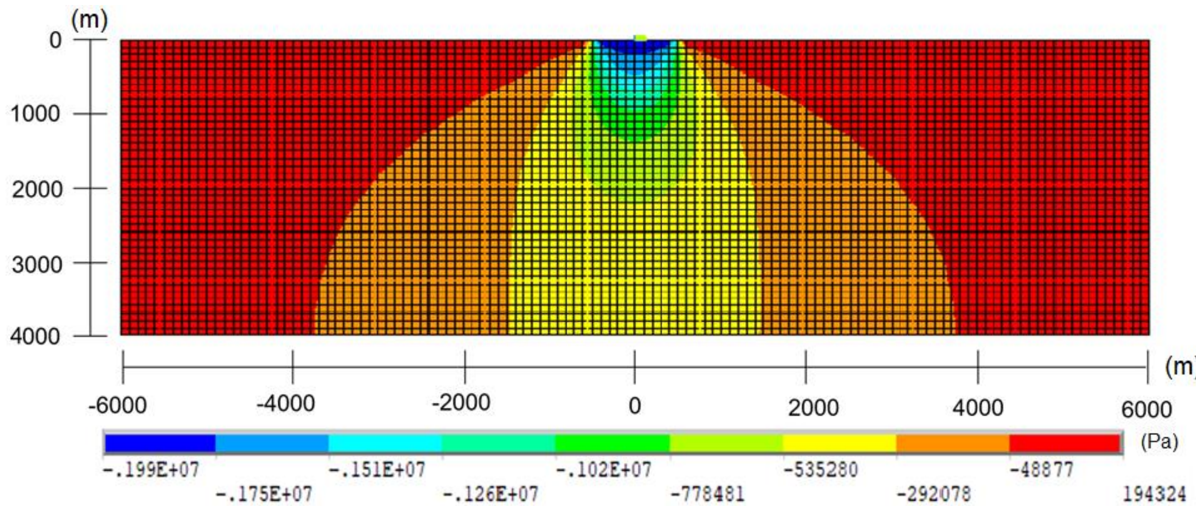

Figure 10 – Vertical stresses in the profile for a fine mesh.
Source: Authors (2022).

When observing the stress distributions caused by water load for the two compared cases in Figure 11, one can see a good convergence, and already at the first refinement level the stress values are satisfactory. The intermediate refinement level to the advanced refinement level showed little significant differences, with the first example having a shorter processing time, thus being more advantageous for analysis.

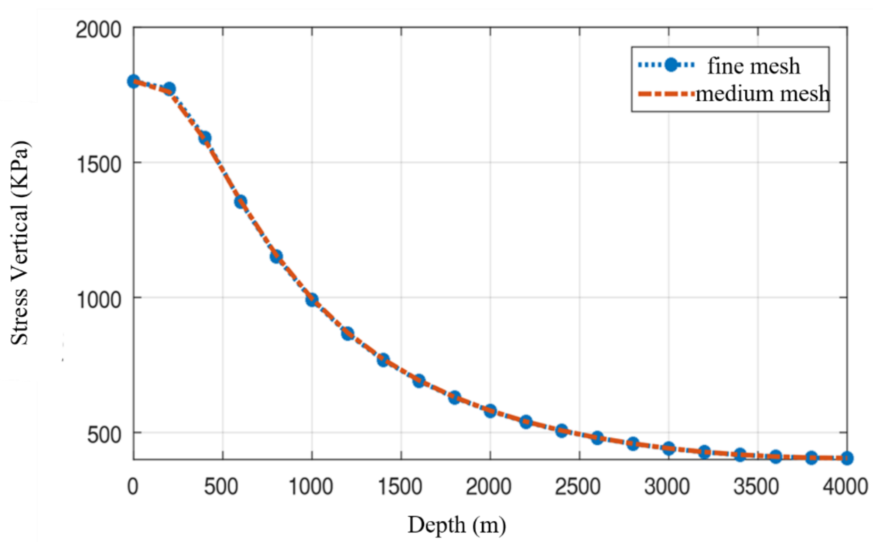

Figure 11 – Vertical stresses along the Y0 - Y4000 control line.
Source: Authors (2022).

The stresses due to water load along the control line have a semi-parabolic profile, having the maximum stress in the superficial part of the crust and gradually decreasing along the depth. In numerical terms, it had a maximum stress of 1800 KPa at elevation zero and stresses above 500 KPa up to 2500 m depth. This already shows how the stresses along the crust occur, which enable modifications of the natural state of the local environment with the addition of water loading to the reservoir.

Similar to the study of stresses, similar characteristics were observed for the analysis of the displacements along the control line. It was noticed that the increase of stresses caused by the insertion of the additional load produces a displacement in the direction of the load, which is greater in the superficial part and reduces along the depth, as shown in Figure 12.

It is clarified that the stress level shown corresponds vertically to the additional load introduced by the water into the reservoir and does not include the soil load at the points considered.

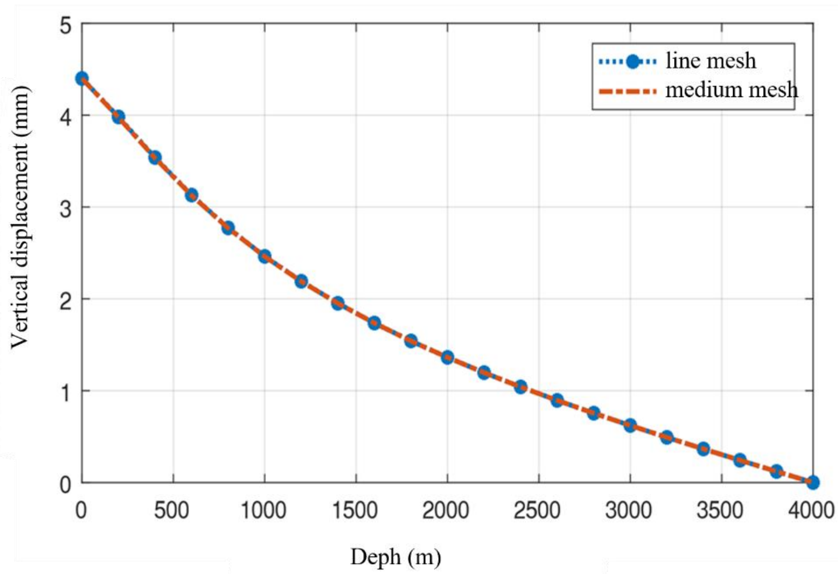

Figure 12 – Vertical displacements along the Y0 - Y4000 control line.
Source: Authors (2022).

From preliminary studies obtained by validating the model, it can already be seen that the earthquakes triggered by the reservoir are in places with small depths, for which it was observed that the highest magnitudes for both displacements and stresses occurred for depths less than 2000 m. Moreover, it should be noted that the vertical stresses are preponderant for the maximum principal stresses because they have much larger magnitudes than the other horizontal and shear components (Alves do Nascimento Júnior, 2016).

4.2. Case study: Irapé HPP Profile

After the mesh validation and convergence study, the study of the influence of the additional strain on the profile near the dam (Figure 6) was started, observing the potential for the emergence of reservoir triggered seismicity (RTS).

For the study of the local profile of Irapé we observed similar results to those found in the convergence study, showing a gradual decrease along the profile of stresses and displacements, as well as the highest magnitudes near the surface. This is directly linked to the RTS phenomenon, although it is poorly understood, since this problem can be seen as a response of the shallow crust to changes in the stress field in which it is subjected. SDR events can vary in intensity, frequencies, and distribution of tremors according to the terrain on which the reservoir has developed. Nevertheless, the occurrence cannot be predicted, although it is preferentially associated with large reservoirs (Bell & Nur, 1978). Given this, it is relevant to estimate the capacity of the potentiality of this phenomenon, as well as its most susceptible areas before construction, in order to strengthen the structure already built(Silveira, 2018)

Figure 13 also illustrates that because the load is not constant as presented in the evaluated item in the convergence study, i.e., the load is greater in the center and decreases at the edges, there is also a decrease in the contribution area. Furthermore, it can be seen that this variation of the stress state is restricted to a certain region, which can relate where and which earthquakes are related to those triggered by the reservoir. Figure 14 shows the displacements along the studied profile and it is also noted that they are restricted to this particular region of contribution, presenting maximum magnitude of 3.11 cm below the reservoir.

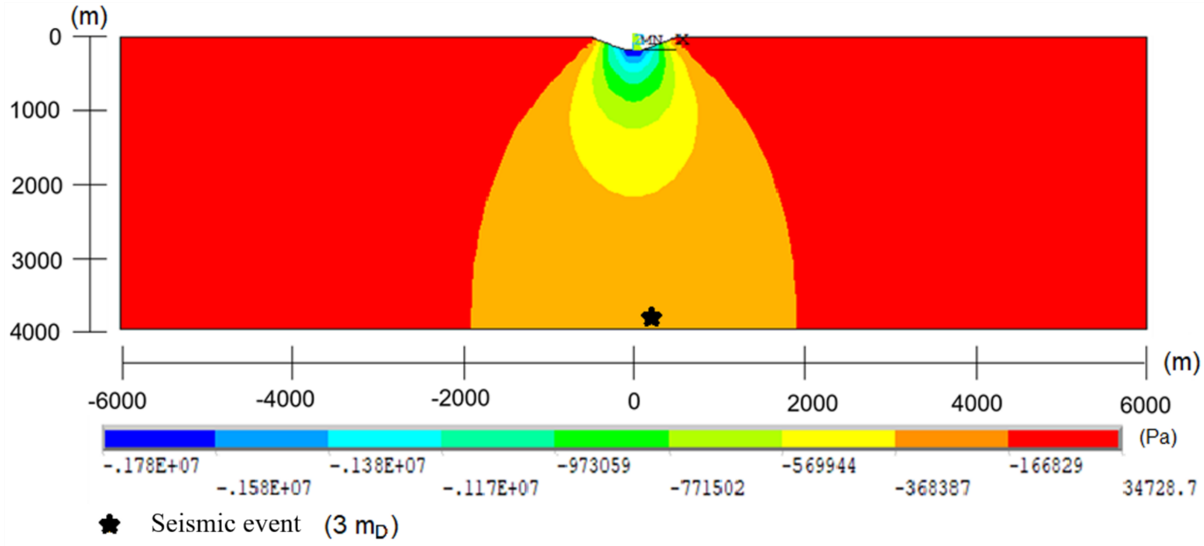

Figure 13 – Distribution of vertical stresses along the homogeneous Irapé profile.
Source: Authors (2022).

It should be noted that induced earthquakes usually have small magnitudes, but because they are close to the dam, they do not suffer much attenuation in their signal until they reach the structure.

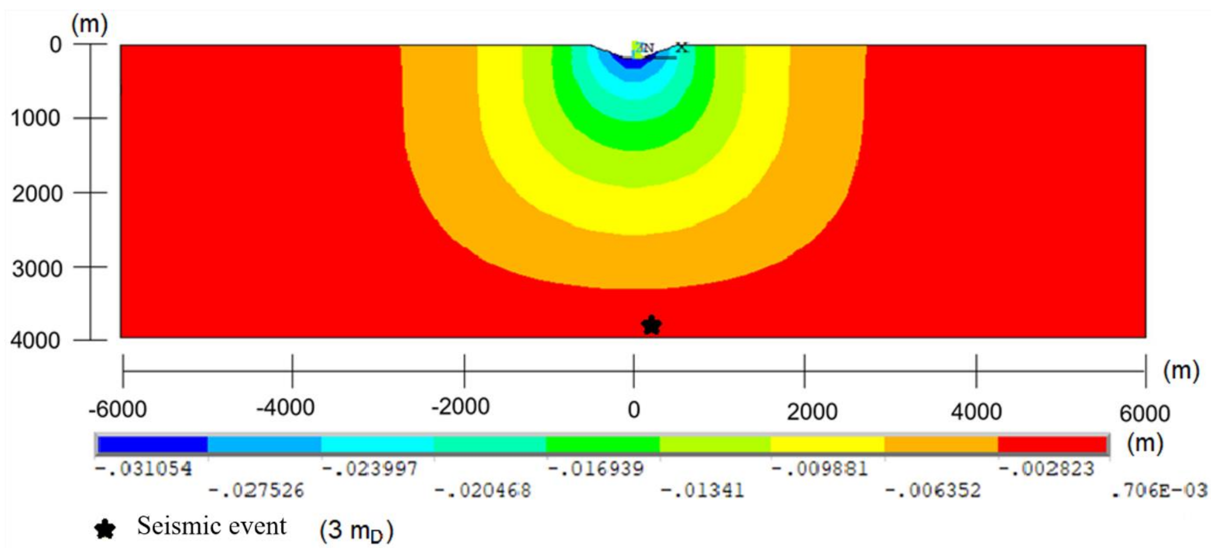

Figure 14 – Distribution of vertical displacements along the homogeneous Irapé profile.
Source: Authors (2022).

For this region of Irapé it is observed that the location of the strongest earthquake was close to the dam, as well as the other epicenters of the earthquakes, effectively showing the correlation of load increase with the small local tremors.

Since the largest magnitude earthquake of 3.0 mD was captured by the three activated seismographic stations near the dam body, with another one deactivated. Figure 14 shows the signals obtained for each station.

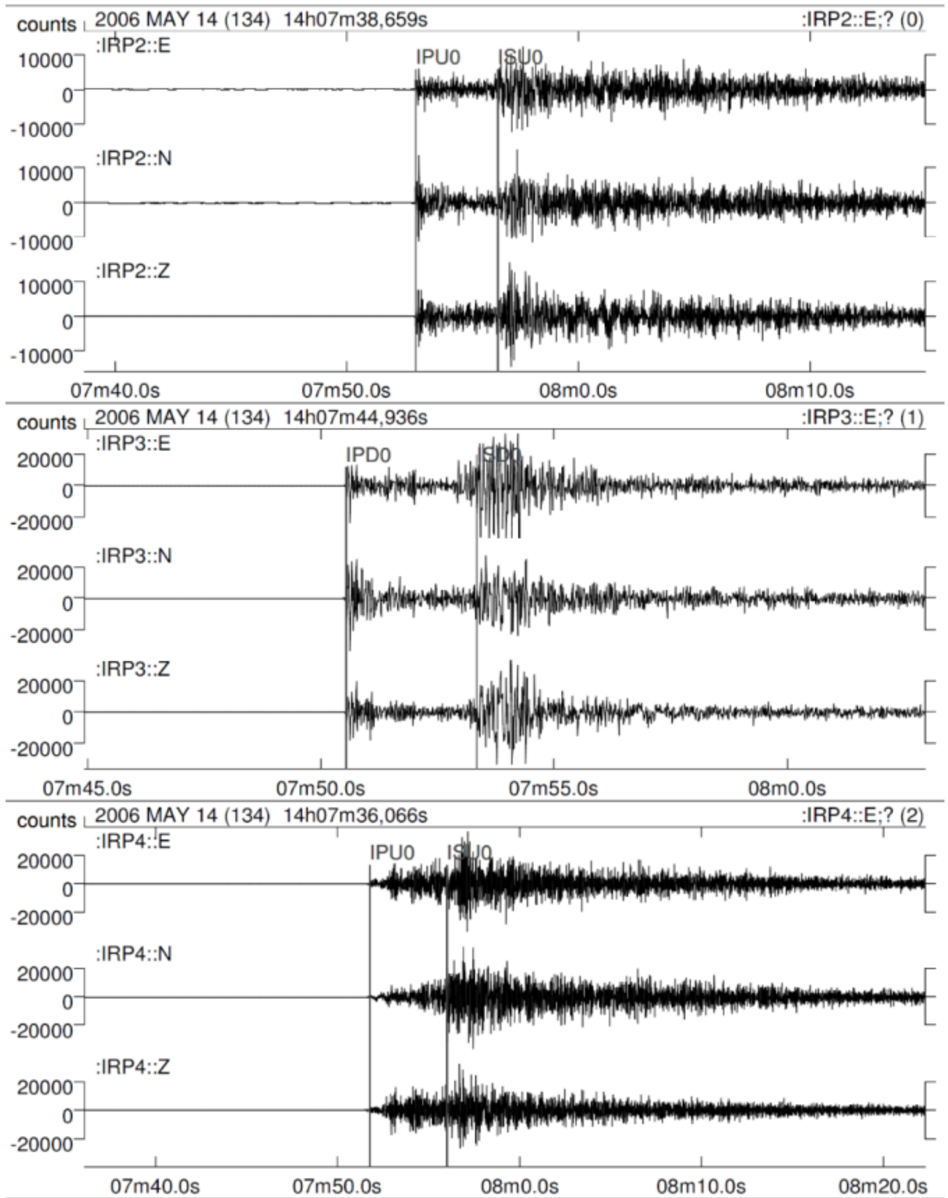

Figure 15 – Recording of the waveforms of RTS event with the marking of the arrival of the P and S waves in the three components.
Source: Silva, 2014.

The record shows that for different signal capture points, differentiation occurs between the waveforms, station IRP3 is closest to the epicenter, followed by IRP4 and IRP2, due to the arrival of the P wave is first at this station. These data show that there is an attenuation in the magnitude of the signal with increasing distance between the epicenter and the point of capture, as evidenced from the data presented at station IRP2, which is more distant and with little differentiation between the amplitudes.

Regarding the 3mD seismic event, identified in the analyzed profile (Figures 13 and 14), it is observed that its occurrence was within the region of stress state variation, between 268 kPa and 167 kPa (Figure 13). However, it is possible to verify that the occurrence of the same earthquake was in a region with minimum displacement, between 3 mm and 0 mm. In this case, despite the displacement, we consider the possibility of activation of shear zones, not mapped, below the dam and within the region whose stress state variation was identified.

According to the above analysis, the distribution of stress field and displacements are related to the magnitude of strain, depth, and the rock type (Cheng et al., 2012). In the surface part the rock resistances are low, the stress due to water load is possibly higher than the rock resistance which can lead to the surface micro earthquake. This causes an increase of water diffusion to the deeper place and consequently softening of the rock. The mass of water in the reservoir, on the other hand, represents an additional stress, which causes an increase in vertical stresses at the site, in addition to the water exerting a hydrostatic pressure on the pores. The combination of these effects can trigger local earthquakes that will strike the dam body.

Especially, the first principle of local crustal stress is tensile stress, which entails the expansion of the divisional planes and the fault planes. When the water level rises, water diffuses along the rupture surfaces, which cannot neutralize the total shear stress that includes crustal stress by adding water load, then the faults start to slide and consequently earthquakes occur. Thus, a local earthquake is observed in the Irapé region at a low depth and originating from the filling of the reservoir. Similar examples to the process at Irapé have also been diagnosed at other sites (Cheng et al., 2012; Gupta, 2002; Tuan et al., 2017), showing the importance of the debate on the subject.

5. Final considerations

From the results presented it can be seen that the variation of the stress state evaluated by the reservoir filling is delimited in a certain region, in which one can relate the earthquakes that are triggered by the additional stress of the water load.

Furthermore, the events that occurred during the filling of the Irapé HPP, within the limits of variation of the voltage state, can be characterized as events induced by the reservoir.

Although the stress levels obtained in the analyses do not show considerably high values, they serve to assimilate, that the zones of influence of these stress increases correspond to the same areas where the largest induced earthquakes were observed.

Finally, the authors recommend that for a study of structural evaluation in dams, the influence of the weight of the reservoir in the region of installation of the structure should be evaluated, considering all the geomechanical and geological parameters of the crust which can influence the appearance of local earthquakes. Because these seismological events are close to the structural elements and the dam body, the attenuation of seismic movement is very low, causing movements to occur in the structure that can lead to possible stability and safety problems.

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