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Case Study

Source Structure Characterization and Seismic Hazard Assessment of Reservoir-Triggered Earthquakes: A Case Study of Song Tranh 2 Hydropower Reservoir, Vietnam

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Abstract

The Song Tranh 2 hydropower reservoir (ST2), located in Bac Tra My district, Quang Nam province (Vietnam) was impounded in November 2010 and soon after that earthquakes began to occur with the largest earthquake of M = 4.9 occurred on 15 November 2012. Seismic activity has not shown any signs of stopping, by the end of 2021 there have been 1161 events of M≥1.5 recorded. The identification of the generating source zones, the maximum of triggered earthquake and its impact on the safety of the ST2 dam is a necessary task. This paper presents a three-step process to determine the generating triggered seismic source: identifying the existence of subsurface faults, determining the generating triggered seismic source and studying the structure of the generating source segments. This information is used to assess seismic hazard by applying the OpenQuake program. The studied results have identified five source segments including: segment F1.1 (maximum observed earthquake - $M_{Ob.max}$ = 4.2) belongs to Tra Bong River fault; F2.1 ($M_{Ob.max}$ = 4.7) belongs to Tra My fault; F3.1 ($M_{Ob.max}$ = 4.1) and F3.2 ($M_{Ob.max}$ = 4.1) belong to Nuoc Le River fault; and F4.1 ($M_{Ob.max}$ = 3.6) belongs to Tra No River fault. The assessment of pick ground acceleration (PGA) of triggered earthquake that has potentially impact on the ST2 dam conducted with two scenarios: 1) $M_{Ob.max}$ at respective source segments and 2) Maximum credible triggered earthquake (M_{Max} = 4.9) at all source segments. In the second scenario (M_{Max}=4.9) will result in a value of PGA = 0.180g, PGV = 6.0cm/s and PGD = 1.30cm (at 10% probability of exceedance in 50 years) at the ST2 dam will not adversely affect dam safety as it is designed to resist earthquakes at acceleration of 0.245g (M5.5).

Introduction

It was established that the Song Tranh 2 (ST2) hydroelectric reservoir was the cause of the earthquakes in the region; the two greatest earthquakes, measuring M4.6 and M4.7, respectively, happened on October 22 and November 15, 2012 [1-3]. Seismologists in Vietnam and throughout the world have been interested in the Song Tranh 2 hydropower reservoir because, prior to the reservoir's impoundment in 2010, there had been no recorded earthquakes in the reservoir area or its surroundings [4,5]. Since 2012, there has been a seismic network with ten stations that records hundreds of M≥1.5 earthquakes annually. In addition to ST2, which has a reservoir capacity of 0.740 billion m3, other locations in Vietnam that experience earthquakes are Hoa Binh and Son La hydropower reservoirs, which are part of Song Da hydropower, one of the country's primary hydropower systems (Figure 1, Table 1). With a reservoir capacity of 9.260 billion m3, Son La hydropower is the largest in Southeast Asia. Hoa Binh hydropower has a reservoir capacity of 4.871 billion m3, and in July 2014 and May 1989, respectively, earthquakes with magnitudes of 4.4 and 4.9 were reported."

Same as Koyna reservoir (India) and Aswan reservoir (Egypt), reservoir-triggered seismicity in the ST2 region has

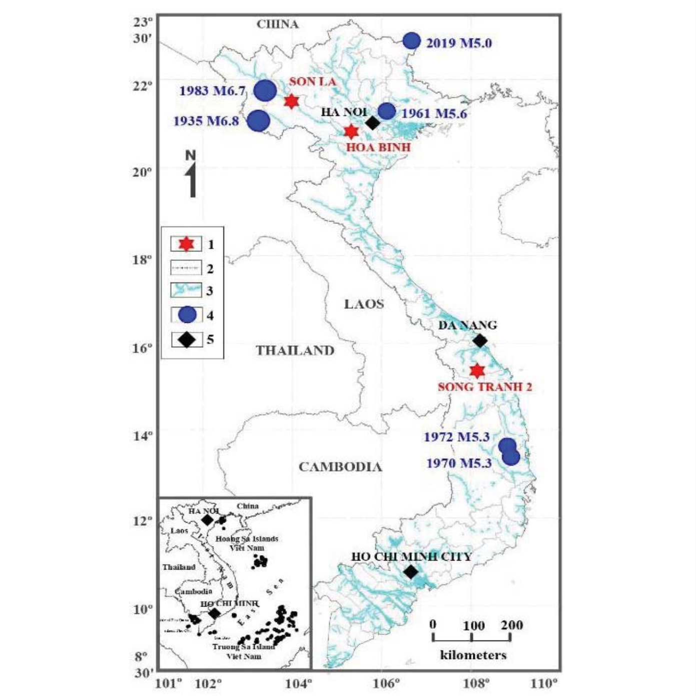

Figure 1: Location of Son La, Hoa Binh and Song Tranh 2 hydropower reservoirs on the map of Vietnam. (1-study areas; 2-border lines; 3-rivers; 4-earthquake; 5-places)"

No	Content	Unit	Hoa Binh	Song Tranh 2	Son La
1	River		Da river	Tranh river	Da river
2	Coordinates		105°19'26.00"E 20°48'02.90"N	108°08'52"E 15°19'53"N	103°59'42.00"E 21°29'47.00"N
3	Area of Basin	Km2	51.7	1.1	43.76
4	Average of water level	m	117	175	215
5	Reservoir capacity	109m3	4,871	0,740	9,260
6	Dam type		Mixed soil and rock	Concrete	Concrete
7	Elevation of dam crest	m	123	170	228,1
8	The dam height	m	128	96	137
9	Dam length	m	734	640	1
10	Wattage	MW	1.92	190	2.4
11	Number of generating unit		6	2	6
12	The year of full reservoir impoundment		1988	2010	2011
13	Maximum Triggered earthquake		4,9 (1989)	4,7 (2012)	4,3 (2014)

Table 1: Detailed information of hydropower in Vietnam, which caused reservoir-triggered seismicity of magnitude lager than 4.0 [1].

been continuously occurred since the reservoir impoundment [2,6-9]. Although the maximum observed earthquake in the ST2 region ($M_{Ob.max}$ = 4.7) is smaller than that of the Hsinfengkiang earthquake of $M_{Ob.max}$ = 6.1 (China, 1962); Kariba, Zambia Zimbabwe ($M_{Ob.max}$ = 6.2, 1963); Kremasta, Greece ($M_{Ob.max}$ = 6.2, 1966) and Koyna, India ($M_{Ob.max}$ = 6.3, 1967) etc.... However, this earthquake (November 15, 2012) caused some transverse cracks in the dam with a sub-latitude direction [1] and caused the cracking of the houses of the people living here. Some studies have been conducted in the ST2 region [10], these studies are mainly concerned with: Overview of geological, tectonic and active faults; Manifestations of reservoir-triggred seismic activity and focal mechanism; The connection between changes in water level and earthquake activity; Evaluation of the dam's stable based on seismic method. However, no detailed study has been conducted about characteristics of seismic source structure, estimation of maximum credible reservoir-triggered earthquake and thereby evaluating the impact of the triggered earthquake on safety of the ST2 hydroelectric dam.

This paper deals with the research problem of determining the source structure and assessing the impact of earthquakes on the ST2 dam by calculating the seismic hazard of triggered earthquakes (PGA, PGV and PGD). The process of establishing the triggered seismic source carried out in the following sequence: 1) Identification of subsurface fault existence according to gravity document; 2) Determining the triggered seismic source according to the criterion that the subsurface fault is interconnected to the ST2 reservoir and earthquakes occurred; 3) Study on the structure of generating source segments. The assessment of pick ground acceleration (PGA) of triggered earthquake that has potentially impact on the ST2 dam conducted with two scenarios: 1) $M_{Ob.max}$ at respective source segments and 2) Maximum credible triggered earthquake (M_{Max}) at all source segments."

Study area and data

The study area is limited to the coordinate frame: $107^0 57'$ ÷ $108^0 22'$ E; $15^0 07'$ ÷ $15^0 32'$ N (at scale 1:50 000).

Features of tectonic movement in the Cenozoic

Tectonic movement in the Cenozoic are blocky [1], probably starting from the Oligocene up to now. The average lifting speed belongs to the northwest-southeast structure, with an average value of 0.04mm/year (the highest is 0.06mm/year, the lowest is 0.02mm/year). Weak subsidence structures in the Cenozoic have a velocity of about -0.02mm/year belonging to the sub-latitude and coastal structures.

Geological structure

The area of ST2 reservoir (Figure 2) has the following three geological stratigraphic units [11]: "

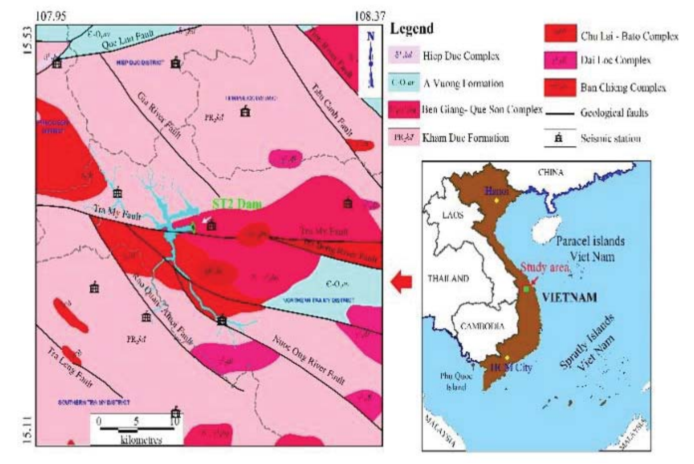

Figure 2: Geological map and geological fault system in the Song Tranh 2 region and its vicinity.

1) Kham duc formation (PR_2kd, meso-neoproterozoic): Amphibolite, amphibolite schist, biotite schist, quartz-biotite-disthene-garnet schist, amphibolite, quartz-muscovite schist, two-mica garnet schist, biotite-disthene schist, and feldspar-hornblende schist; dolomitic marble.

2) Ben Giang -- Que Son Complex (Last Paleozoic, δ14-γ14bq): Granodiorite, porfyritic hornblende granodiorite, gabrodiorite, diorit, and hornblende-biotite granite.

3) Chu Lai – Ba -- To Complex (γ_2cb, Neoproterozoic): Granodiorite, granite, granite-migmatite.

All rocks have a common sub-latitude direction, rather sloping, and have many fracture systems (Figure 2). It changes the physical of rock mechanical properties caused by weathering and lead to unsustainable and proning to landslides."

Geomorphological features

Topographic deformation's manifestation (Figure 3) within According to Dinh TC, et al. [1], the study region is documented as follows: 1) 2) The Song Tranh and Tra Bong valleys' topographic development is dominated by the Tra My and Tra Bong fault zones, which generate deformation. The mountain direction develops along the latitude parallel that runs from Bong Son to Kham Duc area, providing tectonic facies that visibly plug to the north. Along active fault zones, the morphology of sizable river valleys and streams descends to the northeast and southwest (from over 1.000m to 10-30m) [1].

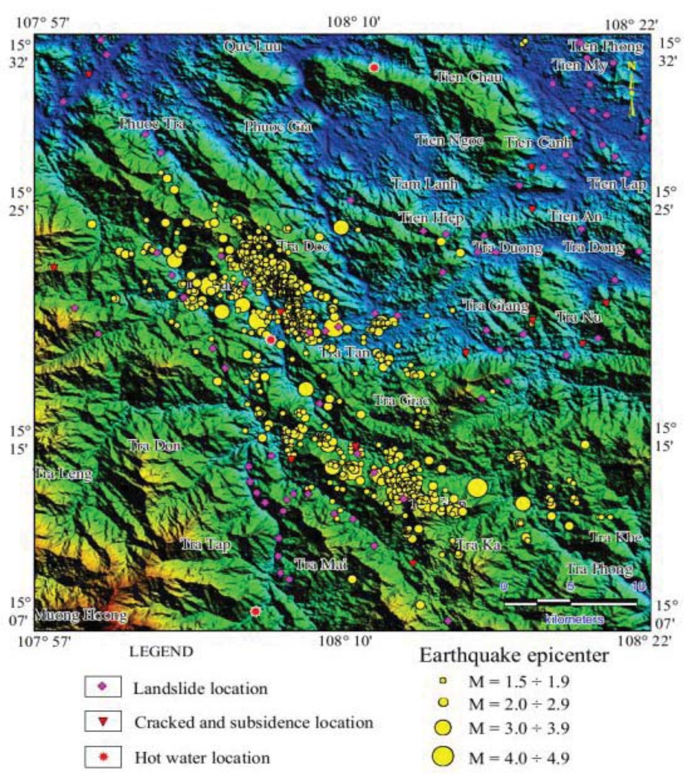

Figure 3: Distribution of earthquake epicenters in the ST2 region3z.

Expressions of seismic activity, landslide and land subsidence

1. Tectonic earthquake: Although there is no detailed study to prove that there have been tectonic earthquakes in Tranh 2 Song region [1].

2. Reservoir-triggered seismicity: According to the report of the "Institute of Geophysics, from August 2011 to the end of 2021 at Song Tranh 2 reservoir and its vicinity, 1.161 earthquakes of magnitude 1.5 ÷ 4.7 were detected, among these: 731 earthquakes of M = 1.5 ÷ 1.9; 392 earthquakes of M=2.0 ÷ 2.9; 33 earthquakes of M=3.0 ÷ 3.9; and 5 earthquakes of M≥4.0; The largest earthquake of M=4.7 occurred on November 15, 2012."

3. Land subsidence: Land subsidence in the area under examination (Figure 3) is mainly a collection of active tectonic cracks with different origin types [1]: shear cracks, expansion cracks and compression cracks. They were formed and developed in the context of modern geodynamics with sub-longitude compressive stress fields, sliding and sliding - stretching; Right-lateral strike slip faults operating toward the NW-SE and NE-SW, subsidence with sub-longitude faults. Land crack is represented as a set of shear cracks, expansion cracks and compression cracks combined to create a characteristic architectural shape in the form of "horsetail" and "chicken wing". Land crack is concentrated at the junctions of active faults and at the tip of the fault with maximum stress reduction. At the observed points of land crack, most of the main cracks are shear cracks with NW-SE and NE-SW directions. The secondary cracks are expansion cracks with sub-longitude direction, compression cracks with sub-latitude direction.

4. Landslide: Landslides mainly occur in the ferrosialite and siafelite weathering crusts of metamorphic acid magmatic rocks and on the mixed crumbly - coarse - loosely mixed Quaternary sediments with weak cohesion. In particular, landslides took place quite strongly in the places with large weathering crust thickness, reaching 30m - 40m such as in Tien Phuoc district, Bac Tra My district and Nam Tra My district. Some landslides occur in both weathered crust and bedrock. These landslide blocks are often accompanied by land crack, formed and controlled by tectonic cracks [1].

Methodologies

To achieve a comprehensive assessment of the reservoir-triggered seismicity (RTS) at Song Tranh 2, a multi-disciplinary approach combining potential field geophysics, seismic tomography, and probabilistic hazard modeling was employed.

Subsurface fault identification using gravity data

The boundaries of geological blocks and subsurface fault systems were delineated using Bouguer gravity anomaly data. Two primary filter techniques were applied to enhance the signal of structural discontinuities:

Total horizontal gradient (THG): This method identifies the edges of density bodies by calculating the maximum rate of change in the gravity field. The THG is defined as [1,12-14]:

$$G = \sqrt{\left(\frac{\Delta g(x,y)}{dx}\right)^2 + \left(\frac{\Delta g(x,y)}{dy}\right)^2}$$

here $\Delta g(x, y)$ is Bouguer gravity anomaly.

Modified theta map (MTM): This filter improves the resolution of deeper or more subtle structural lineaments by normalizing the horizontal gradient with the total gradient, providing a sharper image of the fault boundaries [15,16].

Structural analysis of seismic sources

Once the fault network was identified, the internal structure of the active segments was analyzed using:

2.5D Gravity Inversion [12,17,18]: To determine the density contrast and geometry of the faults at depth.

Local Earthquake Tomography [19].

Using the LOTOS-12 algorithm [20], we calculated the P-wave velocity (V_P) and the V_P/V_S ratio. In RTS studies, a high V_P/V_S ratio often indicates fluid-saturated fractured rock, while a low V_P/V_S ratio (observed in ST2) can indicate highly fractured zones with potential pore pressure anomalies.

Estimation of maximum credible magnitude (M_{Max})

The maximum potential magnitude for triggered earthquakes was estimated using the Modified Gumbel Type-I distribution. Unlike standard tectonic earthquakes, RTS sequences often follow a specific distribution due to the influence of external fluid pressure. The b-value from the Gutenberg-Richter relationship (log N = a - bM) was also calculated to characterize the stress state of the reservoir area [21,22].

Probabilistic seismic hazard analysis (PSHA)

The seismic hazard at the dam site was modeled using the OpenQuake (OQ) engine, an open-source framework developed by the Global Earthquake Model (GEM) Foundation [23-25,].

Source model: Five triggered seismic source segments (F1.1, F2.1, F3.1, F3.2, and F4.1) were integrated into the OQ engine.

Ground motion prediction equations (GMPEs): Due to the shallow nature of RTS, a logic tree approach was used to select appropriate GMPEs that account for near-field, shallow-focus events.

Output parameters: The primary outputs are Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV), and Peak Ground Displacement (PGD) for a return period of 475 years (10% probability of exceedance in 50 years).

The triggered seismic source in the ST2 reservoir region

Identification of subsurface faults according to gravity data

Bougure Gravity anomaly, at scale 1: 50,000, established by the Geophysical Union in 2011 was used to identify subsurface faults in the ST2 region. The Bouguer gravity anomaly vary in the range of -5 mGal to -30 mGal, increasing gradually from southwest to northeast (Figure 4. Subsurface faults are determined on the basis of establishing horizontal maximal gradient (G_{max}) and Modified Theta Map Filter method (MTM): (1) Subsurface faults are claimed to be evident in both G_{max} and MTM; (2) The trend of G_{max} distribution at each upward gravity level roughly reflects the insertion direction of the fault. The results of G_{max} and MTM calculation are shown in Figure 5. G_{max} corresponding to the upward Bouguer gravity anomaly at 2km, 4km, 6km were calculated in order to roughly determine the dip direction of the fault (Figure 5). A program running on Matlab platform is used to calculate G_{max}, and Potensoft software is used to calculate MTM.

A system of 12 subsurface faults was detected, predominating with northwest-southeast direction (9), sub-latitude direction (1), and northeast-southwest direction (2): F1 - Tra Bong river fault; F2 - Tra My fault; F3 – Nuoc Le River fault; F4 - Tra No River fault; F5 – Gia River fault; F6 - Ho Khanh River fault; F7 - Tien River fault; F8 - Tram River fault; F9 - Nuoc Ta River fault. F10- Tien Hiep fault, F11 - Rao Quan - A Luoi fault and F12 - Nuoc Xa River fault (Figure 5).

Some previous study results mentioned fault systems in this region but mainly based on geological and topographic analysis [26]. The subsurface faults identified in this study are quite similar to previous studies and some of them have just been detected in this study.

Determining of the triggered seismic sources

Determining of the triggered seismic sources according to the criteria is the deep fault zone, interconnected to the

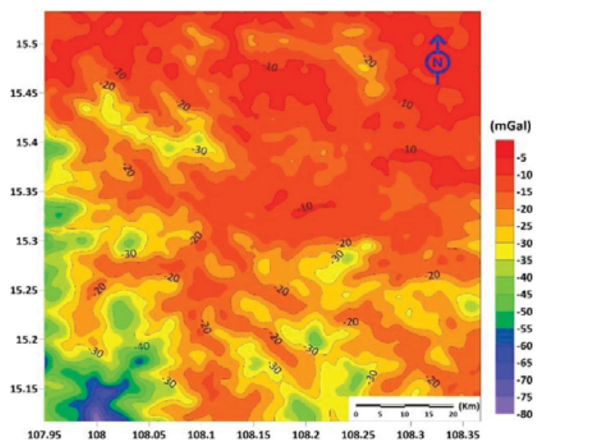

Figure 4: Bouguer gravity anomaly map of Song Tranh 2 region.

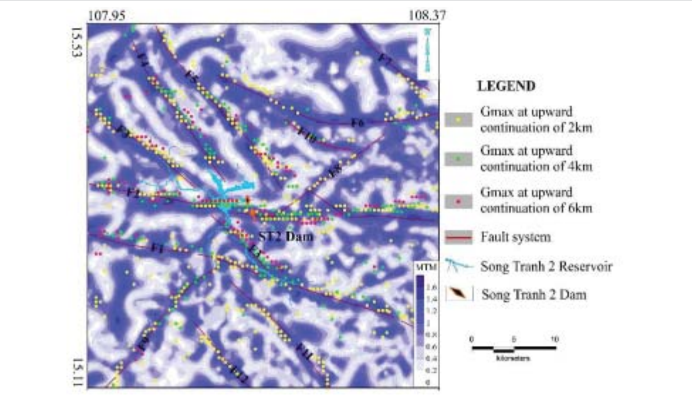

Figure 5: Fault system based on the distribution of Gmax and MTM values in the Song Tranh 2 region.

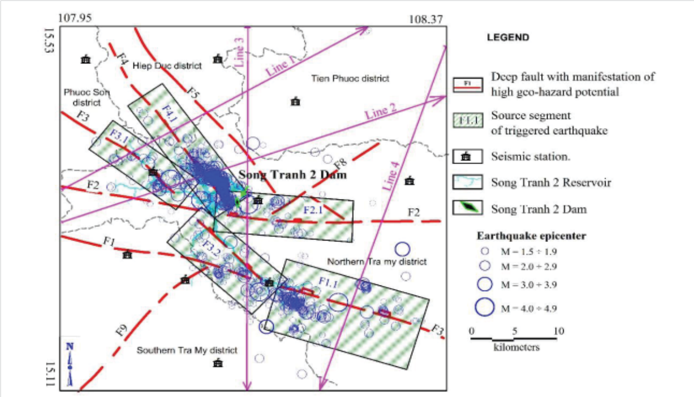

Figure 6: Map of faults interconnected with the reservoir and 5 triggered seismic source zones.

ST2 reservoir and associated with the triggered earthquake. The earthquake catalog used in this study includes 1.161 earthquakes of magnitude larger than 1.5 during the period of 2012 to the end of 2021 (data source from the Institute of Geophysics). The study results are shown in Figure 6 showing the existence of four subsurface faults that generate triggered earthquakes including: F1 (Tra Bong River fault); F2 (Tra My fault); F3 (Nuoc Le river fault); F4 (Tra No River fault). F9 fault interconnects to the ST2 reservoir but doesn't generate triggered earthquakes (Figure 6).

Based on the distribution of the earthquake epicenters, it is possible to identify five triggered seismic sources (Figure 6): F4.1 belongs to the F4 fault; F2.1 belongs to the F2 fault; F3.1, F3.2 belong to F.3 fault and F1.1 belongs to the F.1 fault. Thai Anh Tuan, et al. [3] divided the distribution of triggered earthquakes into 2 clusters (North and South) with distinct b-value characteristics: Northern cluster corresponds to F3.2 and F3.3; Southern cluster corresponds to F4.1, F3.1 and F2.1.

Study on the structure of the generating source segments of the triggered seismicity

Four cross-sections (Figure 5) were built to cross through five triggered seismic sources with the goal of defining source characteristics, cross-section 1 and 2 both cross through the source F3.1 and F4.1; cross-section 3 cross through source F2.1 and F3.2 and cross-section 4 only cross-section through source F1.1. All cross-sections cross nearly perpendicular to the triggered seismic sources to evaluate the structural parameters of the sources. The width, dip and strike angles of the sources were determined by 2D gravity inversion and 2D seismic wave tomography. ZondGM2D software was used to construct cross section of the 2D inverse gravity [12,18,]. LOTOS software was used in constructing seismic wave tomography sections (ratio Vp/Vs) [20].

Superposition of three-layer data including: Contrast density; Ratio of Vp/Vs; and earthquake hypocenter allows to determine the depth, width and dip angle of the triggered seismic (Table 2, Figure 7). The most common feature of the triggered seismic source segments is: There is a relatively small contrast of negative density, varying in the range of -0.06 to 0; Ratio of Vp/Vs vary in the range of 1.634 ÷ 1.656. Contrast values of negative density and low Vp/Vs ratio reflect strong tectonic rupture zone, where soil and rock are no longer monolithic and have high porosity. When water penetrates into this rupture zone, Vp decreases, leading to a decrease in Vp/Vs ratio, which has also been demonstrated in previous research by Cao Dinh Trong, et al. [19]. In this study, it can be seen that the location of the triggered earthquakes is located at the boundary of the decrease in the value of the ratio Vp/Vs.

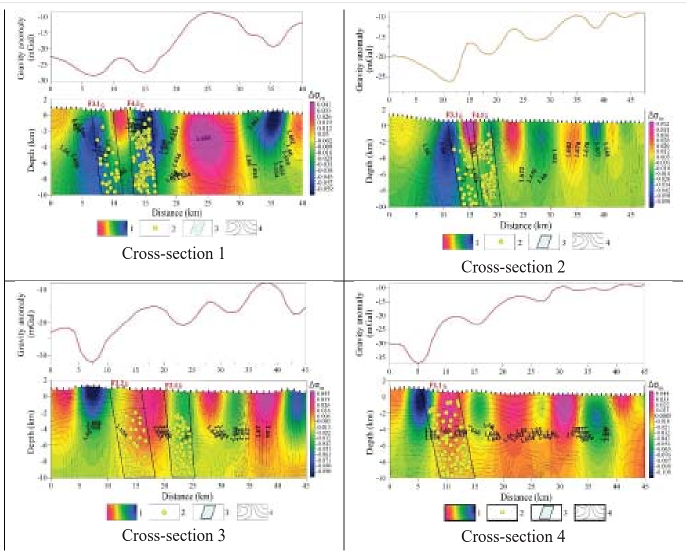

Figure 7: The cross-sections reflect the structural characteristics of the triggered seismic source along the cross-section 1, 2, 3 and 4 respectively: a) Bouguer gravity anomaly (ΔgB, mGal); b) Density contrast based on 2D inverse gravity; c) Ratio of Vp/Vs; d) Earthquake hypocenters.

Table 2: Ratio of Vp/Vs and density contrast at triggered seismic sources in the ST2 reservoir.

Source	Vp/Vs ratio	Density contrast
F4.1	1.642 ÷ 1.652 1.638 ÷ 1.654	-0.060 ÷ -0.030 -0.042 ÷ 0
F3.1	1.636 ÷ 1.654 1.640 ÷ 1.656	-0.060 ÷ -0.024 -0.058 ÷ 0
F3.2	1.638 ÷ 1.650	-0.042 ÷ -0.022
F3.3	1.636 ÷ 1.654	-0.098 ÷ -0.020
F2.1	1.634 ÷ 1.652	-0.042 ÷ -0.013

Based on the results along the cross-sections and spatial analysis, the parameters of five triggered seismic sources were determined and shown in Table 3.

These source parameters (Table 3) are used to assess Triggered Seismic Hazard in the Song Tranh 2 region.

Triggered seismic hazard assessment in the ST2 reservoir (Vietnam)

Assessment of the triggered seismic hazard in the Song Tranh 2 reservoir region with two magnitude scenarios: 1) The maximum observed triggered earthquake magnitude scenario ($M_{Ob.max}$) at each source segments and 2) Maximum credible of triggered earthquake at all source segments (M_{Max} = 4.9). “

Gutenberg richter distributions and M_{Max} in the ST2 region

Gutenberg Richter distribution function in the study area has the following form, where T is the observation period and N is cumulative number of earthquakes of magnitude greater than or equal to M. Based on the function we have: b - value = 0.67 and a value = 3.87.

$$\log(N(M)/T) = 3.79 - 1.01*M$$

b - value in this study is higer than that of Thai Anh Tuan, et al. [3]. High b-values indicate a large number of small earthquakes, to be expected in regions of low strength and large heterogeneity, whereas low values indicate high resistance and low heterogeneity.

The calculation results by Modified Gumbel Type-I extreme value distribution in M_{Max} assessment results are: β = 1.985; u = 2.589; ν = 4.866; R-squared (Coefficient of determination) = 0.9865. It is possible to determine the maximum credible of triggered earthquake M_{Max} of 4,866 (rounded, M_{Max} = 4.9), which is similar with that of Nguyen Hong Phuong, et al. and Trieu CD, et al. [5,27] using the maximum likelihood method.”

Some other methods assessing M_{Max} such as: using the relationship between source area size (length and width) with M_{Max} [28]; Each method has its own criteria for M_{Max} estimation, to use the source region size in M_{Max} estimation requires determining the source length and width with high accuracy. The neural network method is often used in small map scale, large earthquake catalog coverage (in terms of spatial and temporal distribution). The most suitable for Song Tranh 2 is to use the improved Gumbel I method.

Table 3: Characteristics of the triggered seismic sources in the Song Tranh 2 region.

No	Segments	Belongs to the fault	Strike	Dip	Rake	Maximum observed magnitude ($M_{Ob.max}$)
1	$F_{4.1}$	Tra No River fault	145	80	-81.6	3.6
2	$F_{3.1}$	Nuoc Le river fault	125	76	179	4.1
3	$F_{3.2}$	Nuoc Le river fault	134	73	-104.1	4.1
4	$F_{2.1}$	Tra My fault	95	80	-110	4.7
5	$F_{1.1}$	Tra Bong River fault	106	75	-137.8	4.2

Triggered seismic hazard assessment in the Song Tranh 2 Reservoir

The triggered seismic hazard assessment for the Song Tranh 2 region is calculated with 2 scenarios:

Scenario 1: The maximum observed earthquake ($M_{Ob.max}$) at each source segment that occurred at respective source segment (Table 2).

Scenario 2: The maximum credible triggered earthquake M_{Max} = 4.9 may occur simultaneously at 5 source segments (Table 2).

To objectively evaluate the seismicity of the study area, taking into account the different effects of the source segments, weighting for the logic tree is used into the calculation. Depending on the distance from sources to the dam, weight coefficients for each segment are derived as follow: F1.1 - 0.15; F2.1 - 0.25; F3.1 - 0.2; F3.2 - 0.2 and F4.1-0.2. The logic tree tool is an important difference between OpenQuake software with other software like Crisis. The evaluation of the weights follows the following logic, the segments near the dam will be more important than the faults far from the dam, such as F2.1 to value 0.25 because the largest triggered earthquake of 4.7 occurred on the fault. This is also the segment closest to Song Tranh 2 reservoir, in contrast to segment F1.1 with a weight value of 0.15 because the segment has the longest distance from the dam. In addition, the remaining segments are equivalent with the same value of 0.2, the weight values are determined so that the sum of the weights of all the sources in the study area is equal to 1.

The results for 2 scenarios of triggered earthquakes ($M_{Ob.max}$ and M_{Max}) are shown in Figure 8, Figure 9, Figure 10 and Table 4.

1) For scenario 1, PGA has the highest value at Song Tranh 2 respectively (Table 4). For Song Tranh 2 dam affected by PGA = 0.150g, PGV = 4.60cm/s and PGD = 0.65cm (at 10% probability of exceedance in 50 years).

2) For scenario 2, PGA has the highest value at Song Tranh 2 respectively (Table 4). For Song Tranh 2 dam affected by

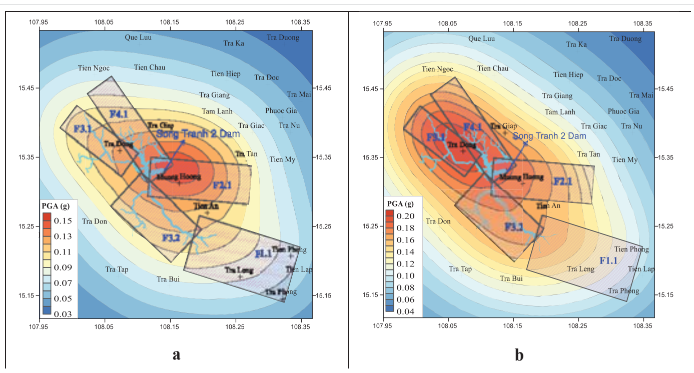

Figure 8: Distribution diagram of PGA (at 10% probability of exceedance in 50 years) in the Song Tranh 2 region: *a)* $M_{Max} = M_{ob.max}$; *b)* M_{max} = 5.0

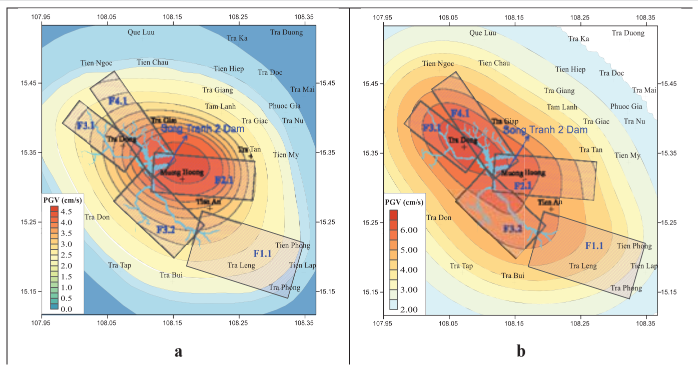

Figure 9: Distribution diagram of PGV (at 10% probability of exceedance in 50 years) in the Song Tranh 2 region: *a)* $M_{max} = M_{ob.max}$; *b)* $M_{max} = 5.0$.

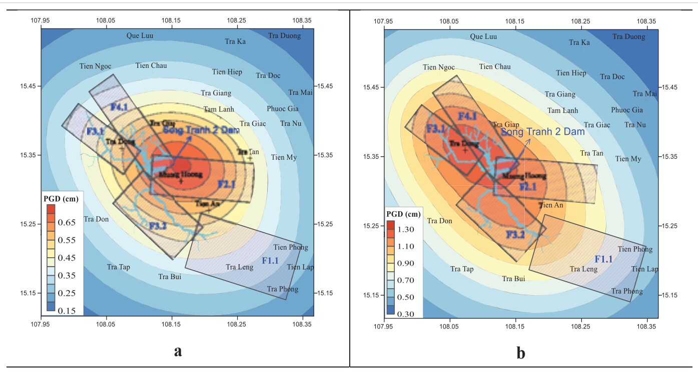

Figure 10: Distribution diagram of PGD (at 10% probability of exceedance in 50 years) in the Song Tranh 2 region: *a)* $M_{max} = M_{ob.max}$; *b)* $M_{max} = 5.0$

Table 4: Triggered seismic hazard assessment at the ST2 dam (probabilities of exceedance 10% in 50 years).

Scenario	PGA	PGV	PGD
$M_{Ob.max}$	0.150g	4.60cm/s	0.65cm
$M_{Max} = 4.9$	0.180g	6.0cm/s	1.30cm

PGA = 0.180g, PGV = 6.0cm/s and PGD = 1.3cm (at 10% probability of exceedance in 50 years).

In the project report "Seismic hazard assessment in Song Tranh 2 region", of Nguyen Ngoc Thuy et al., (2003) proposed that the design of the ST2 dam to withstand the ground acceleration of earthquakes of M5.5 coresponding PGA of 0.245g in the 500-year repeatability period (probabilities of exceedance 10% in 50 years). With scenario 2, the $M_{Max} = 4.9$ will affect the ST2 dam with an acceleration of 0.180g, much lower than the design acceleration. This proves that the ST2 dam is completely resilient to the impact of triggered earthquakes both now and in the future.

Discussion

Mechanism of reservoir-triggered seismicity (RTS)

The temporal and spatial distribution of seismicity at the Song Tranh 2 (ST2) reservoir suggests a complex interaction between hydraulic loading and pre-existing tectonic stress. The high b-value (approx 1.01) and the shallow focal depths (<10 km) are diagnostic of fluid-induced seismicity. We interpret the triggering mechanism through two primary processes:

Pore pressure diffusion: The infiltration of reservoir water into the highly fractured zones of the Tra My (F2) and Tra Bong (F1) faults reduces the effective normal stress. This allows the faults to slip under much lower shear stress than would be required in dry conditions.

Vp/Vs ratio anomalies: The observed low V_P/V_S ratios (1.634–1.656) in the source segments F2.1 and F1.1 indicate that these zones are not only fractured but also characterized by high compressibility, likely due to the presence of micro-cracks saturated with fluids under anomalous pressure.

Evaluation of maximum credible magnitude (M_{Max})

The estimation of $M_{Max} = 4.9$ using the Modified Gumbel Type-I distribution aligns with the maximum observed event in 2012. While some tectonic models for the region suggest a potential for M > 5.0, the specific characteristics of RTS—where energy is released through frequent, moderate-sized events rather than a single large rupture—support our M_{Max} estimate. This value is consistent with other documented RTS cases in similar geological settings, such as the Aswan reservoir in Egypt.

Implications for dam safety and seismic hazard

The calculated Peak Ground Acceleration (PGA) of 0.180g at the ST2 dam site is a critical finding for risk management.

Comparison with design standards: The ST2 dam was engineered to withstand a ground acceleration of 0.245g (corresponding to a design earthquake of M approx 5.5 and an intensity of VII-VIII on the MSK-64 scale).

Safety margin: Our hazard assessment demonstrates that even under the most conservative scenario $M_{Max} = 4.9$ occurring at the closest fault segment), the resulting PGA (0.180g) remains approximately 26% below the design threshold.

However, it is important to note that the Peak Ground Velocity (PGV) of 6.0 cm/s and Peak Ground Displacement (PGD) of 1.30 cm could still cause minor non-structural damage to local infrastructure and residential buildings in the immediate vicinity of the epicenter. Therefore, while the dam structure remains robust, public safety measures and building reinforcement in the Bac Tra My district should be maintained.

Limitations and future monitoring

While the current hazard is within safety limits, the duration of RTS sequences can be unpredictable. Experience from the Koyna reservoir (India) suggests that triggered activity can persist for decades. The continuous monitoring of pore pressure at depth and the maintenance of the local seismic network are essential to detect any migration of seismicity or changes in the stress field that could lead to larger events.

Conclusion

This study successfully characterized the seismic source structures and assessed the hazard levels associated with reservoir-triggered seismicity at the Song Tranh 2 hydropower project. The key findings are as follows:

1. Structural control: Seismicity is controlled by a system of NW-SE trending faults, particularly the Tra My and Tra Bong River fault segments. These structures act as pathways for water to penetrate deep into the crust.

2. Physical indicators: The identified seismic source zones are characterized by low density and low V_P/V_S ratios, which are diagnostic features of fluid-saturated, highly fractured rock volumes typical of RTS environments.

3. Hazard thresholds: The maximum credible triggered earthquake is estimated at M_{Max} = 4.9. The corresponding Peak Ground Acceleration at the dam site is 0.180g.

4. Operational safety: The seismic hazard remains within the safety margins of the dam's design (0.245g). However, continuous seismic monitoring is mandatory, as the long-term evolution of pore pressure at depth could potentially lead to events closer to the design limit.

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