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POSSIBILITY OF RESERVOIR-TRIGGERED EARTHQUAKE OCCURRENCE IN THE HUOI QUANG AND BAN CHAT HYDROPOWER DAM AREA

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ABSTRACT: The possibility of reservoir-triggered earthquake occurrence in the Huoi Quang and Ban Chat hydropower dam area has been assessed based on studying and analyzing the relationships between the reservoir-triggered earthquake occurrence and the following factors: (1) the types of rocks underlying the reservoir; (2) the oscillating reservoir loads on faults in the reservoir area; (3) the incremental stress caused by reservoir loads; (4) the slip tendency of faults in the reservoir area; and (5) the Coulomb stress change of faults in the reservoir area. The results show that these factors have interactive effects and simultaneously contribute to the favorable conditions for reservoir-triggered earthquake occurrence. The Huoi Quang and Ban Chat hydropower reservoirs are located in the area of moderate seismicity; however, with the favorable conditions due to these five factors, reservoir-triggered earthquakes can possibly occur. If reservoir-triggered earthquakes occur, they will be concentrated around the Ban Chat hydropower dam area within a radius of 11 - 12 km and at a depth of about 6 ± 1 km.

Keywords: Fault, reservoir, stress, tectonic, triggered-earthquakes.

INTRODUCTION

Currently in Vietnam as well as in the world, many artificial reservoirs have been created for the purpose of electricity production, flood control and irrigation. In some reservoirs, the water accumulation has resulted in geological hazards, including earthquakes. Earthquakes caused by artificial reservoirs (reservoir-triggered earthquakes) can possibly occur, but they are not the inevitable consequence of river damming [1]. Reservoir-triggered earthquakes are often associated with the water accumulation and discharge in the early years when the water is accumulated in reservoirs. Until 2013, 128 reservoir-triggered earthquakes have been reported worldwide, of which 4 earthquakes have $M \geq 6.0$, 15 earthquakes have $5.0 \leq M \leq 5.9$, 33 earthquakes have $4.0 \leq M \leq 4.9$, and 76 earthquakes have $M < 4.0$ [1-3]. In Vietnam, reservoir-triggered earthquakes with $4.0 \leq M \leq 4.9$ have also been recorded in the Hoa Binh and Song Tranh 2 hydropower reservoirs [4-6].

Reservoir-triggered earthquakes have occurred in reservoirs with different dam heights. Normally, reservoir-triggered earthquakes increase as the dam height increases [1]. Until 2012, in the world the reservoir-triggered earthquakes have occurred in 37 reservoirs among a total of 573 reservoirs with the dam height of 100 - 150 m [1]. In addition, many reservoir-triggered earthquakes have occurred in small reservoirs (capacity ≤ 1 billion m^3) such as Song Tranh 2 hydropower reservoir (capacity of 0.7292 billion m^3) [7].

The Huoi Quang and Ban Chat hydropower plants were constructed in 2006. Huoi Quang hydropower plant is the lower cascade of Ban Chat hydropower plant and is the upper cascade of Son La hydropower plant. The Huoi Quang and Ban Chat hydropower reservoirs (HQ-BC reservoirs) are located on the Nam Mu river in Than Uyen and Tan Uyen districts, Lai Chau province (fig. 1). These two reservoirs have great dam height. The Ban Chat and Huoi Quang hydropower dams are 132 m high and 104 m high, respectively. The total capacity of Ban Chat reservoir is 2.1 billion m^3 and that of Huoi Quang reservoir is 0.1842 billion m^3. The water in Bat Chat reservoir was accumulated up to a building grade of 475 m in February 2013; the water in Huoi Quang reservoir was accumulated up to a building grade of 370 m in February 2015.

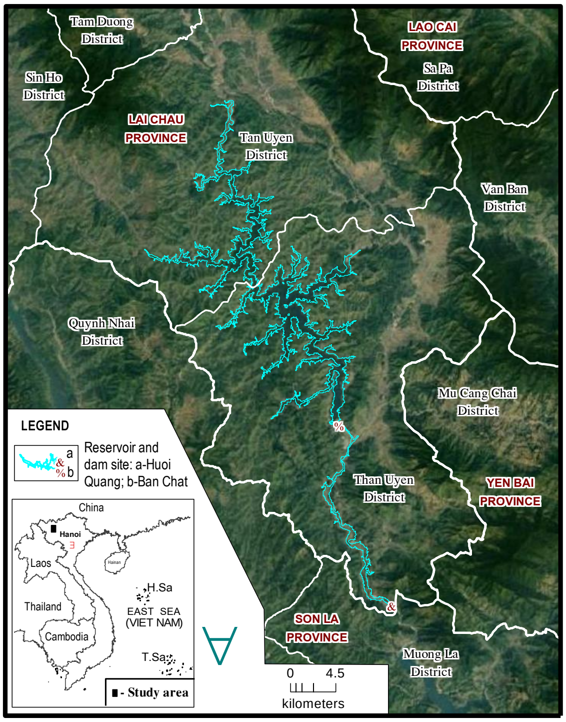

Fig. 1. Locations of Huoi Quang and Ban Chat reservoirs

Based on these realities, a question has been raised: When the water in HQ-BC reservoirs is accumulated up to the building grade, is there any possibility of reservoir-triggered earthquake occurrence? In response to this question, several factors related to the reservoir-triggered earthquake occurrence in this area have been simultaneously examined: (1) the types of rocks underlying the reservoir; (2) the oscillating reservoir loads on faults in the reservoir area; (3) the incremental stress caused by reservoir loads; (4) the slip tendency of faults in the reservoir area; and (5) the Coulomb stress change on faults in the reservoir area. The obtained results will make the safe operation of dams and reservoirs of Huoi Quang and Ban Chat hydropower plants more effective.

METHODS

In addition to traditional methods such as the analyses of geological maps, tectonic data, and seismic data, we have used the following methods:

The calculation of incremental stress under the reservoir caused by reservoir loads: When studying reservoir-triggered earthquake in Kariba reservoir (Zimbabwe), Gough and Gough (1970) examined the increment of stress and the subsidence of rocks under the reservoir caused by reservoir loads. To calculate the incremental stress under the reservoir caused by reservoir loads according to different components, the authors built the algorithm in three dimensions [8]. The details of method and algorithm can be seen in Gough and Gough (1970).

The assessment of the effects of oscillating reservoir loads on faults based on their locations and features: Roeloffs (1988) suggested that the effects of oscillating reservoir loads depended on the locations and features of faults [9]. The oscillating reservoir load maintains a stable effect on the fault if it is located on the hanging wall of a reverse fault with a steep dip or directly on a thrust fault with a low dip, or if a strike-slip fault or a normal fault is located on the edge of the reservoir. The instability of fault (earthquake) occurs if the reservoir is located on the footwall of a reverse fault with a steep dip or on the hanging wall of a thrust fault with a low dip. The earthquake can possibly occur beneath the reservoir if there is a vertical strike-slip fault or a normal fault.

The calculation of Coulomb stress change: The method was developed into the COULOMB program by Toda et al. (2011) based on the elastic half-space theory proposed by Okada (1992) and the Coulomb failure criterion proposed by King et al. (1994), in which the failure on faults occurs when there is a great change in Coulomb stress, which is determined by the formula:

$$\Delta\sigma_f = \Delta\tau_s + \mu'\Delta\sigma_n$$

Where $\Delta\sigma_f$ is the stress change on the faults due to the slip on the source faults, $\Delta\tau_s$ is the change in shear stress, $\Delta\sigma_n$ is the change in normal stress, and μ' is the coefficient of friction on the faults. Calculations were made in an elastic, isotropic and homogeneous half-space. The method was devised to calculate displacement, deformation and static stress at any depth caused by slip fault, intrusive magma, and extension or narrowing of dyke [10-12].

The analysis of slip tendency on the fault surface in three dimensions: The method was developed into a subprogram of COULOMB program by Neves et al., (2009) based on the definition of slip tendency on the fault surface of Morris et al., (1996). The slip tendency on the fault surface is defined as the ratio of shear stress (τ) to normal stress (σ_n) on the fault surface and denoted by T_s [13], thus the fault tends to slip when $T_s \geq 0.5$ [14]. The details of method and algorithm can be seen in Neves et al., (2009).

RECENT REGIONAL TECTONIC STRESS FIELD AND FEATURES OF MAJOR FAULTS IN THE RESERVOIR AREA

Recent regional tectonic stress field

The convergent or divergent motion of lithospheric plates will generate the compressive or tensile stress field respectively. This motion induces a field of tectonic force that propagates in the plates and is called the regional tectonic stress field. It does not remain in a certain form but changes according to time, space and magnitude [15]. The recent tectonic stress fields in geological structural units occurring at various locations are different; however, they still carry the typical morphology of regional tectonic stress field. The force direction of recent regional tectonic stress field is quantitatively expressed through the orientation values of three principal stress axes (σ_1, σ_2, σ_3). There are several methods for determining the orientation values of σ_1, σ_2, and σ_3 such as using the methods of conjugate joint sets (Gzovski) and superposition of compressive-tensile regions on the chart (Gusenko) to determine the orientation of maximum compressive stress axis [16], using the method of inverse problem solution based on a set of striations on the fault surfaces and focal mechanisms in a specific region to determine the most appropriate stress tensor [17], using the results of earthquake focal mechanism analysis to determine the orientation values of three stress axes [18-20].

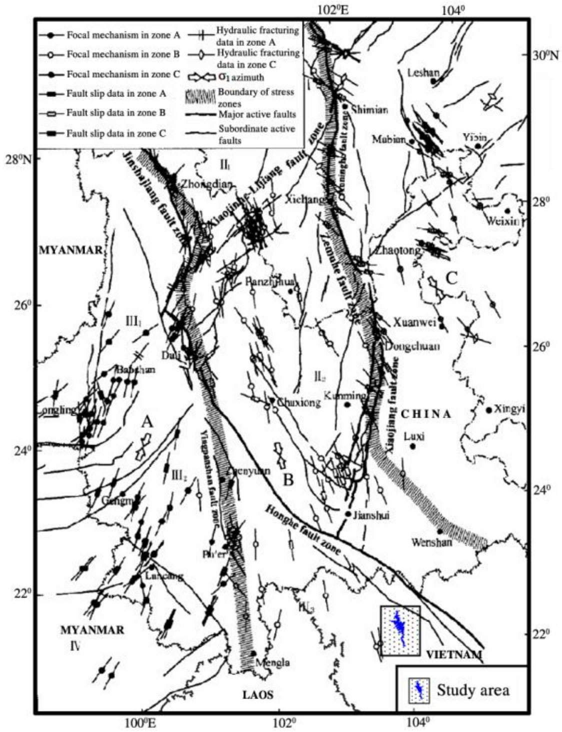

Fig. 2. Study area on the map of recent tectonic stress field zoning of Sichuan-Yunnan region (China). This map was modified after Cui et al., (2006)

The study area is located in Northwest Vietnam, where the maximum compressive stress axis (σ_1) and the maximum tensile stress axis (σ_3) of Pliocene-Quaternary regional tectonic stress field have been determined to be nearly horizontal in the sub-longitudinal direction and nearly horizontal in the sub-latitudinal direction respectively [16, 21-23]. These results do not reveal the quantitative values for the orientations of three principal stress axes of recent regional tectonic stress field. Currently, the result of earthquake focal mechanism analysis is considered as a reliable indicator to evaluate the state of regional tectonic stress field. However, in Vietnam, the results of earthquake focal mechanism analysis are few and asynchronous, thus the utilization of these results in determining quantitative values for three principal stress axes of recent tectonic stress field faces many difficulties. In order to overcome this limitation, we have referred to the similar research results in the vicinity and then have applied them in our study area. Because the study area is adjacent to the Sichuan-Yunnan stress zone (zone B), in this paper we have referred to the result of Cui et al., (2006) (fig. 2).

When studying the recent tectonic stress field in Sichuan-Yunnan region (China), Cui et al., (2006) established three tectonic stress zones based on the results of focal mechanism analysis of 201 earthquakes from 1933 to 2004. The authors determined the orientation values of three principal stress axes of recent tectonic stress field for each zone, of which the values of zone B were σ_1 (ψ=343, δ=5), σ_2 (ψ=122, δ=83) and σ_3 (ψ=252, δ=4) [8]. This result was similar to that of Ha Thi Giang (2012) when analyzing the focal mechanism of the earthquake in Muong La on November 26, 2009, M_W = 3.9 and two aftershocks (table 1) [24]. Therefore, in this paper the orientation values of three principal stress axes of recent regional tectonic stress field have been determined to correspond to those of zone B.

Table 1. The focal mechanism solutions of three earthquakes occurring in Muong La area [24]

Date	Location		M_W	P		T		Remark
	Lat. (°)	Long. (°)		Azimuth (°)	Plunge (°)	Azimuth (°)	Plunge (°)	
26/11/2009	21.316	104.176	3.6	167 (*347*)	6	258	9	Main shock
26/11/2009	21.309	104.163	3.5	168 (*348*)	6	258	3	Aftershock
08/12/2009	21.315	104.164	2.9	163 (*343*)	9	254	5	Aftershock

Features of major faults in the reservoir area

The major faults located in the connected region of HQ-BC reservoirs were determined based on the results of ~30 m resolution DEM image analysis (SRTM images and GMRT images), including F-II1, F-II2, F-III, F-III2, F-III3 and F-III4 faults (fig. 3) [3].

F-II1 fault is a segment of the Muong La - Bac Yen fault zone. This is a second order fault, coinciding with the foot of tectonic scarp with the height of about 1000 m [25]. This fault develops in the NW - SE direction. Along the fault zone, the geological formations are extremely cataclased, sheared and contorted with many slip surfaces containing striations and cross-cutting quartz veins [23, 26]. According to Le Tu Son et al., (2005), the slip surface of the fault inclines northeastwards with the inclination of 70 - 80° and the dipping depth of 35 - 40 km. The destruction zone on the fault surface shows the linear fracture structures extending continuously, forming the steep cliff and sometimes leaving the sharp facets. Under the impact of recent tectonic stress field, the slip type of the fault is mainly dextral strike-slip, along with inverse component [23].

F-II2 fault is a segment of the Than Uyen fault zone. This is a second order fault zone, extending in the NE - SW direction. According to Le Tu Son et al., (2005), the geological formations distributed along the fault are severely laminated, contorted and crystallized into quartz; in addition, the tectonic fracture and cataclasis are observed in some places; the slip surface attitude of the fault is determined to dip southeastwards with the dip angle of 80° and the dipping depth of 30 - 35 km. Under the impact of recent tectonic stress field, the slip type of the fault is mainly sinistral strike-slip, along with normal component [23].

F-III1, F-III2, F-III3 and F-III4 faults are segments of the Muong Khoa - Ta Gia fault zone, which were determined based on the results of DEM image analysis [3]. These faults coincide with the IV-40 fault zone determined by Le Tu Son et al., (2005). The slip surface of fault zone dips eastwards with the dip angle of 75°. The geological formations distributed along the faults are laminated, fractured and cataclased by faulting activities. The dipping depth of the faults reaches 10 - 20 km [23]. According to our assessment, these faults are probably the extension of the Muong La - Bac Yen fault zone but they are smaller in scale. Under the impact of recent tectonic stress field, the slip type of these faults is mainly normal type, along with dextral strike-slip component.

Some basic features of F-II1, F-II2, F-III1, F-III2, F-III3 and F-III4 faults are summarized and presented in table 2 below.

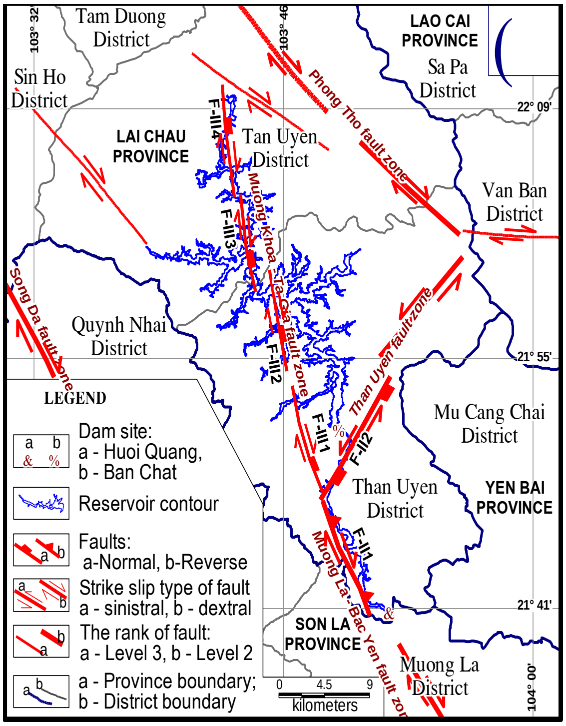

Fig. 3. The major faults in the study area

Table 2. Basic features of major faults within the Huoi Quang and Ban Chat reservoir area [3, 23, 26]

No.	**Faults**	**Strike** (°)	**Length** (km)	**Depth** (km)	**Dip angle** (°)**/Dip direction**	**Slip type** (N_2-Q)
1	F-II1	157	12.5	35 - 40	80 / NE	Dextral strike-slip
2	F-II2	211	14.5	30 - 35	80 / SE	Sinistral strike-slip
3	F-III1	164	11.1	10 - 20	75 / E	Normal
4	F-III2	170	10.4	10 - 20	75 / E	Normal
5	F-III3	171	9.9	10 - 20	75 / E	Normal
6	F-III4	174	11.4	10 - 20	75 / E	Normal

SOME FACTORS RELATED TO THE POSSIBILITY OF RESERVOIR-TRIGGERED EARTHQUAKE OCCURRENCE IN THE HQ-BC RESERVOIR AREA

Types of rocks underlying the reservoir area

According to global statistics results of Qiu (2012) based on 115 reservoir-triggered earthquakes occurring in the reservoir areas, among four types of rocks underlying the reservoirs (crystalline rock, limestone, volcanic rock and clastic rock), crystalline rock and limestone are most likely to experience earthquakes (39.13%) [1]. Limestone is the most vulnerable rock because of being chemically dissolved by water. When being chemically dissolved, the cohesion of the rock decreases, the friction also decreases, thus weakening the strength of fault [27]. The dissolved materials can also be removed by the water flow, the rock fractures are extended, thus reducing the strength of rock, accelerating the slip process and finally resulting in the reservoir-triggered earthquake occurrence.

Based on the distribution of geological formations on the sheets of Geological and Mineral Resources Map of Vietnam on 1:200,000 such as the Kim Binh - Lao Cai sheet [28], the Phong Sa Li - Dien Bien Phu sheet [29], we have delineated six areas in which there are limestone, marl, light-grey porous limestone of Muong Trai Formation (T_2l mt_2). These areas are distributed into six narrow strips, of which only three strips (A, B, C) are located beneath the reservoirs. Based on this feature, it can be concluded that the A, B, C areas are more likely to experience earthquakes (fig. 4).

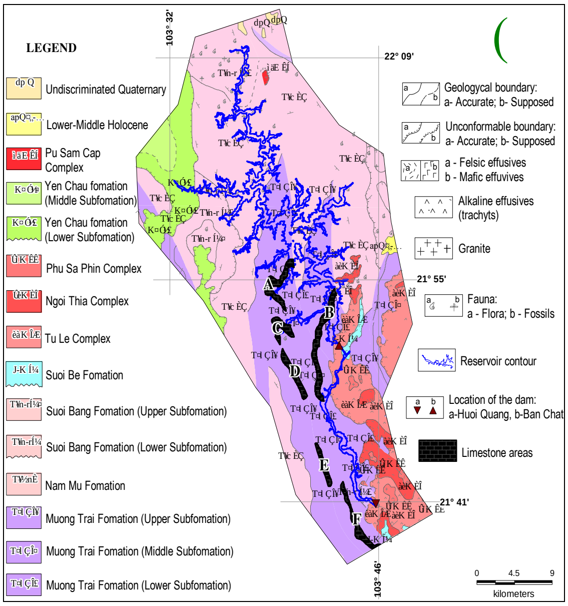

Fig. 4. Distribution of limestone on the Geological and Mineral Resources Map of Vietnam

Oscillating reservoir loads on major faults in the reservoir area

Based on the locations of the faults and with the HQ-BC reservoirs in fig. 3, it can be seen that the F-II1, F-III2, F-III3 and F-III4 faults will be directly affected by oscillating reservoir loads. To examine the effect of oscillating reservoir loads on faults in the HQ-BC reservoir area, we have used the method of Roeloffs (1988) [9]. The results show that the Huoi Quang reservoir is located on the fault with the dominant strike-slip type (F-II1 fault), and the Ban Chat reservoir is located on the faults with the dominant normal slip type. Thus, under the impact of oscillating loads of HQ-BC reservoirs, F-II1, F-III2, F-III3 and F-III4 faults become unstable. It means that under the impact of oscillating loads of HQ-BC reservoirs, the reservoir-triggered earthquakes are likely to occur on the F-II1, F-III2, F-III3 and F-III4 faults.

Incremental stress under the full reservoir

The algorithm proposed by Gough and Gough (1970) to calculate the incremental stress caused by reservoir loads has been successfully used in some reservoirs in Vietnam such as Hoa Binh, Son La, Song Tranh 2 hydropower reservoirs [7, 30, 31]. These calculation results show that the value of incremental stress under the reservoir caused by reservoir loads reaches the maximum and vanishes at the certain depth; this value gradually decreases with depth.

In accordance with the building grades of Huoi Quang and Ban Chat hydropower reservoirs, Bui Van Duan et al., (2014) calculated the incremental stress under the reservoir caused by reservoir loads. The results show that the value of incremental stress caused by reservoir loads reaches the maximum at the depth h = 0.123 km, gradually decreases and vanishes at the depth h=6.217 km [3]. The increments of downward normal stress (σ_Z) and maximum shear stress (τ_{max}) at depths of 3 km, 6 km under HQ-BC reservoirs caused by reservoir loads are presented in table 3.

Table 3. Maximum values of incremental stress (σ_Z, τ_{max}) at 3 km and 6 km depths under HQ-BC reservoirs caused by reservoir loads [3]

Depth (km)	Maximum values of incremental stress	
	σ_Z (bar)	τ_{max} (bar)
3	1.96	1.09
6	0.99	0.56

With the results shown in table 3, it can be seen that at depths of 3 km and 6 km under HQ-BC reservoirs, there are the increments of σ_Z and τ_{max} caused by reservoir loads. The incremental stress caused by reservoir loads is mainly concentrated in the Ban Chat reservoir area and reaches the maximum value in the center of the reservoir (fig. 5 and fig. 6).

Rajendran (1995) argued that the stress change caused by reservoir loads was associated with reservoir-triggered earthquakes when the incremental stress under the reservoir was about 0.1 bar [32]. The values of σ_Z and τ_{max} under HQ-BC reservoirs are not considerable but > 0.1 bar. Thus, the incremental stress of rocks under HQ-BC reservoirs caused by reservoir loads is one of the favorable conditions for reservoir-triggered earthquake occurrence in this area and its vicinity. With this increment, the possibility of reservoir-triggered earthquake occurrence will be concentrated in the Ban Chat reservoir area at the depth of 6 ± 1 km.

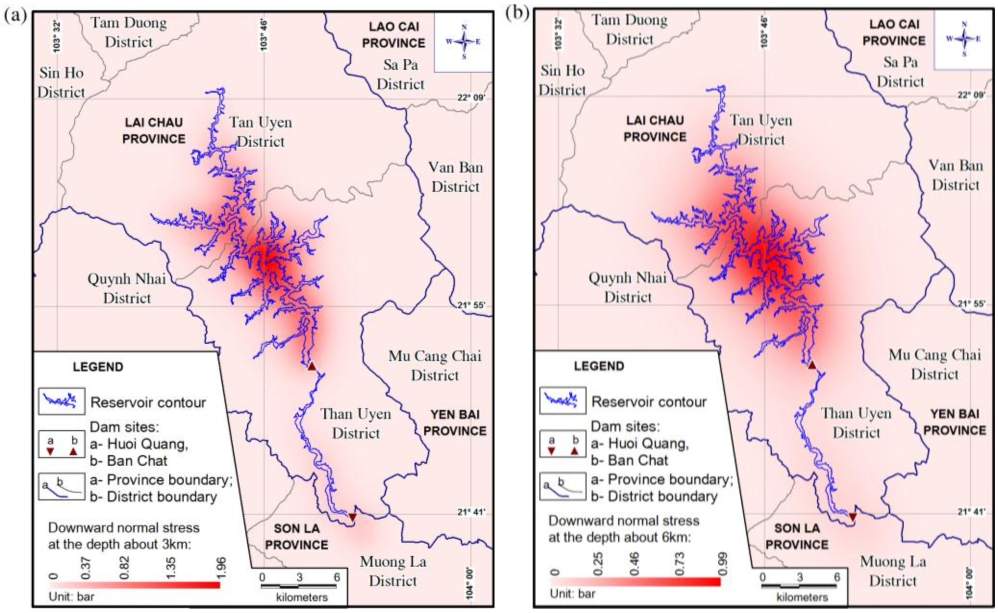

Fig. 5. Distribution of the downward normal stress (σ_Z) under HQ-BC reservoirs at 3 km (a) and 6 km (b) depths

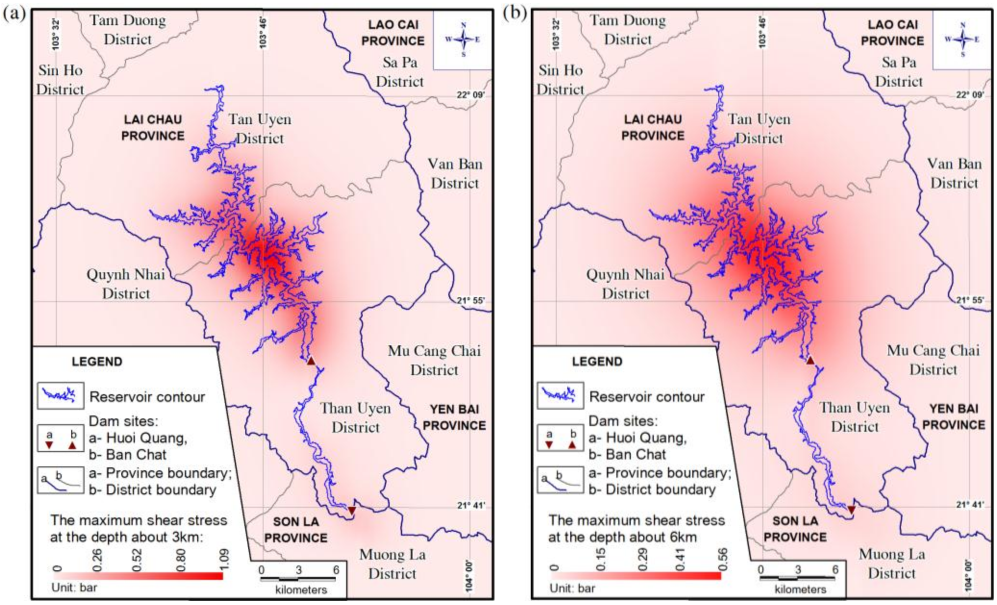

Fig. 6. Distribution of the maximum shear stress (τ_{max}) under HQ-BC reservoirs at 3 km (a) and 6 km (b) depths

Slip tendency of major faults in the reservoir area

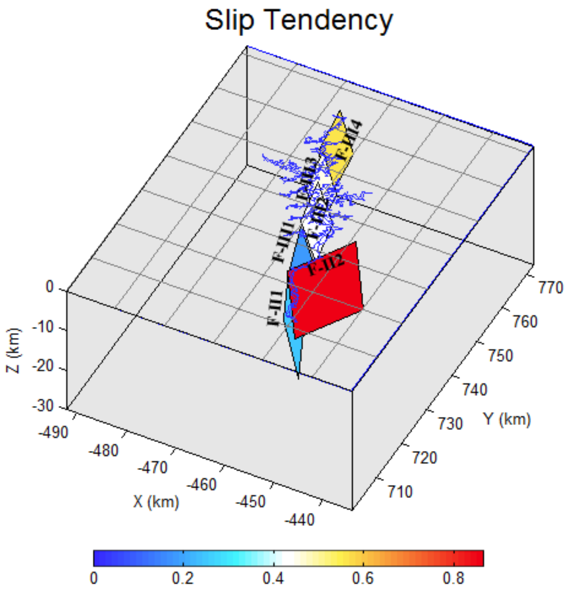

Fig. 7. Slip tendency of major faults in the HQ-BC reservoir area on a 3D grid with red color indicating the highest slip tendency

The majority of earthquakes in reservoirs are caused by the reactivation of pre-existing faults rather than the occurrence of new faults [13]. The possibility of reactivation of major faults in the HQ-BC reservoir area is related to the recent regional tectonic stress field. Using a program for analyzing slip tendency of faults in three dimensions developed by Neves et al., (2009), we have assessed the slip tendency on F-II1, F-II2, F-III1, F-III2, F-III3 and F-III4 faults. The results of slip tendency analysis on major faults in the HQ-BC reservoir area under the impact of recent regional tectonic stress field are presented in fig. 7.

The results in fig. 7 show that F-II2 and F-III4 faults tend to slip, of which F-II2 fault has strong slip tendency ($T_s \geq 0.8$), F-III4 fault has moderate slip tendency (T_s = 0.5 - 0.6). In addition, Le Tu Son et al., (2005) showed that the slip surface of F-II2 fault coincided with the laminated surface of shale of Muong Trai Formation (T_2l mt_3) [23]. With this feature, after the water accumulation in HQ-BC reservoirs, the water will soak through fault surface and reduce the friction on fault surface, thus creating the favorable conditions for slip process. Therefore, under the impact of recent regional tectonic stress field, reservoir-triggered earthquakes are more likely to occur on F-II2 fault.

Coulomb stress change of major faults in the reservoir area

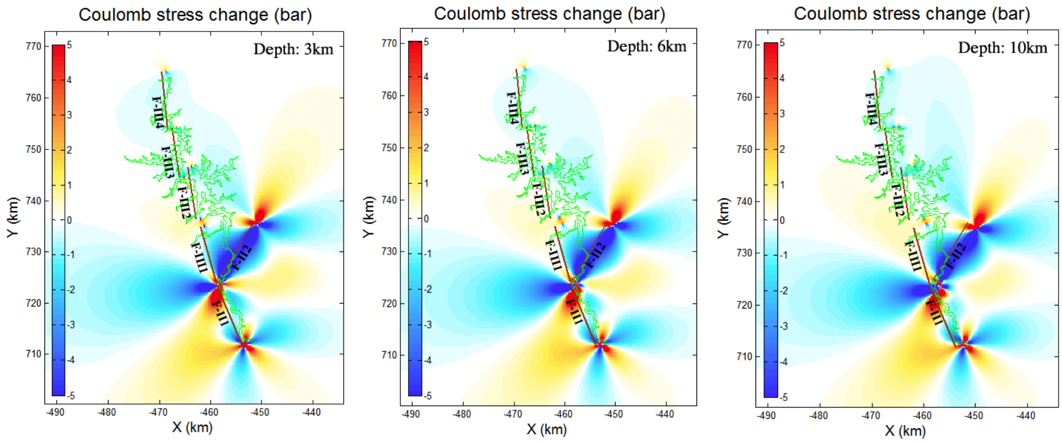

Fig. 8. The Coulomb stress change of major faults in the HQ-BC reservoir area at different depths (red color indicating the stress rise; blue color indicating the stress drop)

Using the method of calculation of Coulomb stress change developed by Toda et al., (2011), we have examined Coulomb stress change of major faults in the HQ-BC reservoir area at different depths. To examine this factor, a maximum earthquake scenario is assumed to occur on faults in the reservoir area as follows: on F-II1 and F-II2 faults the maximum earthquake has a magnitude M_{Smax}=5.9 [33]; on F-III1, F-III2, F-III3 and F-III4 faults the maximum earthquake has a magnitude M_{Smax}=5.0 [34]. This scenario is input into the COULOMB 3.3 program to calculate the stress change on the faults. Coulomb stress change on the faults in the HQ-BC reservoir area is calculated at depths of 3 km, 6 km, 10 km and presented in fig. 8. The results indicate that in the recent regional tectonic stress field, Coulomb stress change is clearest and greatest on F-II2 fault. Thus, reservoir-triggered earthquakes in the HQ-BC reservoir area are more likely to occur on F-II2 fault and in the regions of stress rise (red- and yellow-colored regions). With this result, in the recent regional tectonic stress field, the activity of F-II2 fault will control and direct the distribution of reservoir-triggered earthquakes occurring in this area.

DISCUSSION

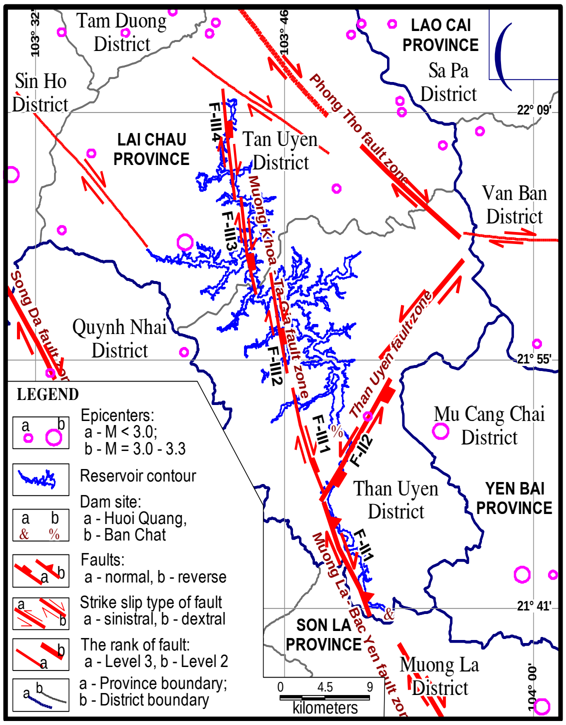

Fig. 9. Distribution of earthquakes occurring in the study area in the period of 1900-2012

The HQ-BC reservoir area is located in the Northwest, which is considered the most active seismic region in the territory of Vietnam [34, 35]. However, the study area has the moderate seismicity. This was assessed by Le Tu Son et al., (2005) based on the results of Gutenberg-Richter graph drawing for the Huoi Quang and Ban Chat hydropower plant area in the period of 1920-2004 [23]; the graph is defined by:

$$\log N = 5.66 - 0.86 * M$$

In this paper, the seismic data in the HQ-BC reservoir area before the water accumulation up to building grade (from 1900 to 2012) have been collected. According to the record of the Institute of Geophysics, before the water was accumulated up to building grade in the Ban Chat reservoir (before 2013), no earthquakes occurred within the reservoir area but some occurred outside (fig. 9).

Thus, the HQ-BC reservoirs are located in the area where earthquakes rarely occur. This feature is quite consistent with the result of research on tectonic deformation in Northwest Vietnam using GPS measurement technology by Nguyen Anh Duong (2012). This result shows that the tectonic deformation in the HQ-BC reservoir area is mainly extensional (extensional strain rate axis is greater than compressional strain rate axis) [36], the stress is not accumulated; consequently, earthquakes rarely occur.

The results from the assessment of five associated factors show that these factors have interactive effects and simultaneously contribute to the favorable conditions for reservoir-triggered earthquake occurrence. The HQ-BC reservoirs are located in the area of moderate seismicity (even low seismicity); however, with the favorable conditions due to five associated factors, reservoir-triggered earthquakes can possibly occur. It should be emphasized that whether reservoir-triggered earthquakes in the HQ-BC reservoir area occur or not, they depend on the complex relationship between these factors and the earthquake occurrence. Due to the complexity and diversity of factors related to reservoir-triggered earthquakes, all assessments and researches to minimize the hazards of river damming must be considered simultaneously. It has no significance if any factor is considered separately and allowed to play an overwhelming role.

CONCLUSION

The possibility of reservoir-triggered earthquake occurrence in the Huoi Quang and Ban Chat hydropower reservoirs is related to the following factors: (1) the types of rocks underlying the reservoir; (2) the oscillating reservoir loads on faults in the reservoir area; (3) the incremental stress caused by reservoir loads; (4) the slip tendency of faults in the reservoir area; and (5) the Coulomb stress change of faults in the reservoir area. These factors interact with each other and simultaneously contribute to the favorable conditions for reservoir-triggered earthquake occurrence.

The Huoi Quang and Ban Chat reservoirs are located in the area of moderate seismicity; however, the assessment results based on five associated factors show that reservoir-triggered earthquakes can possibly occur. If reservoir-triggered earthquakes occur, they will be concentrated around the Ban Chat hydropower dam area within a radius of 11 - 12 km and at a depth of about 6 ± 1 km.

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