Vietnamese-Polish investigation of Reservoir Triggered Seismicity – measurements and first conclusions

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Abstract

The Institute of Geophysics Vietnam Academy of Science and Technology (IGP VAST) and the Institute of Geophysics Polish Academy of Sciences (IG PAS) has been cooperating for decades in the field of seismology. It started in the International Geophysical Year 1957-1958. For a long time, the cooperation was based on a seismic analysis of shocks. An example of such cooperation was the earthquake in 1989 in Hoa Binh, North Vietnam.

New horizons of cooperation appeared in 2013, when an Agreement for Research Co-operation between the IGP VAST and the IG PAS was concluded to provide a framework for co-operative research in the field of Reservoir Triggered Seismicity (RTS) research in Song Tranh 2 (STR2) area. The cooperation was expanded in 2015, when next agreement covering second reservoir in Lai Chau was concluded.

The measurement and results of common investigations in STR2 and Lai Chau are the scope of this work. In both areas dense local networks were installed which allowed estimate focal parameters. The Lai Chau case is under initial study now. Contrary to most cases of RTS, the local network in Lai Chau had been built before the filling of the reservoir started. It allows to study full cycle of changes of seismogenic processes. The seismicity in STR2 began in 2010, just after the dam was filled. Result of investigations were already published. We discovered there two regimes of seismic response to the filling of the reservoir, which occur in clusters. They differ in periods of seismic activity and frequency-magnitude distributions.

***Keywords**: Reservoir Triggered Seismicity, Focal Mechanism, Clustering, completeness of catalogs, b-value.*

1. Introduction

Poland has been cooperating in the field of geophysics with Vietnam for 60 years. (Teisseyre et al., 2014). The Department of Geophysics in the Vietnam Meteorological Survey and the Department of Geophysics PAS participated in the huge international project – the International Geophysical Year (IGY) 1957-1958. In Vietnam, two geophysical observatories were built and equipped: in Phu-Lien and at Cha-Pa and seismic stations Phulien and Sapa. These were serviced and modified during consecutive expeditions. The last expedition, which serviced the Phu-Lien observatory, took place in

Fig. 1 During the IGY expedition to Vietnam. In those days, young scientists prof. Józef Hordejuk (and the left) and prof. Sławomir Gibowicz (on the right) were posing with a Kirnos seismometer. From the archives of the IG PAS.

1964. Then, scientific cooperation was continued including RTS, which resulted in joint scientific research projects (e.g. Gibowicz et al., 1987).

Closer partnership was resumed in 2013. Agreement for Research Cooperation was concluded on 4th April, 2013, between the IGP VAST and the IG PAS. The purpose of the Agreement was to provide a framework for promotion of cooperative research between IGP VAST and IGP PAS in the field of RTS including particularly: the installation seismic stations in the Song Tranh 2 area, collection, processing and interpretation of data provided by abovementioned seismological systems, exchange information on seismological methods, and publication of scientific works. Results of cooperation were presented on international conferences in geophysics, seminars took place in Poland and Vietnam, and three papers were published in reviewed scientific journals (Wiszniowski et al., 2015; Giang et al. 2015; Lizurek et al., 2017). Next Agreement for Research Cooperation, concluded on 15th June 2015, expanded the research partnership in the field of reservoir-induced seismicity of the Lai Chau area and other reservoirs along Black River in Northwest part of Vietnam.

The Vietnamese-Polish cooperation is currently aimed on investigation of the association of earthquakes with the impounding of artificial surface water reservoirs. Earthquakes can be caused by natural processes (tectonic movement, volcanic activity, etc.) or by human industrial activity. The earthquakes associated with human activity are defined as anthropogenic seismicity, which includes seismicity associated with a surface water reservoirs, underground mining, large-scale surface quarrying, high-pressure fluid injection for geothermal power generation, conventional and unconventional hydrocarbon exploitation, underground storage of fluids and CO_2, removal of underground fluids, and underground explosions. The technological operations can trigger or induce earthquakes under certain geological conditions. The socioeconomic importance of anthropogenic seismicity is enormous. Very often, important areas of industry may lose public confidence if seismic risks associated with them will not be identified and properly presented to the public. The filling of the reservoirs has triggered the strongest anthropogenic events. The largest earthquakes triggered by water impoundments have exceeded a magnitude of 6, like damaging earthquake at Koyna Dam in India of magnitude 6.3, which took place in December 1967 (Gupta 2002). In Vietnam the strongest case of a reservoir triggered seismic event of magnitude 4.9 took place in Hoa Binh Province, Northern Vietnam, in 1989 (Tung, 1996). Such seismicity occurs also in Poland. The strongest reservoir induced earthquake so far occurred on 1 March 2013 in Niedzica dam region. Its magnitude was Mw=3.5. This event was felt by the inhabitants of the area (Białoń et al., 2015).

2. Seismic monitoring of the Song Tranh 2 region

The recording of seismicity in STR2 area can be divided into three phases. At the beginning of the reservoir filling, the STR2 area was monitored by two seismic stations located in Binh Dinh and Hue more than hundred kilometers away from the reservoir. From January, 2011 to September 2012, these two stations recorded more than 100 earthquakes in the Bac Tra My and surroundings, having magnitude M =1.8÷4.2.

Phase II began when IGP VAST deployed a five station seismograph network in the vast STR2 region. There were stations in Tra Doc, Tra Bui, Tra Nu, Tra Mai and Tien Lanh (Fig. 2 and 4). The network gave the possibilities to record events with completeness magnitude 1.0 and to locate earthquakes more accurately. Unfortunately, the greatest seismic activity and the strongest events had taken place when the network was installed.

In August 2013 a team from IGP VAST together with a team from IG PAS installed 10 seismic stations. The integrated seismic network was called VERIS (**V**i**E**tnam **R**eservoir **I**nduced **S**eismicity). Stations provided by IGP PAS were equipped with short-period seismometers Lennartz LE-3DLite (1 s), whereas station provided by IGP VAST were equipped with long-period seismometers Guralp CMG-6TD (30 s). Signals from Lennartz seismometers were recorded by the Net Data Logger (NDL), which served in the project with dynamics 132 dB. Seismometers Guralp are integrated with the on-board digitizer and recorder of 130 dB dynamics. In 2017 Lenartz seismometers were replaced be GeoSIG VE-53/BB (5 s).

In the period from 24 Aug 2013 to 30 Apr 2016, 6142 seismic events were localized and magnitudes were calculated. The M_L range of these events was -0.6 to 3.6, with event depth varying from 0.24 km to 13.7 km (Fig. 2). The focal mechanisms of 94 events was estimated.

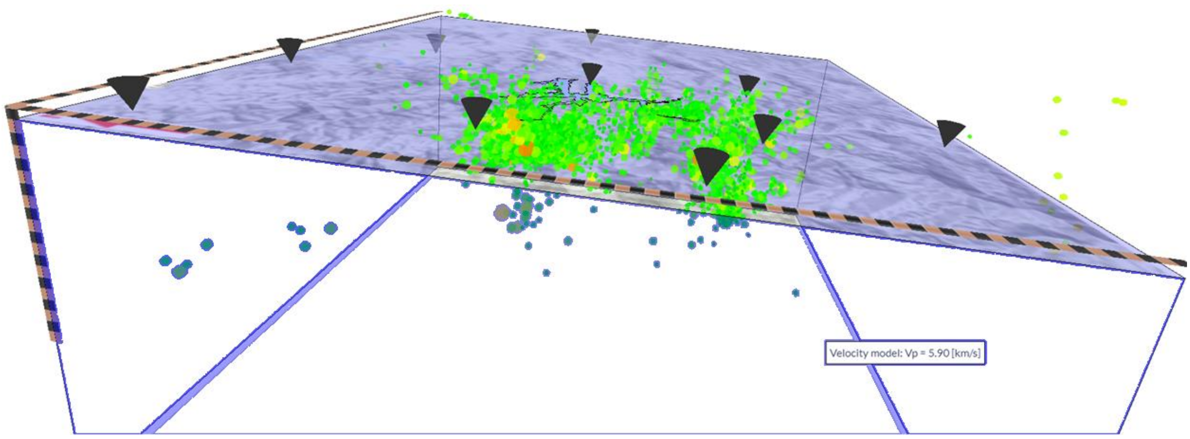

Fig. 2 The 3D visualization of events in STR2. View from the west. Black triangles indicate seismic stations of the VERIS network. (https://tcs.ah-epos.eu/#episodes:SONG_TRANH)

3. Seismic monitoring of the Lai Chau Dam region

Monitoring similar to the STR2, where stations were installed after the appearance of seismic, does not allow to do research in the full life cycle of water reservoir management. Measurements preceding the water impoundment are required, however such research is connected with the risk of unnecessary expenses, because not all artificial reservoirs cause the appearance of measurable seismicity. (Gupta, 1992). The dam in the Lai Chau region gives a unique chance to perform such seismic measurements thanks to the high natural seismicity in the area and simultaneous chance of the appearance of anthropogenic seismicity. A local network of four stations (NNU, MTE, CCA, and NNA3) (Fig. 3) had been installed there before the impounding started in June 2015. Next 5 stations provided by IG PAS (HUBD, KHOD, CNUD, PUDD, and MLAV) were installed in July 2016. The last stations were installed in June 2017. Stations provided by IGP PAS were equipped with VE-53/BB sensors, whereas station provided by IGP VAST were mostly equipped with CMG-6TD seismometers.

The investigation of the Lai Chau is currently at the stage of collecting seismic, geological, and anthropogenic data.

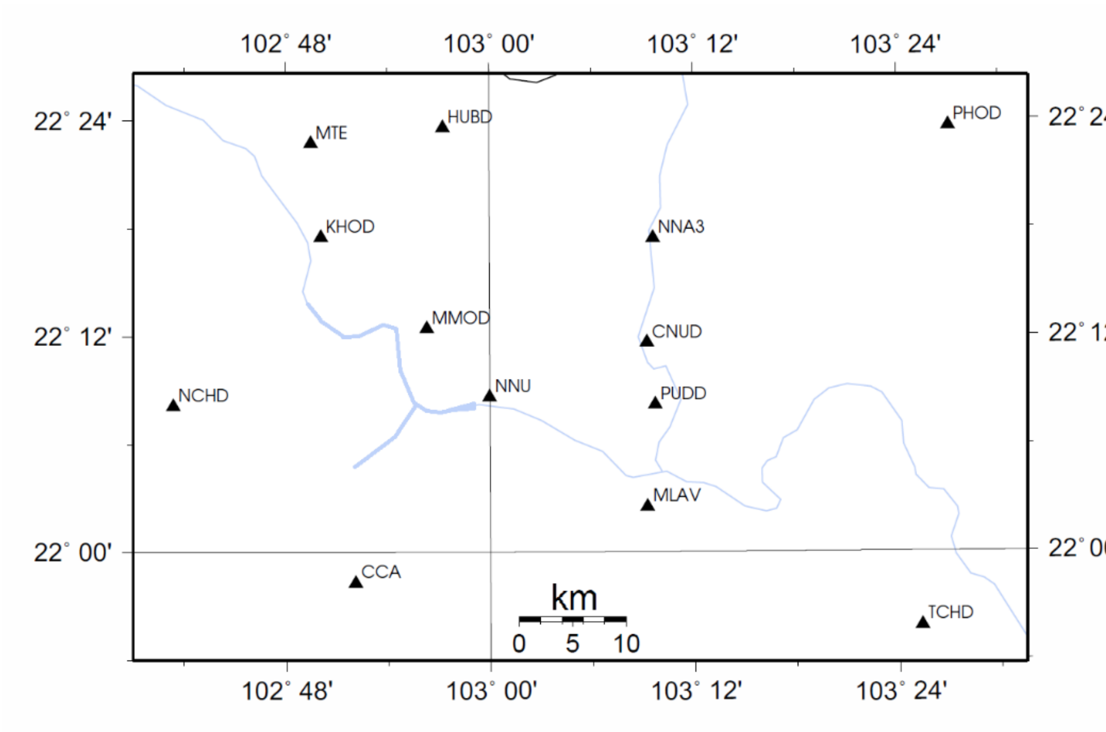

Fig. 3 Seismic stations (triangles) in Lai Chau region. Status from July 2017

4. Analysis of seismicity in Song Tranh 2 region

The interpretation of seismic data in the STR2 included location of events, magnitude calculation, and, if it was possible, estimation of moment tensor and other source parameters. Based on that stress inversion was calculated, clusters of events distinguished, and magnitude distributions were estimated.

The applied full moment tensor inversion method is based on the P-wave displacement amplitude of the first pulse (Lizurek, 2016). The method is limited by minimum number of eight stations that the P-waves were clearly recorded, therefore reliable focal mechanisms of 94 events were estimated so far. The magnitude range was 0.9 to 3.6. An overview of the double-couple (DC) MT solutions is presented in Fig. 4. The general features of full MT decomposition to double-couple (DC) components and remaining isotropic (ISO) and compensated linear vector dipole (CLVD) and are shown in Fig. 5. Most events do not have dominant non-DC components, which may indicate a significant role of the local tectonic stress field in the seismogenic process.

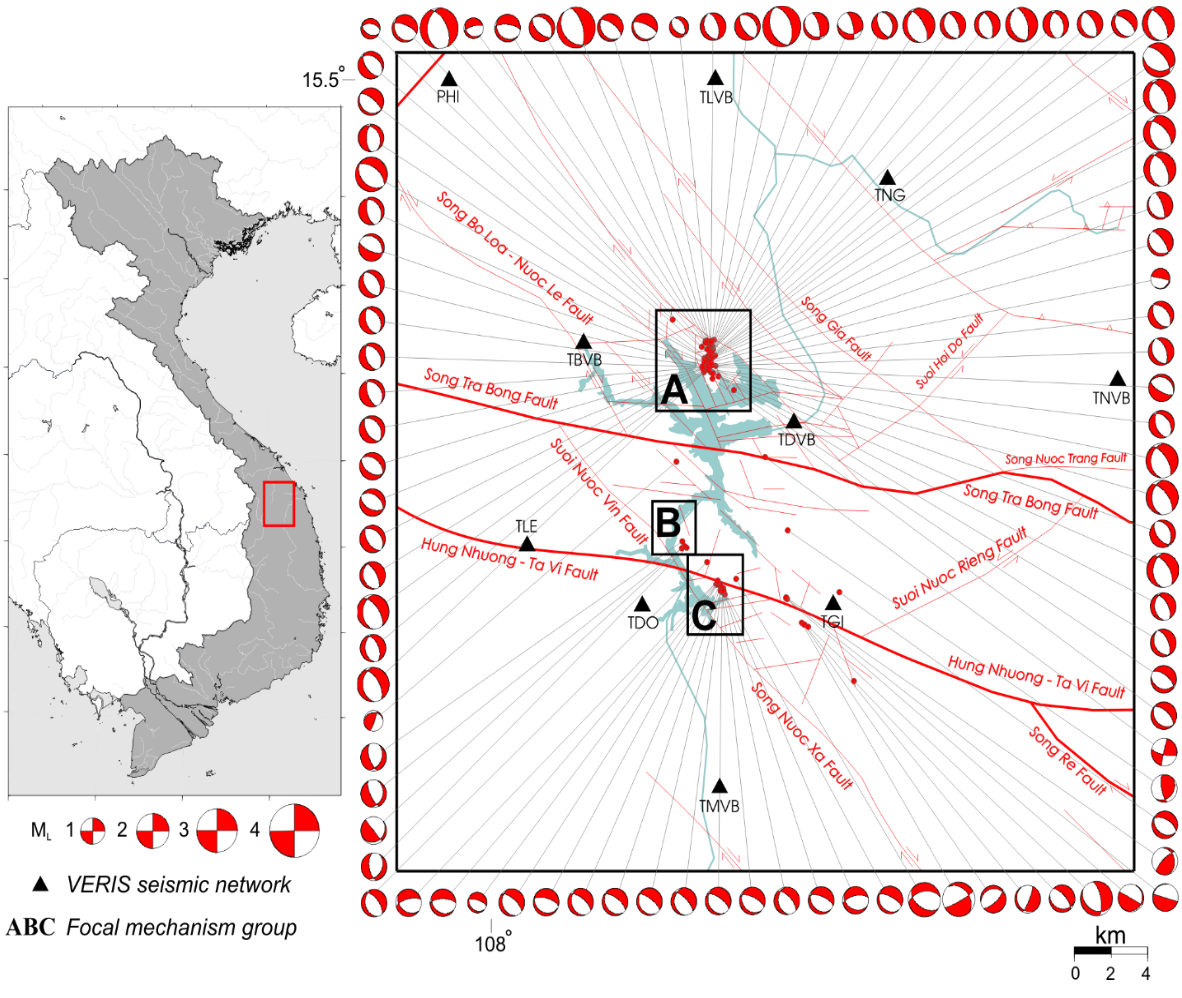

Fig. 4 Full moment tensor solutions of seismic events occurring in the Song Tranh 2 reservoir vicinity, with seismicity clusters A, B, C. Black triangles indicate seismic stations. Red lines indicate known tectonic faults.

Stress inversion, which provides orientations of the three principal stress axes and a quantity reflecting the relative stress magnitude *R*, was calculated using the Formal Stress Inversion approach (Hardebeck and Michael, 2004). Only a 0D approach was employed, because of the small number of available MT solutions. Stress inversion method requires at least 30 events and only cluster A fulfills this condition, therefore clusters B and C were treated as a single southern cluster (SC) and the cluster A as a northern cluster (NC). The NC includes 59 events with MT solutions, whereas the SC consists of 31 such events. A few event far from clusters, which did not have single dominant event mechanism, were excluded from the analysis. The most compressive stress (σ_1) is almost vertical and corresponds to the water volume mass pressing on the bottom of the reservoir. The intermediate compressive stress (σ_2) has a magnitude closer to that of the least compressive (σ_3) than that of the σ_1. Orientation of stress axis σ_2 and σ_3 is almost horizontal and corresponds to some major discontinuities, such as the Song Gia and Song Bo Loa – Nuoc Le faults (Fig. 6). However, event locations are connected with other, more local discontinuities (Fig. 4). In general, magnitudes and orientations of the principal stress axes may be interpreted as a main directions of the local tectonic stress field in the STR2.

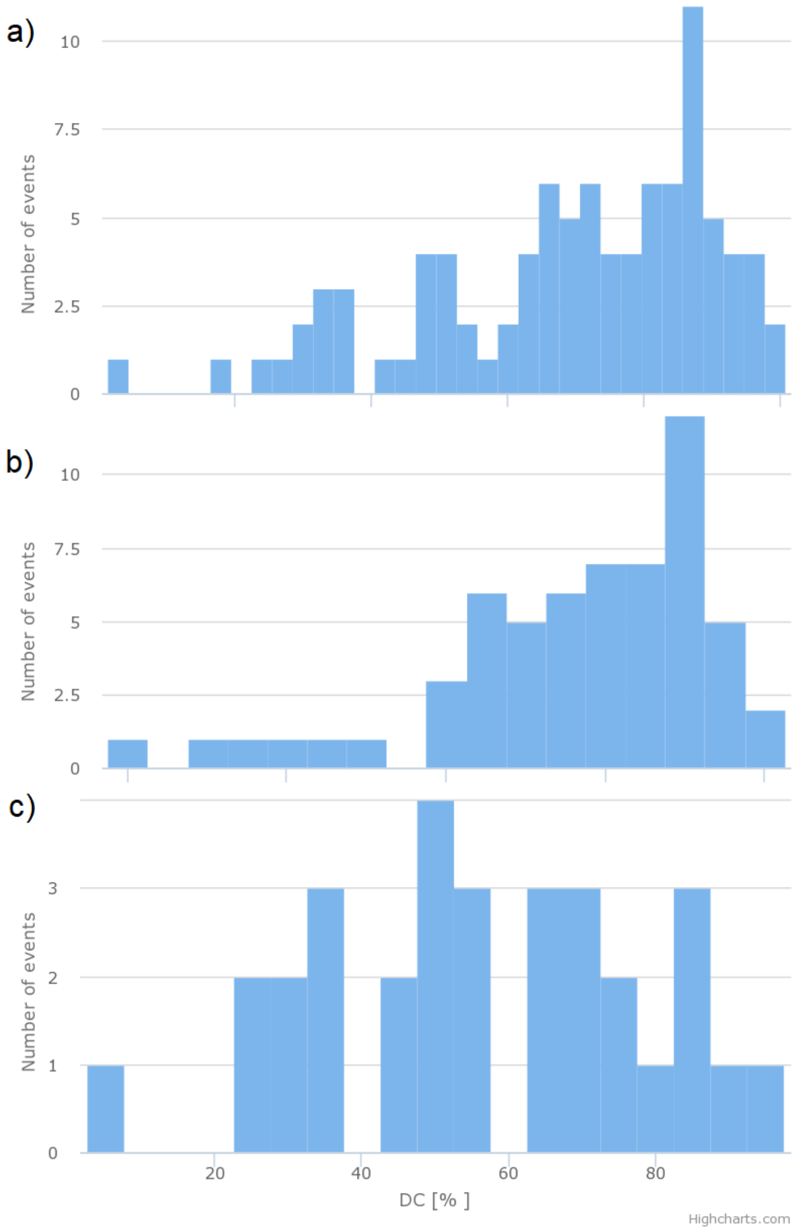

Fig. 5 Double-Couple component histogram of the Full MT solutions of: a) all events, b) NC, and c) SC.

Most of events in the NC exhibited a dominant shearing component in full MT (Fig. 5b), with a normal faulting regime of mostly NW-SE strike. The strike of the nodal planes was mainly NW-SE with range of 60 degrees and most of the events within dip range of 25 degree. Axis σ_2 and σ_3 are almost horizontal and correspond rather to smaller local tectonic discontinuities with orientation parallel to the Song Gia fault rather than the main faults (Fig. 6b). The variability of the MT in the SC solutions is higher, (Fig. 6c), with strike variability more than 90 degrees and dip of 90% of events within range of 30 degrees. The MT solutions are there characterized with a greater

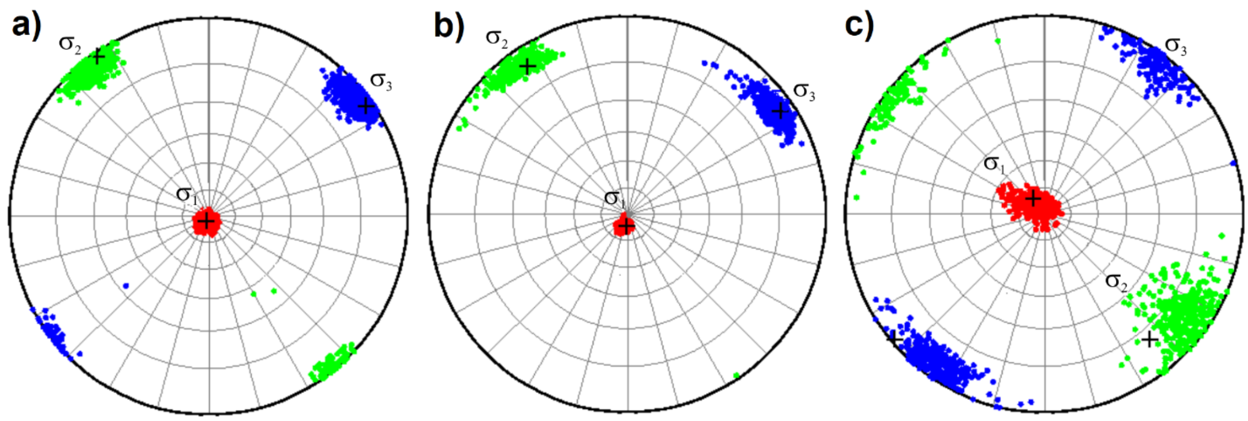

Fig. 6 Principal stress orientation obtained from MT inversion of: a) all events, b) NC, and c) SC. The principle axis orientations are represented by black crosses, and the colored dots correspond to the 95% confidence interval area of bootstrap sampling data.

number of non-DC mechanisms, however, DC components dominant in most events (Fig. 5c). The σ_1 stress axis is almost vertical, like in the northern cluster, but the σ_2 and σ_3 axes orientations differ by about 180 degrees in comparison to the NC (Figs. 6b and 6c). The difference is now hard to explain in terms of Song Tranh area tectonics. It may indicate both the influence of reservoir exploitation on the seismogenic process, or the differences between clusters B and C. The analyzed events also happened during the smallest changes in water level (WL) and the lowest WL. It suggest a delayed response to the triggering factor mainly in the NC.

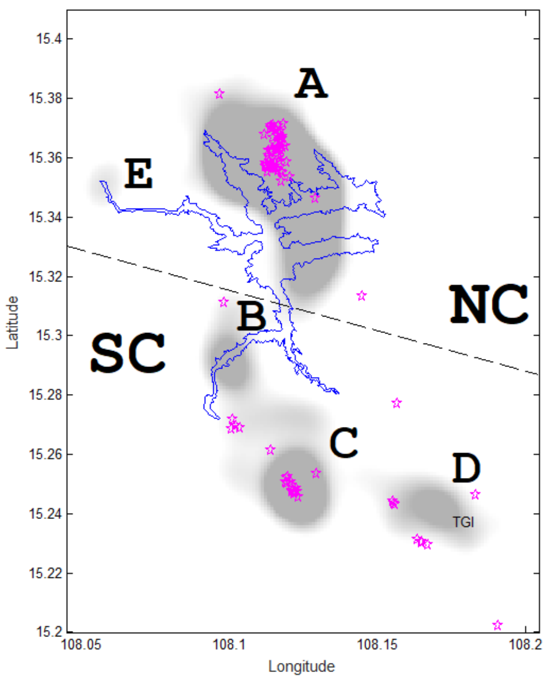

Fig. 7 Density of epicenters calculated via the use of exponential Parzen (1962) kernels with market sub-clusters. The dashed line separates the northern cluster from the southern cluster. Starts show events with computed MT. The nearest seismic stations are marked by triangles (Lizurek et al., 2017).

Clustering based on the MT corresponds to clustering based on epicenters of events. Fig. 7 shows the density of seismic events (Lizurek et al, 2017). They can be separated into two main clusters: the NC and the SC. Four additional sub-clusters can be distinguished: three clusters in the SC: B, C and D, and one further sub-cluster (E) in the north, which is characterized by a small number of event (70 events) and absence of MT solutions, however it is located significantly far from cluster A. The seismicity in the sub-cluster E appeared in August 2015 – much later than in the rest of the area. The Cluster D has no single dominant event mechanism.

Magnitude distributions were estimated assuming the Gutenberg-Richter (G-R) distribution (Gutenberg and Richter, 1944). For the study region as a whole and for each of the identified clusters, the maximum completeness magnitude (Mc) value and the b-value of the G-R were estimated (Aki, 1965).

The Mc estimation was accomplished using methods based on variety of seismic catalog (Leptokaropoulos et al., 2013). Results are presented in Table 1. The values of Mc in clusters are similar. Only Mc in clusters B and E differ more, but they contain the smallest number of events.

Table 1. Results of Mc estimation

Method of Mc estimation	All events	Clusters						
		Northern	A	E	Southern	B	C	D
GFT at 90% confidence bounds	0.6	0.6	0.6	0.3	0.7	0.9	0.7	0.8
GFT at 95% confidence bounds	0.9	0.9	0.9	-	1.0	-	0.9	-
MAXC	0.4	0.6	0.6	0.4	0.8	0.3	0.1	0.8
MGFT	1.0	1.0	1.0	0.3	0.8	0.3	0.8	0.8

Table 2 presents the b-values of magnitudes distributions together with the Mc values taking for estimate the b-values. The calculated for the SC b-value is significantly higher than that for the NC. The b-values calculated for all southing sub-clusters separately are all higher than for northing clusters. The b-value estimated for cluster E is particularly small.

Table 2. Results of b-value estimation

	All events	Clusters						
		Northern	A	E	Southern	B	C	D
b-value	1.094	1.056	1.076	0.506	1.288	1.559	1.309	1.047
Error of b-value	0.027	0.030	0.031	0.066	0.066	0.223	0.105	0.074
Minimum magnitude	1.0	1.0	1.0	0.4	1.0	0.9	0.9	0.8

Seismic activity rate (SAR) diagrams was created by summing events within 10 days moving window (Silverman, 1986). Fig. 8 presents SAR diagram for all clusters and water level changes in the period from August 2013 to May 2015, when the VERIS was recording events. Seismic activities differed significantly between clusters and occurred in different time periods. It is noticeable that seismic activity in the SC (Figs. 8d, f, g, and h) appeared before the activity in the NC (Figs. 8c and i), and the cluster E was inactive until July 2015 (Fig. 8i).

Similar analysis of earlier activity (before August 2013) was done, although it was impossible to use the full MT inversion method based on the P-wave. Because the Mc is higher than 2, significantly fewer events can be used in analyses. Furthermore, the location error in the first phase ranged a few kilometers, which could lead to misclassification of many events. Fig. 9 show SAR diagrams of events $M_L > 1.8$ for the period from January 2011 to August 2013. Likewise in the later period, the seismic activity appeared earlier in the SC (Fig. 9d) than in the NC (Fig. 9c). The greatest seismic activity in the NC occurred after the emptying of the reservoir.

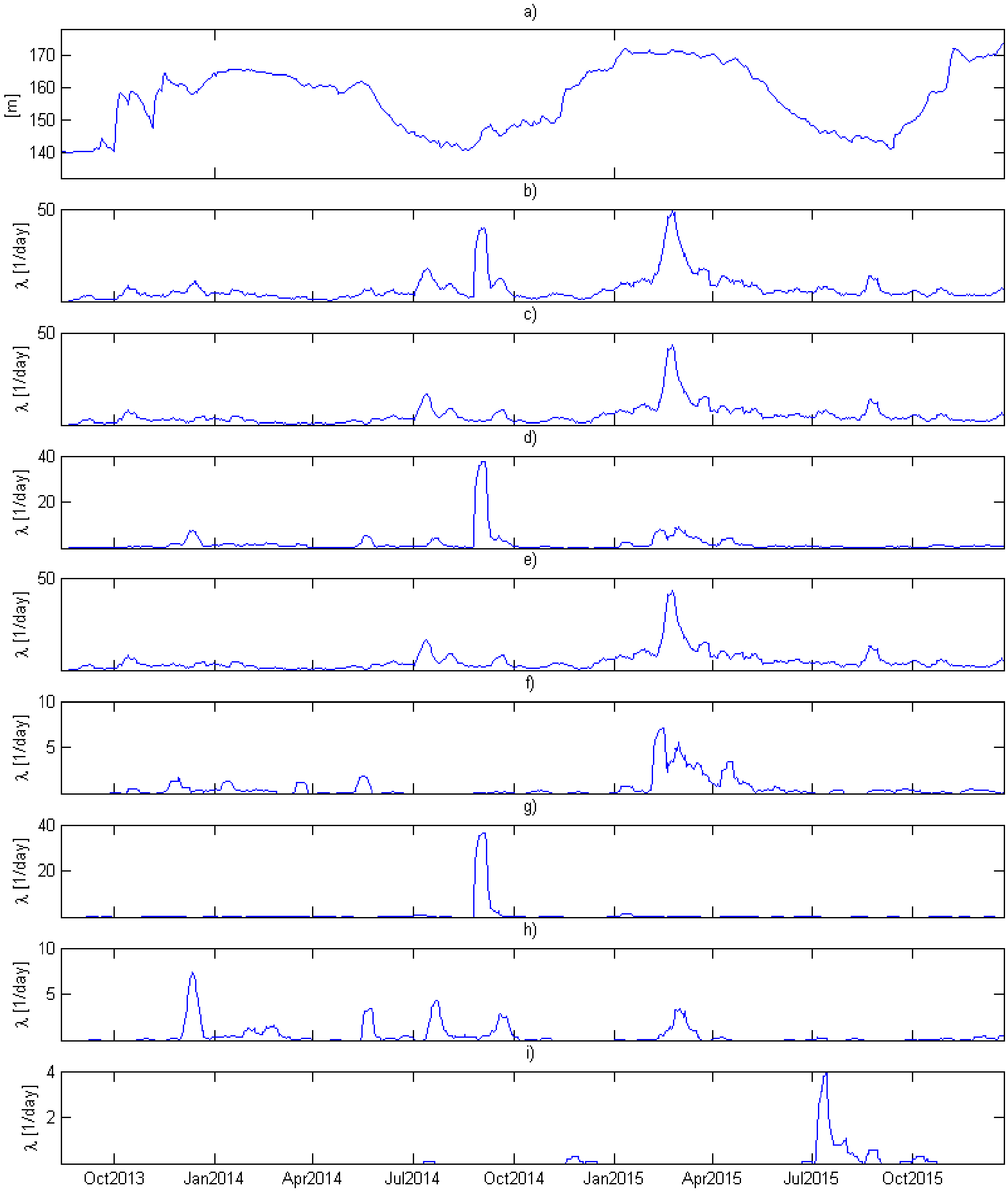

Fig. 6 Mean 10-day activity rate (number of events M_L > 0.9 per day) recorded in period from August 2013 to May 2015 vs water level: a) water level, b) all events , c) NC, d) SC, e) cluster A, f) cluster B, g) cluster C, h) cluster D, and i) cluster E.

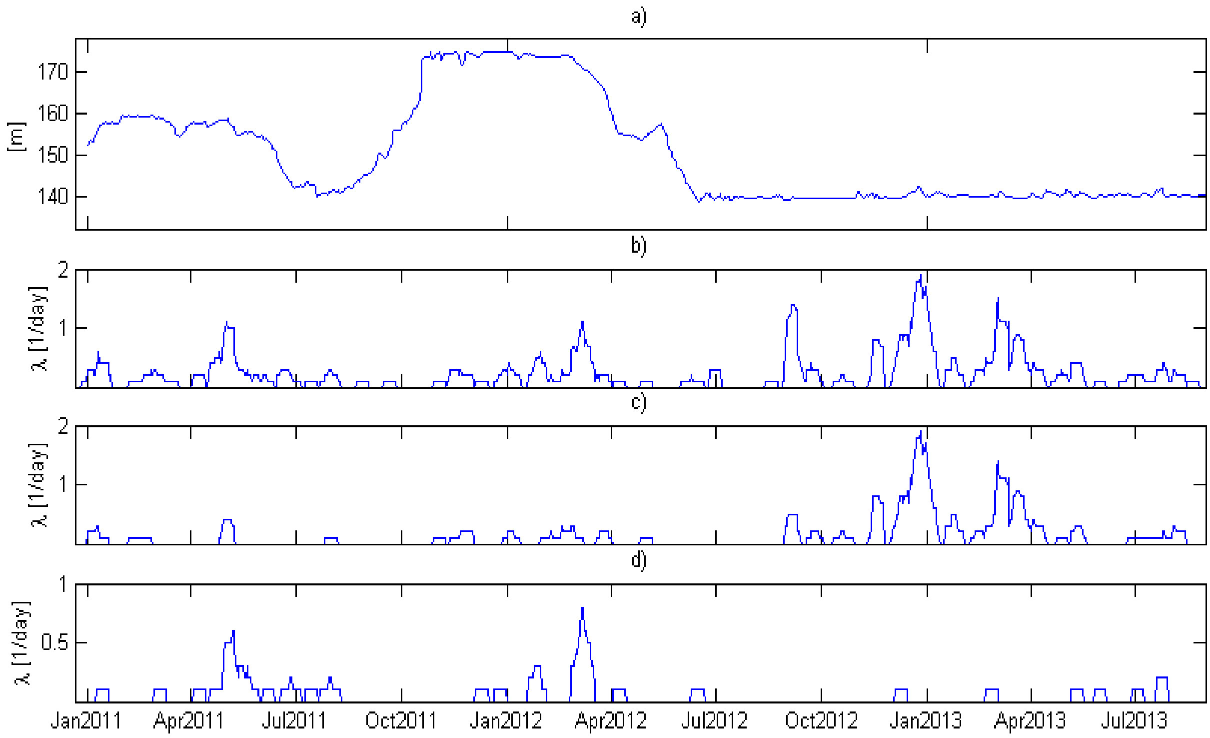

Fig. 7 Mean 10-day activity rate (number of events $M_L > 1.8$ per day) recorded in period from January 2011 to August 2013 vs water level: a) water level, b) all events, c) NC , and d) SC.

Conclusions

The installment of VERIS network increased significantly the earthquake detection and location capacity in the region of Song Tranh 2 reservoir. It also made it possible to calculate focal mechanisms and other source parameters. Unfortunately, the most intense seismic activity occurred earlier, when only two remote stations recorded seismic events. In order to monitor the whole development of seismicity triggered by reservoir impoundment, the monitoring should start before the exploitation of the reservoir. Therefore, the seismic network in Lai Chau was installed before filling the tank.

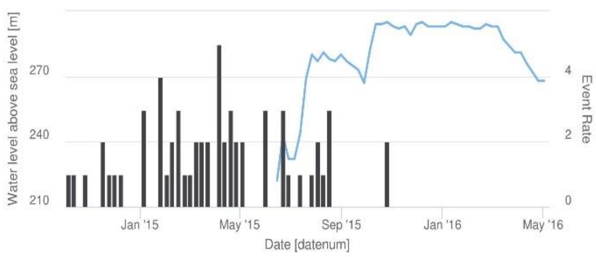

Fig. 8 Seismic activity versus water level at the beginning of monitoring in Lai Chau.

The monitoring in Lai Chau confirmed the seismic activity before filling the reservoir (Fig. 10). Although the monitoring started early, the network was developed during the beginning of exploatation of the dam. Therefore, the first task will be combining data from periods with varies state of the network. The base interpretation of seismogram is now proceeded. Such measurement results will be valuable material for further research.

Interpretation of seismic events in the STR2 revealed the clustering of them based on location and focal mechanisms with two main groups: north and south of the reservoir. Seismic activity in the NC is much greater than in the SC, and also differs in magnitude distribution. In the SC it is around 1.3, while in the NC it is around 1.0 (Lizurek et al., 2017). The clusters also differ in terms of temporal variation in seismic activity. Activity in the SC occurred first, during the filling of the reservoir, whereas activity in the NC was significantly delayed (Figs. 9). The strongest events in the NC appeared during the emptying of the reservoir and low water level period. The greatest activity in the SC occurred before that in the NC also in later periods of monitoring (Fig. 8). Additionally, the activity in cluster E confirms the delayed response of seismicity in the north. On the other hand, the SC cannot be classified as representing the long-delay type of seismicity, as suggested by Gahalaut et al. (2016). It is rather seismicity of the short-delay type.

Focal mechanisms of most events are of normal faults type with dominant DC events. It confirms the triggered seismicity in the STR2. The local tectonic stress field plays an important role in the seismicity, although event locations do not lie on the main faults. However, the stress orientation of the NC, nodal plane orientation, and event locations may be interpreted as connected to an unknown part of the transform fault zone linking the main discontinuities and parallel to the Song Gia fault in the north, mapped as striking NW-SE. Nodal plane orientations and epicenter locations in clusters (B and C) in the south, which characterized by different mechanisms and locations, are parallel to the existing side fault lines of the Hung Nhuong – Ta Vi fault zone. Also, event locations in the cluster (D), which is characterized by MT variety, suggest a link with the Hung Nhuong – Ta Vi fault zone. (Fig. 4).

The results of investigation reveal that seismic activity is triggered by the exploitation reservoir on existing small discontinuities, whereas the seismicity on the main tectonic fault - Tra Bong, which crosses the lake, is low. The main tectonic stress in Central Vietnam exhibits a N-S trend (Hoai et al., 2014), which is not in agreement with the stress orientation obtained here for the STR2 area based on MT data. It can be explained by the fact that seismicity in the STR2 is connected more with the reservoir than with the regional tectonic features.

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