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Investigations of the Reservoir-triggered Seismicity of Nova Ponte and Irapé, Brazil

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"Man is made for science; he reasons from effects to causes, and from causes to effects, but he does not always reason without error. In reasoning, therefore, from appearances which are particular, care must be taken how we generalize; we should be cautious not to attribute to nature, laws which may perhaps be only of our own invention."

~ James Hutton (1788). "Theory of the earth; or an investigation of the laws observable in the composition, dissolution, and restoration of land upon the globe. (From. the Trans., Roy. soc. of Edinb.).", p.65*

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ABSTRACT

The rise of large hydropower plants with extensive reservoirs has raised the need for a deeper understanding of reservoir-triggered seismicity, a phenomenon that causes significant challenges for safe reservoir management. Reservoir-triggered seismicity is an increasingly relevant topic of interest throughout the world. The global distribution cases involve a large number of hydroelectric power plants as well as future planned dams and reservoirs, with many documented cases for more than six decades. In this scenario, Brazil has experienced 29 cases of RTS in which the mechanism of magnitude m_R 4.0 Nova Ponte and m_R 3.0 Irape is not well understood. The $M_{4.0}$ RTS mechanism at Nova Ponte is still important to understand, the second-largest known case of Reservoir reservoir-triggered earthquake in Brazil. The main event occurred in the year 1998 along predominantly reverse faulting and roughly oriented NE-SW. But it still remains to be understood whether it occurred by state pore pressure or undrained response of excess loading of the reservoir is such low permeable rocks that are needed to trigger RTS. If the pore pressure diffusion could not propagate deep into vertical low permeable rocks it can take hundreds of years to reach the depth of the earthquakes. So, in such above conditions, the two major events of triggered earthquakes occurred in 1995 and 1998 just 1.5 years after the impoundment of the reservoir when the water reached the highest level. Thus, in this study, we made an attempt in this area to explore the causal mechanism by creating the 3D Reservoir model and its effect on the subsurface both in terms of pore pressure and stress changes with the help of numerical modeling. We numerically simulate the poromechanical subsurface response to reservoir impoundment using a 3D model that includes three geological rock layers down to 10 km depth. From the proposed potential nodal planes of the 1995 $M_{3.5}$ earthquake, we show that the earthquake has most likely occurred on a vertical, E-W-

oriented strike-slip fault with a reverse-displacement component. The deviatoric stresses generated by the water column loading on the surface, superimposed by undrained pore pressure enhancement in deep low-permeability layers can explain the fault reactivation. We find that for the 1998 M4.0 earthquake to occur, conductive flow pathways with permeability as high as $6.6 \cdot 10^{-15} \text{ m}^2$ should exist to transmit pore pressure to a deep critically oriented fault. The analysis owned by us raises the importance of accounting for coupled poromechanical mechanisms controlling fault stability, hydromechanical properties of different rock layers, and realistic shape of the reservoir to accurately assess the potential for reservoir-triggered seismicity. We remarked that our findings can explain the triggered seismicity by the undrained response of excess loading of the reservoir filling due to pore pressure perturbation such as in deep underground low permeable rocks. The second case study Irapé, in Brazil, is a prominent RTS site where seismicity surged after reservoir filling, with a maximum event of magnitude 3.0 in May 2006, 6 months after the start of reservoir impoundment. Despite more than a decade has passed since the seismicity occurred, the factors governing these earthquakes and their connection to subsurface rock properties remain poorly understood. Here, we attempt to understand the potential causes of RTS at Irapé dam, which is the highest dam in Brazil with 208 m, and the second highest in South America. Permeability and porosity measurements of cylindrical cores from hard and intact rock samples, which have been extracted near the RTS zone, by pitting 10 cm from the surface, reveal a low-permeability rock. Porosity values range from 6.340 to 14.734%. Only 3 out of the 11 tested samples present permeability higher than the lowest measurable value of the apparatus (0.002 mD), with the highest permeability being 0.0098 mD. The undrained response of the low-permeability rock placed below the reservoir results in an instantaneous increase in pore pressure and poroelastic stress changes due to elastic

compression, which brings potential faults located below the reservoir closer to failure conditions. According to our analytical calculations, the increase in 136 m of the reservoir-water level caused a 0.54 MPa pore pressure buildup at the depth of the M3.0 earthquake, i.e., 3.88 km, resulting in an increase of 0.82 MPa in the vertical effective stress and a decrease of 0.34 MPa in the horizontal effective stress. These changes resulted in an increase in the deviatoric stress that led to fault destabilization, causing the RTS. The laboratory measurements and analytical calculations corroborate the hypothesis that the initial seismic activity was induced by the undrained subsurface response to the reservoir loading at Irapé.

Keywords: Brazil, Reservoir-triggered seismicity, Irapé, Nova Ponte, Coupled poromechanical processes, permeability, porosity

RESUMO

A ascensão de grandes centrais hidroelétricas com extensos reservatórios levantou a necessidade de uma compreensão mais profunda da sismicidade desencadeada por reservatórios (SDR), um fenómeno que causa desafios significativos para a gestão segura dos reservatórios. A sismicidade desencadeada por reservatórios é um tema de interesse cada vez mais relevante em todo o mundo. Os casos de distribuição global envolvem um grande número de centrais hidroelétricas, bem como futuras barragens e reservatórios planejados, com muitos casos documentados há mais de seis décadas. Nesse cenário, o Brasil registrou 29 casos de SDR, entre os quais, o caso de magnitude mR 4.0 em Nova Ponte e de magnitude mR 3.0 em Irapé é ainda bem discutido. Ainda é importante entender o mecanismo M4.0 SDR em Nova Ponte, o segundo maior caso conhecido de SDR de reservatório no Brasil. O evento principal ocorreu no ano de 1998 ao longo de falhas predominantemente reversas e aproximadamente orientadas NE-SW. Mas ainda não foi possível esclarecer se isso ocorreu por pressão dos poros ou pela resposta não drenada do excesso de carga do reservatório em rochas de baixa permeabilidade que são necessárias para acionar o SDR. Se a difusão da pressão dos poros não puder se propagar profundamente nas rochas verticais de baixa permeabilidade, pode levar centenas de anos para atingir a profundidade dos eventos sísmicos. Assim, nessas condições acima, os dois principais eventos de SDR ocorreram em 1995 e 1998, apenas 1,5 anos após o represamento do reservatório, quando a água atingiu o nível mais alto. Assim, neste estudo, fizemos testes a nesta área para explorar o mecanismo causal criando o modelo 3D do reservatório e seu efeito no subsolo tanto em termos de pressão dos poros quanto de mudanças de tensão com a ajuda da modelagem numérica. Simulamos numericamente a resposta poromecânica do subsolo

ao represamento do reservatório usando um modelo 3D que inclui três camadas de rochas geológicas até 10 km de profundidade. A partir dos potenciais planos nodais propostos para o evento de magnitude M3.5 de 1995, mostramos que o terremoto provavelmente ocorreu em uma falha vertical, orientada para E-W, com um componente de deslocamento reverso. As tensões desviantes geradas pelo carregamento da coluna de água na superfície, sobrepostas pelo aumento da pressão dos poros não drenados em camadas profundas de baixa permeabilidade podem explicar a reativação da falha. Descobrimos que para que o evento de magnitude M4.0 de 1998 ocorra, deveriam existir caminhos de fluxo condutivo com permeabilidade tão alta quanto $6,6 \cdot 10^{-15} \text{ m}^2$ para transmitir a pressão dos poros para uma falha profunda e criticamente orientada. A análise de nossa propriedade aumenta a importância de levar em conta os mecanismos poromecânicos acoplados que controlam a estabilidade da falha, as propriedades hidromecânicas de diferentes camadas rochosas e a forma realista do reservatório para avaliar com precisão o potencial de sismicidade desencadeada pelo reservatório. Observamos que nossas descobertas podem explicar a SDR pela resposta não drenada do excesso de carga do enchimento do reservatório devido à perturbação da pressão dos poros, como em rochas subterrâneas profundas e pouco permeáveis. O segundo estudo de caso Irapé, no Brasil, é um local proeminente de SDR onde a sismicidade aumentou após o enchimento do reservatório, com um evento máximo de magnitude 3,0 mR em maio de 2006, 6 meses após o início do represamento do reservatório. Apesar de ter passado mais de uma década desde a ocorrência da sismicidade, os factores que governam estes terremotos e a sua ligação às propriedades das rochas subterrâneas permanecem pouco compreendidos. Aqui, tentamos entender as possíveis causas do SDR na barragem de Irapé, que é a barragem mais alta do Brasil com 208 m, e a segunda mais alta da América do Sul. Medições de permeabilidade e porosidade de

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Palavras-chave: Brasil, Sismicidade desencadeada por reservatório (SDR), Irapé, Nova Ponte, Processos poromecânicos acoplados, permeabilidade, porosidade

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CHAPTER 1

INTRODUCTION

1.1 Global boom of dam and reservoirs

For the developments of future large hydropower dams primarily concentrated in developing countries and emerging economies of Southeast Asia, South America, and Africa (Figure 1.1). Over 40% of the hydropower capacity under construction or designed/planned will be installed in low and low-middle income countries (The World Bank, 2014).

As per information March 2014, a total of 3,700 hydropower dams with a capacity of more than 1 MW (Megawatt) each were either planned (83%) or under construction (17%). These dams are forecast to increase global hydropower electricity capacity from 980 GW (Gigawatt) in 2011 (International Journal on Hydropower and Dams, 2012) to about 1,700 GW in next 10–20 years. However, small and medium-sized dams (1–100 MW) will dominate in number (>75%), 93% of the future hydropower capacity will be provided by 847 large dams with a capacity of more than 100 MW each.

In Brazil, Amazon and La Plata basins will have the huge total number of new dams in South America, while the Ganges–Brahmaputra basin (mainly India and Nepal) and the Yangtze basin (China) will overlook the highest numbers of dam construction activity in Asia. Enormous dams, each with a capacity of more than 1 GW, will foremost be located in Asian region, mainly in the Yangtze basin, and in South America, in the main in Amazon basin. The Xi Luo Du dam in the Yangtze basin (14.4 GW) and the Belo Monte dam on the Xingú River in the Amazon basin (11.2 GW) are cases of very large dams already under construction.

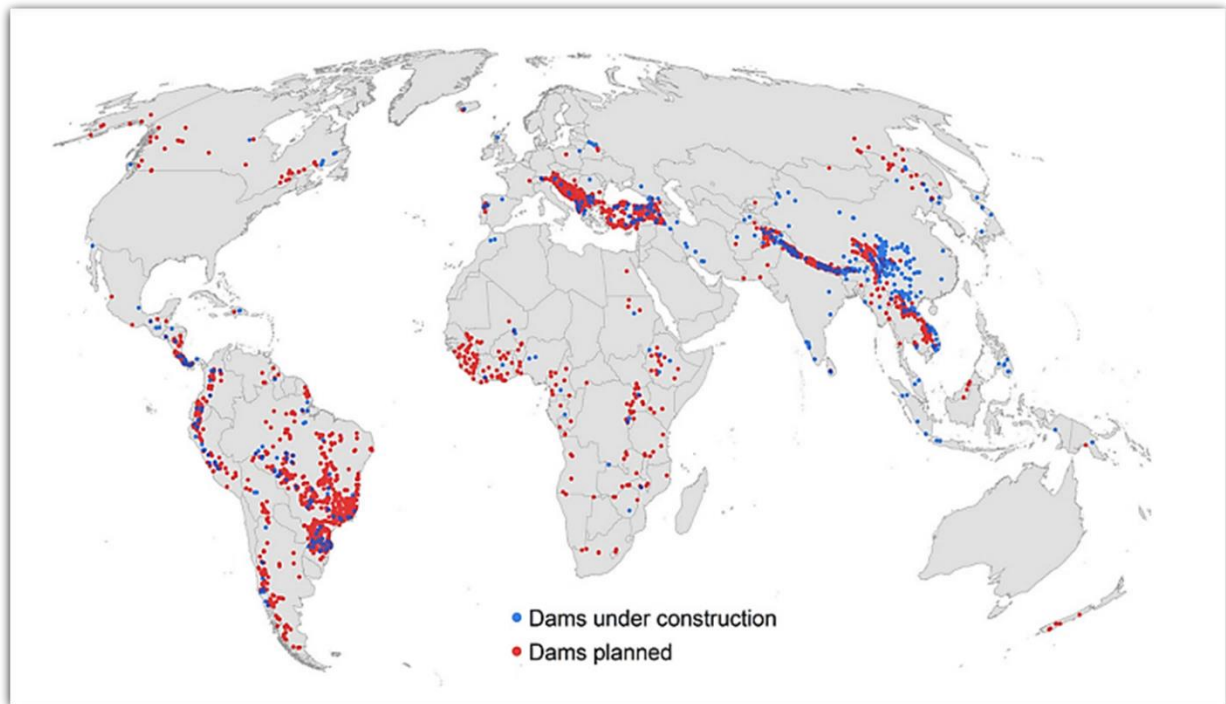


Figure 1.1 Worldwide spatial distribution of future hydropower dams, under construction (blue dots 17%) or planned (red dots 83%) (after Zarfl et al., 2015).

Worldwide 3,700 dams construction may increase global hydropower production by 73%, by correlating to an increase in the exploitation of the technically practicable hydropower potential from a total of 22% (International Commission on Large Dams 2011) to 39%. Nevertheless, the contribution of hydropower in total global electricity production will arise moderately from 16% in 2011 to 18% until 2040 because of the concurrent increase in global energy demand.

1.2 Artificial water Reservoir-triggered seismicity

Reservoir impoundment, deep underground mining, fluid injection into and withdrawal from the subsurface are some of the well-known causes of induced/triggered seismicity which become global issue from the past few decades (Foulger et al., 2018; Kivi et al., 2023). The understanding and identification of these form of human-induced

earthquakes become one of the essential topics in terms of environmental, economic impact, socio-political and scientific discussion throughout the world (Gonzalez et al., 2012; Vilarrasa et al., 2019). In recent times, some widely known cases debating potential either induced or triggered seismicity and attracted for societal interest throughout the world, counting as the Oklahoma earthquake in 2011 of Mw 5.7 and in 2016 of Mw 5.8 sequences (Ellsworth, 2013; Keranen et al., 2013; Yeck et al., 2017), Emilia, Italy, earthquakes in 2012 of Mw 6.1 and 5.9 (Cesca et al., 2013a), Pohang, South Korea, earthquake in 2017 of Mw 5.5 (Grigoli et al., 2018; Kim et al., 2018; Boyet et al., 2023), Lorca, Spain, earthquake in 2011 of Mw 5.1 (González et al., 2012), Castor, Spain, earthquake sequence in 2013 of Mw 4.3 (Cesca et al., 2014; Vilarrasa et al., 2021; Vilarrasa et al., 2022). Most significantly these earthquakes not only because they may injure people and damage infrastructures, but they can also cause a negative result on public perception that may lead to project cancellation. Apart from these numerous reported cases caused by human-related activities have been detected and compiled in different studies (McGarr et al., 2002; Ellsworth, 2013; Foulger et al., 2018).

From the above correspondence one more human-induced/triggered earthquakes is well known throughout the world. The impoundment of reservoirs is necessary to construct the hydroelectric dam, these dams can cause significant anthropogenic effects unless they are not built and managed correctly then if an earthquake happening in these areas mainly triggered by reservoirs is so-called reservoir-triggered seismicity.

The world-wide seismic events have occurred near large dam sites or in reservoir areas at more than 100 sites (Figure 1.2) (Gupta, 2002), and these sites have been triggered by major and minor changes in the physical environment conditions as a result of impounding and operation of reservoirs.

The earthquakes triggered by the filling of artificial water reservoirs is well known for more than six decades, the very first time RTS (Reservoir-triggered seismicity) was called to attention by Carder (1945) at Lake Mead of ~M4.0 in the United States of America. The earthquakes exceeding magnitude 6.0 occurred and notify enough to cause damage at various sites like Hsinfengkiang, China in 1962; Kariba, Zambia-Zimbabwe Border in 1963; Kremasta, Greece in 1966; and Koyna, India in 1967. The Koyna earthquake of M6.3 that occurred on 10 December 1967 is so far the largest scientifically accepted reservoir-triggered earthquake till now. Till now, there are four RTS cases that have more than M6.0 earthquakes in which two have normal and another two have strike-slip faulting (Table 1.1).

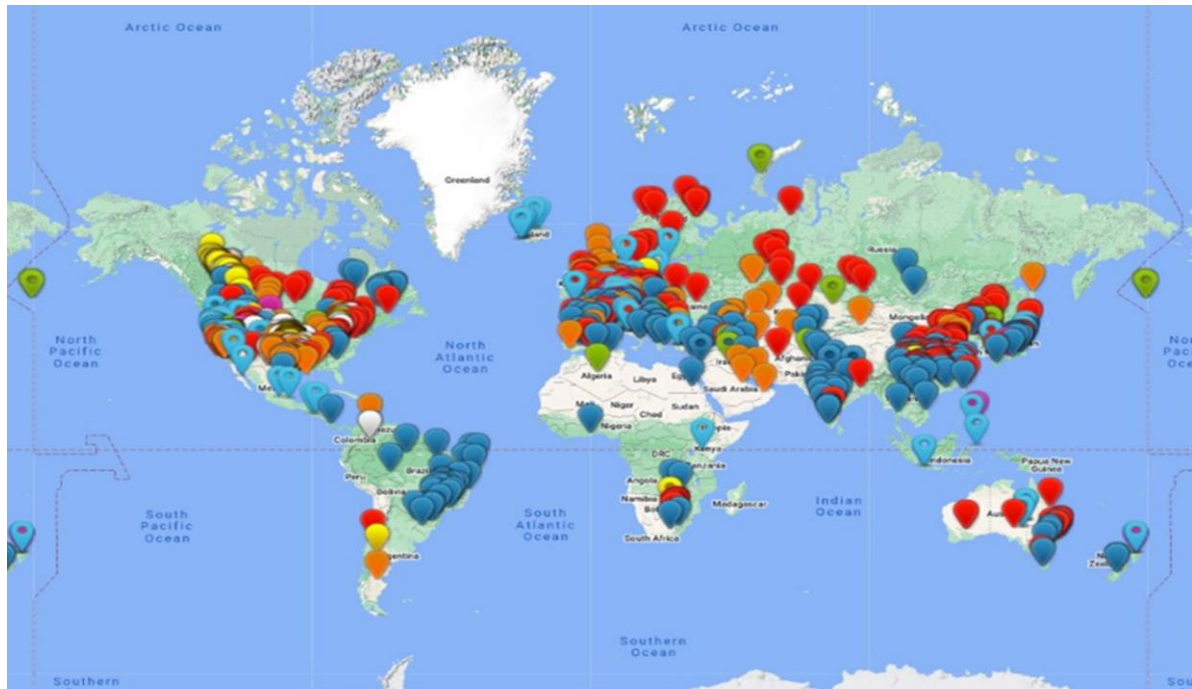


Figure 1.2. World-wide maps of human-induced Earthquake Database (*HiQuake*) is the largest and most up-to-date database of industrial projects proposed to have induced or triggered earthquakes, the dark blue dots showing reservoir-triggered/induced earthquakes (source: <https://inducedearthquakes.org> Last access on 20 November, 2023).

However, there is an argument that the Sichuan in China, M7.9 earthquake that occurred on 12 May 2008, which claimed over 80,000 human lives was triggered due to the filling of the adjacent Zipingpu reservoir or natural earthquake (Gupta, 2011). It is matter of debate either RTS or natural seismicity, so still, it is not in classified in RTS category. It has also been proposed that flooding of a river near the San Andreas Fault in California caused at least two ~M6.0 earthquakes (McGarr et al., 1997). Earthquake occurrence around Aswan reservoir is also considered to be a case of reservoir-triggered seismicity (RTS) where earthquakes continue to occur for the past ~35 years with the most significant event of M5.3 on 14 November 1981 (Telesca et al., 2015).

1. Reservoir/sites where the largest earthquake occurred $M > 6.0$ (4 sites) (Table 1.1)
2. Reservoir/sites where the largest earthquake occurred $M 5.0$ to 5.9 (~14 sites)
3. Reservoir/sites where the largest earthquake occurred $M 4.0$ to 4.9 (~38 sites)

Table 1.1 World-wide RTS having magnitude more than >6.0 .

Country	Reservoir / dam Name	Year of Impoundment	Year of largest earthquake	Max. magnitude	Depth of Earthquake (~km)	Focal Mechanism	Predominant Geology	Ref.
China	Hsinfengkiang	1959	1962	6.1	4.7	Strike-slip	Granite	Lipeng et al., 2018
Zambia	Kariba	1958	1963	6.2	10	Normal Faulting	Sedimentary /Granite	Gregory and Langston 1983
India	Koyna	1962	1967	6.3	4.5	Strike-slip	Basalt/granite	Gupta ,2016
Greece	Kremasta	1965	1966	6.2	15	Normal Faulting	Sedimentary	S.C. Stiros and S. Pytharouli 2018

In the above major cases of RTS is concern throughout the world (Figure 1.2). The RTS cases are booming around the world, with Brazil being one of the concerned countries with 29 RTS cases to date (Franca et al., 2010). The study of RTS in Brazil started in 1972 with the $M 3.7$ at Carmo do Cajuru reservoir, southeast Brazil (Foulger et al., 2018). The largest recorded event, a $M 4.2$ in 1974, caused damage to several buildings without any fatalities and was associated with nearby reservoirs at Porto Colombia and Volta Grande, both of which started damming in the early 1970s.

1.3 Typical characteristics of Reservoir-triggered seismicity

The typical characteristics of reservoir-triggered seismicity succession are reported by Gupta et al., (1972 a, b), who differentiated them from the natural earthquake succession occurring in close by regions but not associated with reservoirs. These characteristics are:

1. The foreshock-aftershock succession pattern belongs to Type II of Mogi's model (Mogi, 1963), whereas the natural earthquake succession pattern connection with Type I of Mogi's model (Figure 1.3).
2. The earthquake frequency-magnitude in relation ($\log N = a - bM$, where N is the number of earthquakes with magnitude M, and a and b are constants), the foreshock b-value is higher than the aftershock b-value, and both b-values of the RTS sequences are higher than the b-values for natural earthquake successions in the regions concerned, and the regional b-values.
3. Additionally, to the high b-values, the magnitude ratio of the largest aftershock to the main shock is also at a high level.
4. The activity aftershock decomposes slowly compared to normal earthquake successions.

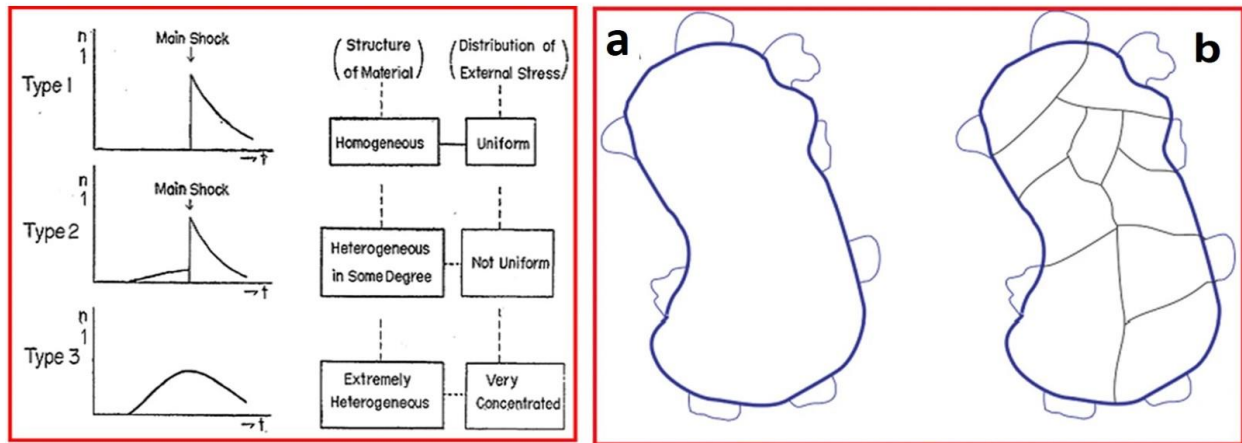


Figure 1.3. Reservoir impoundment by water increases heterogeneity. **(a)** Homogeneous rock volume before impoundment. **(b)** After impoundment. For (a) the earthquakes order falls under Type 1 of Mogi's (1963) models (Right side): no foreshocks and a few aftershocks. For (b), earthquake order falls under Type 2 of Mogi's (1963) models: substantial foreshock activity.

The observations raised above are controlled by the mechanical properties of the media, and their deviation from the normal implicit changes in these properties results in the impoundment of the artificial water reservoir.

1.4 Mechanism and modeling approaches of Reservoir-triggered seismicity

The main three effects of reservoir loading are pertinent to the triggering of earthquakes as designated by Gough and Gough (1970 a, b) and also some others reseracher like D.W. Simpson (1988) (Table 1.2 and Figure 1.4).

1. Increase of elastic stress following the filling of the reservoir
2. Increase in pore fluid pressure in saturated rocks, basically due to a decrease in pore volume due to compaction, in response to increases in elastic stress
3. Pore pressure changes related to the migration of fluids

Table 1.2. The time-distribution types responses to reservoir-triggered earthquakes (by D.W. Simpson (1988)).

Response type	Mechanism	Description	Main features	Cases
Instantaneous response	Instantaneous elastic response and undrained response due to reservoir loading	The type of RTS increases immediately after the initial impoundment of reservoir or changes rapidly after rapid changes in the water level.	Changes in water level have a strong correlation with the change of seismicity, this generally occurs around the reservoir area, and the earthquake magnitude is small, the majority of them are swarm seismicity.	Monticello, Manico-3, Nurek, Kariba, Kremesta et al. <i>Nova Ponte and Irape(this study)</i>
Delayed response	Increase of pore pressure caused by pressure diffusion through permeable rock below reservoir	It is only after a period of reservoir impoundment that the seismicity changes continuously	No significant correlation between changes in water level and seismicity, the time delay is obvious, the magnitude is generally large, and the earthquake occurrence point is not limited	Koyna,Aswan, Orovill et al. <i>Nova Ponte (this study)</i>

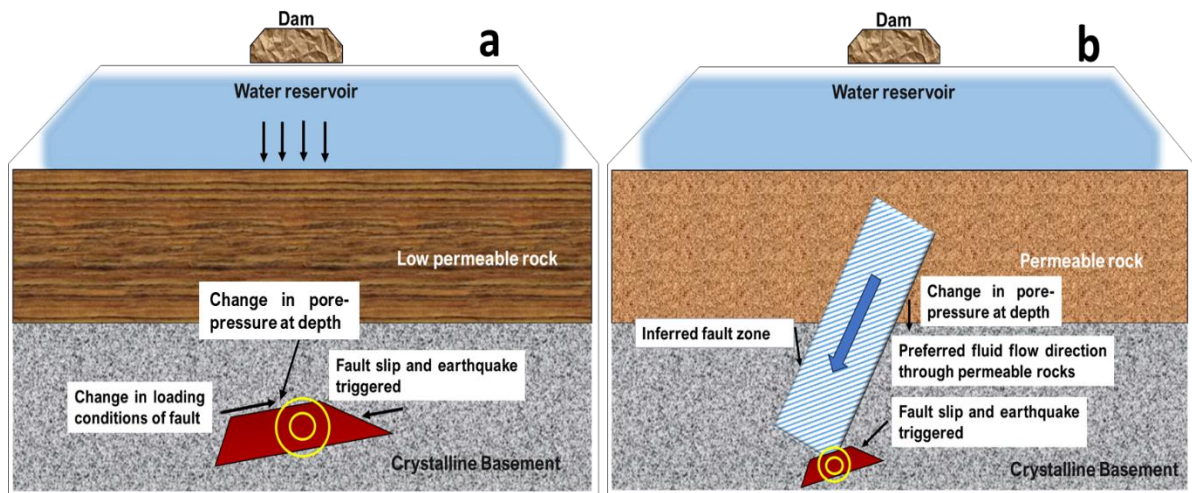


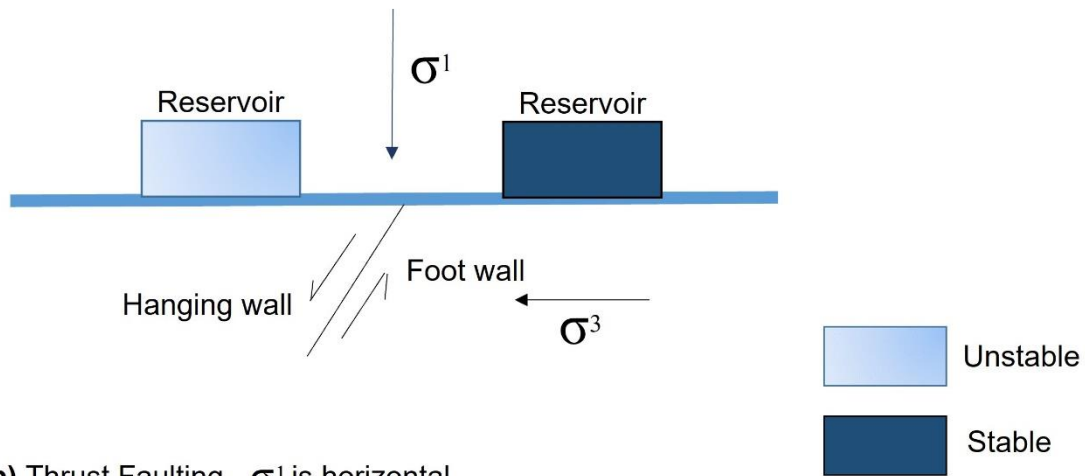
Figure 1.4. Mechanism of reservoir-triggered seismicity (a) undrained response (b) pore pressure diffusion.

The review was conducted to understand reservoir-triggered seismicity, which refers to earthquakes that are triggered by human activities rather than natural tectonic processes. The focus on the mechanisms involved in inducing seismic events. The mechanism suggests that when a reservoir undergoes loading/unloading, it causes only minimal changes in the stress field in the surrounding region. However, for these small changes to lead to earthquakes, the area needs to be already stressed close to a critical location. In another word, the reservoir-induced changes alone may not be sufficient to trigger earthquakes, there needs to be existing stress in the region for them to have an impact.

Additionally, it is also noted that most of the energy released during induced/triggered seismicity is not directly caused by the loading or unloading of the reservoir. Instead, it is attributed to accumulated stress from natural tectonic processes. This implies that while human activities may play a role in triggering earthquakes, the underlying tectonic forces in the earth's crust are crucial contributors to the energy released during induced seismic events.

Gough and Gough (1970 a, b) extended the first conclusive quantifiable analysis of the important function of the load of the water reservoir in triggering earthquakes at Lake Kariba. Bell and Nur (1978) and Roeloffs (1988) also examine the role and function of reservoir load (Figure 1.4 and Figure 1.5). They identify that reservoir-load-induced stresses at seismogenic depths are very small and can only disrupt the ambient stress field. The recognition by Gupta et al., (1972 a,b) that the rate of increase of reservoir water levels, maximum water levels reached, and the duration of retention of high water levels as factors that influence the frequency and magnitude of triggered earthquakes. Snow (1972) presented the influence of pore fluid pressure in inducing earthquakes in very simple 1D reservoir models. According to his analysis, he considered the original stress state in which one of the principal stresses is essentially vertical and the other two are horizontal. He put on view his analyses of fault stability using the concept of the Mohr circle and inspected analytically the effect of filling an limitless reservoir in the vicinity of normal, thrust, and strike-slip faulting. His argument is that reservoir loading would destabilize normal and strike-slip faults but stabilize thrust faults. More sophisticated models were dealt with by Withers and Nyland (1976), Bell and Nur (1978), and Roeloffs (1988) based on the consolidation theory of Biot (1941). This was later generalized by Rice and Cleary (1976) by recognizing that the fluids too may be compressible. The very interesting results related to the modeling of pore pressure diffusion have been reported for Acu Reservoir in Brazil (Do Nascimento et al., 2004).

a) Normal Faulting- σ^1 is vertical



b) Thrust Faulting- σ^1 is horizontal

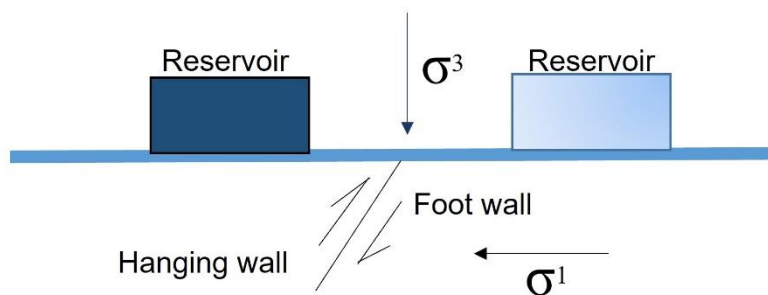


Figure 1.5. The schematic diagram shown the change in stability of Normal and Thrust fault plane corresponding to the reservoir position (a) normal faulting when σ^1 is vertical (b) thrust faulting when σ^1 is horizontal.

The pore pressure diffusion plays a vital role in triggering earthquakes. However, there are very few direct measurements of diffusivity, and it is mostly inferred from the temporal migration of seismicity. The report according to Talwani et al., (1999), in-situ measurements of hydrological diffusivity and Skempton's coefficient at the Bad Creek Reservoir in South Carolina, USA. The phenomenon has been observed by well located approximately 250 meters away from the reservoir. A change in the water level of the well had a direct correspondence with the changes in the water level of the reservoir, initially with a delay of 98 hours, which later stabilized at 72 hours. This led to a

frequency-independent estimate of diffusivity of $0.076 \text{ m}^2/\text{s}$ and Skempton's coefficient of 0.66 for an undrained response of the reservoir. After, Talwani et al., (2007) analyzed more than 90 case histories of RTS and found diffusivity to vary between 0.1 and $10 \text{ m}^2/\text{s}$. This range of diffusivity values corresponds to a range of intrinsic permeability between 5×10^{-16} and $5 \times 10^{-14} \text{ m}^2$. There also mention to this range of the permeability of fractures as seismogenic permeability by Talwani et al., (2007). The permeability related to seismogenic is an intrinsic property of fractures where pore-pressure diffusion is associated with seismicity. The illustration by schematic diagram shows the permeability of the fracture affects pore pressure changes by examining three cases, where the fracture permeability k is less than, equal to, and the seismogenic permeability k_s is greater than this (Figure 1.6). The increase in pressure at one end of the fracture such as by an increase in lake level is followed by diffusion of pore pressure (undrained response) and fluid flow (drained response) through the fracture. The rate of increase in pore pressure, dp/dt , and the rate of fluid flow determine if the fractures will be seismogenic or not. The increase in dp/dt conducts to delayed seismicity, whereas an increase in fluid flow rates lowers dp/dt , and results in the nonappearance of seismicity. The effects of these tend to be more noticeable for rapid filling rates and silence for slower filling. For rocks with permeability $k < k_s$, there is great resistance to the flow of water through the fracture and there is a negligible pore pressure increase by diffusion. Any increase in pore pressure away from the reservoir is instantaneous and due to Skempton's effect (Figure 1.6). For fractures with $k < k_s$, the application of very large differential pressures can cause the fractures to open, thereby increasing the value of k to k_s and triggering seismicity.

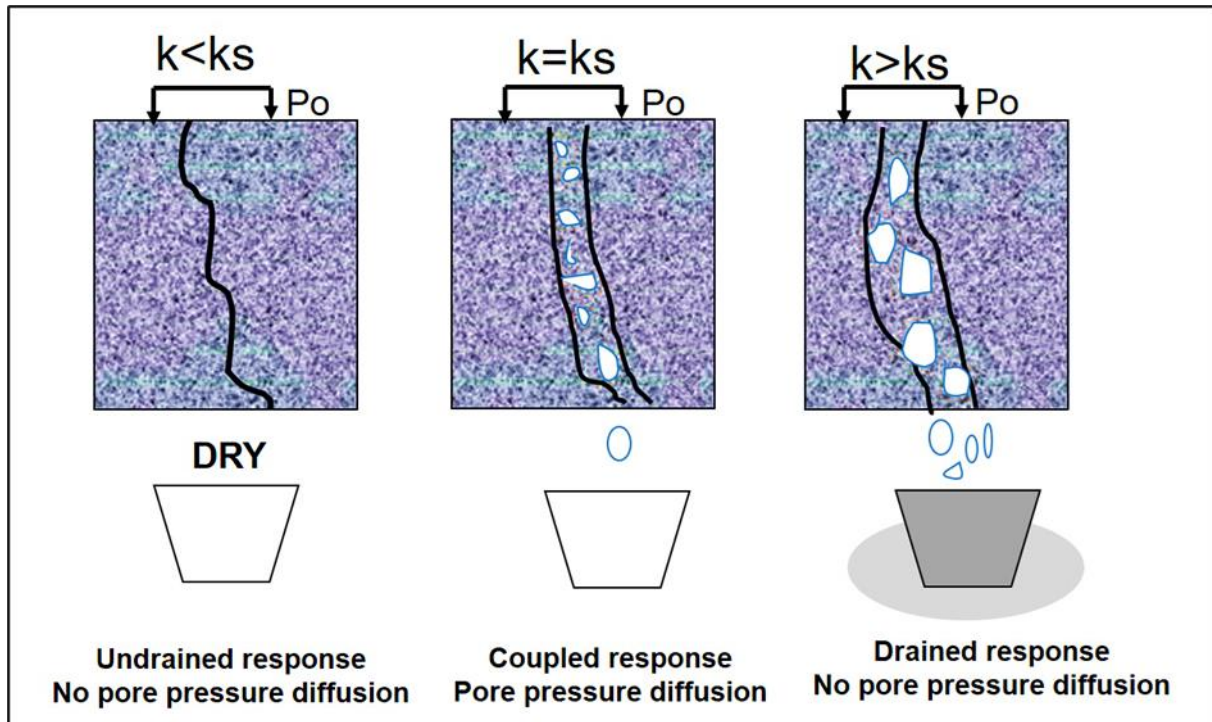


Figure 1.6. A simple schematic diagram to explain the outcome effect of loading a fracture with permeability k , where k is less than, equal, and greater than k_s .

The in-situ measurements of physical properties and examination of the physical mechanism controlling triggered seismicity at Monticello Reservoir, South Carolina, USA, provided the much-needed field verification of the theoretical and model hypothesis of the concept of triggered seismicity (Zoback and Hickman, 1982). Simpson and Negmatullaev (1981) convey the idea and other derived parameters on triggered earthquakes have been dealt the effect of changes in lake levels for the Nurek dam. The character played by pore pressure diffusion in triggering earthquakes has been dealt with by Talwani and Acree (1984/1985). The results of inhomogeneities in rock types and properties on triggering earthquakes was addressed by Simpson and Narasimhan (1990).

Several theoretical models discussed about the effect of pore pressure of fluids in isotropic rocks. Chen and Nur (1992) pointed out that the deviatoric effects of pore fluid pressure in anisotropic rocks have wide applications in comprehending triggered seismicity, earthquake precursors, and aftershocks. This suggestion needs to be applied to a few cases of RTS.

The previous models given by various researchers has been reviewed and mentined here. To date, there are several models have been proposed to investigated the response and main causes of initial and delayed RTS at various sites (Bell & Nur 1978; Roeloffs 1988; Talwani 1997; Lee & Wolf 1998; Kalpana 2000; Chen & Talwani 2001) (Table 1.3).

Table 1.3. The modeling approach of Reservoir-triggered seismicity by their features.

Model by Researchers	Investigated response	Media properties	Geometry
Bell and Nur (1978)	Decoupled	Homogeneous rock matrix, homogeneous fault	2D
Roeloffs (1988)	Coupled and decoupled	Homogeneous rock matrix	2D
Talwani (1997)	Coupled and decoupled	Homogeneous rock matrix	2D
Gahalaut and Chander (2000)	Decoupled	Homogeneous rock matrix	3D
Kalpna (2000)	Decoupled	Homogeneous rock matrix	3D
Chen and Talwani (2001)	Decoupled	Homogeneous rock matrix	2D
Do-Nascimento et al. (2005)	Decoupled	Homogeneous rock matrix, homogeneous fault	3D
Gavrilenko et al. (2010)	Coupled	Homogeneous rock matrix, homogeneous fault	3D
Tao et al. (2015)	Coupled	Inhomogeneous rock matrix, homogeneous fault	3D

Another compelling aspect includes the notion of fault stability as a measure of the interplay of frictional stresses mobilized and the resolved shear stresses acting on a fault Chander and Kalpna (1997). Kalpna and Chander (2000) developed a Green's function based on and supported through algorithm for simulation of stresses and pore pressure in a homogeneous porous elastic half-space. They considered 3D models of reservoirs.

Their algorithm can be earning for an actual time differing water level changes of a reservoir load. Results of Bell and Nur (1978), Roeloffs (1988) and Kalpna and Chander (2000) manifest that, for determinate reservoirs, stabilization and destabilization can occur on all types of faults for appropriate spatial relationships between reservoirs and faults. There should also noted that stabilization or destabilization may be time dependent in general conditions.

1.5 Reservoir-triggered seismicity in Brazil

Reservoir-triggered seismicity (RTS) in Brazil started in 1972 with the Magnitude 3.7 earthquake at Carmo do Cajuru reservoir, southeast region. The highest RTS recorded in Brazil at Porto Colombia & Volta Grande (MG/SP) in early 1974 of M4.2 (Sayão et al., 2020; França et al., 2010) (Figure 1.7). The world-wide well known RTS cases are approximately 29 out of 185 cases happened in Brazil (Foulger et al., 2018; Sayão et al., 2020) (Figure 1.7 denoting 29 RTS cases in red circles). Among these, Nova Ponte M4.0 is denoting case number 22 (Chapter 2 of this thesis) is the second largest RTS in Brazil till now which occurred in May 1998 and Irape is denoting case number 13 in Figure 1.7 (Chapter 3 of this thesis), which represents well known instant and initial response of M3.0 RTS near the dam.

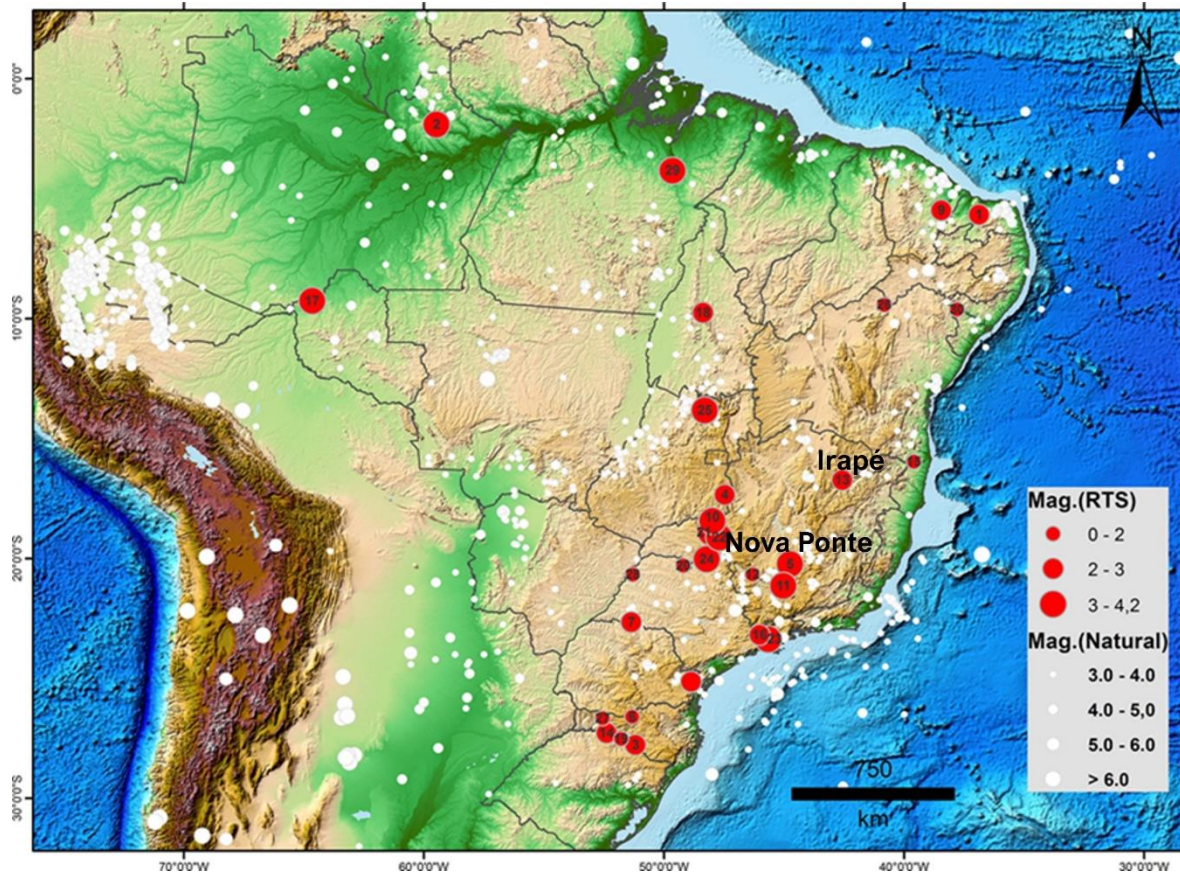


Figure 1.7. Brazil map showing RTS (Reservoir-triggered seismicity) in red circles with magnitude with our study areas Irape and Nova Ponte too. The numbers in red circles denoting the number of sites while natural earthquakes showing in white circles, with magnitude (modified after Sayão et al., 2020).

By concerning and studying these RTS cases, several works have been published on the Reservoir-triggered seismicity in Brazil during the last two decades but still, some questions regarding the understanding of the mechanism of Nova Ponte and Irape RTS have not been cleared yet. These areas are poorly understood about fully mechanism of RTS.

Nevertheless, the clarification of RTS needs to investigate more and there may be more cases in Brazil but still not reported or published, mostly due to the lack of proper

seismic investigations. The most demonstrative cases of RTS come from examples where the monitoring of seismic stations or installation before the impoundment of reservoirs and thus, it is possible to notify the increase of seismic activity after filling of reservoirs. However some cases are also notified that seismic activity started just initial filling of reservoirs e.g. Nova Ponte, Brazil (18% of its total capacity). Some cases are also, in which reported that felt events by the local population are enough to create the relation between seismicity and the reservoir impoundment. So, in the above concern to study of RTS phenomenon, it is essential to understand the basics of the RTS mechanism by contemporary method. Thus, in this thesis, we presented our main findings and results of RTS associated with Nova and Irape which are located in the state of Minas Gerais, Brazil.

1.6 Aim of this study

- To advance in the understanding of the processes that cause reservoir-triggered seismicity.
- To explain the causal mechanisms of RTS M3.5 and M4.0 earthquake at the Nova Ponte reservoir by investigating and developing a numerical 3D hydromechanical model to simulate the poromechanical subsurface response to reservoir impoundment.
- To know the potential causes of RTS by laboratory measurements and analytical calculations to support the hypothesis that the initial seismic activity was induced by the undrained subsurface response to the reservoir loading at Irapé.

This research will employ a multi-disciplinary approach that integrates geology, seismology, modeling approach, and rock properties to interpret the complex processes leading to RTS. The findings will contribute to a better understanding of

reservoir-triggered seismicity and inform mitigation strategies to reduce the associated risks. Finally, the main aims to provide valuable insights into the geological and geophysical factors contributing to RTS, with a focus on reservoir impoundment in hydroelectric projects.

1.7 Thesis structure

This thesis presents two studies areas, first is Nova Ponte and second is about Irapé region which is chapter 2 and 3 respectively, both areas are located in the state of Minas Gerais, Brazil.

Chapter 1 gives an introduction starting with world-wide distribution of large hydropower dams and then context about artificial water reservoir-triggered earthquakes including the general characteristics and mechanism and various 2D/3D modeling approaches of RTS by various researchers. This chapter also given short background about RTS in Brazil. Then at the end of this chapter outlined the Aim of this present studies.

Chapter 2 discusses first study about “The case of M4.0 Nova Ponte earthquake” by build a fully coupled 3D reservoir model including three types rock layers up to basement and simulate the poroelastic response of the subsurface to the reservoir impoundment. In this chapter, we first explain details about geology and present the geological setting where the reservoir is located. Then, we explain the characteristics of the RTS at Nova Ponte, including the temporal evolution of the seismicity in the period 1994-1999 and the location of the main events based on the local velocity model. To assess the contribution of elastic stress transfer and pore pressure diffusion at Nova Ponte, we build a coupled 3D reservoir model including three rock layers and simulate the poroelastic response of the subsurface to the reservoir impoundment.

Chapter 3 describe second study “The case of M3.0 Irape earthquake” by explaining the characteristics of the RTS at Irapé, including the temporal evolution of the seismicity, which occurred in the short period from December 2005 to May 2006 and the location of the main event based on the local velocity model. Then, we present the performed permeability and porosity tests of cylindrical cores samples from hard and intact rock samples, which have been extracted near the RTS zone to identify and describe the primary role of porosity and permeability. We did analytical calculations to estimate pore pressure in response to an increasing of highest water level of the reservoir filling, including vertical and horizontal effective stress. We also calculated the estimated time it takes for the pore pressure diffusion front to reach the depth of the main event. Finally, we present the primary findings regarding the potential causes of RTS at Irapé.

Chapter 4 finally discusses the general conclusion of present research work, and future scope for further research.

C **HAPTER 2**

RESERVOIR-TRIGGERED SEISMICITY OF M4.0 AT NOVA PONTE

2.1 Geological setting and local geology at Nova Ponte

The location of Nova Ponte reservoir is at the boundary between two geotectonic provinces: the Neoproterozoic Brasília Fold Belt and a Phanerozoic volcano-sedimentary basin nominal as Parana Basin. The geological surrounding area where this reservoir is located is characterized by being on the boundary between two lithotectonic that is Tocantins Province and the Paraná Basin. The Geological province at Nova Ponte reservoir is the basin (CEMIG, 1990).

The province Tocantins is an origin of Neoproterozoic age developed in response to the collision and convergence between three continental blocks that well-known as São Francisco, Congo-Amazon and the Paraná Craton or Rio de la Plata Craton (Araújo Filho, 1999; Cordani et al., 2000). Paraguay, Araguaia, and Brasília are the folding belt that comprise to this province. The area of this present study is in the southern segment of the Brasília Belt, where rock types generally consist of Granite-gneissic Complex (Archaean-Paleoproterozoic), the Canastra and Paranoá groups (Meso/Neoproterozoic) and the Araxá, Ibiá and Bambuí groups (Neoproterozoic). This area composed regional stress as NNE-SSW trends.

The local geology at Nova Ponte representing according to lithology (rock layers) are at the topmost meta-basalt to basalt (Serra Geral formation) which is overlying on Araxá Group of rocks and underlying is hard crystalline basement rocks.

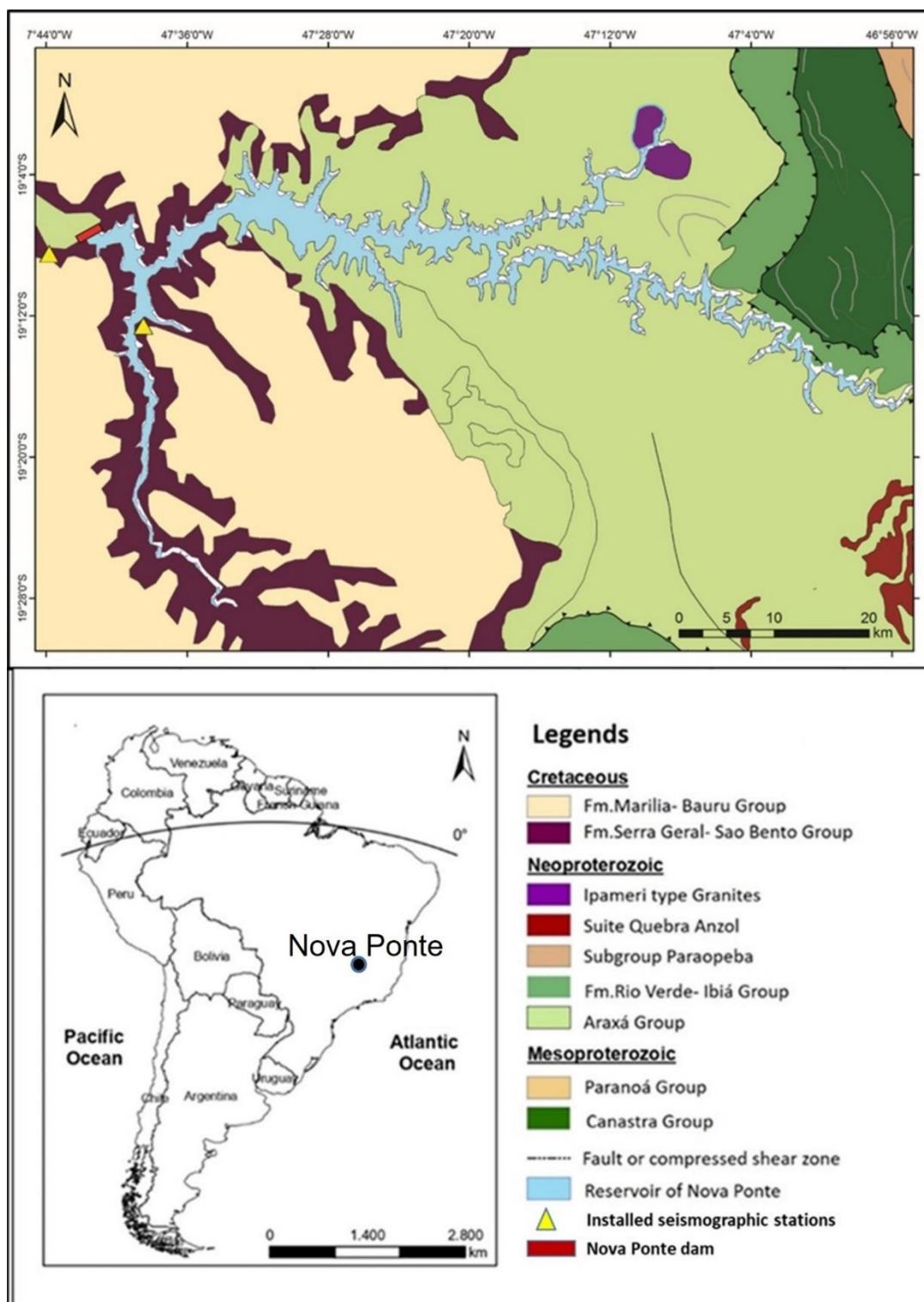


Figure 2.1. Geological map of Nova Ponte reservoir and surrounding area (created after Chimpliganond, C 2002).

2.1.1. Serra Geral formation-São Bento group

The Serra Geral formation is predominantly constituted by basaltic flows that are superimposed on the Botucatu Formation sandstones (Figure 2.1 and 2.2). This volcanism consisting mostly of the intracontinental basin is between 100 and 140 Ma ago. The volcanic as well as basalt rocks of the Serra Geral formation are indicated in this study area characterized as dark grey hard & massive with fine-grained basalt consisting of some amygdaloid structure which is filled with secondary minerals (CEMIG, 1990).

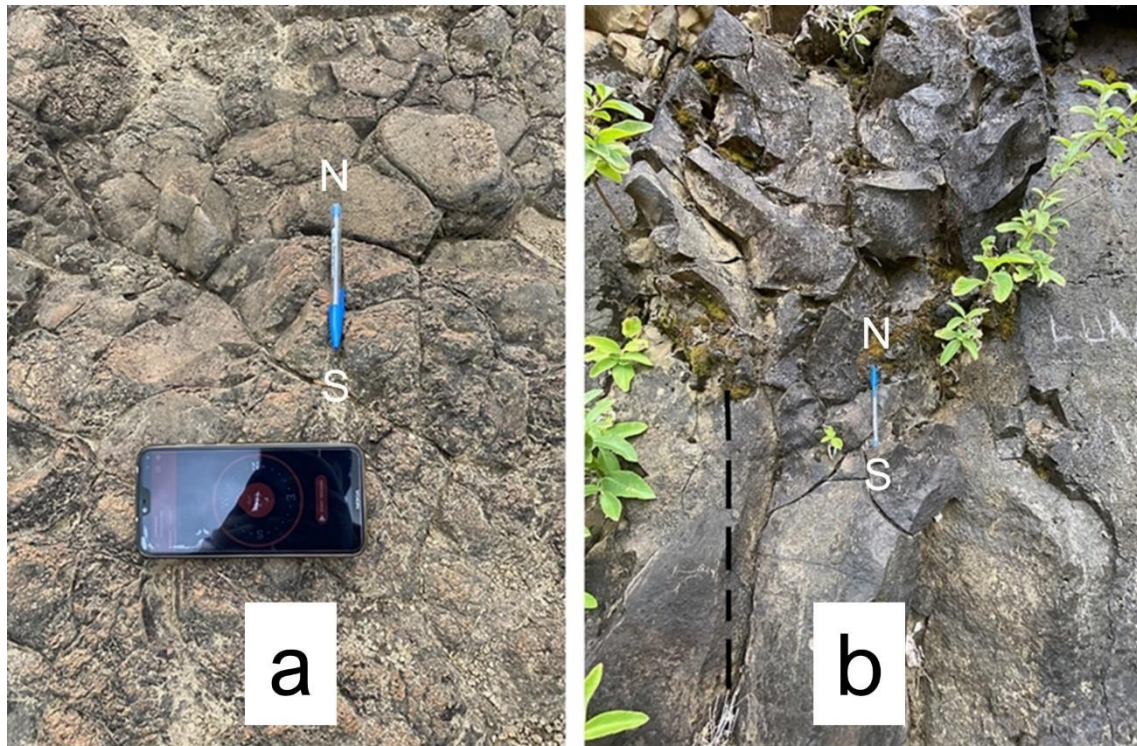


Figure 2.2. Photos taken during field work at Nova Ponte **(a)** showing columnar joints in massive basalt on the surface with respect to geographic north at Nova Ponte reservoir **(b)** sub-vertical fractures in massive basalt showing at Nova Ponte reservoir.

2.1.2. Araxá group

The Araxá group rocks of Neoproterozoic age in general sense its consists of shale, micaceous quartzite, and schist (chalkoxyst, muscovite-quartz schist, muscovite-chlorite schist, biotite-garnet schist, staurolite schist, and feldspathic schist). While the presence of volcanic rocks including amphibolites (metabasalts), meta-andesites, and metabolites are evidence of the volcano-sedimentary character of the Araxá sequence (Cordani et al., 2000). Although, some part of intrusions of amphibolite gabbroid bodies explored and can also be observed. The direction of main planar structure is the foliation trending preferably to N-W, low angle which is associated with nudge with direction towards San Francisco craton (CEMIG, 1990; Pimentel et al., 1999). The Araxá Group rocks show the three patterns of joints vertical to sub-vertical tectonics directed trends NW, N-E, and N-S, which go through reactivations during the period of Phanerozoic (CEMIG, 1990).

2.1.3. Paranoá group

The Paranoá group is represented by metarenitos and metabolites, which occur only in a restricted portion in the extreme N-E of the area (Figure 2.1). The age of this group it is taken as mezo to Neoproterozoic and the sedimentation environment is the passive margin.

2.1.4. Canastra Group

The Canastra Group is considered a metamorphosed equivalent of the Paranoá group, both representing typical passive margin sequences formed on the west margin of the São Francisco-Congo continent (Pimentel et al., 1999). The rocks of the Granite-gneissic complex, there are psammitic (quartzite) and pelitic (phyllite) detrital

metasediments, metamorphosed into the greenschist facies (Cordani et al., 2000), which constitute the Canastra Group (Meso/Neoproterozoic). This study area consists of the lithologies of this group occupying a small portion of the western portion (Figure 2.3), represented by pure and micaceous quartzites, quartz and carbonate phyllites, with a predominance of quartzites (CEMIG, 1990). The metamorphism that affected these rocks reached low greenschist facies. They exhibit structurally, bending and three angled joint patterns directed trending towards NNW and NNE. However, the relationship between the Canastra and Araxá groups is not yet clear, and they are currently considered as laterally equivalents (Cordani et al., 2000).

The Archean/Paleoproterozoic area is represented by the complex of Granite-gneiss. This complex is composed of banded, micaceous, and quartz-feldspathic, massive and gneissified granite, gneiss mylonite, schist-mylonite, phylonite of granitic and basic rocks, amphibolite and schistified ultrabasic rocks (CEMIG, 1990). The mylonitic series of gneissic rocks occur in shear zones, which constitute large structural features directed to N-W, which is important in formation of the Proterozoic and Phanerozoic geotectonic establishment (CEMIG, 1990).

2.1.5. Ibiá Group

The Ibiá Group sediments were deposited in a deep marine environment, in the Neoproterozoic, and may be a stratigraphic equivalent of the Araxá Group (Cordani et al., 2000). The Ibiá Group can be subdivided into the Cubatão Formation (at base) composed of diamictites and the Rio Verde Formation (at top) represented essentially by calciferous phyllite or limestone schist with quartz laminations and some intercalations of fine quartzite and phyllite locally carbonate ash (Cordani et al., 2000).

2.2 Background and Spatio-temporal evolution about RTS at Nova Ponte

The Nova Ponte is a well known Hydropower Plant in Brazil and the reservoir is located in the state of Minas Gerais at triângulo Mineiro region. It lies between the parallels 19°00'S and 19°30'S meridians 46°45'W and 47°45'W. The city of Nova Ponte located on the banks of the reservoir, its well located close to the dam plant, which have distance approximately 80 km from the S-E of Uberlândia and the N-E of Uberaba cities.



Figure 2.3. Photo of Nova Ponte hydroelectric Power Plant which is surrounded by basalt rocks, photo taken during the fieldwork.

The hydropower plant has 142 meters of height and a reservoir volume of 12.8 km³. The lake is formed from the damming of the Araguari rivers with a depth of 132 meters and the dam is constructed along with (Figure 2.3 and Table 2.1). The very initial triggered seismic events were detected after start filling of the reservoir in October 1993

when the reservoir filled to approximately 18% of its total capacity. Then it became a well known site of RTS due to detection of earthquakes activity with strong association between loading/unloading of the reservoir. Since, January 1994 the events started and were located mainly in the southern part of the reservoir (Figure 2.4) and were felt by the local population (Assumpção et al., 2002).

Table 2.1. Characteristics of RTS (Initial and delayed response) at Nova Ponte (by Assumpção et al., 2002; Sayão et al., 2020).

Dam Height (m)	Volume (km ³)	Water depth (m)	Reservoir (km ²)	Seismicity type	Date	Location	Magnitude (mR)	Io (MMI)	ΔT(yr)	Depth of Earthquake (km)
142	12.8	132	443	Initial	21.04.1995	Margin	3.5	IV-V	1.5	~ 2.6
				Delayed	22.05.1998	Outside	4	VI	4.5	~ 3

(ΔT: time interval (years) since the beginning of filling/impoundment of the reservoir; MMI: modified Mercalli scale).

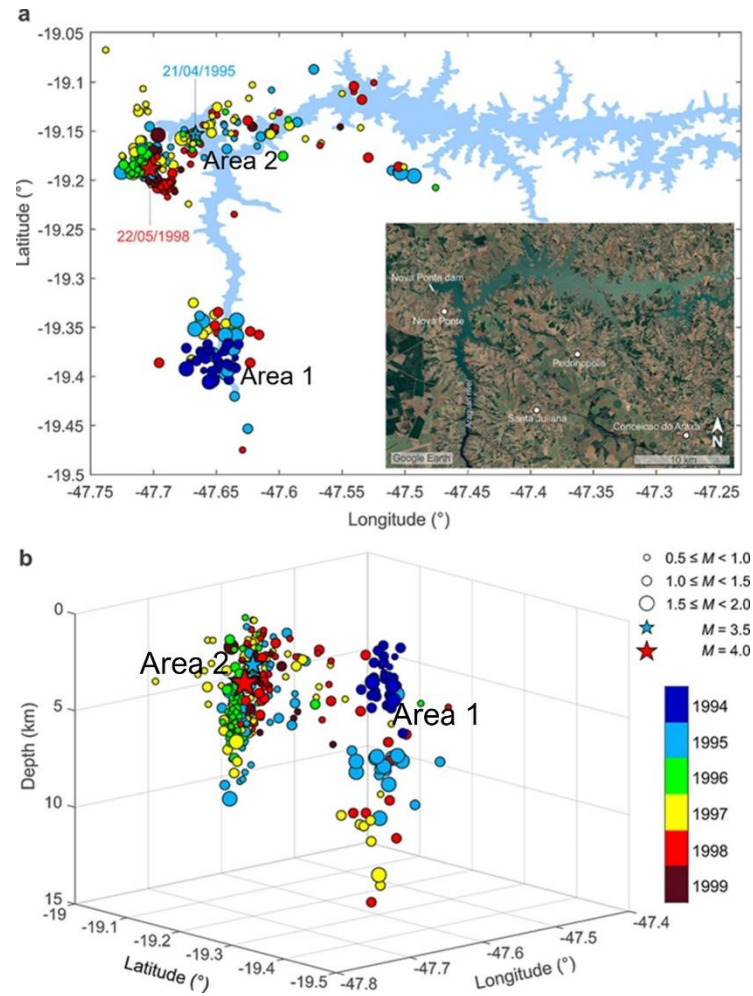


Figure 2.4 (a) The RTS epicentral location at the Nova Ponte reservoir and seismic events $M \geq 0.5$ of Areas 1 and 2 **(b)** distribution of these events with depth which have epicentral error range from 0.3 to 1.5 km color-coded by year from 1994 to 1999. The insert in **(a)** shows the reservoir location obtained from google earth.

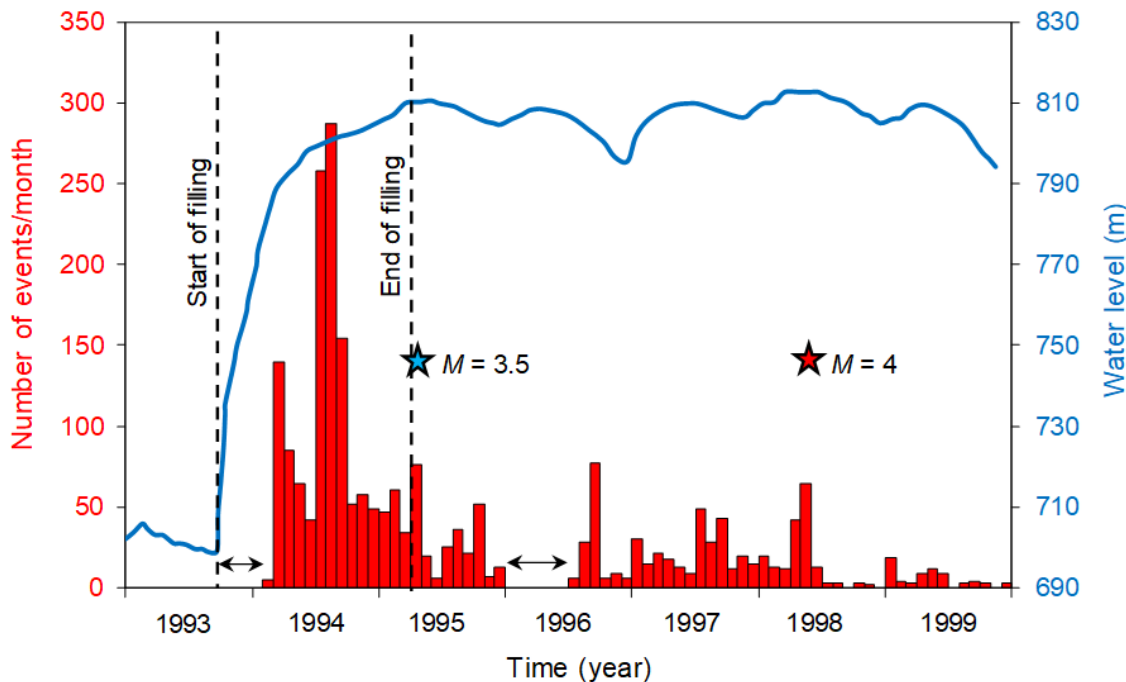


Figure 2.5. The RTS temporal evolution at Nova Ponte. The number of monthly events (histogram) and monthly average water elevation above the mean sea level (blue line) are illustrated. The two largest largest events showed in blue and red stars (initial and delayed response). The arrows indicate the two periods without data when the stations were down (adopted and modified after Assumpção et al., 2002).

The local station faced some operational problems during the impoundment which started in October 1993. So, there is little uncertainty about location (Assumpção et al., 2002). The accuracy of earthquake location data is highly dependent on the quality and distribution of seismic equipment in the region. RTS in many cases occurs in regions with limited monitoring infrastructure, which can lead to uncertainties to detect the exact location and depth of the seismic event. As a result of these complexities and uncertainties, detecting the exact location and depth of shallow RTS can be challenging. That's why monitoring and research efforts are crucial to better understand the mechanisms and characteristics of RTS.

The initial phase of seismicity had a magnitude of 3.5 and was nucleated at a depth of approximately 2.6 km. In this area the event occurred approximately 3 to 4 km east of the dam about 1.5 years since the start of reservoir impoundment (on 21.04.1995) (Table 2.1 and Figure 2.5), at the same time when the water level reached at 110.6 meters seismic activity continued near the dam (Marza et al., 1997) (Figure 2.5). Nevertheless, the seismic activity continued near the dam (Figure 2.4) for 4.5 years after its impoundment (on 22.05.1998), the M4.0 is the largest event which occurred further away from the reservoir margin due to a delayed response. This main event depth has been detected to be approximately 3 km (Table 2.1). However, the accuracy of hypocentral depth is still not accurate but close to these depths. The events location for Area 1 are grouped into a region of approximately 5 km in radius. The epicenters show poor alignment in the NNW direction in 1994 and there was a migration from a restricted area near the reservoir to the vicinity of the margin in 1998. A striking feature is the increase in the depth and lateral dispersion of the hypocenters over time, showing both vertical and lateral diffusion. The epicenters of these events are distributed between 0 and 15 km in depth, presenting a progressive increase in depth. Major events of Area 1 ($M > 1.5-2.0$) were deeper than 5 km in 1994, mostly between 5 -10 km in 1995, and between 7-14 km in 1997 (Figure 2.4).

The events in Area 2 are grouped in a cluster delimited by an area of approximately 4 km wide and 7 km long. This cluster contains the two largest events, the initial M3.5 earthquake in 1995 and the delayed M4.0 event in 1998, as well as the earthquakes associated with them, i.e., fore- and after-shocks. The uncertainty of earthquakes was generally less than 0.1 of the root mean square residual, both in horizontal and depth errors. In this work, we did not consider this factor as an influencing element in the modeling process.

2.2.1 Local velocity model

The local velocity model has been adopted by seismic refraction method which relates and represents the Sao Francisco craton as well as South American crustal plate. Perosi, 2000 has identified the thickness rock layers down to the basement which is approximately close to the crustal structure of the South-American plate. From the local velocity model the top most rock layer has thickness about 300 m which consists of meta basalt to basalt with a P wave velocity (V_p) of 5.0 km/s and below this the rocks have Araxá group which is mainly representing the schist to mica-schist rocks that have thickness approximately 5.7 km and below is hard and crystalline basement rocks which have been considered the thickness approximately 4.0 km (Figure 2.6). Petrographically this area is poorly studied.

It is also noted that the rock types of Araxá group with V_p of 5.7 km/s, variably in different types like mica-schist, schist, but the exact classification of these rocks is poorly known. Therefore, from the local velocity model schist has been considered as major rocks in this particular area.

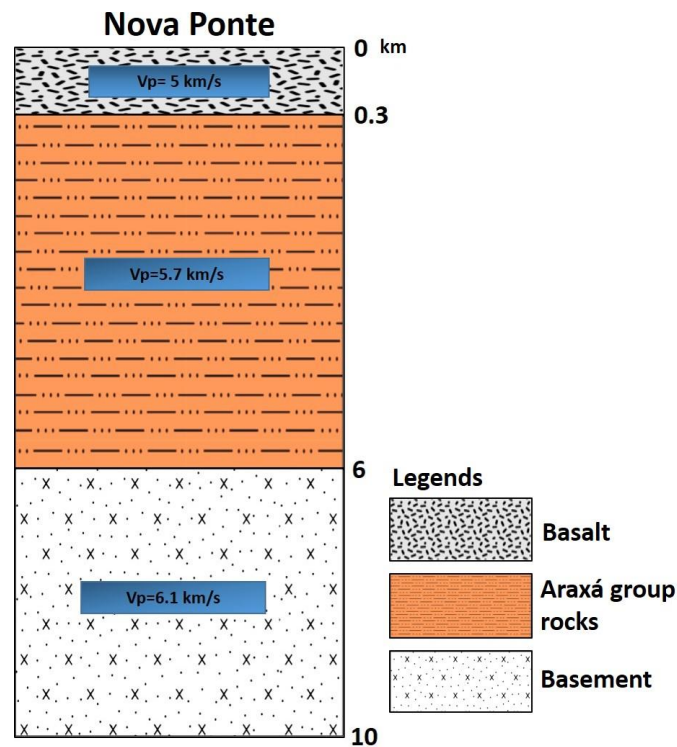


Figure 2.6. Velocity model developed with corresponding vertical layers of rocks to used in the relocation of RTS at Nova Ponte that occurred between 1994 to 1999 (modified after Perosi, 2000; Chimpliganond, C 2000).

The basement is located below these two layers, with a V_p of 6.1 km/s. A compressional-to-shear velocity ratio (V_p/V_s) of 1.7 can be considered for these layers (Assumpção et al., 2002b). Appropriately, there is two different sets of fault plane solutions for the initial April 21, 1995, M3.5 earthquake have been proposed (Table 2.2). The one points indicate to reverse faulting with a strike-slip component (Assumpção et al., 1997), (the other includes mainly a strike-slip fault (Marza et al., 1997), Therefore, the accuracy of these focal mechanisms remains debated because of the low quality of the recorded seismic data by analog seismograms and uncertainties associated with the velocity model. By concerning the same reasons, the focal mechanisms of the May 22, 1998, M4.0 earthquake have not yet been resolved.

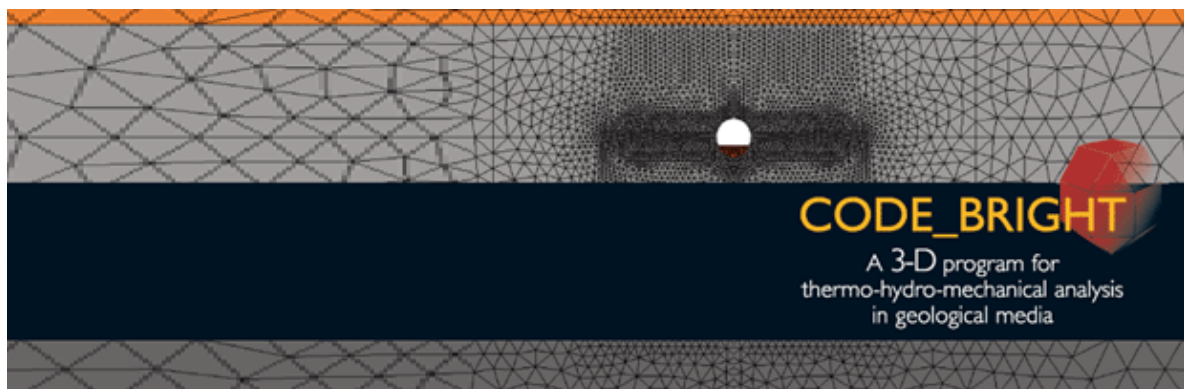
Table 2.2. The proposed focal mechanisms of the 1995 M3.5 earthquake at Nova Ponte.

Strike angle	Dip angle	Rake angle	References
85	38	20	Assumpção et al. (1997)
190	46	168	Marza et al. (1997)
272	89	42	Marza et al. (1997)

2.3 Materials and Methodology

2.3.1 CODE_BRIGHT/GiD: General Features

CODE_BRIGHT is a Finite Element Method (FEM) program that has the ability to perform coupled thermo-hydro-mechanical (THM) analysis in geological media. This method has integrated work with the pre/post-processor GiD, which was developed and brought by the International Center for Numerical Methods in Engineering (CIMNE) (Figure 2.7 with source).

**Figure 2.7.** Photo source at https://deca.upc.edu/en/projects/code_bright/downloads.

The program CODE_BRIGHT is described as a tool designed to handle coupled problems in geological media. This code initially, was developed and started on the basis of a new basic theory for saline media. Then the program was extrapolated for

modeling thermo-hydro-mechanical (THM) processes in a coupled way in geological media. Fundamentally, this code couples mechanical, hydraulic, and thermal problems in geological media. The theoretical approach consists of a set of governing equations, a set of constitutive laws and a special computational approach. The data includes the definition of the geometry, materials, conditions, solution information and other parameters. The program can also generate the finite element mesh and write the information for a numerical simulation program in its adequate format for CODE_BRIGHT. The most important difference is that the geometry is developed in a hierarchical mode. All materials, conditions, and solution parameters can also be defined on the geometry without the user having any knowledge of the mesh. The meshing is performed once the problem has been fully defined. The advantages of doing this are that, using associative data structures, modifications can be made to the geometry and all other information will be updated automatically. Full graphic visualization of the geometry, mesh, and conditions is available for comprehensive checking of the model before the analysis run is started. More comprehensive graphic visualization features are provided to evaluate the solution results after the analysis has been performed. This post-processing user interface is also customizable depending on the analysis type and the results provided (Figure 2.8).

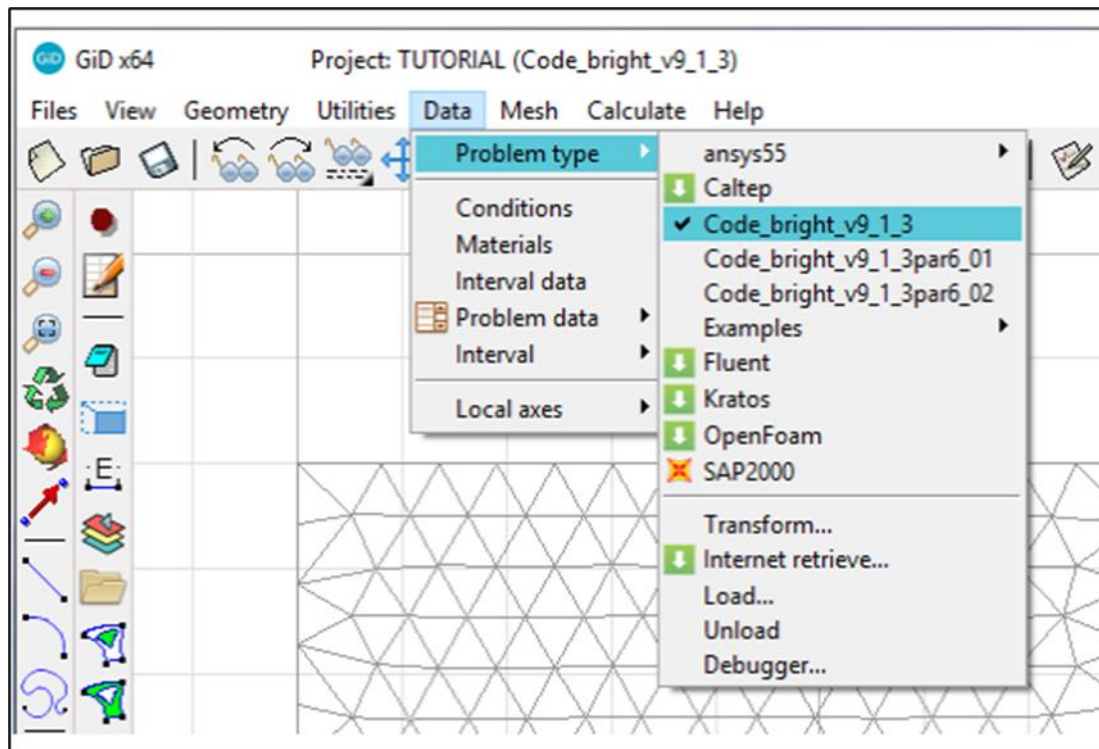


Figure 2.8. Initial process to create the models through program CODE_BRIGHT (Olivella et al., 1996).

1. Define geometry: points, lines, and surfaces
2. Define attributes and conditions
 - 2.1. *Problem data*
 - 2.2. *Materials*
 - 2.3. *Conditions*
 - 2.4. *Interval data*
3. Generate mesh
4. Carry out simulation
5. View results
6. Post-process and interpretation

The inquiry window appears for some confirmations or selections. This feature is also extended to the end of a session, when the system prompts the user to save the changes, even when the normal ending has been superseded by closing the main window from the Window Manager, or in most cases with incorrect exits.

2.3.2 3D fully-coupled hydromechanical numerical simulations: Poroelastic modeling of fault stability

We carry out the coupled hydromechanical numerical simulations of the Nova Ponte reservoir impoundment to understand as well as acknowledge whether and how the resulting pore pressure and stress perturbations caused earthquakes at depths. By considering a conceptual 3D model of the upper most 10 km of the crust, including the basalt layer, extending from the surface to a depth of 300 m, the 5.7-km thick Araxá group, and a 4-km thick portion of the crystalline basement at the bottom (Figure 2.9) (Perosi, 2000). By neglecting the topography, the reservoir cross-section area is reproduced as a T-shape surface on the top of the basalt layer. However, the water in the reservoir is not modelled, but a hydrostatic pressure and an overburden stress of equivalent weight are applied on the top of the reservoir cross-section. To exclude potential boundary effects, the model extends more than 50 km on each side of the reservoir in the x and y directions.

We supposed that all geological media are homogeneous and isotropic and deform elastically. By identifying the lack of direct measurements of the hydraulic and mechanical properties of the modeled layers, we assign typical values of the considered rock types (Table 2.3) (Fjær et al., 2008; Cheng, 2016). Initial conditions include hydrostatic pressure distribution with a gradient of 0.01 MPa/m. The published and resolved focal mechanism of the M3.5 earthquake yields a strike-slip/reverse faulting

stress regime, with a maximum horizontal stress direction ranging from 42 to 66°, which are consistent with the regional tectonics (Schindler et al., 1998). By corresponding this, the initial vertical stress, σ_v , is calculated with the average bulk density of the rock layers and is taken equal to the minimum horizontal stress, σ_h , with $\sigma_v = 0.45 \sigma_H$, where σ_H is the maximum horizontal stress. We carry out a steady-state calculation to derive distributions of the pore pressure and stresses at equilibrium.

We simulate reservoir impoundment by increasing the pore pressure and vertical stress on top of the reservoir section over 1.5 years from atmospheric conditions to 1.3 MPa, coinciding with the final water column height of about 120 m. We extend the simulation to 10 years by maintaining the stress and pressure conditions in the reservoir to address the post-impoundment period. The pressure and stress conditions in the area surrounding the reservoir are kept atmospheric throughout the simulation. We impose no-flow boundary conditions on the bottom and lateral boundaries. The mechanical boundary conditions comprise no displacement perpendicular to these boundaries. We used GiD v14 to create the contour plots and Matlab version 2023b. We numerically solve the described hydromechanical problem using the fully-coupled finite element code CODE_BRIGHT (Olivella et al., 1996). The mesh consists of $55 \times 46 \times 55$ (139,150 in total) hexahedral elements, which are both vertically and horizontally refined toward the reservoir. The spatiotemporal distributions of the pore pressure and stresses are used to estimate the fault stability evolution on the orientation of the M3.5 earthquake by adopting the Coulomb Failure Stress, $CFS = \tau - \mu \sigma_n'$, where τ and σ_n' are the shear and effective normal stresses acting on the fault plane, respectively. The fault is assumed to be cohesionless and have a frictional coefficient μ of 0.6 (Barton, 1976). Fault slip is promoted if the CFS increases (i.e., $\Delta CFS > 0$) and hindered if CFS decreases (i.e., $\Delta CFS < 0$).

Table 2.3. The mechanical and hydraulic properties for some common rock types used in the numerical simulations (Fjær et al., 2008, Cheng et al., 2016). The symbol ($\perp$) refers to the parameters measured perpendicular to the bedding planes.

Rock types	Basalt	Schist $\perp$	Granite
Rock density, $\rho \times 10^3$ (kg/m ³)	2.8	2.81	2.7
Young's modulus, E (GPa)	60	20	70
Poisson's ratio, ν (-)	0.25	0.3	0.25
Intrinsic permeability, k (m ²)	10^{-15}	10^{-17}	10^{-19}
Porosity, ϕ (-)	0.05	0.1	0.01

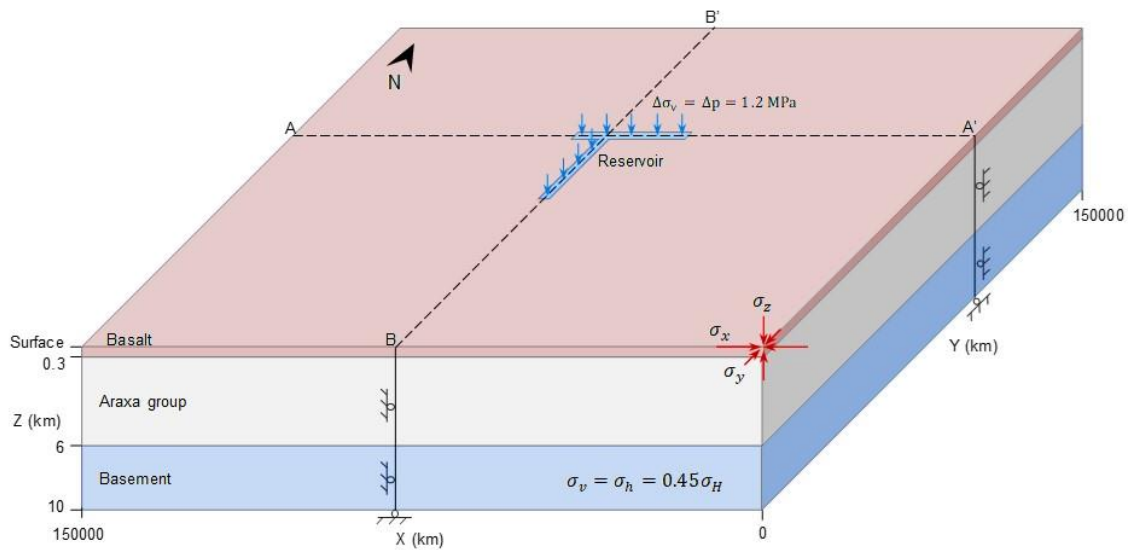


Figure 2.9. The 3D model geometry and boundary conditions used in this study to understand the triggering mechanisms of the Nova Ponte RTS due to effects of reservoir filling on the subsurface response.

In short, this study explains the causal mechanisms of the two largest earthquakes that were triggered by reservoir impoundment in Brazil: a M3.5 earthquake occurring in 1995 and a M4.0 earthquake occurring in 1998, at the Nova Ponte reservoir. We

investigated this topic by developing a numerical 3D hydromechanical model to simulate the poromechanical subsurface response to reservoir impoundment. The model was composed of three layers, representing with increasing depth: a basaltic layer, the Araxa Group, and the underlying basement crystalline rock. At the surface, the deviatoric stresses generated by water column loading were represented by a T-shaped reservoir, where a hydrostatic pressure and an overburden stress of equivalent weight were applied.

2.3.3 Understanding Coulomb Failure Stress: Unraveling its Role in RTS

In Coulomb failure stress theory, positive stress changes are interpreted to promote failure, while negative stress changes inhibit failure (King et al., 1994).

$$\text{CFS} = \tau - \mu \sigma_n \quad (1)$$

where τ and σ_n are the shear and effective normal stresses acting on the fault plane, respectively. The spatiotemporal distributions of the pore pressure and stresses are used to estimate the fault stability evolution on the orientation of the M3.5 earthquake.

2.4 Results

The focal mechanisms that are two obtained from initial Reservoir-triggered seismicity occurred in 1995 are available in the literature (Table 2.2) (Assumpção et al., 1997; Marza et al., 1997). The nodal plane of Assumpção et al. (1997) corresponds to a reverse fault with strike 85°, dip 38° and rake 20°. The maximum horizontal stress has orientation such as (within the range of proposed values in the literature, i.e., azimuth ranging from 42° to 62°) should be 42° to make this plane as much critically oriented for shear slip as possible. During the time of 1995 M3.5 earthquake, i.e., 1.5 years after the start of the reservoir filling, pore pressure diffusion has not reached the depth of the

hypocentre where the event was nucleated (2.6 km). For that reason, the pore pressure and stress changes occurring at depth are due to the undrained response of the subsurface to the loading of the retained water by the dam. Coulomb Failure Stress (ΔCFS) changes are negative at the depth of the hypocentre and thus, the focal mechanism proposed by Assumpção et al. (1997) could not set out with RTS. So, we try out whether an enhanced permeability of the schist of $8 \cdot 10^{-15} \text{ m}^2$, sufficiently high to allow the pore pressure propagation front to reach the depth of the earthquake, could explain the seismicity due to the pore pressure build-up at depth. Likewise, the case of low-permeability schist (10^{-17} m^2), the ΔCFS presents negative values at the location of the 1995 M3.5 earthquake (Figure 2.10).

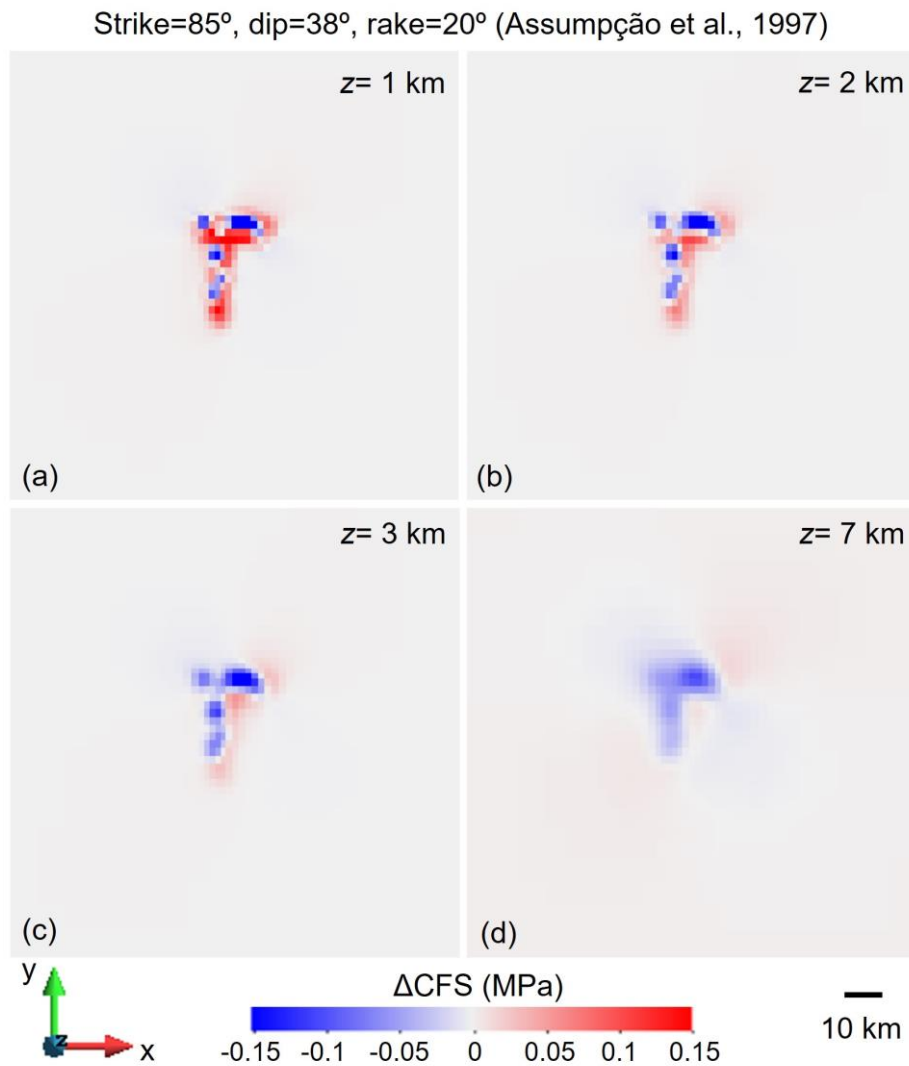


Figure 2.10. The Coulomb Failure Stress (ΔCFS) showing changes for the nodal plane with strike 85°, dip 38° and rake 20° that is proposed by Assumpção et al. (1997) during initial RTS of the 1995 of M3.5 at **(a)** 1 km, **(b)** 2 km, **(c)** 3 km and **(d)** 7 km is the deep horizontal cross sections, for the case of schist permeability equal to $8 \cdot 10^{-15} \text{ m}^2$ and assuming an orientation of the maximum horizontal stress with respect to the North of 42°. The ΔCFS has negative values at the location of the earthquake, i.e., south of the dam approximately 2.6 km depth.

Another focal mechanism of the 1995 M3.5 earthquake (Marza et al., 1997) gives as feasible nodal planes a reverse-faulting plane with right-lateral displacement and a

strike-slip plane with reverse-left-lateral displacement. To make the nodal planes the most favorably oriented planes for slip within the range of orientations of the maximum horizontal stress, the azimuth of the maximum horizontal stress should be 42° for the reverse-faulting plane with right-lateral displacement and 62° for the strike-slip plane with reverse-left-lateral displacement. By assuming a schist permeability of 10^{-17} m^2 , the pore pressure diffusion does not reach the depth of the hypocentre and thus, the subsurface response to the 1995 M3.5 earthquake would have been undrained. Similarly, to the reverse-faulting plane obtained by Assumpção et al. (1997), the ΔCFS of the reverse-faulting plane with right-lateral displacement presents negative values below the reservoir, we can see two profiles $\pm 45^\circ$ to cross check to know best of our knowledge (Figure 2.11). In compared, the strike-slip plane with reverse-left-lateral displacement displays positive values of ΔCFS below the reservoir along the E-W direction (Figure 2.12). Thus, the 1995 M3.5 earthquake most likely occurred in a vertical fault with a strike in the E-W direction.

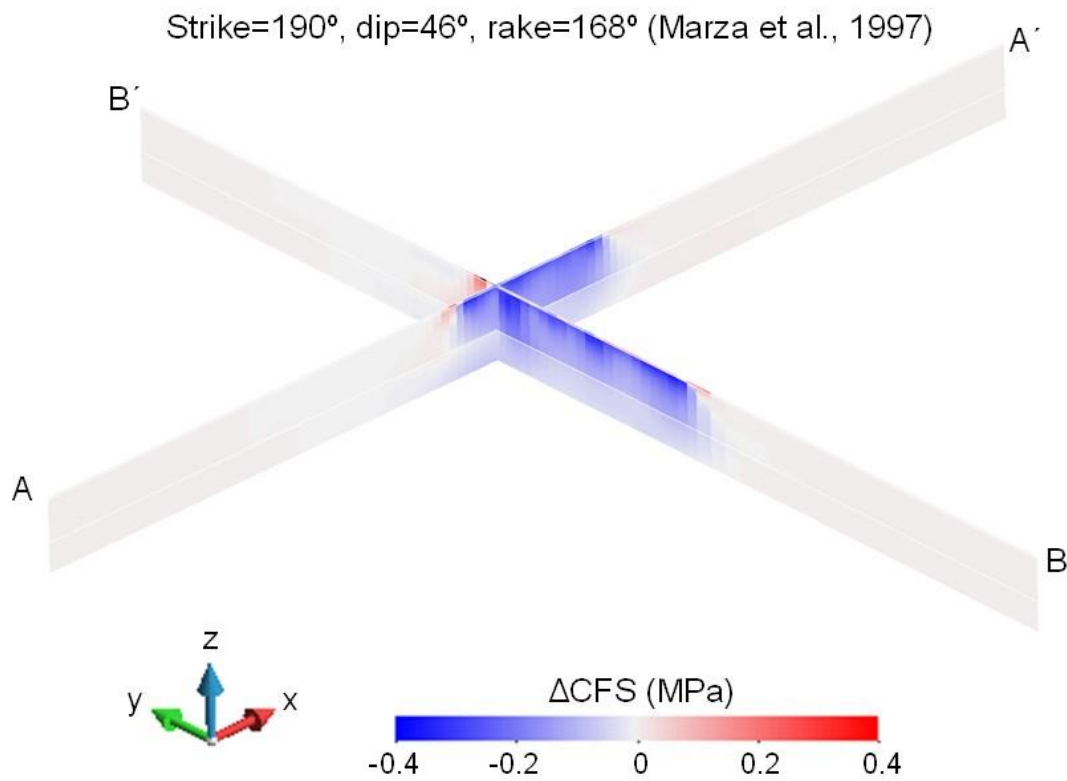


Figure 2.11. Changes in Coulomb Failure Stress (ΔCFS) for the nodal plane with strike 190°, dip 46° and rake 168° proposed by Marza et al. at the time of the 1995 M3.5 earthquake below the reservoir along the N-S and E-W directions (corresponding to sections BB' and AA' in Figure 2.9, respectively), assuming an orientation of the maximum horizontal stress with respect to the North of 42°.

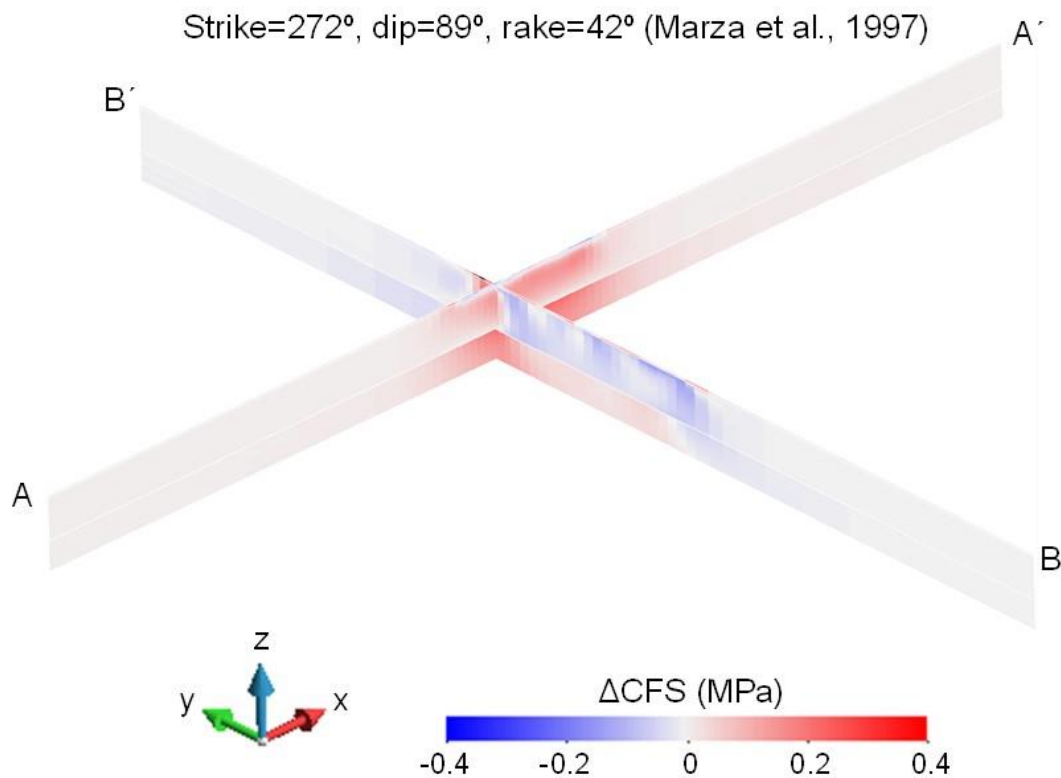


Figure 2.12. Changes in Coulomb Failure Stress (ΔCFS) for the nodal plane with strike 272°, dip 89° and rake 42° proposed by Marza et al. at the time of the 1995 M3.5 earthquake below the reservoir along the N-S and E-W directions (corresponding to sections BB' and AA' in Figure 2.9, respectively), assuming an orientation of the maximum horizontal stress with respect to the North of 62°. The ΔCFS has positive values at the location of the earthquake, i.e., south of the dam at 2.6 km deep.

To recognize the differences for better understanding in the ΔCFS between the two nodal planes, pore pressure and stress changes should be analysed. The pore pressure increases due to reservoir impoundment on the surface that diffuses at a very small rate because of the low permeability of the rock below the reservoir (Figure 2.13a). So far, the pore pressure increase extends further away than the pressure diffusion front. This is indicated as a consequence of the undrained response of the low-permeability rock to the reservoir-impoundment loading. Likely the rock is compressed by the loading of the

water column (Figure 2.13b), the pore volume is reduced, but the pore water cannot diffuse rapidly and, consequently, pore pressure increases. To the content stress equilibrium and displacement compatibility, the horizontal stresses also change in response to the vertical loading and pore pressure changes (Figure 2.13c and 2.13d). The rock layer in schist, the horizontal stresses increase in response to the deformation-induced pore pressure build-up. These stress changes induce a stress redistribution around the schist layer that leads to a reduction in the horizontal stresses in the hard crystalline basement. Similarly, the stress redistributions are common in response to stress perturbations induced pore pressure and/or temperature changes (Vilarrasa et al., 2013; Parisio et al., 2019; Kivi et al., 2022). By complying these stress changes, the deviatoric stress decreases in a reverse-faulting plane because the vertical stress, which is the minimum principal stress, increases more than the maximum horizontal stress (Figure 2.14). As a result, fault stability increases, i.e., negative ΔCFS (Figure 2.11). In a strike-slip fault, both horizontal stresses have a similar change, so the deviatoric stress is maintained, and since pore pressure increases more than the total horizontal stresses, the effective normal stress decreases, destabilizing the fault, i.e., positive ΔCFS (Figure 2.12).

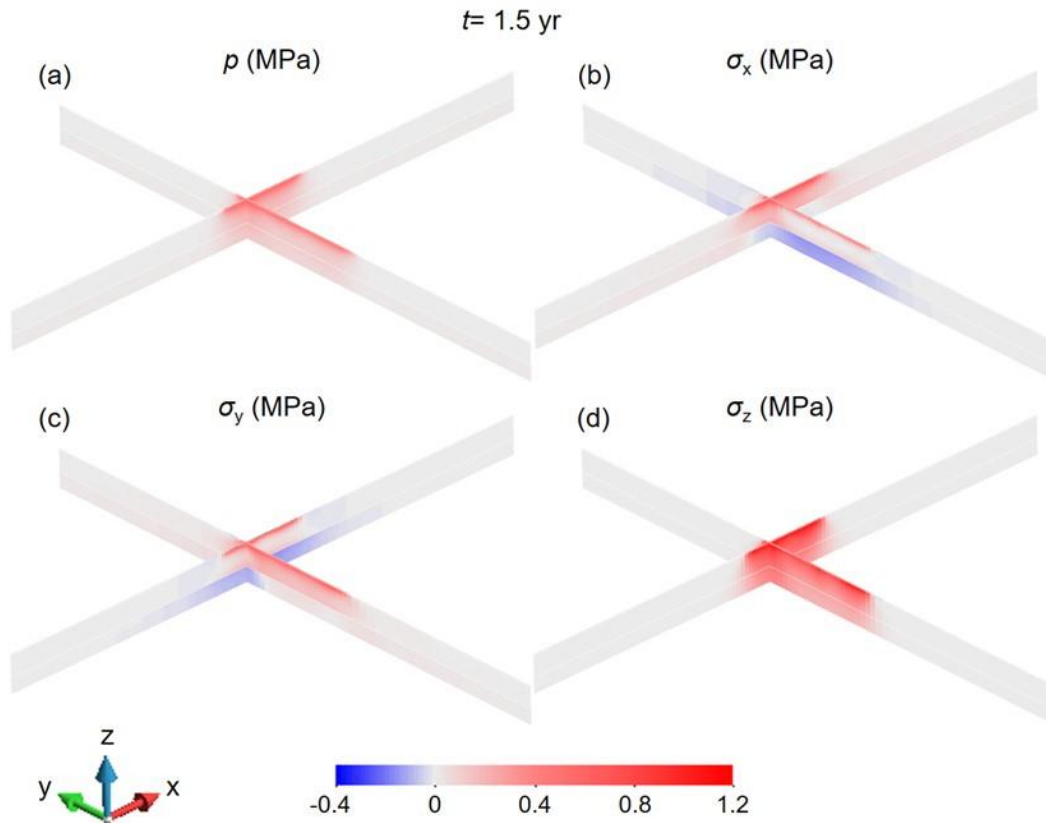


Figure 2.13. Changes in **(a)** pore pressure, **(b)** horizontal stress in the x direction, **(c)** horizontal stress in the y direction and **(d)** vertical stress at the time of the 1995 M3.5 earthquake below the reservoir along the N-S (y coordinate corresponding to section BB' in Figure 2.9) and E-W directions (x coordinate, corresponding to section AA' in Figure 2.9).

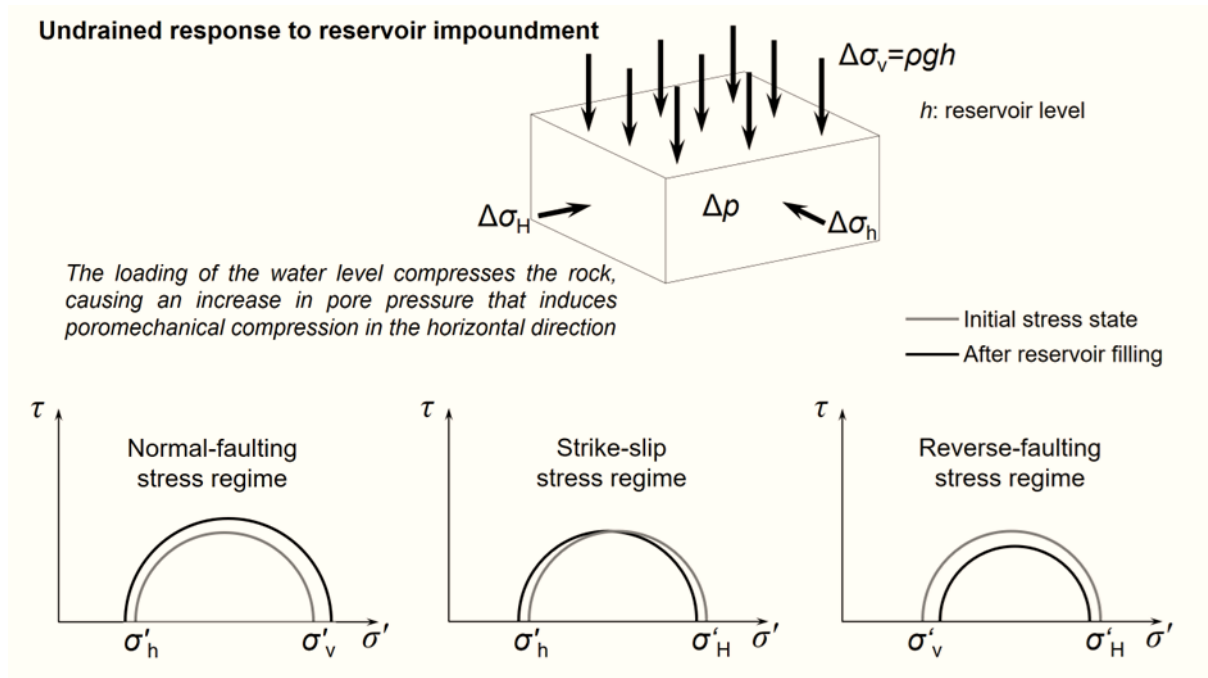


Figure 2.14. The types of effective stress changes triggered by reservoir impoundment for normal-faulting, strike-slip, and reverse-faulting stress regimes.

To the best of our knowledge as well as from literature review, there is no published focal mechanism of the 1998 M4.0 earthquake. This main and delayed event 1998 M4.0 earthquake was located southwest of the 1995 M3.5 initial earthquake, with this region there is absence of seismicity between these two earthquakes (Figure 2.4). This soundless region put forward that the earthquakes were nucleated in different faults or that they belong to different patches of the same fault separated by an aseismic section. In the last mentioned case, the fault orientation could be slightly different from that of the 1995 M3.5 earthquake and needed a higher destabilization, i.e., higher ΔCFS , to nucleate the earthquake. Such higher destabilization can be achieved by **(1)** re-equilibration of fluids from the compressed to the dilated area (Nur & Booker, 1972; Bosl & Nur, 2002; Gavrilenko et al., 2010; Vilarrasa et al., 2021) or **(2)** a delayed increase in pore pressure by diffusion from the reservoir. Thus, we examine here the second possibility. By putting schist permeability of 10^{-17} m^2 , the time required to reach

the depth of the 1998 M4.0 earthquake, i.e., 3.0 km deep, is around 3,000 years. Thus, a high-permeable pathway, like a permeable fault, should be present to hydraulically connect the reservoir with the fault that nucleated the 1998 M4.0 earthquake. The required permeability to reach 3.0 km in 4.5 years is $6.6 \cdot 10^{-15} \text{ m}^2$. By supposing the local orientation of the maximum horizontal stress, i.e., azimuth of 42° (Assumpção et al., 1997), the most critically oriented fault is a vertical strike-slip plane with strike 72° and left-lateral displacement. For such plane, the ΔCFS after 4.5 years of the start of impoundment has positive values below and to the southwest of the reservoir (Figure 2.15). Thus, a fault with an orientation similar to this critically stressed plane could have nucleated the 1998 M4.0 earthquake provided that a high-permeability pathway exists between the reservoir and the deep fault.

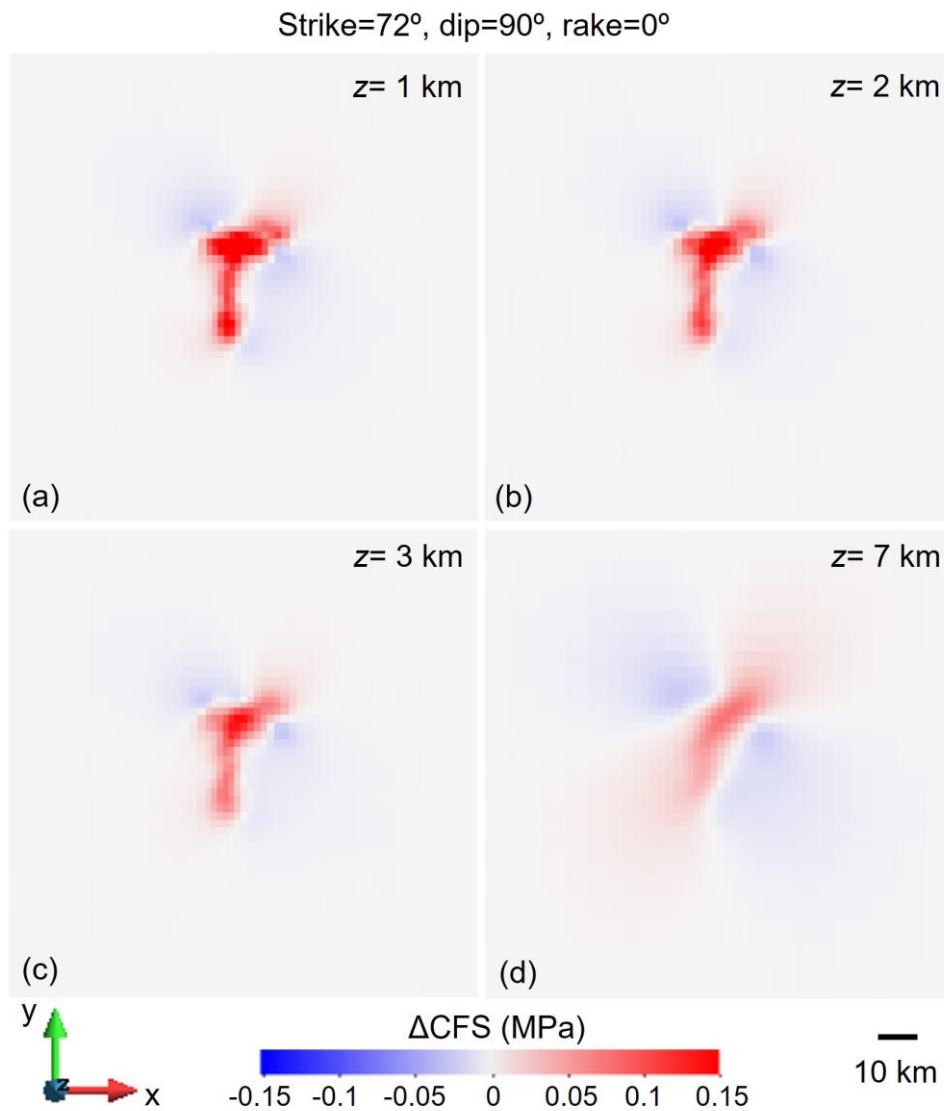


Figure 2.15. The Coulomb Failure Stress (ΔCFS) changes for a plane with strike 72°, dip 90° and rake 0°, which is the most critically-stressed plane for the local orientation of the maximum horizontal stress at Nova Ponte, i.e., an azimuth 42°, at the time of the delayed response of RTS :1998 M4.0 at **(a)** 1 km, **(b)** 2 km, **(c)** 3 km and **(d)** 7 km deeper, for the case of schist rocks permeability equal to $8 \cdot 10^{-15} \text{ m}^2$. The positive values showing ΔCFS has at the location of the earthquake, i.e., south-west of the dam approximately 3.0 km deep.

Triggered events are expected to occur within regions undergoing destabilization, i.e., positive ΔCFS values. Given the limited information on the focal mechanism of most events, we compute the ΔCFS in the nodal plane with strike 190° , dip 46° and rake 168° proposed by Marza et al., 1997 for the M3.5 earthquake. Most of the seismicity coincides with the regions with positive ΔCFS (Figure 2.16). Such correlation highlights that our model captures the spatiotemporal response of the subsurface to reservoir impoundment at Nova Ponte.

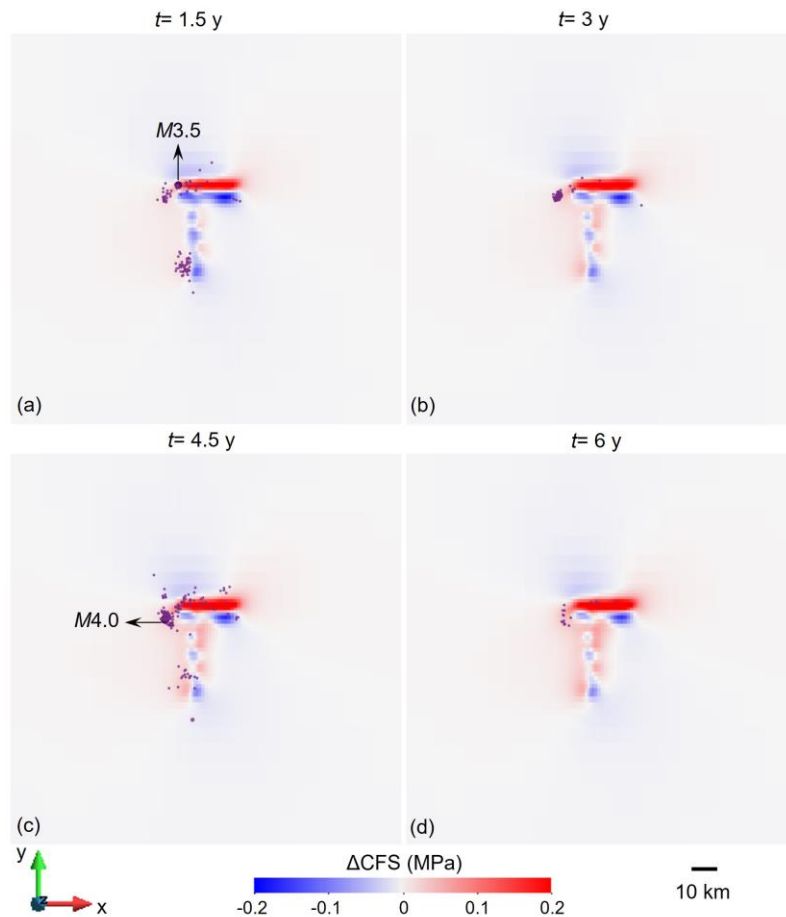


Figure 2.16. Evolution of the changes in Coulomb Failure Stress (ΔCFS) at (a) 1.5, (b) 3.0, (c) 4.5 and (d) 6.0 years after the start of reservoir impoundment, at a depth of 2.5 km for the nodal plane with strike 190° , dip 46° and rake 168° proposed by Marza et al., 1997 for the M3.5 earthquake.

2.5 Discussion

It is prime important to reduce the risk of induced/triggered seismicity, especially large felt earthquakes, is critical for the successful implementation of dam safety projects, both because felt events have a negative effect on public perception and because large events may pose risks to the dam strength and other infrastructure. The process of managing reservoir-triggered seismicity is to perform primarily site characterization, selection, and continuous monitoring to reduce subsurface uncertainties and carry out a real-time risk assessment of triggered seismicity (Langenbruch et al., 2020; Vilarrasa et al., 2021).

Interpretation to understand and forecasting RTS is a challenging task. Two types of stress modifications are believed to be responsible for RTS. One is the rapid undrained response to the loading of the reservoir (from P1 to P2 in Figure 2.17) and the other one is the delayed effect due to the pore pressure diffusion (from P3 in Figure 2.17) (Talwani, 1997). The delay in the pore pressure build-up due to diffusion depends on the hydraulic diffusivity of the rock. The scheme can be applied to explain the RTS at the Nova Ponte reservoir. The initial seismicity was likely due to the rock's undrained response to the reservoir impoundment, while the delayed seismicity that includes the 1998 M4.0 earthquake was due to pore pressure diffusion that brought a pre-existing critically stressed fault to failure conditions. To hydraulically connect the reservoir with the depth of the earthquakes in the Araxá group of schist rock, high-permeability conduits or faults should vertically cross the low-permeability schist. We infer that the vertical permeability of such faults should be at least $6.6 \cdot 10^{-15} \text{ m}^2$, which falls within the typical permeability range that explains RTS, i.e., from $5 \cdot 10^{-16} \text{ m}^2$ to $5 \cdot 10^{-14} \text{ m}^2$ (Talwani et al., 2007). The fact that the nodal plane that better explains the 1995 M3.5

triggered event is a vertical plane (Figure 2.12) could explain the presence of such a fault. Nonetheless, faults crossing relatively soft and clay-rich geomaterials usually present a low permeability enhancement along the fault core and damage zone (Vilarrasa et al., 2022). For awareness and better understanding the hydrogeological properties of the rock layers below the Nova Ponte reservoir, detailed characterization should be performed to identify the faults that triggered the seismicity and their permeability as well possible physical properties.

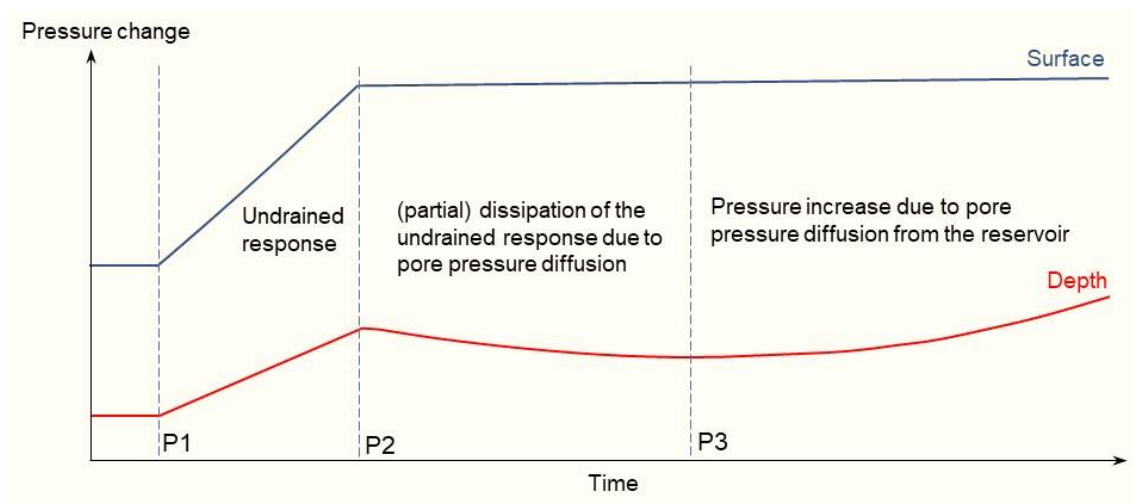


Figure 2.17. The evolution of pore pressure showing by schematic representation depth: initial pore pressure build up as an undrained response to reservoir impoundment (from P1 to P2), (partial) dissipation of excess pressure (from P2 to P3) and delayed response increase by pressure diffusion from the reservoir (from P3).

The presented study as well as investigation is an important step forward in the development of predictive seismic hazard models to understand the casual mechanism of the triggered seismicity. In this study by performing numerical simulations of a 3D reservoir model, we compute the pore pressure, stress and stability changes and identify the nodal plane that is more prone to slip at Nova Ponte. In our search for the nodal plane that nucleated the triggered seismicity, we started with a simpler reservoir

geometry that consisted of a single rectangle. With such geometry, the fault stability changes induced by the pore pressure and stress changes did not convincingly explain the monitored triggered seismicity. To adopting by a T shape of the reservoir (see Figures 2.4 and 2.9), our findings suggest that simulation results show that the nodal plane that triggered the 1995 M3.5 earthquake was the plane with strike 272° , dip 89° and rake 42° (Figure 2.14). This presented model also reveals the importance of accounting for the different rock types that are found below the reservoir. Figure 2.13 clearly shows that the stress changes differ significantly at the interface between the Araxá group and the crystalline basement. Including the crystalline basement in predictive models should enable forecasting deep seismicity within the hydraulically disconnected crystalline basement.

2.5.1 Pore pressure changes due to diffusion-drained response

The perturbation in stress could have occurred due to changes in the pore pressure caused by the loading of the Nova Ponte reservoir. Talwani (1995) presents an “intersection model” that suggests the intersection between two or more NW–SE trending faults and major NNE–SSW/N–S features and fractures. Such intersections could be responsible for the stress build-up. So this hypothesis suggests the conceptual model of RTS at Nova Ponte (Figure 2.18). The general most prominent RTS example suggested by Rajendran and Harish (2000) is that the Koyna fault is mature and gets weakened due to the annual loading reservoir. The failure occurs in this fault due to small changes in stress under high fluid pressure. Talwani (2000) suggested that the rocks in the region and generally in the RTS region are critically stressed and a small change in strength can cause a large earthquake.

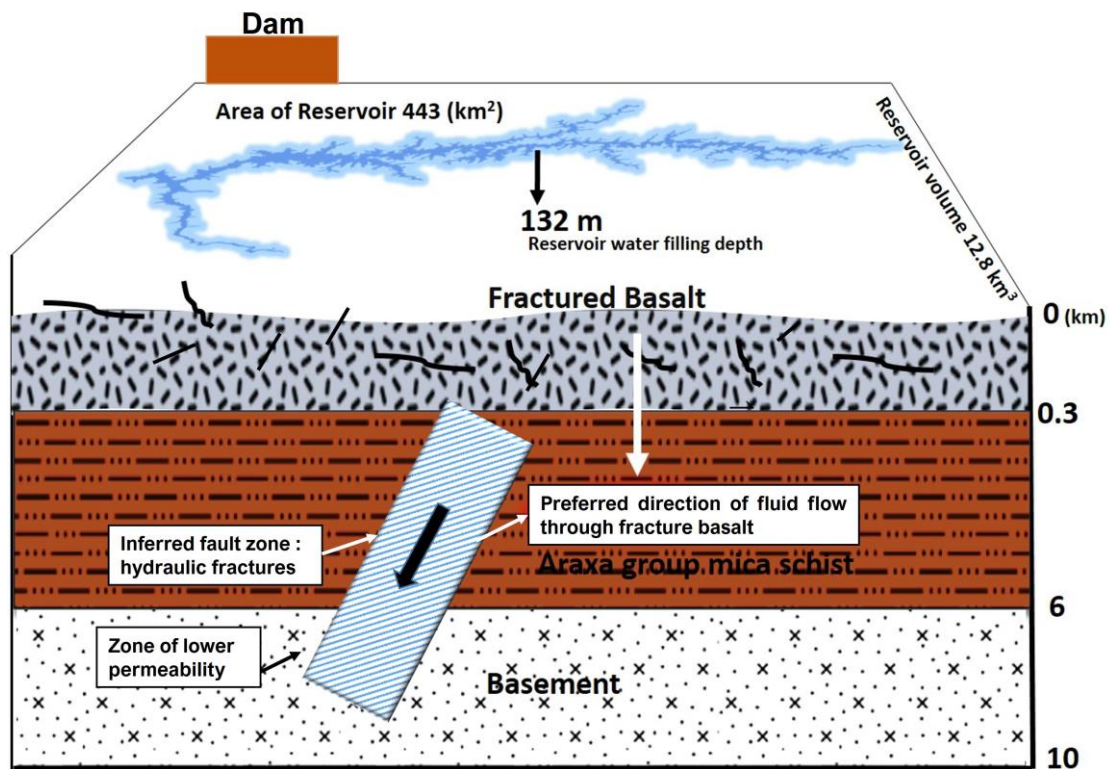


Figure 2.18. Schematic diagram illustrating the geological and hydrological conditions at the Nova Ponte reservoir region. The top layer of basalt and schist is assumed to permit flow through vertical fractures. A perpetually weakening fault zone that is hydraulically connected to the reservoir is the most important feature of this model.

To mitigate and manage the risk of RTS requires reliable forecasting models that include the physics of the problem, i.e., capable of reproducing the undrained response of the subsurface to reservoir impoundment and pore-pressure diffusion, and the geological rock layers and features like faults and regional stress of the areas to correlate the fault trends. By building such a model requires a thorough characterization prior to reservoir impoundment, and preferably, before dam construction to identify the potential high hazard of inducing moderate to large earthquakes. Except the hydro-mechanical properties of the rock layers, i.e., permeability, porosity and stiffness, are well characterized, as well as the presence of pre-existing faults and their permeability

and strength, anticipating undesired RTS is unfeasible. Hence, future efforts should be directed towards achieving comprehensive information of the subsurface to manage RTS in future.

2.6 Conclusions

We have investigated the causal mechanisms of the RTS at Nova Ponte, which represents the second-largest RTS event in Brazil. The simulation results of a coupled hydro-mechanical 3D model that includes the geological layers of the site have revealed that the nodal plane that nucleated the 1995 M3.5 earthquake was a vertical plane with E-W orientation and reverse left-lateral displacement. This initial seismicity was caused by undrained poromechanical changes of the subsurface in response to reservoir impoundment. To this comparison, the delayed seismicity with the 1998 M4.0 earthquake was likely triggered by pore pressure diffusion that pressurized a critically stressed fault at 3.0-km depth. For pore pressure diffusion to reach the depth of the hypocentre, a pathway with permeability higher than $6.6 \cdot 10^{-15} \text{ m}^2$ should cross the schist where the earthquake was nucleated. The vertical fault of the 1995 M3.5 event could have enabled pore pressure propagation at depth. Our model highlights the importance of including a realistic geometry to the reservoir as well as a detailed representation of the subsurface, including the rock layers present below the reservoir. Anticipating such models with these features should be able to reliably forecast RTS.

C **HAPTER 3**

RESERVOIR-TRIGGERED SEISMICITY

OF M3.0 AT IRAPE

3.1 Geological aspects at Irapé

The area of Irapé is inserted in the domain of the Pre-Folding Belt, cambrian Araçuaí, oriented approximately in the N-S direction, which defines the eastern part of the São Francisco Craton in the State of Minas Gerais (Almeida, 1977).

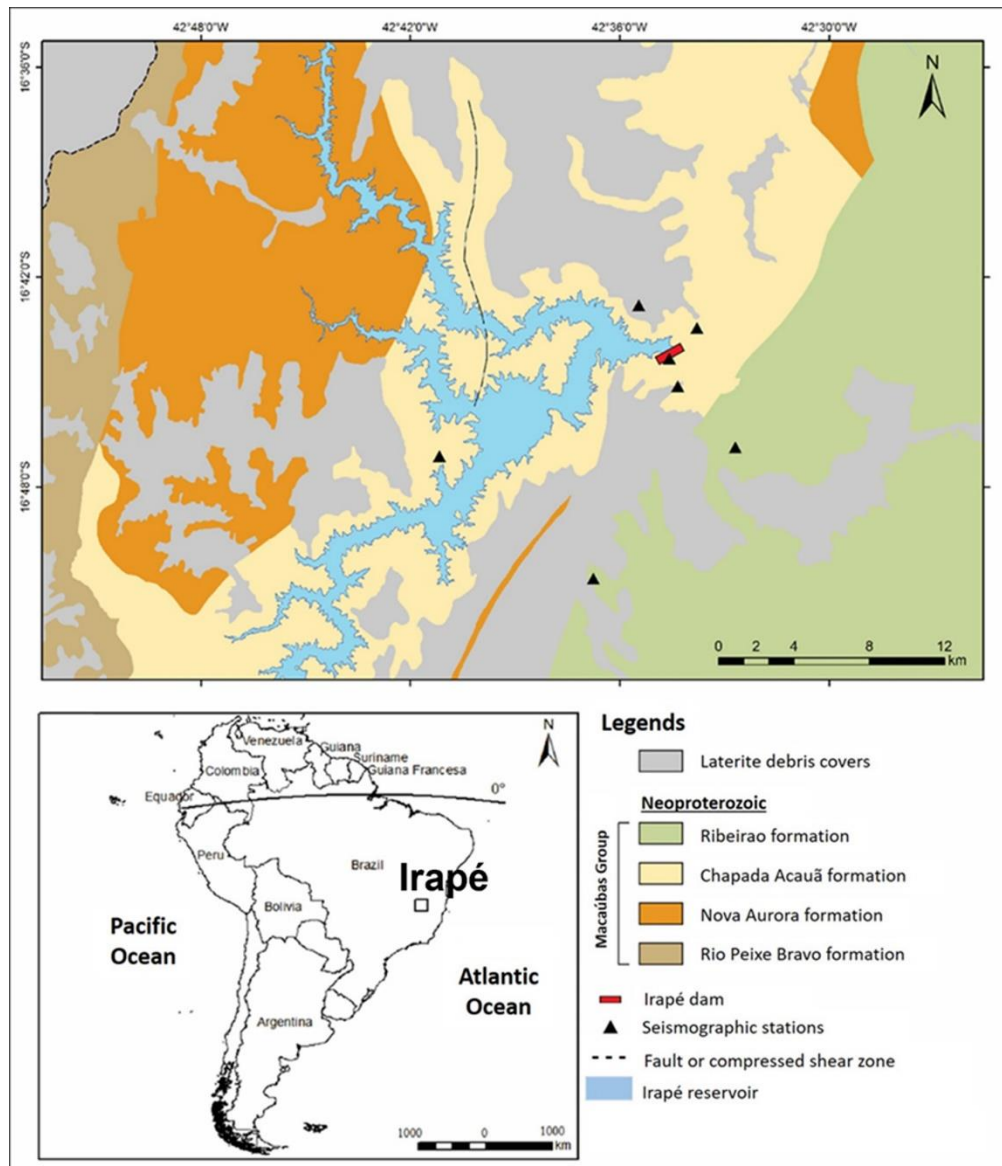


Figure 3.1. Geological map of Irapé reservoir and surrounding area (created after Silva et al., 2014).

The rocks present around the reservoir of Irapé in a structure of contraction faults of the ductile regime of approximate direction N-S, with inclined to the west (direction

São Francisco Craton), developed during the collision of the São Francisco Craton with the Congo Craton. Two deformational phases of the ductile regime were identified, associated with the development of two schistose and consequent folding (Silva et al., 2014).

Formation occurs in Chapada Acauã, composed of meta-diamictites, phyllites, and graphite schists, locally with garnet. It represents, together with the Nova Aurora Formation, typical sedimentation of passive margin associated with deposition in the Macaúbas basin. To the east, the Chapada Acauã Formation Ribeirão da Folha Formation, consisting of mica shales, metaritmitos, quartzite and calc-silicates rocks. The Ribeirão da Folha Formation was divided from the Salinas Formation by Lima (2002), the latter being composed of mica schists and meta-grauvacas, and not belonging to the Macaúbas Group due to geochronological divergence between them. So, the Salinas Formation remains as sediment of the type flysch associated with the Araçuaí Orogen (Figure 3.1).

The Nova Aurora Formation was described as pelitic protolith schist and polymictic metadiamictite, with a composition rich in iron (hematite, magnetite, and iron hydroxides), aluminium and potassium, reaching high greenschist facies (garnet zone). It may consider that the development of a crenulation cleavage, attributed by Marshak et al., (2006) because of the change in the direction of efforts at the time of the collapse of the Araçuaí-Western Congo Orogen and post-kinematic garnet crystals later growing, including opaque minerals, cutting off foliation. The Chapada Acauã Formation consists of carbonaceous mica-schist, locally with pyrite, garnet, or graphite. It is investigated near the Irapé Shear Zone (Araujo et al., 2010). This rock intensely deformed, with the formation and rotation of quartz sub-grains, migration of grain edges.

3.2 Background on reservoir-triggered seismicity at Irapé

The Irapé reservoir covers an area of 137.8 km². The dam was constructed on the Jequitinhonha River, filling the reservoir to a maximum height of 137 meters (Figure 3.1, 3.2 and Table 3.1). The dam area was monitored by a three-component seismic network at three stations prior to 3 years of its impoundment which started on 7 December 2005. This network did not detect any seismicity before the impoundment (Chimpliganond et al., 2007).



Figure 3.2. Photo of Irapé Hydroelectric power plant surrounded by mica-schist rocks, photo taken during the fieldwork.

Table 3.1. Characteristics of the main RTS event at Irapé (França et al., 2010).

Dam height (m)	Length (m)	Volume (km ³)	Max. reservoir water depth (m)	Reservoir area (km ²)	Seismicity type	Date	Magnitude (mR)	Io (MMI)	ΔT (yr)
208	540	5.964	137	137.8	Initial	14 May 2006	3	III-IV	0.5

ΔT : interval time (years) since the start of filling/impoundment; MMI: modified Mercalli scale.

However, one day after the beginning of the impoundment microearthquakes start detected and more than 300 micro-earthquakes have been recorded by October 2006. The largest event occurred on 14 May 2006 with a magnitude of 3 that was felt at the reservoir area (Chimpliganond et al., 2007; França et al., 2010). The seismicity was in a small area with hypocentres in the lake and on its margins (less than 3 km from the narrow lake), near the dam axis. The clear time correlation between the start of the impoundment of the lake and the occurrence of seismicity shows a causative relationship for this seismicity (Figure 3.3). The spatial distribution of the epicentres also concludes that this is another case of reservoir-triggered seismicity in Brazil of the initial response type. Therefore, it is a clear RTS case of undrained response of reservoir loading (Table 3.1 and Figure 3.3).

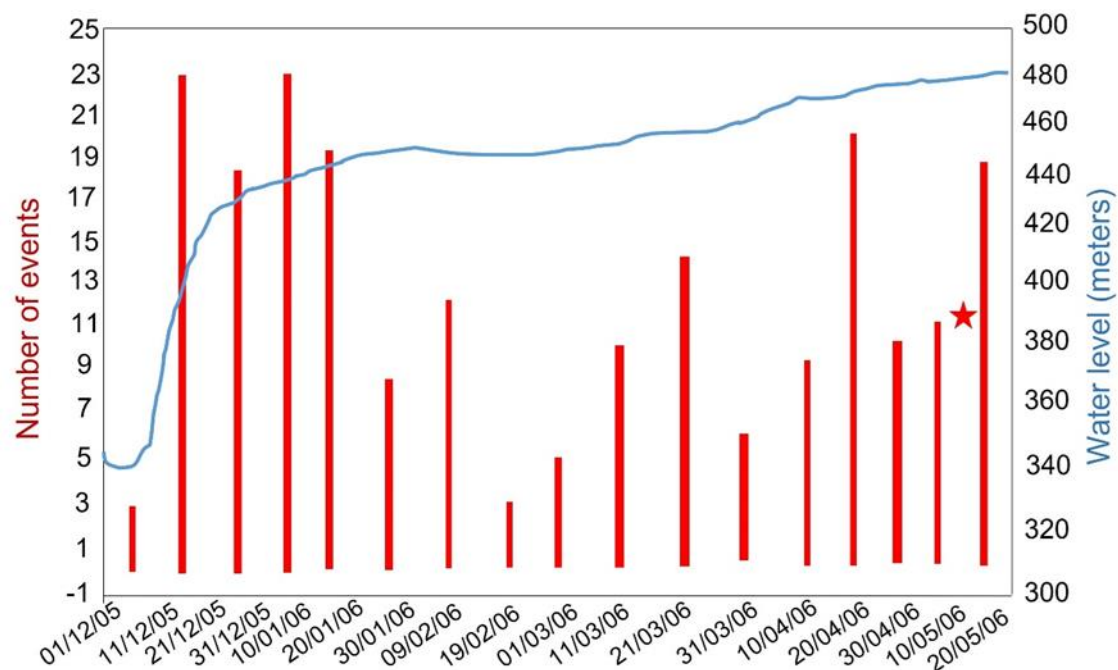


Figure 3.3 Temporal evolution of RTS at Irapé. Number of events during December 2005 to May 2006 (histogram) at Irapé and average water elevation above the mean sea level (blue line) are illustrated. The red star indicates the period where the main and largest event occurred M3.0 on 14 May 2006 (modified from Silva et al., 2014).

The events were analyzed using the program Seismic Analysis Code (Goldstein and Snoke, 2005), where the arrival of the P and S waves and the polarity were performed. The events that were recorded by three stations were highlighted in grey and their hypocentral location was performed by the program HYPO71 (Lee and Lahr, 1975). These were used in the joint interpretations. The analysis of seismograms went through a double-checks routine (Silva et al., 2014).

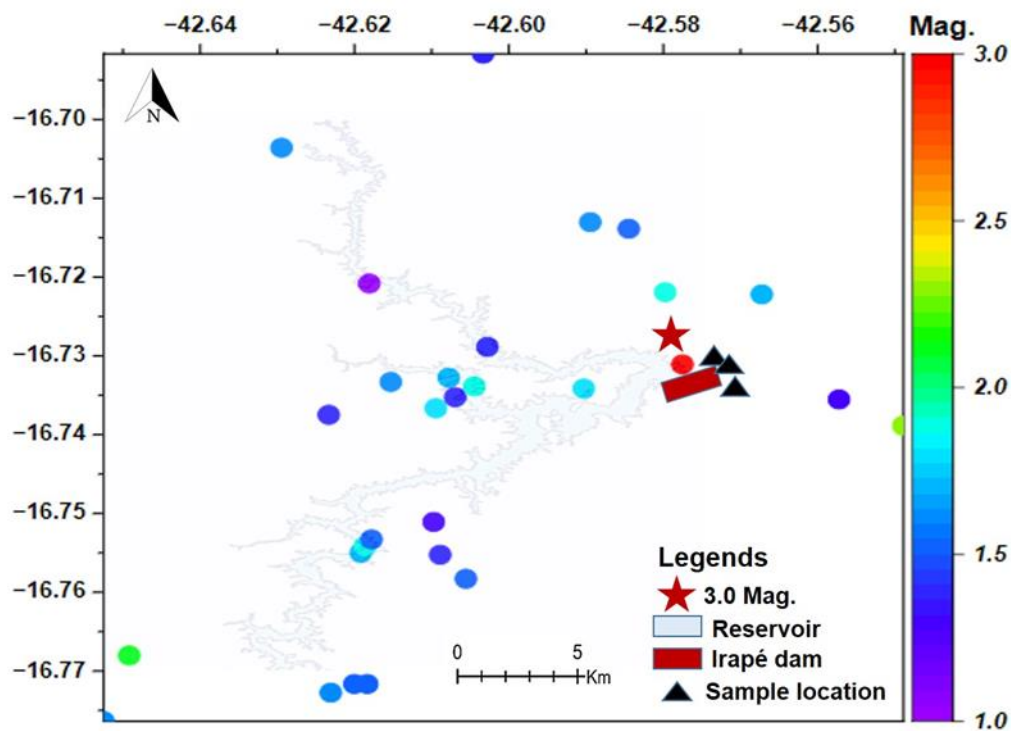


Figure 3.4. Distribution of earthquakes (RTS) in the initial period with location and magnitude according to their colour of occurrence, the red star is the main event felt near the dam and black triangle denoting the samples location.

We selected 29 main events that occurred between 7 January to 15 May 2006 (Figure 3.4), which followed the filling of the Irapé reservoir. These earthquakes were recorded by two or three stations simultaneously and due to this small number of records, this change significantly reflects the accuracy of the epicentral location.

Velocity models were adopted based on a deep seismic refraction survey in combination with local geological interpretations and studies of the crustal structure in south-eastern Brazil to locate seismic events in the Irapé area (Assumpção et al., 2012). The local velocity model consists of a superficial 4.8 km-thick layer with a P wave velocity (V_p) of 4.5 km/s, representing the mica-schist to graphite-schist rocks from surface and second layer schist to crystalline schist rocks has thickness about 11.2 km with P wave velocity (V_p) of 6 km/s (Marshak et al., 2006; Silva et al., 2014).

The repetition of a structural trend in the NE-SW directional trends from the geological and geophysical structuring of the crust (Silva et al., 2014). Therefore, the estimated normal faulting stress regime has been considered in the Irapé region. However, the accuracy of the focal mechanism is unambiguous. The accuracy of the focal mechanisms remains debated because of the low quality of the recorded seismic data by analog seismograms and uncertainties associated with the velocity model. Due to the same reasons, the focal mechanisms of the May 14, 2006, M3.0 earthquake have not yet been resolved (Silva et al., 2014).

3.3 Methodology

Firstly, we inspected the Irapé sites and surrounding areas as well as the outcrop. The dam area is surrounded by mica-schist rock, which is shiny, ranging from blackish to medium grey in colour, with foliated, fine to medium-grained textures. According to the local velocity model, there is a superficial layer that is 4.8 km thick, representing mica-schist to graphite-schist rocks at the surface. Below that, there is a second layer that is 11.2 km thick, consisting of schist to crystalline basement rocks. Measurements from these samples will be crucial for understanding the estimated permeability beneath the subsurface in the context of the main event, which occurred at a depth of 3.88 km

(França et al., 2010). Since the epicenter of the main event was located about 1 km from the dam, we collected bulk rock samples from different locations around the dam, as well as nearby outcrop, by digging pits that were 0.10 meters deep (Figure 3.4 and Figure 3.5).

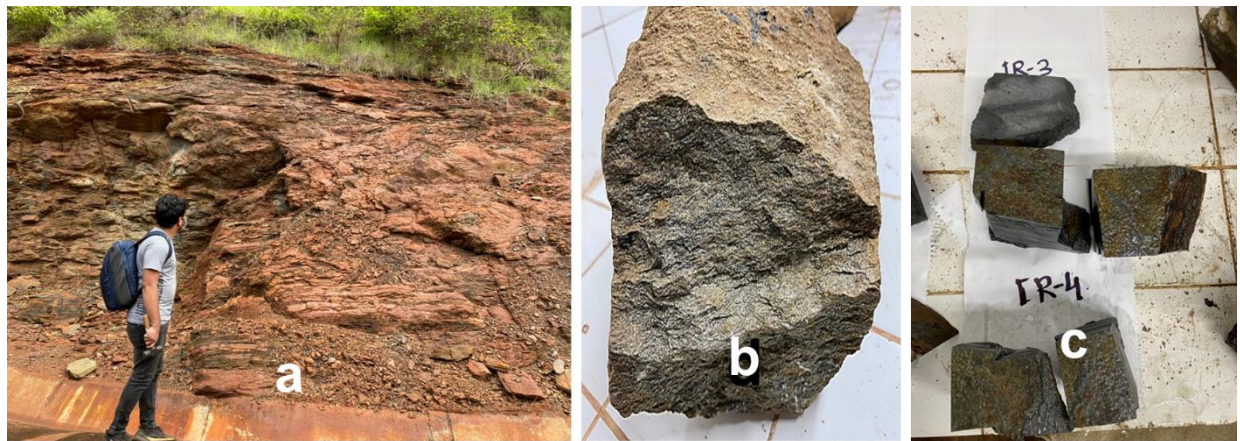


Figure 3.5 (a) Outcrop of mica-schist near the Irapé dam (photos taken during the field trip) (b) bulk sample extracted from the dam area (c) cutting and washing of bulk samples to retrieve the core plugs.

3.3.1 Laboratory experiments

We have extracted cylindrical core samples perpendicular to the bedding plane of mica-schist rock. We have performed tests on three sets of samples, with a total of 11 samples, of hard and intact samples because the rest of the samples were fragile and fractured during the coring from bulk samples (Table 3.2). The retrieved cylindrical plugs have a length ranging from 3.8 to 5.0 cm and a diameter of 2.50 cm, which meets the International standard criteria (Core Lab) to measure core plug samples by Ultra-Pore 300 and Ultra-Perm 610 (Figures 3.6 and 3.7).

We conducted porosity measurements using the Ultra-Pore 300, which is manufactured by Core Lab Instruments in Texas, USA. The Ultra-Pore 300 is a gas

expansion helium pycnometer specifically designed for determining the grain volume or pore volume of both core plug and full-diameter samples. However, there is no weight loss observed during the measurements. To achieve this, we utilized matrix cups designed for samples with diameters ranging from 2.5 to 3.8 cm, equipped with a Setra 204 transducer rated for pressures ranging from 0 to 1.72 MPa. We determined the pore volume using the nitrogen gas (N₂) expansion technique (API,1998; Ceia et al., 2019).

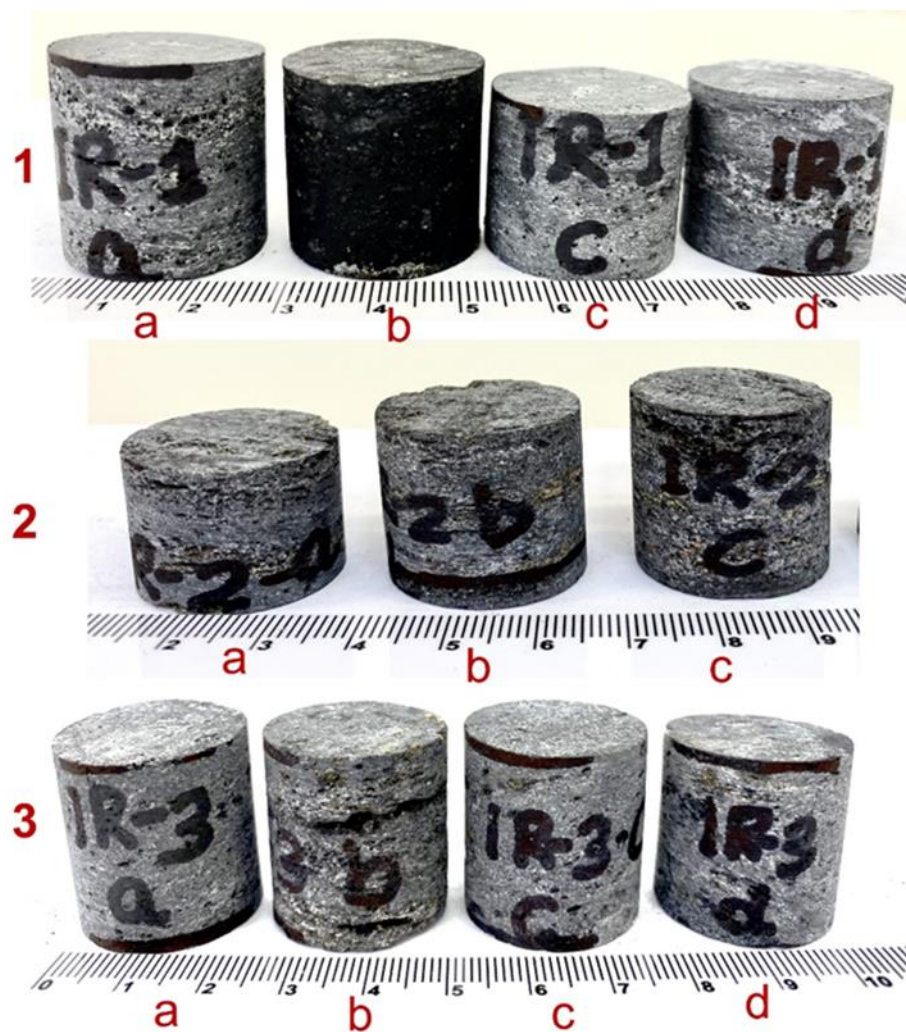


Figure 3.6. The figure shows the three sets of mica-schist rock samples (1,2, and 3) after cylindrical coring from bulk samples ($\perp$ coring of cylindrical plug done by loaded perpendicular to bedding plane).



Figure 3.7. Ultra-Pore 300 Porosimeter with matrix cup and analysis plugs

Our study relies on laboratory experimental results obtained through routine and special core analyses. In routine core analysis, we determined porosity and tested samples. During the special core analysis, we specifically determined capillary pressure data for the tested samples. We describe the experimental procedures employed to determine the properties of mica-schist rock. To estimate the absolute porosity of the eleven (11) tested samples, we utilized the ULTRAPORE-300 system, as depicted. Porosity in a rock is mathematically defined (Figure 3.7).

The ULTRAPORE-300 system software, known as WINPORE, computed the grain volume, pore volume, and grain density of the samples. The testing procedure used was also instrumental in determining the grain volume and pore volume.



Figure 3.8. Ultra-Perm 610 gas permeameter with pressure sample saturator (Core Lab Instruments).

Permeability is expressed as the ability of a medium to transmit fluid and is greatly influenced by the porosity of the medium. There are various methods of measuring a rock sample's permeability. Widely and most common method is the steady-state flow method, which is based on Darcy's law. We measure the intrinsic permeability of rock samples using Ultra-Perm 610 Permeameter. This precision equipment, which controls backpressure, maintains a constant rate or mean pressure at 0.69 MPa. Before testing, samples are cleaned with soxhlet equipment and toluene, followed by drying in an oven. The permeability measurements included a permeameter, nitrogen source, stopwatch, a core holder, a bubble tube, and a digital calliper. The core holder is pressurized to 3.45 MPa confining pressure using compressed air. The bubbles passing through a burette are timed, and outflow gas volume is recorded. The permeability is calculated using

Darcy's law, considering core dimensions. Hard rock core samples, like mica-schist, require long stabilization times due to the low permeability (Figure 3.8).

3.3.2 Analytical calculations of undrained pore pressure and stress changes

Reservoir impoundment causes an undrained effect in the subsurface that manifests as an instantaneous pore pressure and stress changes below the reservoir (Skempton, 1954). The change in the vertical stress, $\Delta\sigma_v$, equals the weight of the water level rise. The horizontal stress, assuming isodometric conditions, changes proportionally to pore pressure changes as (Rutqvist, 2012)

$$\Delta\sigma_h = \alpha \frac{(1-2\nu)}{(1-\nu)} \Delta p, \quad (1)$$

where $\Delta\sigma_h$ is the horizontal stress change, α is Biot's coefficient, ν is Poisson's ratio and Δp is the pore pressure change. Additionally, in an isotropic and homogeneous poroelastic material subject to undrained conditions, the change in pore pressure resulting from a change in stress can be computed as (e.g., Rice and Cleary, 1976; Cocco and Rice, 2002)

$$\Delta p = -\frac{B}{3} \Delta\sigma_{kk}, \quad (2)$$

where $\Delta\sigma_{kk} = \Delta\sigma_v + 2\Delta\sigma_h$ is the stress change and B is the Skempton's coefficient of mica-schist rock (Roeloffs, 1988). Equations (1) and (2) constitute a system of two equations with two unknowns. Its resolution yields the undrained pore pressure change as:

$$\Delta p = \frac{B}{3} \frac{\Delta\sigma_v}{\left(1 - \frac{2B\alpha(1-2\nu)}{3(1-\nu)}\right)}. \quad (3)$$

3.3.3 Analytical calculations of the time at which the pore pressure diffusion front reaches the depth of the earthquake

The advancement of the pore pressure front within the subsurface is controlled by diffusivity

$$D = \frac{k\rho g}{\mu S_s} \quad (4)$$

where, D is diffusivity, k is the intrinsic permeability, ρ is water density, g is gravity, μ is water viscosity, and S_s is the specific storage coefficient. The time at which the pore pressure front reaches a certain distance r is given by

$$t = \frac{r^2}{D} . \quad (5)$$

3.4 Results

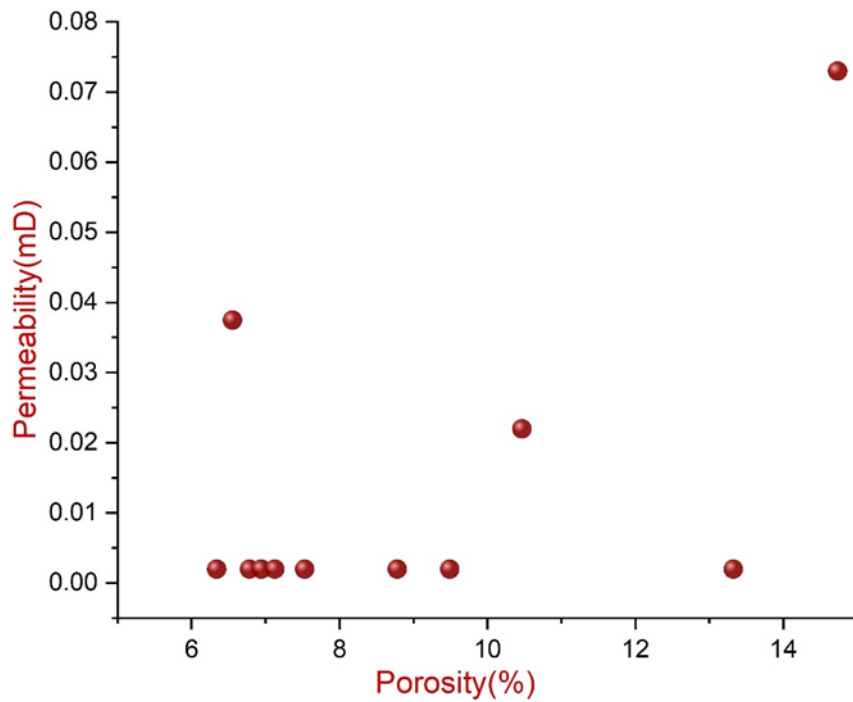
3.4.1 Porosity and permeability measurements

The results of our laboratory measurements are provided in Table 3.2. These data are subject to measurement uncertainties inherent to the experimental equipment used according to the standard procedure. Laboratory measurements of samples of mica-schist reveal a low permeability (Table 3.2 and Figure 3.10). The maximum permeability is 0.0098 mD, but most of the samples present a permeability below the precision of the apparatus, i.e., lower than 0.002 mD. Such permeability is in the range of low-permeability rock, which act as a barrier to flow. Most of the samples have a porosity between 6 to 10%, except for two with higher porosity. The low permeability of mica-schist could be explained by the fact that the larger pores are not well connected (Figure 3.10). In general, there is no correlation between permeability and porosity (Figure 3.9).

Table 3.2. Location of samples with permeability and porosity data from measured cores.

Sample location (lat., long.)	Sample Numbers	Permeability (mD)	Porosity (%)
16.73872	IR-1a	0.002	7.529
42.57680	IR-1b	0.002	6.785
	IR-1c	0.002	8.781
	IR-1d	0.0098	6.555
16.74038	IR-2a	0.002	9.490
42.57652	IR-2b	0.0038	10.465
	IR-2c	0.0038	14.734
16.72438	IR-3a	0.002	6.943
42.56316	IR-3b	0.002	13.323
	IR-3c	0.002	7.126
	IR-3d	0.002	6.340

⊥ Experiments loaded perpendicular to bedding plane.

**Figure 3.9.** Porosity-permeability relation of mica-schist rock samples.

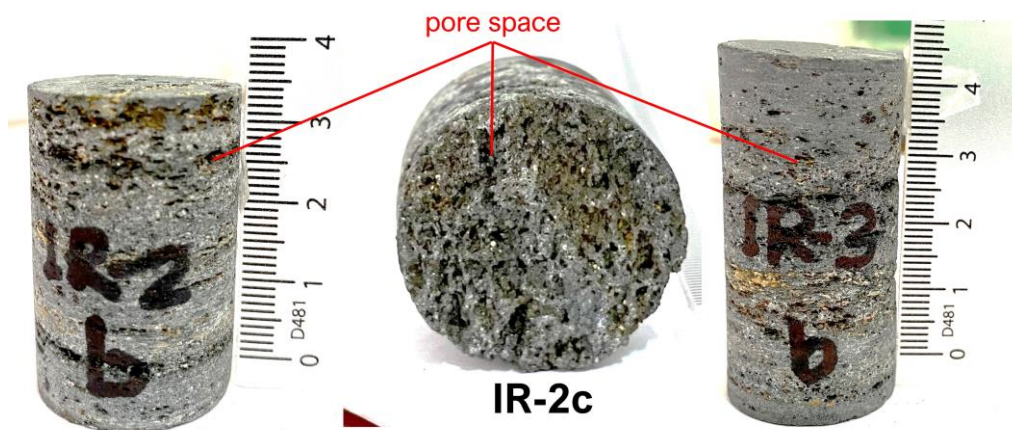


Figure 3.10. Megascopic representation of samples IR-2 b, c, and IR-3b showing pores that are not well-connected.

3.4.2 Undrained response of rock: changes in pore pressure and stress

The 136 m of water level increase at the time of the M3.0 earthquake resulted in an increase in the vertical stress of 1.36 MPa. To compute the pore pressure change caused by the reservoir impoundment, the Biot coefficient, Skempton's B coefficient and Poisson's ratio of mica-schist are needed (Eq. (3)). Since such measurements are not available, we adopt the values of Opalinus Clay because it is a similar rock to mica-schist. Thus, we assume Skempton's B coefficient of 0.92, undrained Poisson's ratio of 0.39 and Biot's coefficient of 1. With these values, the resulting pore pressure change is 0.54 MPa. Consequently, the horizontal stress change is of 0.19 MPa (Eq. (1)). These pore pressure and stress changes result in a vertical effective stress increase of 0.82 MPa and a horizontal effective stress decrease of 0.34 MPa, increasing the deviatoric stress in more than 1 MPa.

3.4.3 Pressure diffusion along mica-schist

The measured intrinsic permeability of mica-schist is in the order of 10^{-18} m^2 (Table 3.2). Assuming a specific storage coefficient in the order of $1.05 \times 10^{-6} \text{ m}^{-1}$, diffusivity

(Eq. (4)) results in $9.5 \times 10^{-6} \text{ m}^2/\text{s}$. Taking into account that the depth of the M3.0 earthquake occurred at 3.8 km, the time at which the pore pressure front would reach this depth by diffusion (Eq. (5)) is in the order of 50,000 years.

3.5 Discussion

RTS has been the focus of many studies, but the origin and development of RTS are still unclear in many cases (Gupta et al., 2016; Arora et al., 2018). There is a general consensus that there are two main triggering mechanisms (Simpson et al., 1988). On the one hand, low-permeability rock has an undrained response to the water-level changes of the reservoir, which acts as a loading, instantaneously increasing pore pressure and causing poroelastic stress changes deep underground (Chen and Talwani, 2001; Vilarrasa et al., 2022; Raza et al., 2023). On the other hand, in the presence of permeable rock or a permeable fracture network, pore pressure diffuses downwards, which may eventually trigger an earthquake if a critically stressed fault becomes pressurized (Talwani and Acree, 1985).

At Irapé, the low-permeability of the rock below the reservoir, i.e., mica-schist with permeability in the order of 10^{-18} m^2 or lower, hinders pore pressure diffusion. Given that the hypocentre was located at 3.88 km depth, the pressure propagation front would take in the order of 50,000 years to start pressurizing the depth at which the earthquake was nucleated. Even assuming that the presence of fractures enhanced the rock permeability by three orders of magnitude, which would be the upper limit of observed permeability enhancement of low-permeability rock at the field scale (Neuzil, 1986), the pressure front would take 50 years to reach 3.88 km depth. The necessary permeability of the rock to reach the depth of the largest earthquake within 0.5 years, i.e., the delay of the earthquake with respect to the start of impoundment, would be of 10^{-13} m^2 , five

orders of magnitude higher than the actual permeability of mica-schist. Such high permeability enhancement is deemed unlikely.

Considering the load caused by the water-level rise in the reservoir of 136 m, the low-permeability mica-schist experienced an undrained response, with subsequent poroelastic stress and pore water changes. We have estimated these changes analytically, finding a vertical effective stress increase of 0.82 MPa, a horizontal effective stress decrease of 0.34 MPa, and a pore pressure increase of 0.54 MPa. Given the normal faulting stress regime at Irapé, these changes cause an increase in the deviatoric stress that could destabilize faults in the subsurface. These changes in pore pressure and stress levels provide valuable insights into the dynamic behaviour of the geological formation and are crucial considerations in understanding the reservoir response to alterations in reservoir water levels. We contend that the rapid loading of the reservoir weakens this fault because of the undrained stress and pore pressure changes (Figure 3.11).

In addition, the megascopic representation of core samples in the configuration of the physical evidence illustrates that rock can exhibit relatively high porosities and low permeability when their pores are not well-connected (Figure 3.10). Thus, mica-schist may present preferential lateral fluid migration at depth, following the foliation direction. The surface rock beneath the Irapé reservoir is highly metamorphosed and generally has good porosity and low permeability. Therefore, pore pressure diffusion is disregarded as the potential cause triggering the seismicity at Irapé.

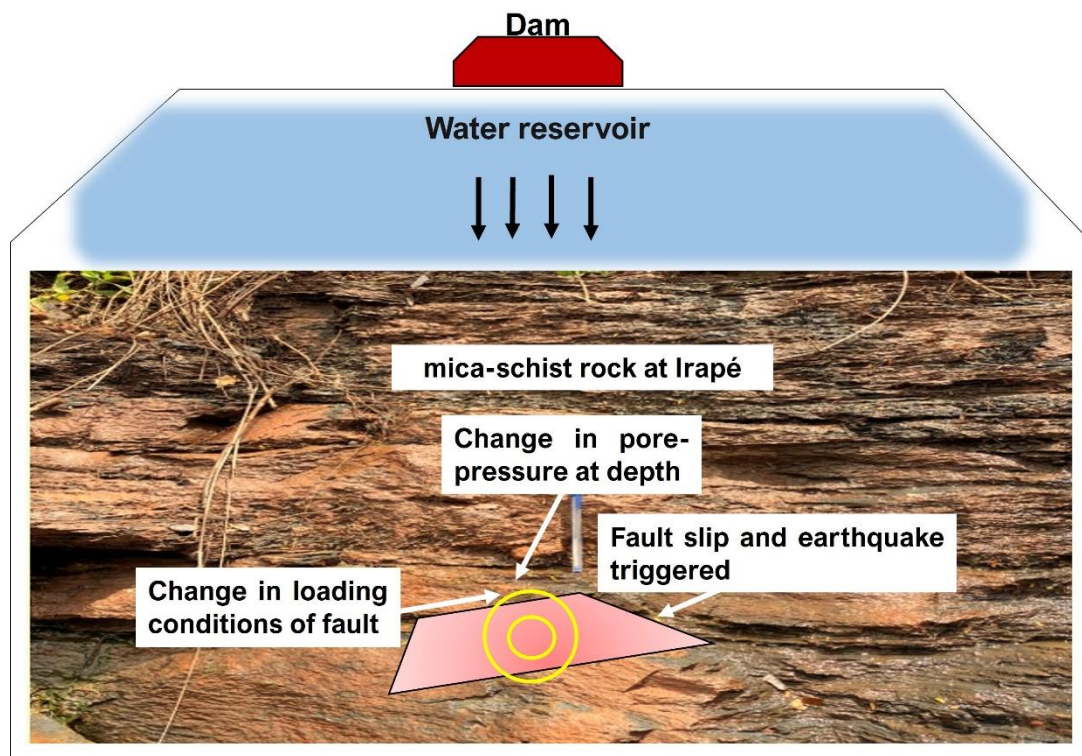


Figure 3.11. Schematic description of the mechanism of RTS at Irapé, indicating the effect of the weight of the reservoir water volume due to undrained response in low-permeable mica-schist rock (the background photo was taken in the field from an outcrop at Irapé).

The regional geology at the eastern part of the São Francisco Craton in the State of Minas Gerais follows a N-S direction (Almeida, 1977) and Silva et al., 2014 also mentioned that the repetition of a structural trend in the NE-SW direction originates from the geological and geophysical structuring of the crust. Figure 3.1 showing fault or compressed shear zone along the reservoir. These trend makes it feasible to assume the existence of a N-S vertical mature fault that could become destabilized by small changes in the effective stress. An association of such seismicity with the shear zone along reservoir /lineaments suggests the reactivation of these faults under the influence

of reservoir impoundment. We contend that the instant loading of the reservoir weakens this fault because of the stress and undrained pore pressure changes (Figure 3.11).

To mitigate the risk of RTS, it is crucial to thoroughly characterize the site by measuring rock physical properties. Analytical and numerical solutions should integrate the physics of the problem, such as poromechanics to assess both the undrained response of the subsurface to reservoir impoundment and pore-pressure diffusion. Such models should include the rock layers below the reservoir down to the crystalline basement and their characteristics, including features like faults. Before the construction of the dam, the hazard of triggering moderate to large earthquakes should be estimated, to disregard locations with high probability of RTS. This estimation requires knowing the hydro-mechanical properties of the rock layers, i.e., permeability, porosity, stiffness, and strength, as well as the design parameters of the dam, i.e., height. The successful management of RTS requires an interdisciplinary approach combining concepts of hydrogeology, geomechanics and seismology.

3.6 Conclusions

We have analysed RTS at Irapé to discern the cause of the triggered seismicity. The measured low permeability of the rock at Irapé disregards pore pressure diffusion as the triggering mechanism and suggests that the M3.0 RTS was triggered by the undrained response of the subsurface to reservoir impoundment. Analytical calculations estimate that pore pressure increased by 0.54 MPa in response to an increase of 136 m in the reservoir-water level. The resulting vertical effective stress increased by 0.82 MPa and the horizontal effective stress decreased by 0.34 MPa. Thus, the deviatoric stress would increase in a normal faulting stress regime, like the one at Irapé, destabilizing the fault and causing RTS. Both laboratory measurements and analytical calculations support the

hypothesis that the initial seismicity was triggered by the undrained response of the subsurface to the loading of the reservoir at Irapé. This study also suggests that the occurrence of such earthquakes may be avoided by carefully manipulating reservoir loading.

C **HAPTER 4**

GENERAL CONCLUSIONS

AND FUTURE SCOPE

4.1 Summary

The new results by modeling approach have been obtained for the Nova Ponte region in Brazil, which demonstrates that it is a clear case of reservoir-triggered seismicity. The availability of a seismic network in the study region has enabled numerical modeling, computing pore pressure, assessing fault stability, compute necessity of permeability to connect reservoirs with depths and focal mechanism solutions for the first time in this region. Finally, poroelastic modeling and Coulomb stability analysis clearly show the role of reservoir impoundment in triggering seismicity in this region.

Our investigation by numerical simulations to gain in-depth understanding of the mechanism by the conceptual 3D reservoir model suggests that stress shows changes in three components (x, y, and z directions). Simulation results of a 3D model of the site have revealed that the nodal plane that nucleated the 1995 M3.5 earthquake was a vertical plane with E-W orientation and reverse left-lateral displacement. This model highlights the importance of including a realistic geometry to the reservoir as well as a detailed representation of the subsurface, including the rock layers present below the reservoir.

The proposed methodology can be used not only to identify and understand the triggering mechanisms of RTS (as we have done in this study), but also to forecast potential triggered earthquakes during site selection, dam design and during the operation of the reservoir. For example, by computing ΔCFS in planes that could be favourably oriented to undergone reactivation given the local stress state, the regions that will be destabilized, i.e., positive ΔCFS , can be identified. Then, efforts on subsurface characterization can concentrate in these regions to identify deep faults that could trigger moderate earthquakes. If faults with potential to trigger damaging

earthquakes are identified, the site could be considered of high risk and disregarded during the screening process of finding proper locations for building dams. Otherwise, studies can continue further until the site is considered appropriate. The mapped faults should be included in numerical models to forecast potential RTS because the reactivation of a fault may lead to the destabilization of nearby faults through static stress transfer. Thus, including all the available geological and hydrogeological information in numerical models is crucial to increase the accuracy of their predictions. 3D numerical models that solve the coupled hydro-mechanical problem including rock layers and mapped faults can certainly reproduce the two main triggering mechanisms of RTS: the rapid undrained response of the subsurface to loading caused by reservoir impoundment and the delayed pore pressure diffusion. Such models would have been of help in 8 out of the 29 cases of RTS in Brazil which presented initial and delayed RTS. Nova Ponte is one of the classic examples of initial followed by delayed RTS. With a M4.0, Nova Ponte is the second-largest RTS in Brazil, certainly exceeded by new dams if a detailed study of the RTS hazard is not performed beforehand. Thus, both the effects of the rapid undrained response to reservoir loading and the delayed effect of pore pressure diffusion should be taken into account in future simulations.

We present primary permeability-porosity data in RTS at Irapé, which represents well known instant and initial response of M3.0 RTS and the highest dam in Brazil as well as second-highest dam in South America. We report porosity values ranging from 6.340 to 14.734% and permeability ranging from 0.002 to 0.0098 millidarcy (mD), near the RTS zone. This low permeability suggests an undrained response of the subsurface.

This study explores the challenges associated with reservoir-triggered seismicity (RTS) at the Irapé site, a significant consideration in the transition from fossil fuels to

renewable energy, particularly hydropower. The study investigates the main RTS event at Irapé, emphasizing the geological setting and rock characteristics near the reservoir. Permeability and porosity tests on rock samples reveal low permeability, discounting pore pressure diffusion as the triggering mechanism for the M3.0 RTS. Analytical calculations suggest that undrained subsurface response to reservoir impoundment was the likely cause. The study focusing the importance of thoroughly characterizing the rock properties to mitigate RTS risk, for analytical and numerical solutions integrating poromechanics to assess subsurface response and pore-pressure diffusion.

4.2 Future Scope and mitigation

The present study of Nova Ponte (chapter 2) marks a major jump in the current understanding of the more comprehensible RTS, geological aspects, local velocity structure, faulting mechanism, depths, and the mechanism of reservoir-triggered seismicity of the two major event that is initial and delayed response. Accuracies of focal mechanism solutions need more broadband seismic waveform data. Modeling of fault stability assumes that the medium around the reservoir is homogeneous, while it may be heterogeneous.

While the second case study Irapé RTS of M3.0 (Chapter 3) also marks the potential causes in the current understanding of the more understandable RTS such as geological aspects of this region, depths of main events, and the mechanism of reservoir-triggered seismicity. The primary laboratory measurements and analytical calculations support the hypothesis that make major jump RTS at Irapé.

After all, in general it is great importance to investigate the cause of reservoir-triggered earthquake and recognize them after the earthquake. Nevertheless, the earthquake is induced/triggered by a variety of coupling effects, so it is important to

conduct and gain in-depth study in combination with seismic engineering, geological tectonic, elastic-plastic mechanics and other contemporary method/discipline. Eventhough many attainment have been made through the continuous efforts by researcher throughout the world, but still there are many insufficiency to the recognition of Reservoir-triggered earthquakes.

Although reservoir-triggered earthquakes are different from tectonic earthquakes in various seismological parameters, because of complication and unreliability of earthquakes, there is still had probability of probabilistic method to distinguish reservoir-triggered earthquakes by some specified seismological parameters. Simultaneously, this probability method is still dimensionally empirical, and it cannot be disfavored under special conditions. For that reason, this method cannot fully distinguish RTS from tectonic earthquake.

Even though the possibility of reservoir-triggered earthquake can be recognized, there is still no ultimate solution. Such as like, what kind and area of reservoir is easy to induce or triggered earthquake and whether it needs to be demolished? Is it important to avoid building a large dam, a certain type of reservoir in future construction? What kind of reservoir will be built under what geological conditions such as rock types below the reservoir? Along with others and these, we need to put forward solutions.

From the past literature, there are few examples of reservoir-triggered earthquakes contrasting with tectonic earthquakes. The gathered data are insufficient, the discrimination method is relatively single and due to lack of experimental method for the time being. Therefore, existing caesareans should be analyzed before there are no new reservoir-triggered earthquakes by installing seismometers surrounding the reservoir and the abundance of induced/triggered cases is insufficient. If a liberated

model of each reservoir is established and substantial database is aggregated according to different geological conditions and rock types, the capacity and storage and filling time during reservoir impoundment, not only the reservoir operation can be under observation in real time, but also adequate data can be provided to gain in depth study for scientific researchers who carry out research on RTS. So, it will be a great asset to promote the development of reservoir-triggered earthquake research for future prospectives.

Induced/triggered earthquakes by elevating water pressure in micro-cracks and fissures beneath and around a reservoir. Increasing water pressure lubricates faults already strained by tectonic forces, overcoming friction that prevents slipping.

Geological variations at dam sites make earthquake prediction challenging due to unique characteristics around the world-wide. The International Commission on Large Dams is concerned, that RTS should be considered for reservoirs that are deeper than 100 meters. New reservoirs can trigger earthquakes through stress changes caused by water weight or heightened groundwater pore pressure, reducing rock strength.

4.2.1 Probing reservoir-triggered earthquakes through deep scientific drilling

It is important to understand and study the RTS phenomenon more closely and precisely by contemporary methods for future perspectives. Therefore, there are several investigations going on throughout the world in which the study of RTS by deep scientific drilling is one of the most advanced methods that has been suggested to gain knowledge in depth as well as to mitigate the RTS.

The San Andreas Fault Observatory (SAFOD) at Depth. The aim of SAFOD is to anticipate direct observational data on the composition, physical state, and mechanical

behaviour of rocks in a primary active fault zone at depth to test hypotheses concerned with faulting and generation of earthquakes. This hypothesis governs supportive research for future prospective to study worldwide-induced seismicity through deep scientific drilling programs (Zoback et al., 2011) (Figure 4.1). To know the character of the main fault zone (young/mature) and to locate appropriate sites for deep drilling, the following recommendations can be made:

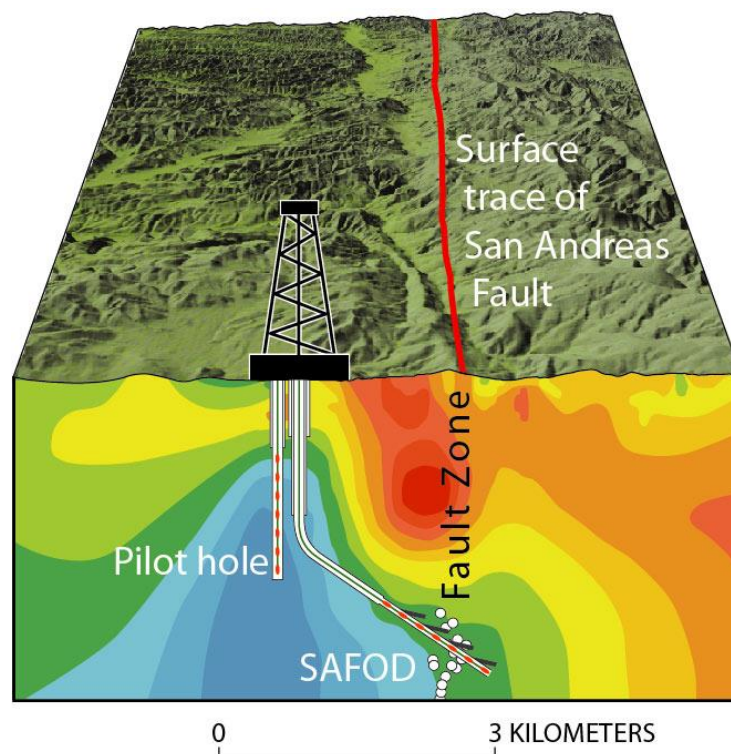


Figure 4.1. The schematic cross-section of the San Andreas Fault Zone at Parkfield, intimate the drill hole for the San Andreas Fault Observatory at Depth (SAFOD) and the pilot hole drilled in 2002. The sites of monitoring instruments are shown in drill holes in red dots. The represent in white of determined minor seismicity at depths of 2.5 to more than 10 km. The subsurface colours show the electrical resistivity of the rocks as dogged from surface surveys. The minor earthquakes may constitute a fluid-rich zone at the lowest-resistivity rocks in red colours (Zoback et al., 2011).

1. How fluid pressure and permeability behave within and adjoining to the fault zone?
2. How is the 3-D/4-D nature of the fault zone?

By deployment of a vertical string of borehole seismometers below at maximum depth to obtain precise hypocentre locations. By conducting hydrological monitoring (pore pressure, fluid conductivity, and temperature) in available exploratory boreholes, if possible.

The following suggestions should be adopted to investigate subsurface structural /fractures /tectonic analysis through detailed studies on cores and cuttings:

1. Orientation of the cores with the image logs
2. Comprehensive study of the brittle deformation in the existing cores
3. Use logs (primarily image logs) to create fracture intensity profiles.
4. Conduct experimental deformation test from basement as well as the depth of RTS from core samples in the laboratory, and compare the physical properties of surface rocks to basement core samples

4.2.2. The operation and Reservoir-triggered seismicity feedback

To mitigate the risk of RTS, it is crucial to thoroughly characterize the site by measuring rock physical properties. Analytical and numerical solutions should integrate the physics of the problem, such as poromechanics to assess both the undrained response of the subsurface to reservoir impoundment and pore-pressure diffusion. Such models should include the rock layers below the reservoir down to the crystalline basement and their characteristics, including features like faults. Before the construction of the dam, the hazard of triggering moderate to large earthquakes should be estimated, to disregard locations with high probability of RTS. This estimation requires knowing

the hydro-mechanical properties of the rock layers, i.e., permeability, porosity, stiffness, and strength, as well as the design parameters of the dam, i.e., height. The successful management of RTS requires an interdisciplinary approach combining concepts of hydrogeology, geomechanics and seismology.

Finally, to address and manage RTS risks, the traffic light protocol (TLP) is being employed. In general, TLP initiates the green light as the primary approach allowing operations without restrictions, the yellow light as the point to activate mitigation measures, and the red light as the point necessitating regulatory intervention. The efforts have also begin by linking the configuration of TLPs with risk-oriented measures, infrastructure harm, and the likelihood of loss or damages while adapting them to real-time data. The occurrences that may ensure after an operation are crucial, given their substantial impact on standard risk management. Nevertheless, these methodologies can be revolved around by assessment of events succeeding in the conclusion of an operation. The utilization of physics-based models holds promising by illustrating and projecting anticipated seismic activity, enabling the anticipation of future warnings and risks, and build up the information for operational adjustments and for future mitigation (Boyet et al., 2023b) (Figure 4.2).

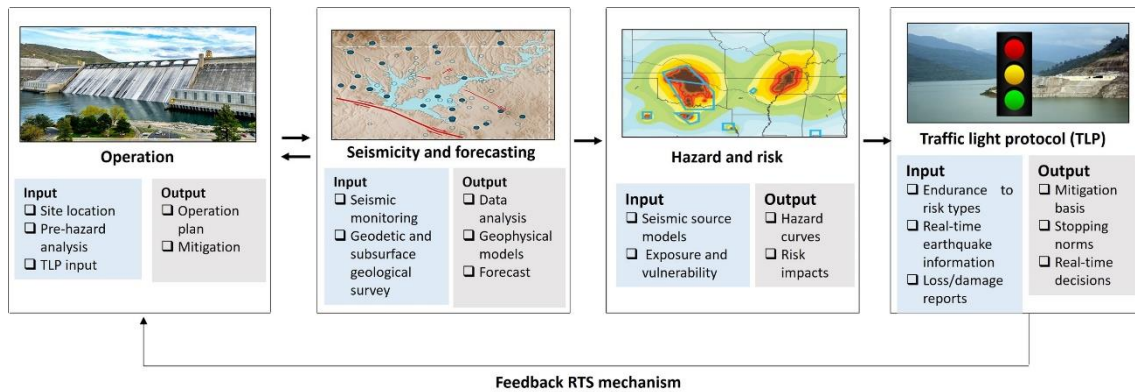


Figure 4.2. Reservoir operations and impoundment are strategically designed to reduce the risk of RTS. Monitoring seismic and geophysical activities yields information for predictive earthquake models. The catalogues of earthquakes and source/origin models are applicable in the assessment of hazard and risk. These assessments of risk and hazard can guide the development of a traffic light protocol (TLP), functioning as a dynamic decision module during operations. The display of each box shows the classifications of input data (blue boxes) and output results (grey boxes).

Regarding the mitigation approaches for RTS within the framework of a TLP, the effectiveness of an operator heavily relies on the efficiency of mitigation strategies implemented at the yellow-light stage. Ideally, these strategies would proficiently diminish seismic risks and hazards, ultimately circumventing the red-light scenario that terminates the operation. Thus, TLPs can be one major strategy and strong decision-making tool for operators to minimize the risk of RTS for future developments of dams.

So, in the above context we can say that Reservoir-triggered seismicity is a serious concern and should be carefully addressed. Seismic activity triggered by the impoundment of water reservoirs for large hydropower dams shows a significant concern. The findings of this study propose that rapid mitigation of RTS is achievable

through the deliberate adjustment of reservoir loading, targeting the identified primary triggering mechanisms. Careful design of the project can lead to acceptably low seismic risk, and with continued focus will provide the reverse public perception of triggered activity so we believe this trend can continue in the future. The phased approach provides and can assist operators in effectively managing seismic risk. Thoughtful project design can result in low seismic risk, thereby positively influencing public perception.

REFERENCES

- Almeida FFM 1977. The São Francisco Craton. *Brazilian Journal of Geosciences*, 7:349-364.
- API, 1998. Recommend Practices for Core Analysis. RP40. American Petroleum Institute. 2nd Edition.
- Araujo Filho, J. O; Silva, G. F; Lima, E. A. M; Ferreirara, V. N; Batista, O. C. A; Franca, G. S. 2010. Mapeamento Geoestrutural da área de influência da Usina Hidrelétrica de Irapé, Grão Mogol, MG. *Anais do 45º Congresso Brasileiro de Geologia, Sociedade Brasileira de Geologia*.
- Araujo Filho, J.O. 1999. Structural characteristics and tectonic evolution of the Pirineus Syntaxes, Central Brazil. PhD Thesis, Univ. of Illinois, USA, 417 p.
- Arora, K., Srinu, Y., Gopinadh, D., Chadha, R.K., Raza, H., Mikhailov, V., Ponomarev, A., Kiseleva, E. and Smirnov, V. 2018. Lineaments in Deccan Basalts: The Basement Connection in the Koyna–Warna RTS Region. *Bull. Seismol. Soc. Amer.*, v.108 (5), DOI: 10.1785/0120180011.
- Assumpção, M., V. I. Marza, L. V. Barros, C. N. Chimpliganond, J. E. Soares, J. M. Carvalho, D. F. Caixeta, A. Amorim, and E. Cabral. 2002a Reservoir-induced seismicity in Brazil, *Pure Appl. Geophys.* 159, 597–617.
- Assumpção, M.; Barbosa, J. R.; Berrocal, J.; Bassini, A. M.; Marza, V. I.; Huelsen, M. G. V. & Ribota, L. C. 1997. Seismicity patterns and focal mechanisms in SE Brazil. *Rev. Bras. Geof.* 15: 119-132.
- Assumpção, M; Feng, M; Tassara, A; Julia, J. 2012. Models of crustal thickness for South America from seismic refraction, receiver functions and surface wave tomography. *Tectonophysics*, 609:82-96.
- Assumpção, Marcelo, James, D., and Snoke, A., 2002b. Crustal thicknesses in SE Brazilian Shield by receiver function analysis: Implications for isostatic compensation, *J. Geophys. Res.*, 107(B1), doi:10.1029/2001JB000422.
- Barton, N. The shear strength of rock and rock joints. 1976. In *International Journal of rock mechanics and mining sciences & Geomechanics abstracts* (Vol. 13, No. 9, pp. 255-279). Pergamon.

- Bell, M.L., Nur, A., 1978. Strength changes due to reservoir-induced pore pressure, stresses, and application to Lake Oro-Berrocal. *J. Geophys. Res.* 83, 4469–4483.
- Biot, M. A., 1941. General theory of three-dimensional consolidation. *J. Appl. Phys.*, 12, 155- 164.
- Bosl, W. J., and Nur, A., Aftershocks and pore fluid diffusion following the 1992 Landers earthquake, *J. Geophys. Res.*, 107(B12), 2366, doi:[10.1029/2001JB000155](https://doi.org/10.1029/2001JB000155), (2002).
- Boyet, A., De Simone, S., Ge, S. et al. 2023. Poroelastic stress relaxation, slip stress transfer and friction weakening controlled post-injection seismicity at the Basel Enhanced Geothermal System. *Commun Earth Environ* 4, 104. <https://doi.org/10.1038/s43247-023-00764-y>
- Boyet, A., De Simone, S., Vilarrasa, V.; Physics-Based Modeling to Understand and to Propose Forecasting Methods of Induced Seismicity. *Seismological Research Letters* 2023; 94 (6): 2666–2678. doi: <https://doi.org/10.1785/0220230109>
- Carder, D. S. (1945). Seismic investigation in the Boulder Dam area, 1940-1944, and the influence of reservoir loading on earthquake activity, *Bull. Seism. Soc. Am.* 35, 175-192.
- Ceia Marco, Roseane Missagia, Ricardo Fasolo, Irineu Lima Neto, 2019. Relationship between porosity, permeability, and pore compressibility; DOI: 10.22564/16cisbgf2019.287
- CEMIG - Minas Gerais Energy Company (2001). Geological observations in the UHE Irapé sector - Consultancy Report. Belo Horizonte, MG, 6p
- CEMIG. Projeto Executivo Geologia. Relatório Final, Vols. 1 e 2, -Estudos Ambientais - Usina Hidrelétrica de Nova Ponte. Leme Engenharia S.A., Belo Horizonte, MG (1990).
- Cesca, S., Braun, T., Maccaferri, F., Passarelli, L., Rivalta, E., and Dahm, T. (2013a). Source modelling of the M5–6 Emilia-Romagna, Italy, earthquakes (2012 May 20–29). *Geophys. J. Int.* 193, 1658–1672. doi: 10.1093/gji/ggt069
- Cesca, S., Grigoli, F., Heimann, S., González, Á, Buforn, E., Maghsoudi, S., et al. (2014). The 2013 September–October seismic sequence offshore Spain: a case of seismicity triggered by gas injection? *Geophys. J. Int.* 198, 941–953. doi: 10.1093/gji/ggu172

- Chander, R., Kalpna (1997). On categorising induced and natural tectonic earthquakes near new reservoirs. *Engineering Geology*, 46, 81-92.
- Chang, K.W., Yoon, H. Permeability-controlled migration of induced seismicity to deeper depths near Venus in North Texas. *Sci Rep* 12, 1382 (2022). <https://doi.org/10.1038/s41598-022-05242-7>
- Chen, L., & Talwani, P. (2001). Mechanism of initial seismicity following impoundment of the Monticello Reservoir, South Carolina. *Bulletin of the Seismological Society of America*, 91(6), 1582-1594.
- Chen, Q., Nur, A., (1992). Pore fluid pressure effects in anisotropic rocks: mechanisms of induced seismicity and weak faults. *Pure Appl. Geophys.* 139, 463–480.
- Cheng AHD Poroelasticity. Book series: Theory and Applications of Transport in Porous Media, Vol.27 Springer, US (2016).
- Chimpliganond, C. N.: Characterization of induced seismicity at the Nova Ponte Reservoir/MG, Brasil, MSc Dissertation, University of Brasilia, Brazil, 2002.
- Chimpliganond, C., G. S. França, A. E. Bandeira, and L. Bevilaqua (2007). Reservoir-triggered seismicity at the highest Brazilian dam, AGU 2007 —Meeting of Americas Joint Assembly Abstract, Acapulco, Mexico, Acapulco, Mexico, 22–25 May.
- Cocco, M., Rice, J.M., 2002. Pore pressure and poroelasticity effects in Coulomb stress analysis of earthquake interactions. *Journal of Geophysical Research* 107. doi:10.1029/2000JB000138
- Cordani, U.G.; Milani, E.J.; Thomaz Filho, A. & Campos, D.A. 2000. Tectonic Evolution of South América, Rio de Janeiro.
- Cornet, F. H., and J. Yin (1995), Analysis of induced seismicity for stress field determination and pore pressure mapping, *Pure Appl. Geophysics.*, 145, 677–700
- CPRM - Mineral Resources Research Company (2004). Project Registration of Groundwater Supply Sources. Jequitinhonha Valley: Diagnosis of the Municipality of Berilo-MG. Belo Horizonte, 43p
- Crane, L. J., & Friedman, A. (1956). The diffusion of chemically reacting systems in a laminar flow of fluid. *AIChE Journal*, 2(2), 186-191

- Developments in Structural Geology and Tectonics, Elsevier, Volume 5, 2019, Pages 119-128,
- do Nascimento, A.F., Cowie, P.A., Lunn, R.J., Pearce, R.G., (2004). Spatio-temporal evolution of induced seismicity at Açú reservoir, NE Brazil. *Geophys. J. Int.*, 158, 1041-1052.
- Do-Nascimento, A. F., Lunn, R. J., & Cowie, P. A. 2005. Numerical modeling of pore-pressure diffusion in a reservoir-induced seismicity site in northeast Brazil. *Geophysical Journal International*, 160, 249–262.
- Durá-Gómez and P. Talwani 2011. Finding Faults in the Charleston Area, South Carolina: 2. Complementary Data' by P. Talwani and I. Durá-Gómez" by R. Marple. *Seismological Research Letters*; 82 (4): 606–608. doi: <https://doi.org/10.1785/gssrl.82.4.606>.
- Durá-Gómez, Pradeep Talwani; 2009. Finding Faults in the Charleston Area, South Carolina: 1. Seismological Data. *Seismological Research Letters* 80(5):883–900. doi: <https://doi.org/10.1785/gssrl.80.5.883>.
- Ellsworth, W. L. (2013). Injection-induced earthquakes. *Science* 341, 1225942. doi: 10.1126/science.1225942
- Evans, M.D., (1966). Man made earthquakes in Denver. *Geotimes* 10, 11 –17.
- Foulger, G. R., Wilson, M., Gluyas, J., Julian, B. R., and Davies, R. 2018. Global review of human-induced earthquakes, *Earth-Sci. Rev.*, 178, 438–514.
- França, G. S., Assumpção, M., Ribotta, L. C., Von Huelsen, M. G., and Chimpliganond, E. C. N., Updated compilation of reservoir triggered seismicity in Brazil, in: 2010 The Meeting of the Americas (AGU – American Geophysical Union), Foz do Iguaçu, Paraná, Brazil, 2010.
- Gahalaut, K., & Chander, R. 2000. Green's function-based stress diffusion solutions in the porous elastic half space for time varying finite reservoir loads. *Physics of the Earth and Planetary Interiors*, 120, 93–101.
- Gavrilenko, P., Singh, C., & Chadha, R. K. 2010. Modeling the hydromechanical response in the vicinity of the Koyna reservoir (India): Results for the initial filling period. *Geophysical Journal International*, 183(1), 461–477.

- Ge, S., M. Liu, N. Lu, J.W. Godt, and G. Luo. 2009. Did the Zipingpu Reservoir trigger the 2008 Wenchuan earthquake? *Geophysical Research Letters* 36: L20315. <https://doi.org/10.1029/2009GL040349>.
- Golstein P. & Snoke A. 2005. "Sac Availability for the Iris Community" Incorporated Institutions for Seismology Data Management Center Eletronic Newsletter. Disponível em: Acesso em: 15 dez 2013. <http://www.iris.edu/news/newsletter/vol7no1/page1.htm>
- González, P., Tiampo, K., Palano, M. *et al.* The 2011 Lorca earthquake slip distribution controlled by groundwater crustal unloading. *Nature Geosci* 5, 821–825 (2012). <https://doi.org/10.1038/ngeo1610>
- Gough, D. I., and Gough, W. I., (1970a). Stress and deflection in the lithosphere near Lake Kariba, 1. *Geophysical Journal*, 21, 65–78.
- Gough, D. I., and Gough, W. I., (1970b). Load induced earthquakes at Kariba. 2. *Geophysical Journal of the Royal Astronomical Society*, 21, 79–101.
- Gregory and Langston 1983 *Photogrammetric Engineering and Remote Sensing*, Vol. 49, No. 4, April 1983, pp. 513-525.
- Grigoli, F., Cesca, S., Rinaldi, A. P., Manconi, A., López-Comino, J. A., Clinton, J. F., *et al.* (2018). The November 2017 Mw 5.5 Pohang earthquake: a possible case of induced seismicity in South Korea. *Science* 360, 1003–1006. doi: 10.1126/science.aat2010
- Gupta H.K. (2016) Triggered Earthquakes. In: Bobrowsky P.T. (eds) *Encyclopaedia of Natural Hazards. Encyclopaedia of Earth Sciences Series*. Springer, Dordrecht. doi.org/10.1007/978-1-4020-4399-4_55
- Gupta, H. K., K. Arora, N. P. Rao, S. Roy, V. M. Tiwari, P. *et al.*, 2016. Investigations of continued reservoir triggered seismicity at Koyna, India, *Geol. Soc. Lond. Spec. Publ.* 445, 151–188.
- Gupta, H. K.: 2002. A review of recent studies of triggered earthquakes by artificial water reservoirs with special emphasis on earthquakes in Koyna, India, *Earth-Sci. Rev.* 58, 279–310, [https://doi.org/10.1016/S0012-8252\(02\)00063-6](https://doi.org/10.1016/S0012-8252(02)00063-6).
- Gupta, H.K., Rastogi, B.K., Narain, H., (1972a). Common features of the reservoir associated seismic activities. *Bull. Seismol. Soc. Am.* 62, 481– 492.

- Gupta, H.K., Rastogi, B.K., Narain, H., (1972b). Some discriminatory characteristics of earthquakes near the Kariba, Kremasta and Koyna artificial lakes. *Bull. Seismol. Soc. Am.* 62, 493– 507.
- He, L., Sun, X., Yang, H., Qin, J., Shen, Y., & Ye, X. (2018). Upper crustal structure and earthquake mechanism in the Xinfengjiang Water Reservoir, Guangdong, China. *Journal of Geophysical Research: Solid Earth*, 123, 3799–3813. <https://doi.org/10.1029/2017JB015404>
- International Commission on Large Dams (2011) World Register of Dams. <http://www.icold-cigb.org>
- International Journal on Hydropower and Dams (2012) World Atlas and Industry Guide. Wallington
- Jones, SC. 1972. A Rapid Accurate Unsteady-State Klinkenberg Permeameter. *Society of Petroleum Engineers Journal*. SPE3535-PA. p. 383-397. October
- Kaiser, J., 1953. *Arch. Eisenhüttenwesen* 24, 43–45 (in German)
- Kalpna, Chander, R., (2000). Green's function based stress diffusion solution in the porous elastic half space for time varying finite reservoir loads. *Physics of the Earth and Planetary Interiors*, 120, 93-101.
- Keranen, K. M., Savage, H. M., Abers, G. A., and Cochran, E. S. (2013). Potentially induced earthquakes in Oklahoma, USA: Links between wastewater injection and the 2011 Mw 5.7 earthquake sequence. *Geology* 41, 699–702. doi: 10.1130/G34045.1
- Keranen, K. M., Weingarten, M., Abers, G. A., Bekins, B. A., and Ge, S. (2014). Sharp increase in central Oklahoma seismicity since 2008 induced by massive wastewater injection. *Science* 345, 448–451. doi: 10.1126/science.1255802
- Kim, K.-H., Ree, J.-H., Kim, Y., Kim, S., Kang, S. Y., and Seo, W. (2018). Assessing whether the 2017 Mw 5.4 Pohang earthquake in South Korea was an induced event. *Science* 360, 1007–1009. doi: 10.1126/science.aat6081
- King, G. C., Stein, R., & Lin, J. (1994). Static stress changes and the triggering of earthquakes. *Bulletin of the Seismological Society of America*, 84(3), 935–953.
- Kivi, I. R., Boyet, A., Wu, H., Walter, L., Hanson-Hedgecock, S., Parisio, F., and Vilarasa, V.: 2023. Global physics-based database of injection-induced seismicity, *Earth Syst. Sci. Data*, 15, 3163–3182, <https://doi.org/10.5194/essd-15-3163-2023>.

- Kivi, I.R., Pujades, E., Rutqvist, J., Vilarrasa, V. 2022. Cooling-induced reactivation of distant faults during long-term geothermal energy production in hot sedimentary aquifers. *Scientific Reports*, 12, 2065. <https://doi.org/10.1038/s41598-022-06067-0>.
- Langenbruch, C., Ellsworth, W. L., Woo, J.-U., & Wald, D. J. 2020. Value at induced risk: injection-induced seismic risk from low-probability, high-impact events. *Geophysical Research Letters*, 47, e2019GL085878. <https://doi.org/10.1029/2019GL085878>.
- Lee, M.-K. & Wolf, L.W., 1998. Analysis of fluid pressure propagation in heterogeneous rocks: Implications for hydrologically induced earthquakes, *Geophys. Res. Lett.*, 25, 2329–2332.
- Lee, W. H. K; Lahr, J. C, 1975. HYPO 1971 (revised a computer program for determining hypocentre, magnitude and first motion pattern of local earthquakes. USGS, Open file report. 64 p.
- Lima SAA, Martins-Neto MA, Predrosa-Soares AC, Cordani UG, Nutman A. 2002. The Salinas Formation in the Type Area, NE of Minas Gerais: a proposal to review the stratigraphy of the Araçuaí Belt based on sedimentary and metamorphic evidence and U-Pb SHRIMP ages. *Brazilian Journal of Geosciences*, 34(4):491-500.
- Marshak, S; Alkmim, F. F.; Whittington; Pedrosa-Soares, A. C. 2006. Extensional collapse in the Neoproterozoic Araçuaí orogen, eastern Brazil: a setting for reactivation of asymmetric crenulation cleavage. *Journal of Structural Geology*, 28(1):129-147.
- Marza, V. I.; Veloso, J. A. V.; Carvalho, J. M.; Barros, L. V.; & Gomide, L. C. 1997. Reservoir induced seismicity at Nova Ponte (MG): Revisited, *Anais do 50 Congresso Internacional da SBGf*, p. 968-971.
- McGarr, A., Simpson, D., (1997). Keynote lecture: a broad look at induced and triggered seismicity, in *Rockbursts and Seismicity in Mines*, Gibowicz and Lasocki (eds). Balkema, Rotterdam, 1997, 385-396.
- McGarr, A., Simpson, D., and Seeber, L. (2002). 40—Case histories of induced and triggered seismicity. *Int. Geophys.* 81A, 647–661.

- Mogi, K., (1963). Some discussions on aftershocks, foreshocks and earthquake swarms – The fracture of a semi-infinite body caused by an inner stress origin and its relation to earthquake phenomena. *Bulletin. Earthquake Research Institute*, 41, 615–658.
- Neuzil, C. E. (1986). Groundwater flow in low-permeability environments. *Water Resources Research*, 22(8), 1163-1195.
- Nur, A. & Booker, J.R., 1972. Aftershocks caused by pore fluid flow? *Science*, 175, 885–887.
- Olivella S, Gens A, Carrera J, Alonso EE. 1996. Numerical formulation for a simulator (CODE_BRIGHT) for the coupled analysis of saline media. *Engineering Computations* ;13(7):87e112.
- Parisio, F., Vilarrasa, V., Wang, W., Kolditz, O., & Nagel, T., 2019. The risks of long-term re-injection in supercritical geothermal systems. *Nature Communications*, 10(1), 1-11.
- Perosi, F. A. 2000. Refração sísmica profunda no setor sudeste da Província Tocantins. Dissertação de 470 mestrado. IAG-USP.
- Petroleum Related Rock Mechanics 2nd Edition Edited by E. Fjær et al., (2008).
- Pimental, M.M.; Fuck, R.A. & Botelho, N.F. 1999. Granites and the geodynamic history of the Neoproterozoic Brasília belt, Central Brazil: a review. *Lithos*, 46, 463-483
- PLANVALE-Water Resources Master Plan for the Jequitinhonha and Pardo Valleys (1994). Diagnostic Report carried out by Geotécnica and DHV Consultants BV, Annex B, Hydrogeology, 133p.
- Rajendran, K. & Harish, C.M., 2000. Mechanism of triggered seismicity at Koyna: an assessment based on relocated earthquake during 1983-1993, *Curr. Sci.*, 79, 358–363.
- Raza, H., Kivi, I.R., França, G.S. and Vilarrasa V. 2023. Reservoir impoundment-triggered seismicity in Brazil: the case of M4.0 Nova Ponte earthquake. *Sci Rep* 13, 22226. <https://doi.org/10.1038/s41598-023-48924-6>

- Rice, J. R., Cleary, M. P., (1976). Some basic stress diffusion solutions for fluid-saturated elastic porous media with compressible constituents. *Am. Geophys. Union, Rev. Geophys. Space Phy.* 1976, 14, 227-242.
- Roeloffs, E. A., (1988). Fault stability changes induced beneath a reservoir with cyclic variations in water level. *J. Geophys. Res.*, 93, 2107–2124.
- Rutqvist, J. (2012). The geomechanics of CO₂ storage in deep sedimentary formations. *Geotechnical and Geological Engineering*, 30, 525-551.
- S. C. Stiros, S. Pytharouli; Interpretations of Reservoir-Induced Seismicity May Not Always Be Valid: The Case of Seismicity during the Impoundment of the Kremasta Dam (Greece, 1965–1966). *Bulletin of the Seismological Society of America* 2018;; 108 (5B): 3005–3015. doi: <https://doi.org/10.1785/0120170359>
- Santoyo, M.A., Garcia-Jerez, A., and Luzon, F., A 2010. Subsurface Stress Analysis and its Possible Relation with Seismicity Near the Itoiz Reservoir, Navarra, Northern Spain, *Tectonophysics*, doi: 10.1016/j.tecto.2009.06.022.
- Sausse, J., Fourar, M. and Genter, A. (2006) Permeability and alteration within the Soultz granite inferred from geophysical and flow log analysis. *Geothermics*, v.35(5-6), pp.544-560.
- Sayão, E., França, G. S., Holanda, M., and Gonçalves, A.2020: Spatial database and website for reservoir-triggered seismicity in Brazil, *Nat. Hazards Earth Syst. Sci.*, 20, 2001–2019, <https://doi.org/10.5194/nhess-20-2001-2020>.
- Schindler, A., Jurado, M. J., Müller, B. 1998. Stress orientation and tectonic regime in the north-western Valencia Trough from borehole data. *Tectonophysics* 300 (1), 63-77.
- Silva, G. F., J. O. Araújo Filho, M. G. Von Huelsen, C. N. Chimpliganond, and G. S. França (2014). Influence of Brazilian structures on the reservoir-induced seismicity case of Irapé Hydroelectric Plant, Minas Gerais, Brazil, *Braz. J. Geol.* 44, no. 3, 375–386, DOI: 10.5327/Z2317- 4889201400030004.
- Simpson, D. W., and Negmatullaev, S. K., (1981). Induced seismicity at Nurek Reservoir, Tadjikistan, USSR. *Bull. Seismol. Soc. Am.*, 71(5), 1561–1586.
- Simpson, D. W., Narasimhan, T. N., (1990). Inhomogeneities in rock properties and their influence on reservoir induced seismicity. *Gerl. Beitr. Geophysik*, 99, 205-219.

- Simpson, D.W. (1976) Seismicity change associated with the reservoir loading. *Engg. Geol.*, v.10, pp.123-150.
- Simpson, D.W., Leith, W.S. and Scholz, C.H. (1988) Two types of reservoirs induced seismicity. *Bull. Seism. Soc. Amer.*, v.78, pp.2025–2040..
- Simpson, DW 1986. Triggered Earthquakes. *Annual Review Earth Planetary Sciences*, 14: 21-42.
- Skempton, A. W. (1954). The pore-pressure coefficients A and B. *Geotechnique*, 4(4), 143-147.
- Snow, D.T., 1972. Geodynamics of seismic reservoirs. *Proceedings of the Symposium on Percolation through Fissured Rocks*. Deutsche Gessellschaft für Erd- und Grundbau, Stuttgart, Germany, pp. 1–19 (T2-J).
- Talwani, P, C. Chen, C., Gahalaut Kalpna, (2007). Seismogenic permeability, *ks*. *Journal Geophysical Research*, 112, B07309.
- Talwani, P. and Acree, S. (1984/85), Pore pressure diffusion and mechanism of reservoir induced seismicity. *Pure and applied Geophysics* 122,947-965
- Talwani, P. 1997. On the nature of reservoir-induced seismicity. *Pure and applied Geophysics*, 150 (3), 473-492.
- Talwani, P., and L. Chen (1998), Are seismogenic faults associated with a characteristic permeability? Introducing “Seismogenic” permeability, *ks*, *Eos.Trans.AGU*,79(45), Fall Meeting Suppl. F583
- Talwani, P., Chen, L., and Gahalaut, K. 2007. Seismogenic permeability, *ks*, *J. Geophys. Res.*, 112, B07309, doi:10.1029/2006JB004665.
- Talwani, P., Cobb, J.S., Schaeffer, M.F., 1999. In-situ measurements of hydraulic properties of a shear zone in north-western South Carolina. *J. Geophys. Res.* 104, 14993–15003
- Talwani, P., Seismogenic properties of the crust inferred from recent studies of reservoir-induced seismicity - Application to Koyna (2000) *Current Science*, 79 (9), pp. 1327-1333.
- Tao, W., Masterlark, T., Shen, Z. K., & Ronchin, E. 2015. Impoundment of the Zipingpu reservoir and triggering of the 2008 Mw 7.9 Wenchuan earthquake, China. *Journal of Geophysical Research*, 112 (10), 7033–7047.

- Telesca. L., Giocoli. A., Lapenna. V., Stabile. T.A., (2015). Robust identification of periodic behavior in the time dynamics of short seismic series: the case of seismicity induced by Pertusillo Lake, southern Italy. *Stoch Environ Res Risk Assess* 29:1437-1446
- The World Bank (2014b) Database World Development Indicators' 'Electricity production from renewable sources, excluding hydroelectric (kWh)'. <http://data.worldbank.org/indicator/EG.ELC.RNWX.KH>. Last accessed 8th Oct 2014
- Todd, D. K., & Mays, L. W. (2005). *Groundwater Hydrology*
- Vilarrasa, V., Carrera, J., Olivella, S., Rutqvist, J., and Laloui, L. 2019. Induced seismicity in geologic carbon storage, *Solid Earth*, 10, 871–892, <https://doi.org/10.5194/se-10-871-2019>.
- Vilarrasa, V., De Simone, S., Carrera, J. et al. 2022. Multiple induced seismicity mechanisms at Castor underground gas storage illustrate the need for thorough monitoring. *Nat. Commun.* 13, 3447 (2022). <https://doi.org/10.1038/s41467-022-30903-6>
- Vilarrasa, V., De Simone, S., Carrera, J., and Villaseñor, A. 2021 Unravelling the causes of the seismicity induced by underground gas storage at Castor, Spain, *Geophys. Res. Lett.*, 48, e2020GL092038, <https://doi.org/10.1029/2020GL092038>.
- Vilarrasa, V., Makhnenko, R. & Gheibi, S. 2016. Geomechanical analysis of the influence of CO₂ injection location on fault stability. *Journal of Rock Mechanics and Geotechnical Engineering*. 8(6):805–818.
- Vilarrasa, V., Raza, H., Kivi, I. R., and França, G. S. 2023. Understanding the triggering mechanisms of reservoir-triggered seismicity at Nova Ponte, Brazil, through hydro-mechanical modeling, *EGU General Assembly 2023*, Vienna, Austria, 24–28 Apr 2023, EGU23-11711, <https://doi.org/10.5194/egusphere-egu23-11711>.
- Vilarrasa, Víctor, et al. 2013. "Liquid CO₂ injection for geological storage in deep saline aquifers." *International Journal of Greenhouse Gas Control* 14: 84-96.
- Wever, T. H. 1989. The Conrad discontinuity and the top of the reflective lower crust – do they coincide? *Tectonophysics*, 157:39-58.

- Withers, R. J., and Nyland, E., (1976). Theory for the rapid solution of ground subsidence near reservoirs on layered and porous media. *Engineering Geology*, 10, 169–185
- Wu, H., Vilarrasa, V., De Simone, S., Saaltink, M. & Parisio, F. 2021. Analytical Solution to Assess the Induced Seismicity Potential of Faults in Pressurized and Depleted Reservoirs. *Journal of Geophysical Research: Solid Earth*. 126(1): e2020JB020436.
- Yeck, W. L., Weingarten, M., Benz, H. M., McNamara, D. E., Bergman, E. A., Herrmann, R. B., et al. (2016). Far-field pressurization likely caused one of the largest injection induced earthquakes by reactivating a large preexisting basement fault structure. *Geophys. Res. Lett.* 43, 10198–10207. doi: 10.1002/2016GL07 0861
- Yeck, W. L., Weingarten, M., Benz, H. M., McNamara, D. E., Bergman, E. A., Herrmann, R. B., et al. (2016). Far-field pressurization likely caused one of the largest injections induced earthquakes by reactivating a large preexisting basement fault structure. *Geophys. Res. Lett.* 43, 10198–10207. doi: 10.1002/2016GL07 0861.
- Zarfl, C., Lumsdon, A.E., Berlekamp, J. *et al.* A global boom in hydropower dam construction. *Aquat Sci* 77, 161–170 (2015). <https://doi.org/10.1007/s00027-014-0377-0>
- Zoback, M. D., and Hickman, S., (1982). Physical mechanisms controlling induced seismicity at Monticello Reservoir, South Carolina. *Journal of Geophysical Research*, 87, 6959–6974
- Zoback, M., Hickman, S., Ellsworth, W., and the SAFOD Science Team: Scientific Drilling Into the San Andreas Fault Zone – An Overview of SAFOD’s First Five Years, *Sci. Dril.*, 11, 14–28, doi:10.5194/sd-11-14-2011, 2011.