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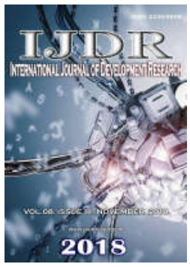

ORIGINAL RESEARCH ARTICLE — OPEN ACCESS

THE SEISMIC REGIME OF THE DA LADDER OF HYDROELECTRIC DAM

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ABSTRACT

In this paper, the authors present some primary study results of studying about seismic regime in the Da Ladder of hydroelectric Dam. The following results have shown that natural earthquakes occurred in the Da Ladder of hydroelectric Dam are the strongest in the Vietnam territory. The largest earthquakes with the magnitude of 6.7 have been observed in Tuan Giao and Lai Chau areas. The b coefficient of the Gutenberg- Richer function has the value of b=0.935, the earthquake with the maximum magnitude in the ranges of 6.0 ÷ 6.9 may occur in 13 locations: MuongTe, Nam Nhe, MuongNhe, Lai Chau - Dien Bien, Son La, Tuan Giao, PhongTho, Muong La- Bac Yen, Song Đa, Nam Tong, Mu Cang Chai, Lao Cai – Ninh Binh (Phan Si Pan) and Mai Chau. In the source, the danger of earthquake with the magnitude of 6.9 might occur in the Muong Te, Lai Chau, Tuan Giao, Yen Chau and Mai Chau areas.

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INTRODUCTION

In June 1983, a strong earthquake with the M= 6.7 occurred in the Tuan Giao town, Dien Bien province. This is the first strong earthquake recorded by Viet Nam seismic network and it is the strongest one recorded in Da Ladder of hydroelectric Dam, where have the 5 biggest hydroelectric plants operate: Hoa Binh, Son la, Lai Chau, Huoi Quang and Ban Chat.

Making sure Da Ladder of hydroelectric Dam operates safely, the project: "*Establishing the seismological observation network for reservoir earthquake in Da Ladder of hydroelectric Dam", coding ĐTĐLCN.27/15* is researched from 2015 to 2018. The project is oriented follow contents as below:

- Establishment and operation seismic station network in reservoir system in Da Ladder of hydroelectric Dam.
- To assess, observe and predict earthquake in order to respond and ensure the safe operation of hydroelectric reservoir in the Da Ladder of hydroelectric Dam.

In this paper, the authors assess seismic activities in the Da Ladder of hydroelectric Dam region (Fig.1.1) to research the project's second purpose.

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MATERIALS AND METHODS

Materials: In this study area, we used an updated earthquake catalogue at the end of 2017 following CN algorithm and data sources [2-9, 12, 14, 15,16] as below:

- Results of Paleo- earthquake investigation;
- History of earthquake catalogue and the inquiry;
- Earthquake catalogue made by the Institute of Geophysics;
- The updated earthquake catalogue issued by ISC;
- The updated earthquake catalogue issued by NEIC;
- The updated earthquake catalogue issued by NOAA.

Methods: The proposed of the paper are present results of studying about seismic regime of Da Ladder of hydroelectric Dam, the analysis methods have been used includes: seismic activity analysis based on Gutenberg- Richer function, determined the generated earthquake layer and earthquake source. Deformation of the Earth's crust in Neo- tectonic and Modern- tectonic. Risk of strongest earthquake based on prediction of maximum earthquake in Artificial Neural Network, assessment of potential maximum earthquake follow the fault segmenting by using empirical formulas. The ArcGIS 10.0 software has been used to determine active fault.

RESULTS

Characteristics of seismic activity in the da ladder of hydroelectric dam: Following the updated earthquake catalogue at the end of 2017, 333 earthquakes were recorded in which 02 Paleo- earthquakes, 36 earthquakes had occurred before 1976 (following historical notes and inquiry with M > 4.0), 295 earthquakes occurred from 1976 to 2017 with the M ≥ 3.0, more important earthquake occurred approximate M=7.0 [5] as below:

A Paleo-earthquake possibility occurred in Tuan Giao 420÷430 years ago: Following studied results Paleo-earthquake, Cao Dinh Trieu et al. discovered ruptured zone of northeast direction nearly perpendicular to Son La fault in area Tuan Giao earthquake (Coordinate: 21°41'20.4''N, 103°27'12.3''E; 1983). This ruptured zone formed in a condition of impacting by sudden internal force and was filled ancient cultivated soils. The displacement, shear thrust of ruptured zone and exposure of topographic structure, geomorphology in the surveyed area allowed us consider to a Paleo- earthquake. The results of absolute analysis showed that earthquake occurred 420 ÷ 430years ago and the same with Tuan Giao earthquake (M=6.7, 1983).

The potential of Paleo-earthquake occurrence in Binh Lu 480 ÷ 520 years ago (Nowadays is Lai Chau town): Investigating landslide locations in the Binh Lu area (Coordinate: 22°23'27.8 N, 103°30'23.9'' E) suddenly occurred with the same displacement of the Earth surface, this placement normally formed by a strong earthquake [5]. Following the investigation and absolute analysis results, Cao Dinh Trieu et al. predicted a strong earthquake may occurred in Lai Chau Town 480 ÷ 520 years ago, the same magnitude with Tuan Giao Paleo- earthquake.

Tuan Giao earthquake: An earthquake (M_S = 6.7± 0.2, I_0=8-9 (MSK)) occurred at 14:18 (local time) 14 June, 1983 in the mountainous area 11km away from the north of Tuan Giao area. The source parameters are determined: L=33.1(km), W=22.1(km), area of source S=21.2×33.1=686.2 (km^2), hypocenter depth h=20-3=17(km) [3-5].

Gutenberg - Richer function: The Gutenberg - Richer function of studied areas is shown in Fig.2.2. with coefficient b= 0.935 and equation Log (N (M)/T)=-0.935Ms+3.923 in which the earthquake catalogue period 1976-2010 is used, because earthquake data in this period is good with M_0= 3.5 in North-West. If repetition cycle in Tuan Giao and Binh Lu is approximate 420-480 years, 02 Tuan Giao and Binh Lu Paleo-earthquakes is the same Tuan Giao earthquake (M=6.7, 1983), where b=0.935 and repetition cycle is 418 years, approximate with Tuan Giao Paleo- earthquake [5-6].

Generated earthquake layer: To establishing generated earthquake layer in Da Ladder of hydroelectric Dam, the authors follow density of released energy through earthquake [5] and thickness of generated earthquake layer is proceed as below:

- Calculation of released energy accord to 7 cross-sections follow Gutenberg- Richer function: Log E= 1.5 Ms +4.2 (unit: Jul) with focal depth from 2, 4, 6÷24 km.
- Using cross-sections results to establish earthquake boundary layer map and the thickness of generated earthquake layer in studied area.

We can estimate active earthquake layer based on distribution characteristics of hypocenter [5]. The obtained results determines active earthquake layer in Da ladder of hydroelectric Dam shown in Fig.3- 6. and given as: The thickness of generated earthquake layer in the range of 9-18.5km and the depth of shallow earthquake in the range of 2-3km in Da Ladder of hydroelectric Dam. The focal depths in studied area are : Hoa Binh (4÷22km), Son La (2÷20km), Lai Chau (2.5÷18km), Ban Chat (2.5÷19km), Huoi Quang (3÷18km), Nam Chien (3.5÷18km) and Tuan Giao earthquake (M=6.7, 1983) is the deepest h= 20÷22km,

Earthquake source

The method determines earthquake source: In this paper, earthquake source is line source, thus accepting active zone is earthquake source. Operating to determine source and characteristic of earthquake source are shown:

- Determine earthquake source: The fault express active to be considered as generated earthquake source;
- Segment and assessment of earthquake source width;

Studying active fault : Establishing recognition criteria systems of active fault by using Son La segment fault, at which Tuan Giao earthquake(1983)[3-6] occurred, following this Cao Dinh Trieu extended 09 criteria recognition systems of active fault for Viet Nam. In this paper, the authors proposed 06 criteria systems recognition of active fault for Da ladder of hydroelectric Dam: DH1: Density of lineament; DH2: Density of geological fault; DH3: Released energy of earthquake; DH4: Density of hot spring; DH5: Density of landslide point; DH6: Value of interrupted topography Hierarchical process: Characteristics of active fault area are classified into 03 levels (see Tab.1) as below:

- Weak or inactive fault;
- Normal active fault;
- Strong active fault

Based on Analytic Hierarchy Process to calculate weight: Weight effect factors determined by comparison matrix (see Tab. 02.). Each element represents for a pair, up word and down word factor of diagonal are inverse, using Eigen vector principle to calculate weight. Average values of rows are weight of each factor that allows comparing the component ratio of chosen method:

$W_{ij} = \sum_j^n a_{ij}$ and we have weight matrix are shown in Tab.3

After hierarchizing and calculating weight, the landslide susceptibility index is determined by equation:

$$LSI = \sum_{j=1}^{n} W_j X_{ij}$$

where:

LSI: Landslide susceptibility index; W_j: Weight of factor the jth; X_{ij}: Value of the ith layer in sequence

In Fig.2.4. we describe the rift active zone in Da Ladder of hydroelectric Dam: Phong Tho – Than Uyen, Muong La - Bac Yen, Song Da, Tuan Giao, Mai Chau, Mu Cang Chai, Lao Cai – Ninh Binh, Muong Te – Nam Nhe, Nam Tong and Muong Nhe. These rift zones are determined by integrating AHP with GIS following equation W_{ij} in ArcGIS 10.0 software.

Segmentation and determination of source width: In the world, there are many empirical formulas to determine M_{max} for sources [17] it is not an easy task to choose the best formulas. In this paper, authors used Cao Dinh Trieu's empirical formulas (2012), following the strongest Tuan Giao earthquake in Son La Fault (discover Paleo -earthquake M=6.7, 420 ÷ 430 years ago) and the authors segmented source based on the theory as following:

- Fault segmentation is determined by integrating seismic signal, geophysics, topographic;
- Fault segmentation is boundary of structures of the Earth's crust;
- Fault segmentation was shown by marks of geological, geophysics, tomography such as: Boundary of gravity and magnetic, boundary of suddenly displacement depth and DEM, satellite images and topography;
- Changing topography, geomorphology and control distribution of valley, sedimentary basin and express neo-tectonic and modern tectonic along rift zone.

Following these, segment fault, M_{max}, width of earthquake source can be proceed as below:

Fault segmentationis proceed based on: Marks of divide gravity and magnetic, suddenly displacement of depth and mode of occurrence, clear expression in modern topography, DEM, transformation of topography -geomorphology (variation tomographic displacement, shifting of flow, shear and displacement mountain ranges, displacement or destroy terrace), expression of hot spring, landslide, deformation neo-tectonic and modern tectonic along with rift fault.

***Width of source is determined based on*:** Correlation between width of active fault (Fig.2.4) in equations as below:

$W = H \times \tan\alpha + w$ and

$\log W = 0.25 \times M_{Smax} - 0.35$

where: W- width of source (kilometer); M_{Smax}- S wave magnitude of earthquake; H- depth of fault; α- dip angle; w-dynamic rift fault

***Earthquake source in Da Ladder of hydroelectric Dam*:** based on methodologies basic of earthquake source in [5]. In this paper, the authors determined 13 sources of earthquake based on distribution of epicenter, characteristic of fault system follow seismic tectonic shown Fig.2.5 are: MuongTe, Nam Nhe, MuongNhe, Lai Chau- Dien Bien, Son la, Tuan Giao, Phong Tho, Muong La - Bac yen, Song Da, Nam Tong, Mu Cang Chai, Lao Cai- Ninh Binh (Fansipan) and Mai Chau. Most of them connects to hydroelectric Dam therefore, possibility occur reservoir earthquake. Actually, after storage in 1988 occurring a resoiver earthquake in Hoa Binh Dam in 1989 [5].

Deformation of the Earth's crust in Neo-Tectonic and Modern- Tectonic Da Ladder of hydroelectric Dam

Deformation characteristics of the Earth crust in Neo-tectonic: Cao Dinh Trieu (1997) carried out a study on vertical deformation characteristics of the Earth crust in Neo-tectonic for Vietnam territory in scale 1/1.000.000 based on age analysis of deformation of flattening plane. Age of terrain level can be arranged as follow (Le Duc An, 1990):

Terrain level	*Formed period*	*Age*
2500 ÷ 3000m	Oligocene	31 ÷ 32
1500 ÷ 2400m	26	
< 1500m	112	
River terrace, sea terrace		
100 ÷ 200m	Q_I - Q_{II}	1.5

Vertical deformation rate can be estimated based on terrain level and formed age. From current elevation, vertical deformation of the Earth crust in Neo-tectonic was calculated, the result has shown in Figure 3.1 indicating that elevation of 500m corresponding to rate of 0.1mm/year, average rate in Muong Te block is 0.3 mm/year; in Song Ma-Thanh Hoa and Son La-Song Da blocks are 0.25 mm/year; in Phong Tho-Tu Le varies in the range of 0.1 to 0.6, the highest is in FanSiPan block about 0.6 mm/year.

Deformation characteristics of the Earth crust in Modern-tectonic

a. Vertical deformation rate of the Earth crust derived from repeated measurement of water-levels

Vertical deformation rate is calculated by using result of repeated measurement of water-level for Da Ladder of hydroelectric Dam region shown in Figure.3.2. Muong Te block has average of vertical deformation rate to be -4 mm/year. In the Son La block, appearance of weak rising in Northeastern part with rate of about 2mm/year and subsidence in Northwest, Central and Southeast with average rate of -4mm/year, the strongest subsidence is in Central part reach maximum of -7mm/year. The Song Ma - Thanh Hoa block tends to subsidence whole region with an average rate of -4mm/year. Weak subsidence in the Northwest and Southeast, and the strongest subsidence in Central with rate of -7mm/year. At the junction of these three blocks in Muong Lay district, the rate of subsidence is strongest then gradually increases to the surrounding area. The Phong Tho-Te Le Phong block tends to raise in the Northwest, average rate of 4mm/year, the highest reaches 7mm/year but subsidence in the Southeast, average rate of -2mm/ year. The results of repeated measurement of water-level in the modern period show that there is a strong vertical separation between the blocks. The strong rising in the NW-SE direction creates boundary between the Northwest and South West and almost coincide with the Phong Tho, Muong La-Bac Yen and Song Da faults.

b. Model of the upward and downward movement of the Earth's crust in the Da River hydroelectric ladder area

Coulomb 3.3.1 program has been used to simulate horizontal and vertical movement. Parameters included in the program consisted of faults divided by grades, length of fault segment, elongation, direction of plug, dip angle and depth of impact. The friction coefficient is 0.4 and the Poisson's ratio chosen for

the Earth's crust is 0.25. The model of vertical movement of the study region is shown in Figure 3.5. The results show that the strongest rising rate of 1.8 mm/year belong to the sub-blocks of Chieng Khuong, Muong Ang, Muong Lat, Moc Chau, Hoa Binh, Da Bac, Tram Tau, Mu Cang Chai, Phan Si Pang and Phong Tho. In contrast, a strong subsidence rate of -1.8 mm/year occurs at the following sub-blocks: Muong Mo, Phu Si Lung, Muong Cha, Sin Ho, Thuan Chau, Quynh Nhai, Than Uyen, Hat Lot, Ta Khoa, Ninh Binh, Van Chan and Thanh Son. The prominent feature in the vertical movement of the Earth's crust is the contrast between blocks and sub-blocks. The strong subsidence block of Son La – Song Da sandwiches between two blocks of Ma River - Thanh Hoa and Phong Tho - Tu Le. Similarly, the sub-blocks: Muong Nhe, Muong Ang, Sin Ho raise, buMuong Mo, Phu Si Lung, Muong Cha subsides. The upward and downward movement of blocks is the cause of earthquake occurrence along their boundaries.
Simulation model of horizontal movement is shown in Figure 3.7. The results show that: The faults developed in the northwest - southeast and northeast - southwest are mostly right lateral strike-slip faults. Meantime, latitude faults are mostly left lateral strike-slip faults. The highest slip rate is 1.1 mm/year at Lai Chau-Dien Bien grade I fault. For grade II faults, the rate is weaker about 0.5 mm/year, especially, Song Da and Tuan Giao faults have slip rate of 0.9 and 1.0 mm/year.

Risks of strongest earthquake in Da Ladder of hydroelectric Dam: In Vietnam, there are many accepted methods to determine M_{max} [2-9, 12-15] such as: Combination geophysical and geological data, characteristics structure of crust, Gumbel distribution, artificial neural network, and empirical M_{max} function and segmentation fault relations. In this paper, 02 methods have been used to predict M_{max} and 01 method has been used to predict potential areas of strong earthquake occurrence:

Prediction of maximum earthquake in Artificial Neural Network (ANN)

Firstly, in order to understand capable application of ANN. We used Feed Forward neural network with back-propagation algorithms to estimate its reliability for some standard patterns [1, 9, 11]. The input data are listed as follows: 1. Density of lineament; 2. Gradient of Bouguer Gravity; 3. Gradient of Magnetic; 4. Gradient of horizontal Earth's crust in Neo-tectonic; 5. Gradient of sedimentary thickness; 6. Gradient of crystal layer thickness; 7. Gradient of Earth's crust thickness; These data are considered to be related to magnitude [9]. Standard pattern is the earthquake catalog in the period 1900-2015. The studied results are shown in Fig.2.4 indicating that M_{max} ranges of 6.5÷6.9 occur in Son La and Muong Te sources, other sources occur earthquake with $M_{max} \leq 6.0$.

Assessment of potential maximum earthquake based on fault segmenting by using empirical formulas: In this paper, Empirical formulas proposed by Cao Dinh Trieu (M_{max} = 6.7, 1983) [8] is used to estimated potential maximum earthquake $M_{max}=1.6 x \text{ LgL} + 4.15$

The studied results are shown in Fig.2.5indicating that:

- Risk of maximum earthquake in studied region is not over 6.9;
- Clearly segments fault in each generated sources and heterogeneous in a source.

Determining position of possible earthquake occurrence based on δ_m – M relation and nodes of active fault.

Using 120 earthquakes with Ms ≥ 4.5 in North of Viet Nam, Cao DinhTrieu (2010) given δ_m–M relations [5] in which the earthquake with M rangers of: 4.5÷4.9; 5.0÷5.4; 5.5÷ 5.9; 6.0÷6.9 were measured, selected, statisticsed and established the distribution of earthquake to calculate average distance and error of δ_m (see Tab. 4), (where $\delta_{m:}$ distance betweens 2 epicenter with the same rangers of magnitude) the next step establishing empirical function of δ_m- M relations: $\text{Log}\delta_m = 0.6M_s - 1.976$. Fig.2.7. and Table 5 show areas of strong earthquake occurrence in studied area, where the authors combined studied results intensity– δ_m relations with nodes – epicenter [5] to determine areas occurrence earthquake (M rangers of 6.5÷6.9). Based on the rules of Magnitude - $\delta_{m,}$-nodes and the position of Paleo- earthquake and Tuan Giao earthquake (M=6.7, 1983), the authors predict that these are 05 possibility generated sources of strong earthquake including Muong Te, Lai Chau, Tuan Giao, Yen Chau, Mai Chau in Da Ladder of hydroelectric Dam. Strong earthquake occurred in areas including Lai Chau, Tuan Giao in the remaining areas including Muong Te, Yen Chau, Moc Chau the earthquakes of magnitude M= 4.5÷4.9 had been occurred which still did not reach maximum Magnitude (M_{max}= 6.5÷6.9). Therefore, the risk of earthquake occurrence in these areas is too large in the coming time.

Conclusions

From the results of the research above the conclusions are:

On the results of characteristic of seismic activity in the Da Ladder of hydroelectric Dam: The largest natural earthquakes occurred in Da ladder of hydroelectric Dam are Lai Chau Paleo- earthquake (480 ÷ 520 years ago), Tuan Giao Paleo- earthquake (420 ÷ 430 years ago), and Tuan Giao earthquake occurred in 1983. The magnitudes of these earthquakes are similar (equivalent to) Tuan Giao earthquake occurred in 1983, i.e. M=6.7±0.2; the b coefficient value of natural earthquake distribution in Da Ladder of hydroelectric Dam is 0.935. The quantity is reflected the level of active natural earthquake activity in the research area and also necessary quantity for computing and delimitating of natural and triggered earthquakes of reservoirs after full water impoundment; 13 earthquake generating sources in Da Ladder of hydroelectric Dam discovered including 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 were observed. The largest earthquake may occurred along these earthquake generating sources with magnitude not over 6.9.

Based on the risks of strongest earthquake in Da Ladder of hydroelectric Dam: Large natural earthquake occurrence areas in Da ladder of hydroelectric Dam with M_{max} may reach a value of 6.9 is the Muong Te, Lai Chau, Tuan Giao, Yen Chau, and Mai Chau. Earthquake of maximum magnitude (M=6.7) has been observed in Lai Chau and Tuan Giao areas. The areas of Muong Te, Yen Chau and Mai Chau still not reached maximum value of magnitude. If distance regulation, degree of magnitude and junction point of earthquake generating faults are correct then risk of earthquake occurrence in Muong Te, Yen Chau and Mai Chau is large enough in the coming time.

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