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Original Article

Tectonic Stress Distribution in the Song Tranh 2 Hydropower Reservoir: Implication for Induced Earthquake

Luong Thi Thu Hoai*, Pham Nguyen Ha Vu, Nguyen Dinh Nguyen, Hoang Thi Phuong Thao, Nguyen Van Vuong

VNU University of Science, 334 Nguyen Trai, Thanh Xuan, Hanoi, Vietnam

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Abstract: The Song Tranh 2 hydropower reservoir was built in Tra My area, Quang Nam province, composing magmatic and high-grade metamorphic rocks of the northern part of the Kon Tum massif. Since the reservoir was put into operation, induced earthquakes have occurred in the Song Tranh 2 hydropower reservoir and its vicinity. Tectonically, the northwest-southeast to east-west striking faults developed strongly. Detailed analysis of slickensides and attitude of faults occurring in the studied area have shown that the northwest-southeast striking faults are reactivated as dextral ones during the Pliocene-Quaternary up to the present day. Based on the geometric distribution of the fault network, kinematic characteristics, and the youngest tectonic stress regime, we computed the distribution of tectonic stress in the studied area. Computation results show two positive anomalies of stress directly related to the northwest-southeast faults numbered 2, 10, 11a, 11b and sub-latitude striking fault numbered 1. These faults run in line with the local river channels and are likely to reactivate and generate induced earthquakes.

Keywords: Song Tranh 2, hydropower reservoir; reactive fault, tectonic stress, induced earthquake.

1. Introduction

The Song Tranh 2 hydropower dam, constructed in Bac Tra My district, Quang Nam province (Figure 1), is located in the Tam Ky-Phuoc Son shear zone [1] that bounded the Kon Tum high-grade metamorphic massif in the south by the Tra Bong dextral shear zone. During the Cenozoic, under the effect of the India-Eurasian collision, the Indochina block intruded southeastward, and the East Vietnam Sea opened [2] and the whole Vietnam in general and the Quang Nam-Quang Ngai area in particular, was strongly deformed. Brittle deformation

* Corresponding author.
E-mail address: hoaigeo@gmail.com

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generated fractures and fault systems that overprinted on the Indosinian schistosity and foliation planes and the reactivation of older shear zones, including Tra Bong, Tam Ky-Hiep Duc, Ta Vi-Hung Nhuong shear zones. The brittle deformation also reactivated the Permian-Triassic disablement planes into slickensides and fault planes [3]. Since 2011, after taking into operation of the Song Tranh 2 hydropower reservoir, thousands of earthquakes have occurred in Tra My district and its vicinity. The seismicity has been generated by the reactivation of the fault systems in Bac Tra My area. The reactivation of the faults in the Bac Tra My region strongly depends on the regional tectonic stress field and pore pressure change of the bedrock during the impoundment and discharge of the Song Tranh 2 reservoir [4, 5]. Despite several studies of earthquakes in the Song Tranh 2 hydropower, identifying which faults to generate earthquakes and the mechanism of faulting are subject to debates.

The study by Trieu et al. 2014 [6] suggested that the strongest reservoir-induced earthquake occurring in the reservoir area was related to the reactivation of sub-latitude striking dextral strike-slip Tra My-Tra Bong fault. Studying the focal mechanism of 3 triggered earthquakes occurring in September and October 2013 by Giang et al. 2015 [7] showed the heterogeneity of the focal mechanism and the faulting directions. Unlike the results obtained by Trieu et al. 2014, studying the hypocenter distribution by Lizurek et al. 2017 [8] suggested that almost triggered earthquakes were related to the NW-SE striking faults with normal focal mechanisms and only a few earthquakes related to E-W striking Bac Tra My-Tra Bong fault. However, studies on the focal mechanism and Coulomb stress change model by Gahalaut et al. 2016 [9], Tuan et al. 2017 [10] revealed a close relationship between triggered earthquake distribution, focal mechanisms and Coulomb stress change related to the NW-SE and sub-latitude faults determined by Hoai et al. 2014 [3].

In order to identify which faults could generate reservoir induced earthquakes in the Song Tranh 2 hydropower area, this paper aims to characterize the youngest regional tectonic and local tectonic stress states and to evaluate the potential reactivation of different faults under the differentiation of the youngest tectonic stress field affecting in the Song Tranh 2 reservoir area.

2. Geological setting

The Song Tranh 2 hydropower reservoir and its vicinity mainly consist of the Early Paleozoic metamorphic rocks [11-14] that overprinted by the Late Permian-Early Triassic ductile deformation event [11, 12, 15-17] of the Tam Ky-Phuoc Son and Tra Bong shear zones. On the Vietnam geological map at the scale 1: 200.000, the metamorphic rocks of the Tam Ky-Phuoc Son shear zone are divided [18] into Kham Duc, Nui Vu and Chu Lai migmatite-granite complexes. Metamorphic rocks of Kham Duc and Nui Vu complexes contain serpentinized ultramafic to mafic bodies of Hiep Duc and Ta Vi complexes. In the northwest of the Bac Tra My district, the very low grade metamorphosed sedimentary rocks of A Vuong formation exposed mostly. Plutonic bodies of Dai Loc, Dieng Bong, Tra Bong, Cha Val, and Hai Van complexes intruded into these low grade metamorphosed rocks. The Late Permian-Early Triassic ductile deformation resulted in the regional sub-latitude striking folded structure of the Tam Ky-Phuoc Son zone and several NW-SE to E-W trending ductile shear zones characterizing by hundreds meter to kilometres thick mylonitic zones. These formations were covered by the Late Triassic angular unconformity of the coal-bearing sedimentary rocks of the Nong Son basin located in the north of Tam Ky-Phuoc Son shear zone. The sedimentary rocks of the Nong Son basin subjected to a post lithification deformation to form two major ENE-WSW oriented synclines. During the Cenozoic, under the effect of southeastward translation of the Indochina block along the Ailaoshan-Red River shear zone and the East Vietnam Sea opening [19], the Indochina block and whole Vietnam, as well as the Tam Ky-Phuoc Son area, were strongly deformed and developed widespread Late Miocene-Quaternary basaltic eruption. Consequently, the southeastward translation of the Indochina block resulted in the Ailaoshan-Red River metamorphic belt with sinistral shear sense, the Bu Khang gneissic dome with NE-SW extensional shear sense [20] and numerous NW-SE, sub-longitude and sub-latitude striking fault zones distributed from the north to south Vietnam. The research on the tectonic stress states in the Hue-Da Nang area by Delphine et al in 1997 [21] and by Rangin et al in 1995 [22] in the south-central Vietnam documented 2 main prior Middle Miocene strike-slip stress states and a younger local extensional stress state. Recently, Vuong et al. 2019 [23] documented that south-central Vietnam has experienced a succession of four clockwise rotation tectonic stress regimes from Oligocene to the present.

In the Song Tranh 2 hydropower reservoir and its adjacent areas, the faults strike is mainly in the NW-SE and sub-latitude trending. The major faults include the sub-latitude striking Tra Bong, Hung Nhuong-Ta Vi faults and NW-SE striking Phuoc Gia-Tra Kot fault. The other NW-SE striking faults are subsidiary ones of the sub-latitude Tra Bong and Hung Nhuong-Ta Vi main faults. Only three NE-SW striking faults weakly developed in this area. The field observation evidenced that all faults located in the area Song Tranh 2 hydropower reservoir and its adjacent areas (Figure 1) were high angle faults with strike-slip displacement [3].

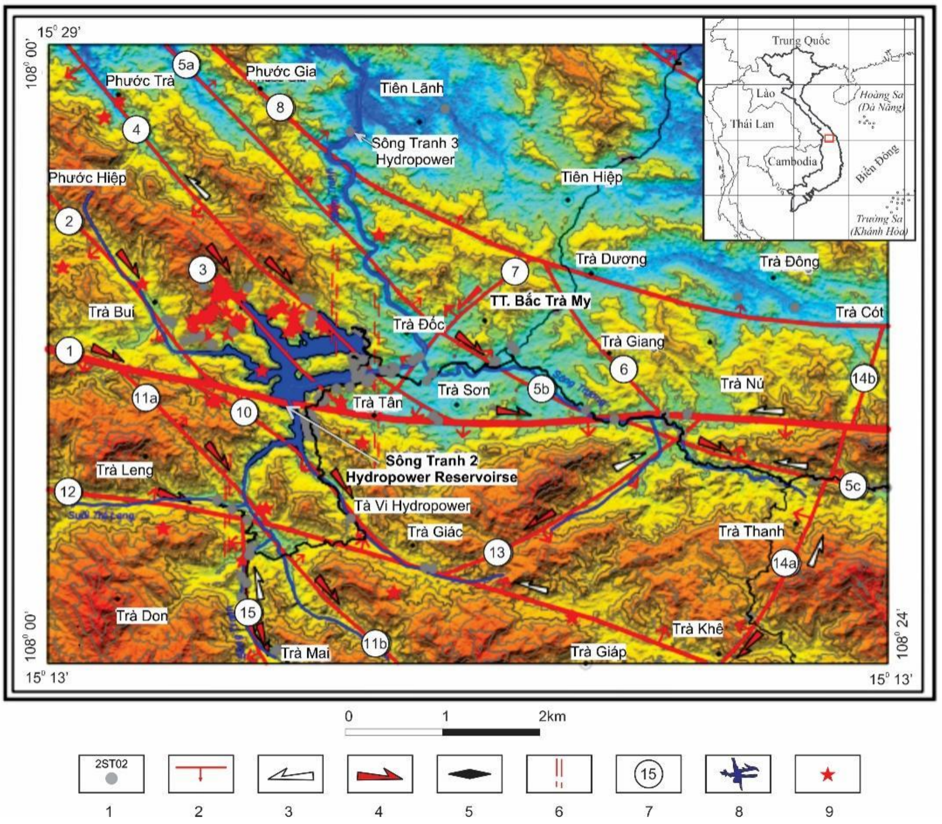

Figure 1. Fault systems in the Song Tranh 2 hydropower reservoir and its vicinity (adapted from Hoai et al., 2014): 1) outcrop number; 2) fault attitude;3) sinistral motion; 4) active dextral motion; 5) dam location; 6) fracture zone; 7) fault number; 8) Song Tranh 2 hydropower reservoir; 9) induced earthquake epicenter.

3. Data and Method

3.1. Fault Geometrical Data

Assessing the impact of tectonic stress fields on the potential fault reactivation within the studied area requires determining precisely geometrical parameters or attitudes of faults. The authors analyzed satellite image and digital elevation model (DEM) data in conjunction with the structural investigation in the field to determine the parameters describing the distribution and characteristics of faults in the studied area. The result of identifying the fault network was presented in Hoai et al. (2014) [3].

3.2 Method for Inversion of Fault Slip Data

Tectonic stress plays an essential role in the research of geology of faulting and active tectonics and natural earthquakes and large reservoir induced earthquakes. The tectonic stress that was responsible for tectonic faulting in the past referred to as paleostress. The determination of paleostress relies on identifying the attitude of slickensides and the sense of relative slip of two fault walls. Parameters of a paleostress state at an outcrop are computed from a population of fault plans or slickensides characterizing by strike, dip angle and dip direction, the pitch angle of sickening, and sense of slip on the fault plane. The methods for computing a stress tensor, a representative for a paleostress state, based on the analysis of slickensides, come into being since the 1970s [24-26]. Since then, the determination of paleostress computed from a population of fault plans that resulted from homogenous stress or an average of multi-stress tensor has been advanced both in physical basics and the method to resolve the inversion problem to get a reduced stress tensor [26-33].

Resolving the inversion problems to get a paleostress states are based on some basic assumptions as following: i) The rock body in which the fault plane to be measured is physically homogenous and anisotropy, ii) The theology of the rock material is linear elastics, iii) Displacement on the slickenside is relatively small compared to the fault length; iv) The rock volume is relatively large enough, and stress tensor responsible for the fault slip is homogenous in the whole volume of rock; and v) The slip occurring on each fault plan is independent to each other, and the slip vector on the fault is parallel to and the same direction with effective shear stress [34]. Such prerequisite assumptions will be satisfied when fault plane attitudes are measured in an area as small and homogenous as possible. A reduced stress tensor is characterized by three principal stress axis, namely sigma 1, sigma 2 and sigma 3 corresponding to maximum, intermediate and minimum principal stress axis respectively and relative magnitude of three axes referred to as stress ellipsoid shape ratio $\Phi = (\sigma 2 - \sigma 3)/(\sigma 1 - \sigma 3)$ [30]. In this paper, we use the INVD method proposed by Angelier [30] to compute paleostress states from the analysis of slickensides in the field. This method considers RUP (%) and ANG (degree) coefficients as quality estimators of the computed stress tensor. The quantity of RUP reflexes the relative magnitude of shear stress responsible for the striation on the fault if it was large enough to move the fault while the other methods do not take into account the relative magnitude of the shear stress but only the misfit angle between the striation on the fault plans and computed shear stress from a population of faults.

3.3. Method for Computation of Tectonic Stress Distribution

To compute the distribution of tectonic stress in the Song Tranh 2 hydropower reservoir and its vicinity, we use the algorithm proposed by Okada 1992 [35]. The distribution of tectonic stress is computed based on the model of internal deformation in a half-space. This model has been widely deployed in researching the stress change due to earthquakes along seismogenic faults [36, 37]. In the model, an interesting area is considered as a cube with the upper and lower limits corresponding to the earth's surface and the fault depth, respectively. Entire the cube is divided into sub-blocks by the faults presented within the considered area. When the studied area is subject to regional tectonic stress, the sub-blocks would be differently deformed. The relative displacements between sub-blocks redistribute the tectonic stress within the interested area. The area with positive stress anomalies and or with high contrary to relative stress magnitude along fault wall might be the locus that initiates the potential reactivation of faults to trigger induced earthquakes.

4. Results

4.1. The youngest Tectonic Stress Field in the Song Tranh 2 Hydropower Reservoir Area

To determine the youngest tectonic stress state for the studied area, we conducted a detailed field survey and analyzed and acquired the attitude and kinematic parameters of slickensides. The separate the youngest displacement on different fault systems from polyphase fault populations was carefully conducted in the field. The separation was based on the crosscutting, overprint relations of fault displacement and the age of affected rocks observed during field research. The field observation of the youngest displacement on the faults revealed that the paleostress responsible for the youngest faulting has probably lasted from Late Miocene to the present day as documented by Vuong et al [23]. The fault data was analyzed by the INVD method developed by Angelier [38]. The computed stress tensors of the youngest tectonic stress state in the Song Tranh 2 hydropower reservoir and adjacent areas are given in Figure 2. This paleostress regime is characterized by a typical strike-slip tectonic regime with maximum principal stress axis (σ1) approximately oriented in N-S direction and plunge angle varying from 1^0 to 25^0 with average 13^0, the minimum principal stress (σ3) axis oriented in sub-latitude direction and plunging from 0 to 29^0 with average 13^0 while the intermediate principal stress axis (σ2) plunges sub-vertically. The stress ellipsoid shape ratio Φ varies from 0.13 to 0.85 with a mean of 0.54. The relative shear stress magnitude is 30% on average with a minimum value of 8% and a maximum value of 51%. The average deviation angle between the striae measured on the slickensides and calculated shear stress from the fault population is 9.5^0 with a minimum deviation of 3^0 and a maximum of 19^0. These values of quality estimators attested to the high reliability of the data. The parameters of the youngest stress state determined in the studied area are given in Table 1.

Table 1. Parameters of paleostress tensor of the Song Tranh 2 hydropower reservoir and its adjacent areas

Site	Number of faults	Trend/plunge of sigma 1	Trend/plunge of sigma 2	Trend/plunge of sigma 3	Φ	RUP (%)	ANG (s,τ ^{0})
2ST03	6	004 23	133 56	263 24	0.418	31	7
2ST12	4	356 10	229 730	088 13	0.126	8	19
2ST37	5	024 57	153 22	253 22	0.523	40	9
2ST40	4	229 12	126 49	329 38	0.333	25	3
2ST46	6	347 17	227 59	085 25	0.536	43	14
2ST56	5	025 20	266 54	127 29	0.347	38	10
2ST60	5	347 16	189 73	079 06	0.778	20	7
2ST65	5	196 06	011 84	106 00	0.503	25	6
2ST78	15	159 21	338 69	069 00	0.682	32	9
2ST79	6	338 01	230 87	068 03	0.511	28	4
2ST80	11	165 25	311 60	068 15	0.717	36	13
2ST83	10	006 07	238 79	097 08	0.617	27	14
2ST91	6	084 07	200 74	352 14	0.571	39	14

Site	Number of faults	Trend/plunge of sigma 1	Trend/plunge of sigma 2	Trend/plunge of sigma 3	Φ	RUP (%)	ANG (s,τ ^{0})
2ST92	7	040 11	175 74	308 11	0.851	51	14
2ST43	7	171 23	340 67	080 04	0.658	33	10
2ST64	5	012 08	212 82	103 03	0.473	17	3

Note: Φ: paleostress ellipsoid shape ratio $\Phi = (\sigma2-\sigma3)/(\sigma1-\sigma3)$. RUP (%): quality estimator for average reduced relative shear stress magnitude computed from fault slip data. ANG: average angle between striae and calculated shear stress on slickenside and standard deviation.

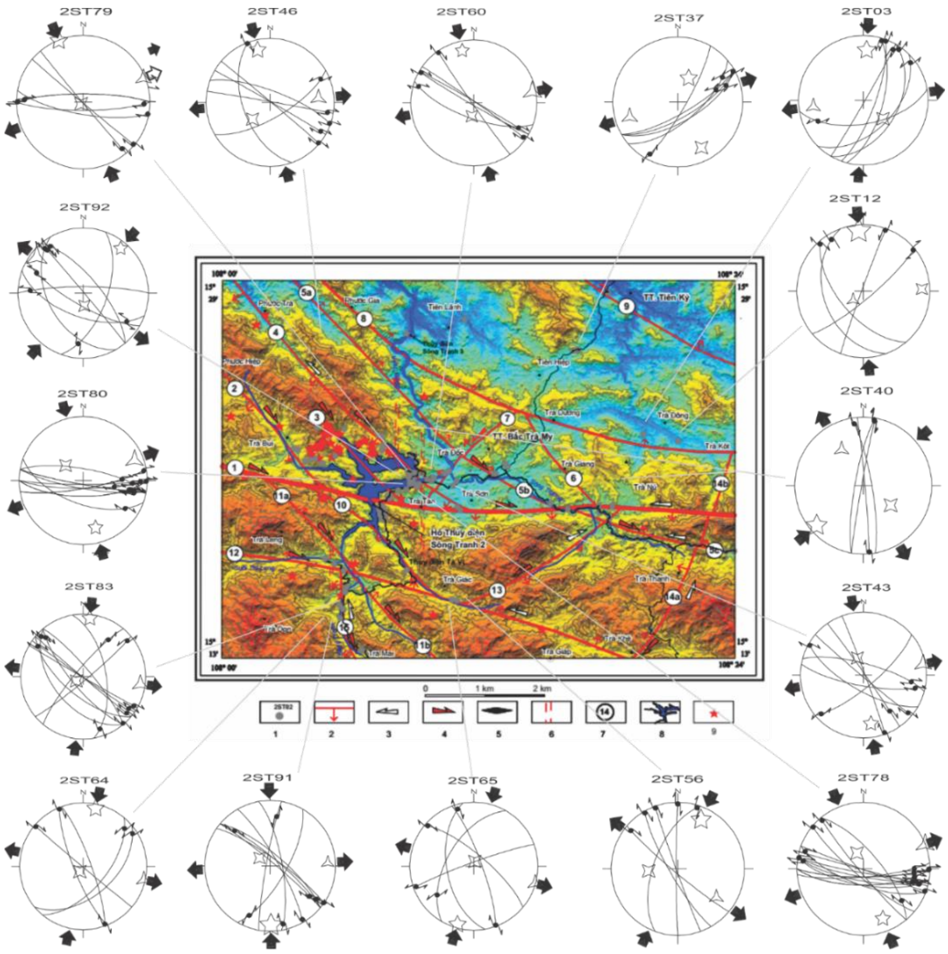

Figure 2: Distribution of the latest paleostress state in the Song Tranh 2 hydropower reservoir and its adjacent areas. For legend, see Figure 1.

4.2. Distribution of Stress Field in the Song Tranh 2 Hydropower Reservoir Area

In order to compute the distribution of tectonic stress for the Song Tranh 2 hydropower reservoir and its vicinity, we used the stress-strain model in half-space proposed by Okada in 1992 [35] coupled with the fault geometry and parameters of determined paleostress in the previous section. The input parameters for computing the latest tectonic stress distribution within the studied area are given in Table 2.

Table 2. Fault parameters for calculation of youngest tectonic stress distribution in the Song Tranh 2 hydropower reservoir area

Fault name	Fault No.	Fault strike	Dip angle and Dip direction	Sense of motion		Length (km)	Pitch
				Older phase	Youngest phase		
Tra Bui-Tra Nu	1	Sub-latitude	60^0 to 90^0 S	Sinistral	Dextral	43,5	08E
Phuoc Hiep-Tra Bui	2	NW-SE	70^0 to 80^0 SW	Sinistral	Dextral	13,5	10SW
Tra Tan	3	NW-SE	70^0 to 80^0 SW	Sinistral	Dextral	11,22	05W
Phuoc Tra-Tra Son	4	NW-SE	70^0 to 80^0 SW	Sinistral	Dextral	28,33	08W
Tra Doc-Truong River	5a	NW-SE	60^0 to 70^0 NE	Sinistral	Dextral	20,7	08W
Tra Doc- Song Truong River	5b	NW-SE	60^0 to 70^0 NE	Sinistral	Dextral	9,5	08W
Tra Doc-Truong River	5c	NW-SE	60^0 to 70^0 NE	Sinistral	Dextral	14,39	08W
Tra Giang	6	NW-SE	70^0 to 80^0NE	Sinistral	Dextral	10,4	05N
Tra Tan-Bac Tra My	7	NE-SW	70^0 to 80^0 NW	Dextral	Sinistral	11,5	10N
Phuoc Gia-Tra Kot	8	NW-SE	60^0 to 80^0 NE	Sinistral	Dextral	38,68	10N
Tien Ky	9	NW-SE	65^0 to 80^0 NE	Sinistral	Dextral	14,5	05E
Ta Vi stream	10	NW-SE	60^0 to 70^0 SW	Sinistral	Dextral	14,8	10E
Tra Leng	11a	NW-SE	65^0 to 90^0 NE	Sinistral	Dextral	11,4	12E
Tra Leng	11b	NW-SE	65^0 to 90^0 NE	Sinistral	Dextral	10,37	12E
Tra Leng stream-Tra Khe	12	Sub-latitude	80^0 to 90^0 N	Sinistral	Dextral	34,96	15W
Tra Giac	13	NE-SW	80^0 to 90^0 E	Dextral	Sinistral	13,82	12N
Tra Khe-Tra Kot	14a	Sub-longitude	70^0 to 80^0 W	Sinistral	Dextral	14,05	07N
Tra Khe-Tra Kot	14b	Sub-longitude	70^0 to 80^0 W	Sinistral	Dextral	5,91	07N
Tranh River-Tra Mai	15	Sub-longitude	60^0 to 90^0 W	Sinistral	Dextral	7,80	08N

The computed results of tectonic stress distribution for the Song Tranh 2 hydropower area are shown in Figure 3. The tectonic stress distribution map shows four tectonic stress small and narrow areas with positive tectonic stress anomalies oriented in the NW-SE direction and some smaller ones located between Phuoc Tra and Phuoc Gia faults in the northwest of Tra Khe and Tra Leng streams. The first positive tectonic stress anomalous area concentrates in the south of Phuoc Hiep, northwest of Tra Bui communes and coincides with the NW-SE striking fault No.2. The second tectonic stress anomalous area distributes in the southwest of the Song Tranh 2 reservoir and coincides with the NW-SE striking fault No.10. The third tectonic stress anomalous area distributes on the western side of the Song Tranh 2 reservoir and in-between Tra Bui and Tra Leng communes. This tectonic stress anomaly coincides with the intersection of the sub-latitude striking Tra Bong fault and the NW-SE striking fault No.11a. The fourth tectonic stress anomalous area coincides with the NW-SE striking fault No.11b and located in-between Tra Giap and Tra Mai communes.

In addition to four tectonic stress anomalous areas, it also displays a few anomalous spots in the studied area. The first spot, located on the footwall of the faults numbered 4 in the southeast of Phuoc Tra commune, tends to extend in the NW-SE direction. The second tectonic stress anomalous spot distributes in the south of Tra Leng commune and on the WNW-ESE striking fault numbered 12. The third tectonic stress anomalous spot isolated in the north of Tra Khe commune and to be unrelated to any identified fault.

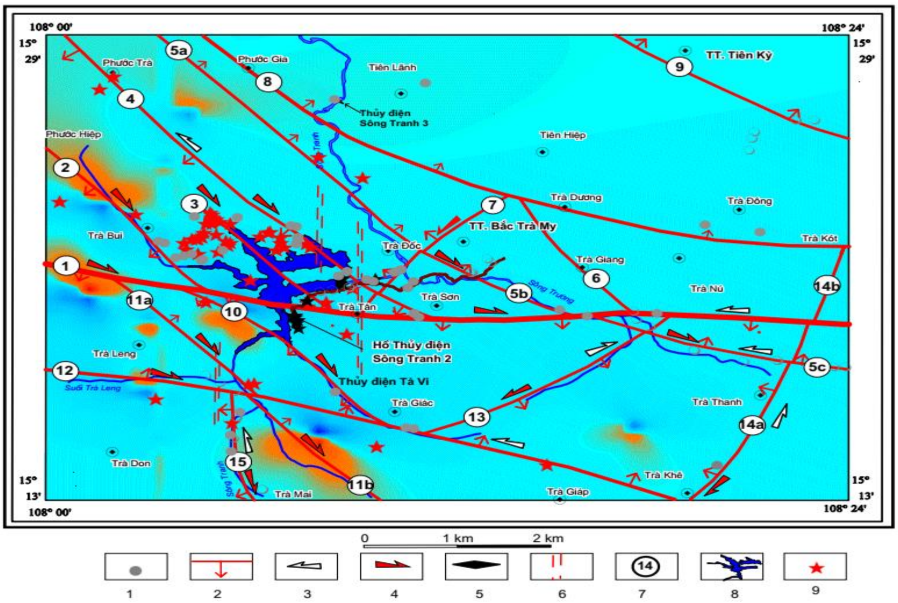

Figure 3. Tectonic stress distribution in the Song Tranh 2 hydropower reservoir area: 1) outcrop; 2) fault with dip direction; 3) sinistral displacement; 4) active dextral displacement; 5) dam location; 6) fracture zone; 7) fault number; 8) Song Tranh 2 hydropower reservoir; 9) induced earthquake epicentre. The dark orange colour indicates the positive tectonic stress anomalies; the blue colour corresponds to the negative tectonic stress anomalies. Light blue is the neutral tectonic stress area.

5. Discussion on the Significance of Tectonic Stress Anomalies and Potential Reactivation of Faults

A close relationship between tectonic stress and potential reactivation of faults is well documented worldwide [5, 39] as well as in Vietnam [23, 40-42]. In the Song Tranh 2 hydropower reservoir, Gahalaut et al. (2016) [9] and Tuan et al. 2017 [10] suggested a close relationship between the Colomb stress change and the NW-SE striking fault numbered 4. However, the distribution of tectonic stress computed in this study revealed four tectonic stress anomalous areas with NW-SE orientation and close to the faults numbered 2, 10 and 11a, 11b. Two others distributed along the fault numbered 4 in both hanging and foot walls. Such small stress anomalies could be generated due to the different amount of offset between the faults numbered 4 and 5. It is noticeable that the fault numbered 2 and 10 coincide with the local river channels. Such coincidence might result in the fast change of pore pressure during impoundment and discharge of the reservoir. The influence of pore pressure change on the internal frictional coefficient of basement rocks of the reservoir and the subsequent increasing the potential reactivation of faults and seismogenic activity in the reservoir as well as in petroleum, geothermal exploitation was well documented [43-46]. On the other hand, basement rocks of the Song Tranh 2 hydropower reservoir area composed mostly of plutonic and high-grade metamorphic rocks with low permeability and porosity but highly fractured.

Therefore, changing the pore pressure occurred fast and mostly along the fault zones and their associated fractures in the area of the reservoir and its adjacent. The permeation of water along the fault zones was faster than that in the porosity media and subsequently induced earthquake occurring soon after the impoundment, as documented by Trieu et al. 2014 [6], Giang et al. 2015 [7]. The percolation of water through the basement of the reservoir might result in the delay of induced earthquakes linking to the impoundment and discharge of the reservoir, as documented by Gahalaut et al., 2016 [9]. Although the role of pore pressure was not taken into account in this paper, the coincidence of the fault numbered 2, 10 and 11a with the river channels could be considered as the engine that triggered the induced earthquakes in the Song Tranh 2 hydropower reservoir and its adjacent areas. Hence, the NW-SE striking faults numbered 2, 10 and 11a are the highest potential one to reactivate and generate reservoir induced earthquakes whereas the fault numbered 4 and 1 are less possibility to reactivate.

6. Conclusion Remarks

The results of identification of fault attitudes and tectonic stress field in the Song Tranh 2 hydropower reservoir and its adjacent areas reveal that the studied areas have experienced a strike-slip tectonic stress field during the Cenozoic. The youngest tectonic stress state is characterized by the sub-horizontal maximum principal stress axis sigma 1 oriented in roughly N-S to NNE-SSW direction, the sub-vertical intermediate principal stress axis sigma 2 and the sub-horizontal minimum principal stress axis sigma 3 oriented in E-W to ESE-WNW direction. This tectonic stress field resulted in dextral and sinistral motions of the NW-SE to N140 to N150 striking faults and N60 to NE-SW striking faults, respectively.

Four large positive tectonic stress anomalous areas existed in the Song Tranh 2 hydropower reservoir and linked to the NW-SE striking faults numbered 2, 10, 11a and 11b and sub-latitude striking fault numbered 1. The river channels developing along these faults probably resulted in the pore pressure change and enhanced faults reactivations, and induced earthquakes.

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