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The characteristics of seismic activity in the ladder zone of Da river hydro-electric plants

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Abstract:

In this paper, the authors describe a study examining the characteristics of seismic activity in the ladder zone of Da river hydro-electric plants. The study results show that:

- The occurrence of natural earthquakes in the ladder zone of Da river hydro-electric plants is the strongest in Vietnamese territory. An earthquake magnitude of M=6.7 has been observed in the Tuan Giao and Lai Chau areas, with a b coefficient value (Gutenberg-Richter law) of 0.935.

- Natural earthquakes with magnitudes in the range of 6.0-6.9 seem to occur in 13 seismic sources, these being: Muong Te, Nam Nhe, Muong Nhe, Lai Chau - Dien Bien, Son La, Tuan Giao, Phong Tho, Muong La - Bac Yen, Song Da (Da River), Nam Tong, Mu Cang Chai, Lao Cai - Ninh Binh (Phan Sipan), and Mai Chau. Of these, an apparent risk of strong earthquakes, with a magnitude of M=6.9, appears in Muong Te, Lai Chau - Dien Bien, Tuan Giao, Yen Chau, and Mai Chau areas.

- Triggered earthquakes with a magnitude M>4.0 have occurred in the region of the Hoa Binh and Son La hydro-electric plant reservoirs, which have a maximum depth of over 100 meters, and a geological structure comprising mainly limestone.

- No likelihood of triggered earthquakes in the region of the Hoa Binh hydro-electric plant reservoir; however, in the Son La hydro-electric reservoir region, a triggered earthquake is expected in the future with a strong magnitude of M=4.3, or possibly even M=5.0.

Keywords: **ladder zone of Da river hydro-electric plants, natural earthquake, triggered earthquake.**

Classification numbers: **4.2, 4.3**

Introduction

The triggering of earthquakes by the filling of artificial water reservoirs has been recognised for over six decades, the first instance of this being pointed out by Carder (1945) at Lake Mead in the United States of America. To date, over 90 sites globally have been identified where earthquakes have been triggered by such activity. Destructive earthquakes exceeding magnitude 6 occurred at Hsinfengkiang, China in 1962; Kariba, Zambia-Zimbabwe border in 1963; Kremasta, Greece in 1966; and Koyna, India in 1967. The Koyna earthquake of M=6.3, that occurred on 10 December 1967, is so far the largest earthquake to be scientifically recognised as 'triggered'. There is argument about whether the Sichuan, China, M=7.9 earthquake of 12 May 2008, which claimed over 80,000 lives, was triggered by the filling of the nearby Zipingpu reservoir [1]. In Vietnam, the study of reservoir triggered seismicity was initiated after the occurrence of earthquakes in the vicinity of Hoa Binh hydro-electric reservoir in 1989. The reservoir was impounded in May 1988. When the water level reached 80 m in December 1988, some weak earthquakes were detected in the vicinity of the dam. Earthquake activity continued, with some earthquakes of M=2.4 being detected during the period January-April, 1989. On 14 April 1989, seven earthquakes were recorded, including two events of M=3.8 and 3.7 with a hypocentral depth of 5 km. On 23 May 1989, the largest earthquake, measuring M=4.9, occurred [2, 3]. Another earthquake, of M=4.7, occurred at Song Tranh 2, Vietnam on 15 November 2012, and was assumed to be triggered by reservoir impoundment, as this region was otherwise regarded as largely aseismic [4-7].

Currently, five hydro-electric plants are operating in the area of the Da river main stream, namely: Hoa Binh, Son La, Lai Chau, Huoi Quang, and Ban Chat - the highest capacity hydro-electric plants in Vietnam (Table 1). Meanwhile, the Da river valley is assessed as an area of high sesmic activity [8-11]; a representative earthquake is that of Tuan Giao, which reached M=6.7, and which occurred in June 1983. This earthquake was recorded by the system of seismostations and is known as the strongest recorded earthquake in Vietnam of the end of

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20th and beginning of the 21st centuries.

In order to contribute to warnings given to the authorities on the safety of operations on the Da river ladder hydro-electric plant system, the authors of this paper have carried out the following:

1. A review of the characteristic manifestations of seismic activity (natural earthquakes), and

2. An assessment of the hazard of triggered earthquakes around hydro-electric reservoirs.

In this paper, a comprehensive study is described which estimates b coefficient values and the densities of released energy, as well as the earthquake generating sources based on fault segmentation. It also predicts the maximum earthquake magnitude of triggered earthquakes based on an Artificial Neural Network algorithm. The main aim of this paper is to give an overview of the characteristics of seismic activity in the ladder zone of Da river hydro-electric plants.

Table 1. Basic parameters of hydro-electric reservoirs on the Da river and its two main branches.

No	Content	Unit	Lai Chau hydro-electric plant	Son La hydro-electric plant	Hoa Binh Hydro-electric plant	Nam Chien hydro-electric plant	Ban Chat hydro-electric plant	Huoi Quang hydro-electric plant
1	River name		Da river	Da river	Da river	Chien spring	Nam Mu spring	Nam Mu spring
2	Coordinate		102°59’ 33”E	103°59’42” E	105°19’ 26” E	104°16’23”E	103°50’ 0”E	103°52’ 25”E
			22°08’ 20”N	21°29’ 47” N	20°48’ 03”N	21°39’ 44¨ N	21°51’ 26”N	21°41’ 05”N
3	Valley area	km^2	26.000	43.760	51.700	332	1.929	282
4	Average water rise level	m	295	215	117	945	475	370
5	Total capacity	10^9 m^3	1,215	9,260	4,871	0,154	2,13	0,18
6	Type of dams		Gravity concrete	Gravity concrete	Soil-Rock mixtures	Vault/dome Gravity concrete	Roll-Rammer concrete	Gravity concrete
7	Elevation to the top of dam	m	303	228,1	123	952,5	48	374
8	Max. elevation of dam	m	137	137	128	139	132	104
9	Top length of dam	m	611	1,000	734	312,5	424,45	267
10	Capacity of installed machine	MW	1,200	2.400	1,920	210	220	520
11	Number of engines	engine	3	6	8	2	2	2

Characteristics of seismic activity (natural earthquake occurrence) in the ladder zone of Da river hydro-electric plants

Earthquake manifestation

A catalogue of earthquakes in the studied areas was established up to the end of 2010, based on all data sources [11], as follows: 1. The results of an investigation of Paleo-earthquakes; 2. The catalogue of historical earthquakes and surveyed earthquakes; 3. The catalogue of earthquakes of the Institute of Geophysics; 4. The catalogue of earthquakes updated from ISC publications; 5. The catalogue of earthquakes updated from publications by NOAA; 6. The catalogue of earthquakes updated from NEIC publications.

In total, 326 earthquakes have been recorded in the ladder zone of Da river hydro-electric plants (Fig. 1); of these, two are Paleo-earthquakes; 36 occurred before 1976 (these are mainly earthquakes determined according to historical data and survey data with magnitudes ≥4.0); and 288 occurred between 1976 and 2010 (with maximum magnitudes ≥3.0). Greater attention is paid to the strong earthquakes, with magnitudes of M=6.7-6.8, which have been found to have occurred within the study area [8, 9]. These earthquakes are:

1. The Tuan Giao Paleo-earthquake (with a definite age of around 420 years ago).

2. The Binh Lu Paleo-earthquake (with a definite age of around 480 years ago).

3. The Tuan Giao earthquake, which occurred at 14:18 (Hanoi time) on 24 June, 1983 in a mountain area about 11 km north of Tuan Giao town. The magnitude of this earthquake was determined to be M=6.7±0.2. Maximum seismic intensity in the epicentral area was I_0=8-9 (MSK64 scale). The source parameters have been determined as follows: the length L=33.1 km; the width W=21.2 km; the source area S=21.2x33.1=686.2 km^2; and the focal depth 20-3=17 km.

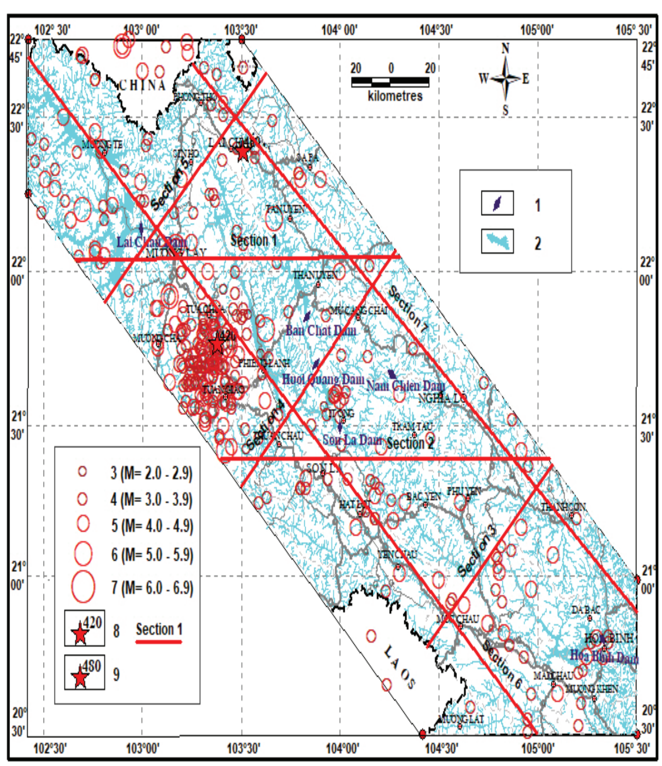

Fig. 1. Map of earthquake epicentres in the ladder valley of Da river hydro-electric plants and analysis of lines of energy generated. 1. Hydro-electric dam; 2. Valley of hydro-electric plant; 3-7. Earthquake epicentres and magnitudes; 8. Tuan Giao Paleo-earthquake and its definite age; 9. Phong Tho Paleo-earthquake and its definite age.

Some manifestation rules of seismic activities

Rule of earthquake recurrence (Gutenberg-Richter law): The Gutenberg-Richter law of earthquake recurrence for the studied areas is presented in Fig. 2, with the b value thus given as 0.935, for which the function has a form of Log [N (M)/T]=-0.935M+3.923. Data for the earthquakes used in computing the function of distribution is the catalogue of earthquakes for the studied area from 1976 to 2010. According to Cao Dinh Trieu [9], earthquake data recorded during this period is sufficient the magnitude of completeness (M_0) of earthquake catalogue in the northwest region has a value of M_0=3.5. If we assume that the repeated cycle of the Tuan Giao and Binh Lu earthquakes is 420 and 480 years, respectively, then it is likely these two Paleo-earthquakes will also have had a similar magnitude to the Tuan Giao earthquake which occurred in 1983 (M=6.7), with

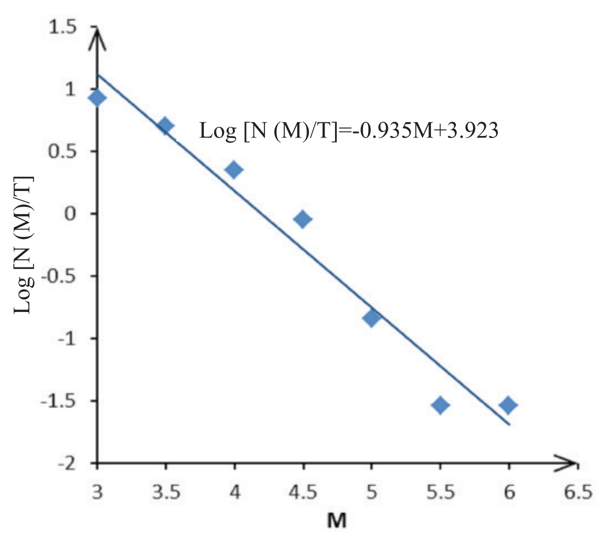

Fig. 2. Graph of the Gutenberg-Richter law for Da river ladder valley hydro-electric plants.

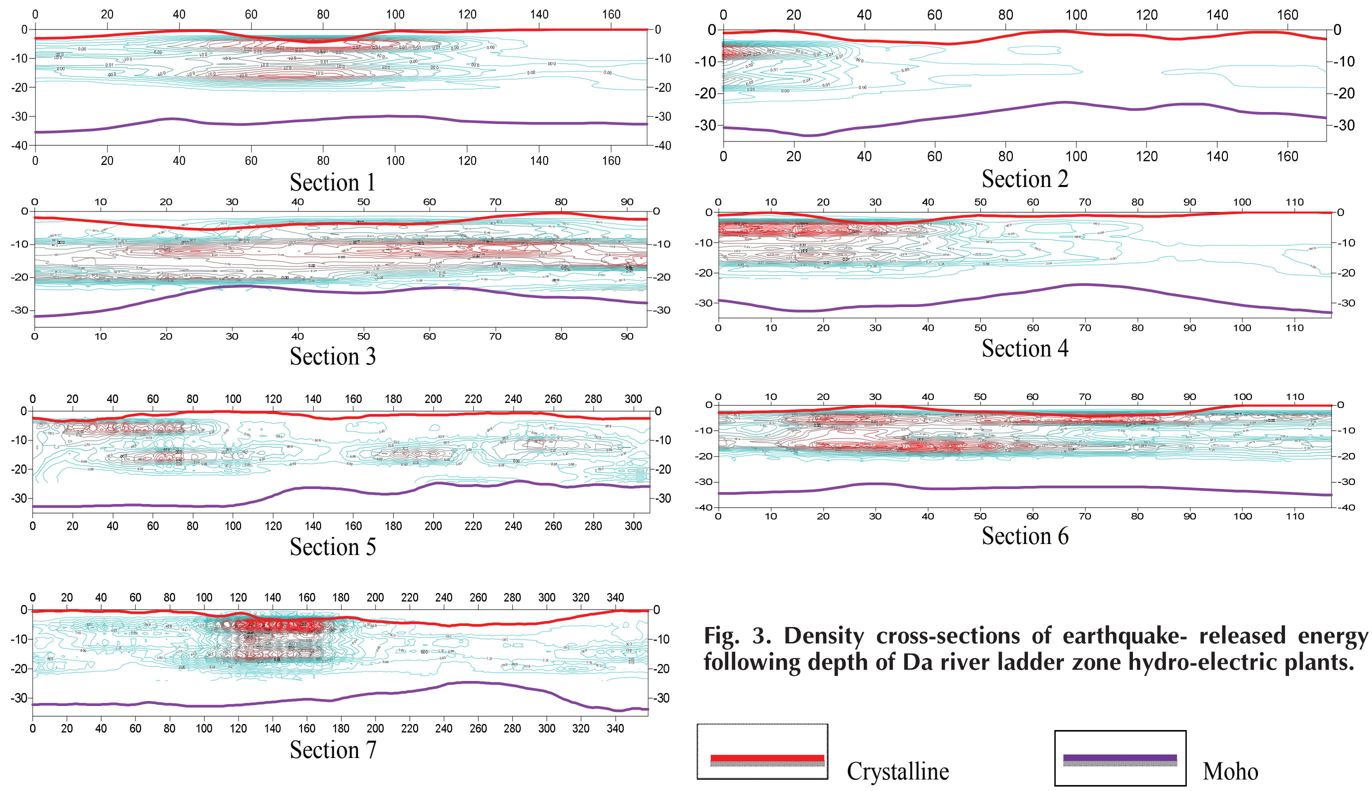

Fig. 3. Density cross-sections of earthquake- released energy following depth of Da river ladder zone hydro-electric plants.

a b value of 0.935. The determined repeated cycle of Tuan Giao will therefore be 418 years, which is approximately the age of the Tuan Giao Paleo-earthquake [8, 9].

Earthquake generating layer: the earthquake generating layer of the ladder zone of Da river hydro-electric plants is established based on determination of the density of energy released through seismic activity [11]:

LogE = 1.5M + 4.2 (E is expressed in Joules) (1)

A computation of released energy was carried out for seven sections (Fig. 1) with varying hypocentral depths of 2, 4, and 6 km, respectively (the sections being 2 km apart) up to a depth of 24 km (Fig. 3). Based on the results for the above-mentioned computed sections, upper and lower boundaries of earthquake-generating layers, coinciding with zero levels of released energy, were established. This allowed for the building of a map of the upper and lower boundaries and the thickness of earthquake-generating layers in the study area, as presented in Fig. 4. The results show that the thickness of earthquake-generating layers varies in the range of 9 km to 18.5 km; this means that earthquake could be observed should have a minimum hypocentral depth of around 2-3 km, and a maximum hypocentral depth of around 20-22 km.

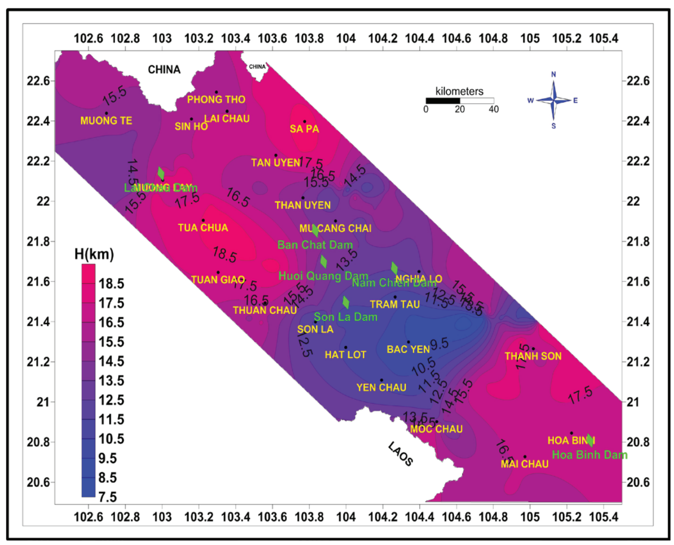

Fig. 4. Thickness of earthquake-generating layers in ladder zone of Da river hydro-electric plants.

Earthquake-generating sources

Earthquake-generating sources in this study are the line-sources [8, 11, 12]. Procedures for terminating sources and source characteristics have been applied in the following order:

1. The determination and classification of faults based on geological and geophysical data;

2. Recognition of active faults on the basis of identification signs.

3. Active faults capable of generating earthquakes with a magnitude $M \geq M_0$ (M_0=3.5 for Northwest zone) being determined as earthquake-generating sources.

4. Earthquake-generating segmentation based on gravitational and magnetic fields, the structure of the Earth's crust, and signs of new tectonics and geomorphology.

5. Width of sources based on the formulas: W (km)=H.tan.α+w and logW (km)=0.25M_{max}-0.35; where: W (km) is the width of the seismic source and M_{max} is the earthquake magnitude, H: the fault depth, α: the dip angle of the fault, w: the zone of dynamic faulting.

Based on the described methodology, there are 13 earthquake seismic- generating sources in the ladder zone of Da river hydro-electric plants which have been discovered by the authors (Fig. 5). These are: Muong Te, Nam Nhe, Muong Nhe, Lai Chau - Dien Bien, Son La, Tuan Giao, Phong Tho, Muong La - Bac Yen, Song Da (Da river), Nam Tong, Mu Cang Chai, Lao Cai - Ninh Binh (Fansipan), and Mai Chau. Numerous segments of these sources are connected to hydro-electric plant reservoirs, giving rise to a high risk of triggered earthquakes that warrants increased attention (Fig. 6).

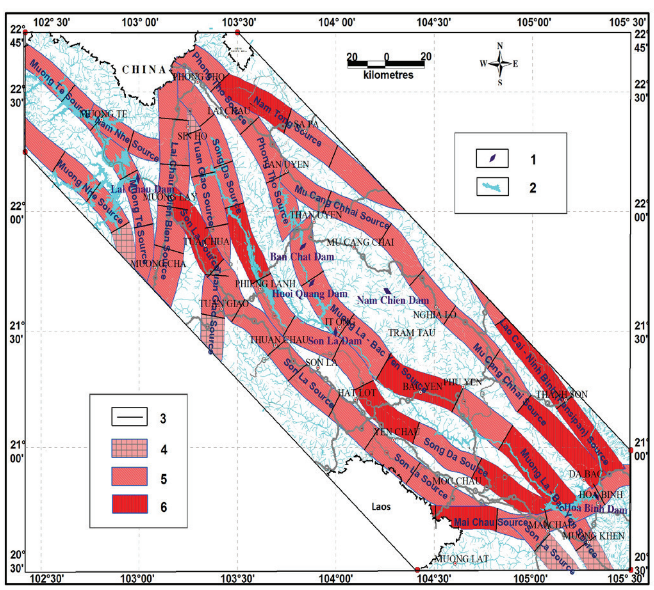

Fig. 5. Earthquake-generating sources and predictions of M_{max} following faulting segmentation of ladder zone of Da river hydro-electric plants. 1. Hydro-electric dam; 2. Reservoir area; 3. Source segmentations; 4. Source segment for earthquake prediction with magnitude of M_{max}=5.5-5.9; 5. Earthquake-forecasting segments with M_{max}=6.0-6.4; and 6. Earthquake-forecasting segments with M_{max}=6.5-6.9.

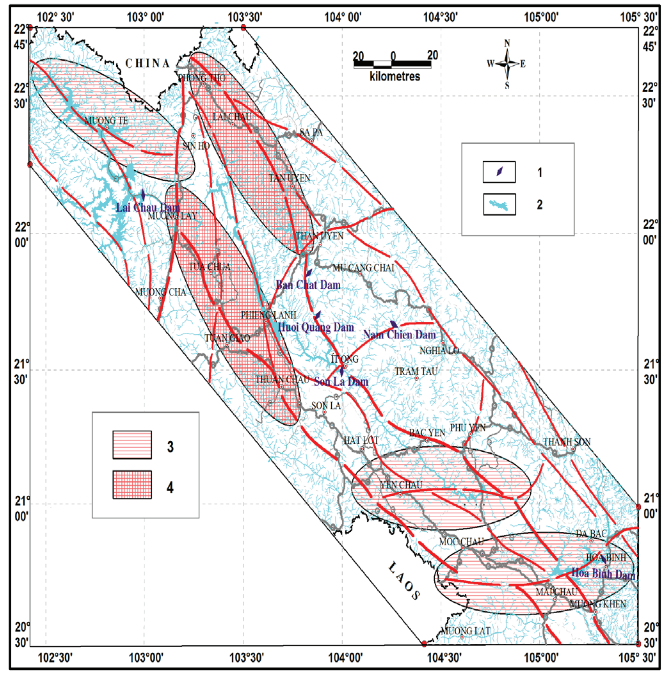

Fig. 6. Areas of high hazard of strong earthquake occurrence (M_{max}=6.5-6.9) in the ladder zone of Da river hydro-electric plants: 1. Hydro-electric dam; 2. Reservoir area; 3-4. Area of strong earthquake risk, of M_{max}=6.5-6.9 (3. Predicted, 4. Occurred).

Hazard of natural earthquake occurrence in the ladder zone of Da river hydro-electric plants

High risk from earthquakes with a maximum magnitude (M_{max}) may be determined in the ladder zone of Da river hydro-electric plants based on faulting segmentation

'Maximum earthquake' is the largest earthquake that can be caused by faulting in a given fixed time or period of time. With the aim of assessing the largest earthquake possible in the area under study, the empirical formula and criteria for fault segmentation established by Cao Dinh Trieu [12] are used:

$$\log L\ (\text{km}) = 0.6M_{max} - 2.5 \qquad (2)$$

where L (km) is the fault length and M_{max} is the maximum earthquake magnitude.

The obtained results for natural earthquake occurrence show that the largest earthquake likely along the sources in the ladder zone of Da river hydro-electric plants would have a maximum magnitude of M=6.9 (Fig. 5).

Determination of maximum earthquake magnitude (M_{max}) based on an Artificial Neural Network algorithm

The results for prediction of earthquake M_{max} based on an

Artificial Neural Network algorithm indicates [13, 14] there is a risk of a strong earthquake of M_{max}=6.0-6.9 occurring at the Son La generating source. For the remaining sources, this hazard is in the range of M_{max}=5.0-5.9 (Fig. 7).

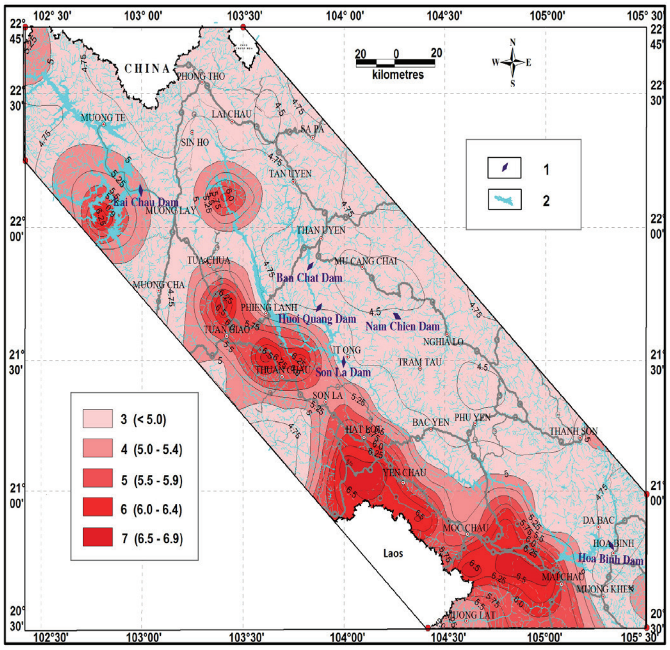

Fig. 7. M_{max} of the ladder zone of Da river hydro-electric plants determined on the basis of an Artificial Neural Network algorithm. 1. Hydro-electric dam; 2. Reservoir area; 3. M_{max}<5.0; 4. M_{max}=5.0-5.4; 5. M_{max}=5.5-5.9; 6. M_{max}=6.0-6.4; 7. M_{max}=6.5-6.9.

Localization of strong earthquake occurrence based on dependent rule between hypocentral distance and magnitude, and knots of the active faults

The dependent rule between hypocentral distance (δ_m) and magnitude (M) was considered by using 120 earthquakes of M≥4.5, which have occurred in northern Vietnamese territory. Distances between earthquakes of the same magnitude (M) within a variation of five units (M=4.5-4.9; 5.0-5.4; 5.5-5.9; 6.0-6.4, and 6.5-6.9) were measured, selected, and counted, and their distribution diagrams established. An average distance and error of determination of distance value was then established (Table 2). Next, the function of the average distance distribution between hypocentres of identical level, according to magnitude (M), was constructed.

The empirical function expressing the dependence between hypocentral distance δ_m and magnitude (M) has the form:

$$\lg\delta_m = 0.6Ms - 1.976 \quad (3)$$

Table 2. Distribution of average earthquake hypocentral distance according to magnitude (M).

No	Strength level (M)	Average hypocentral distance (km)	Error (km)
1	4.5-4.9	7.5	±3
2	5.0-5.4	15	±6
3	5.5-5.9	30	±10
4	6.0-6.4	60	±14
5	6.5-6.9	105	±18

Given the location of Paleo-earthquakes and Tuan Giao's earthquake of M=6.7 (1983), and the relationship between strength of earthquake and hypocentral distance, fault junction and strong earthquake location, five areas are determined to carry a particular risk of strong earthquake occurrence: Muong Te, Lai Chau, Tuan Giao, Yen Chau, and Mai Chau (Table 3). Of these, strong earthquakes have occurred in the areas of Lai Chau and Tuan Giao, and earthquakes of magnitude M=4.5-4.9 have occurred in Muong Te, Yen Chau, and Mai Chau, which have not reached the predicted maximum magnitude (M_{max}=6.5-6.9). Hence, the likelihood of strong earthquakes in these areas in the future is very high.

Table 3. Areas which have high risk of earthquake occurrence of magnitude (M) 6.5-6.9.

No	Name of area	M_{max} observed	M_{max} forecast
1	Muong Te	4.5-4.9	6.5-6.9
2	Lai Chau	6.5-6.9	6.5-6.9
3	Tuan Giao	6.5-6.9	6.5-6.9
4	Yen Chau	4.5-4.9	6.5-6.9
5	Mai Chau	4.5-4.9	6.5-6.9

Manifestation of triggered earthquake activity in the ladder zone of Da river hydro-electric plants

Earthquake occurrence related to human activity is known as "triggered" activity. A number of human activities can lead to the occurrence of triggered earthquakes, amongst which can be listed: large explosions in the ground, the impoundment of reservoirs (high irrigation dams, hydro-electric dams, etc.), the pumping of liquid into deep rock layers, the discharging of water from water-bearing formations on the ground or close to the ground surface, and pit exploitation. Triggered earthquakes occurred at the Hoa Binh and Son La hydro-electric plants following reservoir impoundment [15, 16].

Occurrence of triggered earthquake at Hoa Binh hydro-electric reservoir in the period 1989-1991

In May 1988, water impoundment at Hoa Binh hydro-electric reservoir began. Initially, the water level grew gradually, but this accelerated at the onset of the rainy season in July and August of that year. In December 1988, when the water level had reached an elevation of over 80 m, a number of weak earthquakes (M<2.0) were observed/recorded near the dam area. From January to April 1989, a number of earthquakes with a magnitude of M=2.4-2.8 were recorded near the dam. On one particular day, 14 April 1989, there were seven earthquakes, of which two were M=3.8 and 3.7, with hypocentres of around 5 km. After a quiet few weeks, on 23 May an earthquake of a magnitude of 4.9 (M=4.9) occurred, which caused ground-shaking in the Hoa Binh region of an intensity of 7 degrees (in the MSK-64 scale). After this event, weaker earthquakes continuously occurred. On 27 May, another earthquake occurred, with a magnitude of M=4.0, which made the ground shake to a degree of 5-6 in Hoa Binh town. Since then, there has been frequent earthquake activity; whilst relatively weak, it is picked up by seismographs [16] (Fig. 1).

The earthquake of M=4.9 which occurred on 23 May 1989 in Hoa Binh has been specified as a triggered earthquake linked to the water reservoir. It occurred when the impoundment of the water reservoir had been complete for a certain time (it had been eight months since the date of full water impoundment). Its hypocentral depth was shallow, at around 5 km; prior to the occurrence of the main shock, a fore-shock appeared, and the magnitude of the after-shock matched that of the main shock. A gradual decline of seismic activity has been observed as well as high activity when the water levels are suddenly increased. The strongest measurement of the magnitude of the Hoa Binh triggered earthquake was M_{max}=4.9.

The Hoa Binh triggered earthquake had a Gutenberg-Richter reading as follows [15]:

$$\log\frac{N(M)}{T} = 4.688 - 1.2474M \qquad (4)$$

Triggered earthquake of Son La hydro-electric reservoir

The study of the triggered earthquake of the Son La hydro-electric reservoir was conducted through access to the independent governmental Science and Technology project code DTDL.2009T/09 for the period 2009-2011 [16]. A temporary system of earthquake observation stations (six in total) was installed at the beginning of 2009, and operated until the end of 2012, to monitor earthquake activity around the water reservoir at the initial impoundment. During this period, 400 earthquakes, of a magnitude of M=1.0-3.0, and hypocentral depths of less than 10 km, were observed. These earthquakes were mainly concentrated in the submerged areas of the dam within the Muong La - Bac Yen and Da river (Song Da) faults. The largest earthquake in the bed of the Son La hydro-electric reservoir, measuring M=4.3, was recorded on 19 July 2014.

The Gutenberg-Richter law as applied to the triggered earthquakes of the Son La hydro-electric reservoir is as follows (Fig. 8) [15]:

1. For the group of triggered earthquakes from Huoi Quang lowlands to Son La lowlands:

$$\log\frac{N(M)}{T} = 3.6603 - 1.2008M \qquad (5)$$

2. For the group of earthquakes from the Pa Uon bridge to Son La dam:

$$\log\frac{N(M)}{T} = 2.9917 - 1.0716M \qquad (6)$$

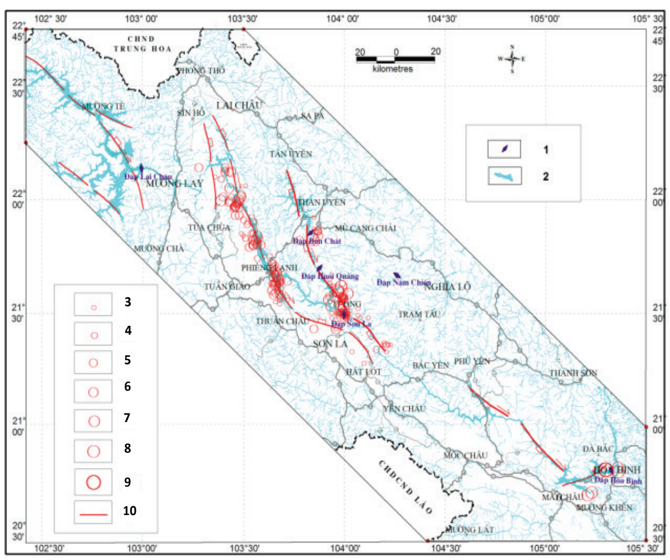

Fig. 8. Distribution of the epicenters triggered earthquakes of Hoa Binh and Son La hydro-electric reservoirs. 1. Hydro-electric dam; 2. Reservoir areas; 3-9. Epicenters and corresponding magnitude (M=1.0-1.4; M=1.5-1.9; M=2.0-2.4; M=2.5-2.9; M=3.0-3.4; M=3.5-3.9; M=4.0-4.4; M=4.5-4.9); 10. Source segment capable of generating triggered earthquake.

Geological features of Hoa Binh and Son La hydro-electric reservoirs

The triggered earthquakes of Hoa Binh and Son La hydro-electric reservoirs were mainly concentrated in the deep fault zones interconnecting with the reservoirs. The hard limestones of Dong Giao formation (T_2a *dg*) were broken down and became water-logged due to compression under high water columns, creating a change in stress pressures around the onset of the triggered earthquakes (Photo 1). In the below cross-section of Dong Giao limestone formation, the structure consists mainly of a strip/ribbon/belt form, of smooth and tight grain; glaze form or creak grain form of light colour (white, yellowish, pink, greenish, brown white); and also black bitumen limestone and silica limestone of bright colour. In the middle of the cross-section, mainly limestone of blocked form is evident [15].

Photo 1. Limestone of Dong Giao formation covering the reservoir bed of Hoa Binh and Son La hydro-electric reservoirs.

Prediction for the maximum triggered earthquake

For prediction of the maximum magnitude of a triggered earthquake ($M_{max.te}$), the relationship between M_{max} and b values for natural and triggered earthquake distribution [15] were used:

$$b_{ne} \times M_{max.ne} = b_{te} \times M_{max.te} \qquad (7)$$

where: b_{ne} is the b coefficient value of natural earthquakes; b_{te} is the b coefficient value of triggered earthquakes; $M_{max.ne}$ is the maximum natural earthquake to have occurred in the determined source; and $M_{max.te}$ is the maximum triggered earthquake predicted to occur in the source if this is interconnected with the water reservoir and conditions for a triggered earthquake being generated are satisfied.

The procedure for determining sources and maximum triggered earthquake was conducted as follows [17, 18]:

Step 1 - Determination of triggered earthquake sources:

Determination of fault segments interconnecting with hydro-electric reservoirs followingreservoir impoundment was carried out based on the generating sources and the maximum magnitude of natural earthquakes to have occurred. The fault segments, where earthquakes occurred following reservoir impoundment, are here considered as sources of triggered earthquakes.

Step 2 - Forecasting maximum value of triggered earthquakes based on formula (7):

- Determination of the b_{ne} value of the Gutenberg-Richter distribution function for natural earthquakes in the research areas of the hydro-electric reservoirs and their adjacent areas was conducted. The results show: a value of b_{ne}=0.6041 [15] for Song Tranh 2 (Tranh river 2); and b_{ne}=0.935 for the ladder zone Da river hydro-electric plants (including Hoa Binh, Son La, Lai Chau, Ban Chat, and Huoi Quang hydro-electric plants - Fig. 4) [15].

- a value of b_{te}=1.2474 for Hoa Binh triggered earthquakes (4); and for Song Tranh 2 hydro-electric reservoir, b_{te}=0.8317 [8]; while in the Son La reservoir two source segments are available (Fig. 8). For the formulas (5) and (6): from the lowlands of Huoi Quang to the lowlands of Son La, the value is b_{te}=1.2008; and from Pa Uon bridge to Son La dam, it is b_{te}=1.0716.

- The estimation of maximum magnitude for natural earthquakes ($M_{max.ne}$) for the triggered earthquake-generating sources based on segmentation of faults shows that [12]: in Hoa Binh, $M_{max.ne}$=6.5; from the lowlands of Huoi Quang to the lowlands of Son La, it is $M_{max.ne}$=6.5; and from Pa Uon Bridge to Son La dam, it is $M_{max.ne}$=6.7.

- The predicted maximum magnitude for triggered earthquakes ($M_{max.te}$) for the Hoa Binh reservoir is $M_{max.te}$=4.9 (Fig. 9); from the lowlands of Huoi Quang to the lowlands of Son La, it is $M_{max.kt}$=4.9; and from Pa Uon Bridge to Son La dam, it is $M_{max.kt}$=5.0 (Fig. 10).

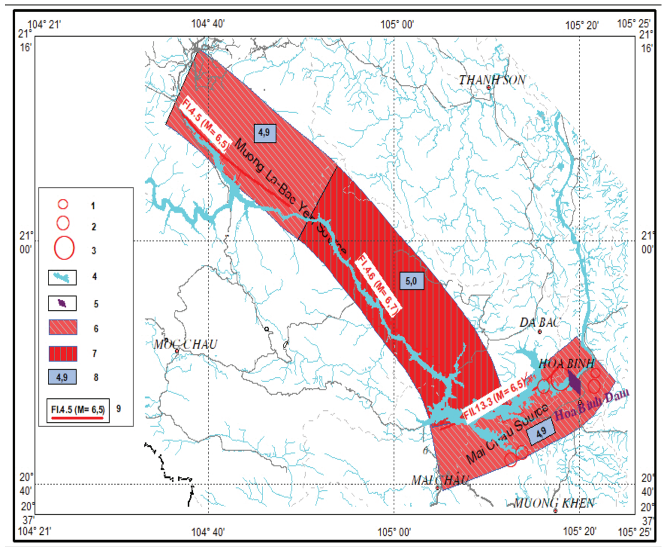

Fig. 9. Source area and maximum value of triggered earthquake for Hoa Binh hydro-electric reservoir. 1. Epicentres of triggered earthquakes of magnitude M≤3.0; 2. M=3.7-3.9; 3. M=4.0-4.9; 4. Reservoir area; 5. Hoa Binh hydro-electric dam; 6. Source segment forecasting of maximum value of natural earthquake, $M_{max.tn}$=6.5; 7. Source segment forecasting of maximum value of natural earthquake occurrence, $M_{max.tn}$=6.7; 8. Maximum value of triggered earthquake risk in the determined source segment; 9. Symbols of source, source segment, and maximum value of natural earthquake (FI.4 is Muong La - Bac Yen source, 5 is the fifth segment top-down; FII.13 is Mai Chau source, 3 is the third segment).

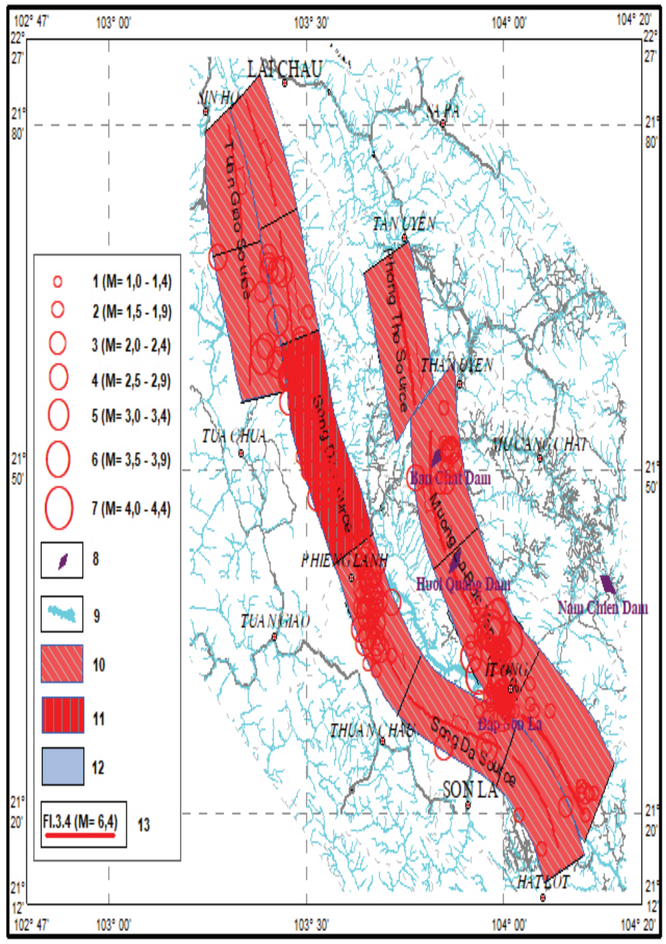

Fig. 10. Source area and maximum value of triggered earthquake for Son La hydro-electric reservoir. 1. Epicentre of triggered earthquake with values of a magnitude of M=1.0-1.4; 2. M=1.5-1.9; 3. M=2.0-2.4; 4. M=2.4-2.9; 5. M=3.0-3.4; 6. M=3.4-3.9; 7. M=4.0-4.4; 8. Hydro-electric location. 9. Reservoir areas; 10. Source segment forecasting maximum value of natural earthquake, M_{max}=6.0-6.4; 11. Source segment forecasting maximum value of natural earthquake, M_{max}=6.5-6.9; 12. Maximum value of triggered earthquake risk in the determined source segment; 13. Symbols of source, source segment, and maximum value of natural earthquake (FI.3 is Phong Tho source; 4 I is the fourth segment top-down; FI.4 is Muong La - Bac Yen source; 1,2,3 are the segments of 1,2,3 top-down; FII.4 is Tuan Giao source and FII.5 is Da river source).

Conclusions

Based on a comprehensive assessment of the characteristics of seismic activity in the ladder zone of the Da river hydro-electric plants, the following can be asserted:

1. The largest natural earthquakes to have occurred in the ladder zone of Da river hydro-electric plants are the Lai Chau Paleo-earthquake (480 years ago), Tuan Giao Paleo-earthquake (420 years ago), and Tuan Giao earthquake, which occurred in 1983. The magnitudes of these two Paleo-earthquakes are equivalent to the Tuan Giao earthquake of 1983, i.e. M=6.7±0.2.

2. The b value of natural earthquakes in the ladder zone of Da river hydro-electric plants is 0.935. The measurement reflects the level of natural earthquake activity in the research area and also the measurement needed for computing and delimiting natural and triggered earthquake activity around the reservoirs following full water impoundment.

3. 13 earthquake-generating sources in the ladder zone of Da river hydro-electric plants were discovered: Muong Te, Nam Nhe, Muong Nhe, Lai Chau - Dien Bien, Son La, Tuan Giao, Phong Tho, Muong La - Bac Yen, Song Da (Da river), Nam Tong, Mu Cang Chai, Lao Cai - Ninh Binh (Fansipan), and Mai Chau. The largest earthquake which might occur within these earthquake-generating sources would be of a magnitude not exceeding 6.9.

4. Large natural earthquakes with an M_{max} of up to 6.9 are predicted to occur in the following areas: Muong Te, Lai Chau, Tuan Giao, Yen Chau, and Mai Chau. Earthquakes of a maximum magnitude of M=6.7 have been observed in the Lai Chau and Tuan Giao areas; this maximum value has

to date not been observed in the areas of Muong Te, Yen Chau, or Mai Chau. If the distance regulation, degree of magnitude, and junction points of the earthquake-generating faults are correct, then there is a notable risk of imminent earthquake occurrence in the Muong Te, Yen Chau, and Mai Chau areas.

5. Triggered earthquakes of medium and above-medium magnitudes (M≥4.0) have occurred at the Hoa Binh and Son La hydro-electric reservoirs, where the maximum depth to the bottom is over 100 m, and the geological structure of the reservoir bed consists of broken down limestone. When reservoir water accumulates, endosmose phenomena in the breakdown tectonical zones caused by water column pressure, change the pressure stress in the direction of previous triggered earthquakes.

6. The largest observed triggered earthquake at the Hoa Binh reservoir was of a magnitude of M=4.9. This maximum value is also predicted for triggered earthquakes. This means that earthquake activity in the Hoa Binh reservoir reached the maximum value. No likelihood of triggered earthquake occurrence at the Hoa Binh hydro-electric plant is predicted, since no earthquake has been observed at the Hoa Binh reservoir since 1996. At the Son La reservoir, triggered earthquakes may continue to occur in the future, with a magnitude exceeding 4.3, and possibly reaching a maximum of 5.0.

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REFERENCES

[1] H.K. Gupta (2011), *Encyclopedia of Solid Earth Geophysics*, Springer, Netherlands.

[2] Nguyen Dinh Xuyen, Nguyen Thanh Tung, et al. (1996), "Database for mitigative solution of risk caused by earthquake in Vietnam", *The summary report of independent theme of National research programme code KT-DL92-07 archive of the Institute of Geophysics* (in Vietnamese).

[3] Nguyen Ngoc Thuy (2008), "Study of modern tectonic and earthquake in order to assessment stable operation of the Hoa Binh hydro-electric", *The summary report of independent theme of National research programme code DTDL.2005/19G archive of the Institute of Geophysics* (in Vietnamese).

[4] Cao Dinh Trieu, C.D. Trong, L.V. Dung, T.A. Tuan, and D.Q. Van, and H.V. Long (2014), "Triggered earthquake study in Tranh River no. 2 (Vietnam), hydro-electric reservoir", *Journal Geological Society of India*, **84**, pp.319-325.

[5] Gahalaut Kalpna, Thai Anh Tuan, and N. Purnachandra Rao (2016), "Rapid and delayed earthquake triggering by the Song Tranh 2 reservoir, Vietnam", *Bull. Seismol. Soc. Am.*, **106(5)**, pp.2389-2394, doi:10.1785/0120160106.

[6] Nguyen Van Giang, J. Wiszniowski, B. Plesiewicz, G. Lizurek, D.Q. Van, and L.Q. Khoi (2015), "Some characteristics of seismic activity in the Song Tranh 2 Reservoir, Quang Nam, Vietnam by local seismic network data", *Earth Sciences*, **4**, pp.101-111, doi:10.11648/j.earth.20150403.13.

[7] Thai Anh Tuan, N. Purnachandra Rao, Kalpna Gahalaut, Cao Dinh Trong, Le Van Dung, Cao Chien, K. Mallika (2017), "Evidence that earthquakes have been triggered by reservoir in the Song Tranh 2 region, Vietnam", *Journal of Seismology,* **21(5)**, pp.1131-1143.

[8] Cao Dinh Trieu (2002), "Some characteristic features of seismotectonic conditions and seismic regime of the Tuan Giao earthquake area", *Journal of Geology,* Series B, **19-20(9-10)**, pp.54-68 (in Vietnamese).

[9] Cao Dinh Trieu (2010), *Earthquake hazards in Vietnam*, Publishing House for Science and Technology, Hanoi, 304pp.

[10] Cao Dinh Trieu, Ngo Gia Thang, Mai Xuan Bach, Pham Nam Hung, Bui Anh Nam (2010a), "Bac Yen and Mai Son earthquakes occurred in 26 November 2009", *Journal of Geology,* Series A, **320(9-10)**, Hanoi, pp.241-252 (in Vietnamese).

[11] Cao Dinh Trieu, Le Van Dung, Thai Anh Tuan (2010b), "Risk of earthquake in the Northwest region and its adjacent", *Journal of Geology,* Series A, **320(9-10)**, pp.253-262 (in Vietnamese).

[12] Cao Dinh Trieu, Nguyen Duc Vinh (2012), "Fault segmentation in assessment of maximum earthquake in Vietnam", *Journal of Geology*, **331-332(8-9)***,* pp.59-68 (in Vietnamese).

[13] Cao Dinh Trong, Cao Dinh Trieu, Nguyen Duc Vinh (2011), "Application of the Neuron network in prediction magnitude of earthquake in northwest region", *Journal of the Earth Sciences,* **33(2)**, pp.51-163 (in Vietnamese).

[14] M.T. Hagan, H.B. Demuth and M. Beale (1996), *Neural Network Design*, PWS Publishing Company, Boston, MA.

[15] Cao Dinh Trong, Nguyen Anh Duong, Thai Anh Tuan, Cao Dinh Trieu (2016), "Characteristics of triggered earthquake in ladder Da river hydro-electric plant", *Journal of Geology,* Series A, **361-362(11-12)**, pp.80-92 (in Vietnamese).

[16] Le Tu Son (theme director), et al. (2012), "Study of triggered earthquake forecasting in Son La hydro-electric reservoir", *The summary report of independent theme of National research programme code- DTDL.2009T/09 archive of the Institute of Geophysics*, 271pp (in Vietnamese).

[17] D.W. Simpson and T.N. Narasimhan (1990), "In homogeneities in rock Properties and their influence on reservoir triggered seismicity", *Gerlands Beitrage zur Geophysik*, **99**, pp.205-219.

[18] H.K. Gupta, B.K. Rastogi, H. Narain (1972), "Common features of the reservoir associated seismic activities"*, Bulletin of the Seismological Society of America,* **62**, pp.481-492.