TEST Engineering & Management

November-December 2019
ISSN: 0193-4120 Page No. 1638 – 1645

Preliminary Non Linear Analysis of Seismic Events Associated with the Hydrothermal of Cangar, Batu, East Java

Sukir Maryanto
Brawijaya Volcano and Geothermal Research Center, Department of Physics
Brawijaya University, Malang, East Java, Indonesia
sukir@ub.ac.id

Rendi Pradila Hab Sari
Brawijaya Volcano and Geothermal Research Center, Department of Physics
Brawijaya University, Malang, East Java, Indonesia
shellyhabsari@gmail.com

Rohmatul Uluwiyah
Brawijaya Volcano and Geothermal Research Center, Department of Physics
Brawijaya University, Malang, East Java, Indonesia
rohma.vrh@gmail.com

Abdurrouf
Department of Physics
Brawijaya University, Malang, East Java, Indonesia
abdurrouf@ub.ac.id

Article Info
Volume 81
Page Number: 1638 – 1645
Publication Issue:
November-December 2019

Article History
Article Received: *5 March 2019*
Revised: *18 May 2019*
Accepted: *24 September 2019*
Publication: *09 December 2019*

Abstract

About 25 seismic events in Cangar hot spring, Arjuno-Welirang Complex has been presented to identify its dynamic process. The delay time has been identified using autocorrelation and embedding dimension has been determined by selecting the False Nearest Neighbour equal to zero. Both of these parameters used to reconstructive the attractor diagram at phase space and to calculate the lyapunov exponent value. The results show the lyapunov exponent in study area are positive and they associated with the chaotic and deterministic system of hydrothermal area.

Keywords: *Lyapunov Exponent, Seismic Events, Embedding Dimension, Nonlinear Analysis, Hydrothermal.*

I. Introduction

Cangar is an outflow area from Arjuno-Welirang volcano complex whose surface manifestation has bicarbonate water type and pH around 8 [1, 2]. Its location is in the Southwest of Welirang flank. Mount (Mt.) Welirang is a post-eruptive volcano whose the last eruption is in 1952. The geology in this area is the results of Arjuno-Welirang side eruption and Anjasmoro products in the past. The geothermal system in Arjuno-Welirang is the high-temperature hydrothermal around 190 - 230°C in its reservoir [3, 4] and the heat source estimated is come from the young Welirang lava flow with the magma evolution degree and geothermal potential mafic to intermediate [5]. The reservoir consists of quarterly volcanic rocks include lava and pyroclastics and the fluid contains the sulphur deposits [2, 3]. Various kind of geophysical research has been carried out in the Cangar area such as gravity, magnetic, seismic, geoelectric (self potential and resistivity), and magnetotelluric). Gravity and magnetic anomaly show that the geothermal in Cangar has a low gravity anomaly due to its low susceptibility [6]. The thermal aquifer in Cangar hot spring has the low resistivity and potential values based on the magnetotelluric, resistivity and self potential methods [6–9]. These low values indicate that Cangar is a conductive zone and outflow part in geothermal system of Arjuno-Welirang complex. The resistivity value limited to 1200 – 1500 meters depth from Welirang summit and indicate as the caprock [7, 10].

Hydrothermal systems are usually identified from surface manifestations such as hot springs, geysers, fumaroles, etc. In the Arjuno-Welirang complex, manifestations that appear on the surface are hot springs in three locations (Padusan, Cangar, Coban), as well as fumaroles and alterations on the summit of Welirang Mountain. Zobin (2013) mentions that manifestations in the hydrothermal system are associated with natural seismic events, usually low-amplitude continuous tremors or distinct short seismic events [11]. The seismic waveform in the hydrothermal region is almost similar to a waveform in a volcanic earthquake, only different in spectral terms. Seismic events in Cangar have spectral frequency range from 8-20 Hz [12], possibly because the vibrational processes at the geothermal source are smaller than in Welirang itself. Liaw & McEvilly (1979) stated that event frequencies greater than 8 Hz are usually associated with manifestations in the form of geysers, fumaroles, or hot springs, so does Nicholls & Rinehart (1967) which states that event frequencies less than 20 Hz are usually associated with hot steam [13, 14]. The depth of seismic events in Cangar varies from shallow less than 264 meters to 985-2152 meters in deeper areas [15].

Basically the hydrothermal system is a very complex nonlinear process. A nonlinear process in a physics system is a process in which a small slight difference in the input will produce a very different output because it has a sensitive dependence on initial conditions. This term is referred to as chaos. This process is very important to understand because it can show the short-term evolution of a system [16]. There is not much research related to the analysis of nonlinear processes in geothermal areas based on its seismic activity. One of the nonlinear processes in the geothermal area was carried out by Nicholl et al. (1994) who examined the geyser's eruption earthquake in Old Faithful, Yellowstone and showed that geysers in Old Faithful erupted at chaotic intervals [17].

In this article, we conduct a study related to nonlinear processes in the Cangar area, Arjuno-Welirang Complex based on earthquake events recorded in the study area. One of the procedure to characterize chaos in a system is by describing the rate of small disturbances increase/decrease at different directions in the orbital phase space [16]. Measurements such as the box-counting dimension and correlation dimension do not accurately quantify the dependence on the initial conditions, but only show how the distribution of points in the orbit. Therefore, to quantify this sensitive dependency can be done by calculating the Lyapunov exponent (LE) value.

In this study, Lyapunov exponent is used to investigating the dynamics of the hydrothermal system in Cangar, Arjuno-Welirang complex and the processes which develop in that system. This process can be stochastic, although the initial conditions are known, there are many directions where the process can be developed or deterministic process that is very difficult to predict due to sensitive to the initial condition [18].

II. Materials and Methods

Digital Portable Seismograph type TDL-303s with sensitivity 2V/g and frequencies responses 0~200 Hz has been installed at 8 locations near the Cangar hot springs and near Arjuno-Welirang (Fig. 1) on June 2015, May, November 2016, May 2018, and August 2019. 2 acquisition points has been installed in same location, e.g. points 3 and 4 (installed on 2015 and 2016) also points 5 and 6 (installed on 2018 dan 2019). Data recorded in 3 components with sampling interval 100 Hz or 0,01 s. Seismic data selected to separate the original signals and noises by applied the Band Pass filter 0,05 – 30 Hz.

The concept of LE can be described as follows: Supposed we have 2 points which have a very close distance x_o and $x_o+\varepsilon$. After the first step, both of these points will separate in accordance with their initial condition and can be written as :

November-December 2019
ISSN: 0193-4120 Page No. 01 – 08

$$d(x_o, x_o+\varepsilon) \rightarrow d(f(x_o), f(x_o+\varepsilon)) \quad (1)$$

where $d(f(x_o), f(x_o+\varepsilon))$ is initial separation times of e^{λ} and express as :

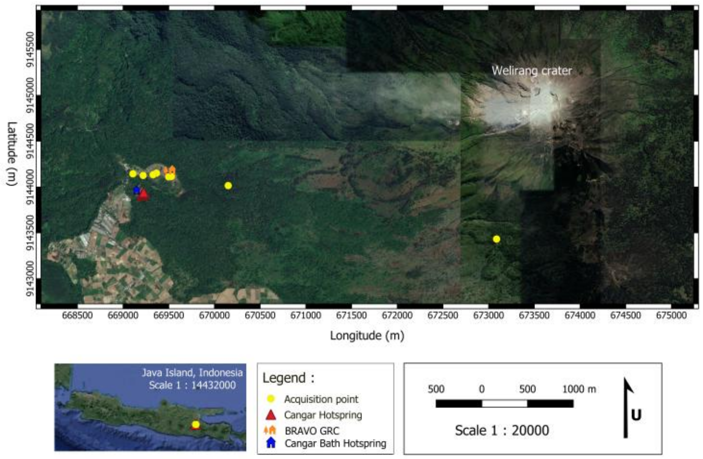


Figure 1. Acquisition points around Cangar hot spring and near Mt. Welirang. The location 1 to 8 follows by yellow points start from left to right. Points 5 and 6 are located in Brawijaya Volcano and Geothermal Research Center (BRAVO GRC) University of Brawijaya building.

λ is Lyapunov Exponent, and to get this LE is by displacing the λ to the left part of Eq. 3 which becomes :

$$d(f(x_o), f(x_o+\varepsilon)) = e^{\lambda} (d(x_o,x_o+\varepsilon)) \quad (2)$$

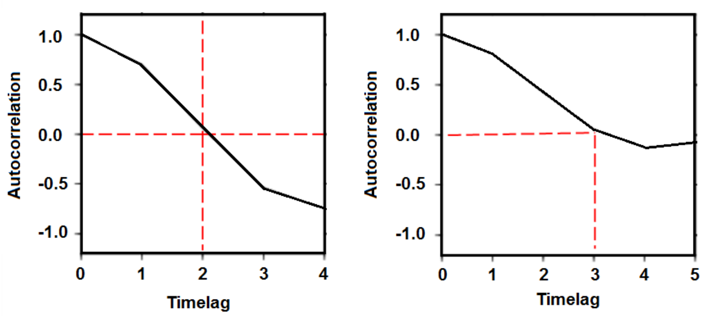
For the *n*th step, Eq. 2 becomes :

$$d(f^n(x_o), f^n(x_o+\varepsilon)) = e^{n\lambda} (d(x_o,x_o+\varepsilon)) \quad (3)$$

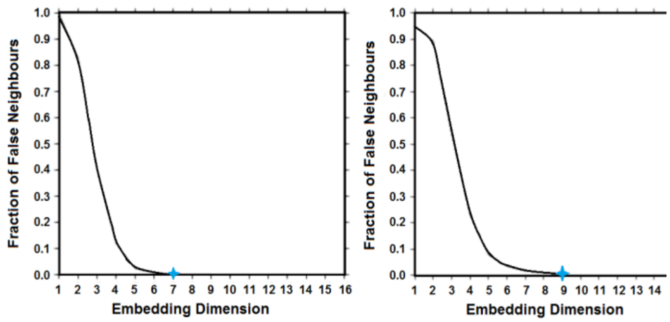
$$\lambda = (1/n) \ln (d(f^n(x_o), f^n(x_o+\varepsilon))/\varepsilon) \quad (4)$$

Due to the very small value of ε, Eq. 4 also can be expressed as [16] :

$$\lambda \approx (1/n) \log_e |df^n/dx| \quad (5)$$



(a)



(b)

Figure 2. Estimation of (a) delay time by using autocorrelation and (b) dimension embedding by using FNN on seismic event 26 November 2016 at 12:54:00 Western Indonesian Time and 29 May 2018 at 23:26:00 Western Indonesian Time.

Eq. 5 is a basic concept of LE where determine the qualitative description of the dynamics system. Although the concept looks simple, actually it is very difficult to measure using the method above. Therefore, in this study, LE value is determined using the method of previous studies [16, 19–21] which start from determining the delay time (τ) by calculating the seismic events autocorrelation on time series data. Autocorrelation is done to see the stationarity of time series data. This is important because the results of the autocorrelation can show clearly whether the seismic event in the Cangar area is a chaotic system or not seen from its stationary. In this study the delay time is determined by timelag between 0-10 (0-0.01 s). Then the embedding dimensions (m) are determined to reconstructed the attractor dyagram in phase space by calculating the False Nearest Neighbor (FNN) and selecting when FNN=0. The FNN value functions as an indicator of the amount of noise in the signal data. Therefore, FNN = 0, means the data is no longer mixed with noise. The attractor diagram that results from a non-linear dynamical system gives the system development after starting from a certain initial condition. Reconstruction of the correct attractor diagram is when the points on the diagram are spread on both sides and not centered on the diagonal phase space [22]. Examples of the delay time and embedding dimensions based on the FNN value can be seen in Fig. 2.

The reconstructed of the attractor diagram then used to calculate the Lyapunov exponent value by using the relationship between the points number in the attractor (N) and the Stretching Factor (S) in accordance with the method proposed by Rosentein et al. (1993) [23]. By applying the Least Square regression method, we get the Lyapunov exponent value from the slope of the regression line on the N and S relationship graphs.

III. RESULTS AND DISCUSSION

25 seismic events are identified from the data selection. One of the waveforms shows in Fig. 3. The frequency of the seismic events in Cangar range from 8 to 24 Hz. Delay time from the 25 seismic events ranges from 0,01 to 0,04 s. The decreasing autocorrelation curve of delay time in Fig. 2a shows the nonstationarity to the seismic events at Cangar and reflected as complexes, dynamics and the nonlinearities of the system. The embedding dimension values range from 7 to 9. Both of these parameters then used to construct the attractor diagram with different delay time.

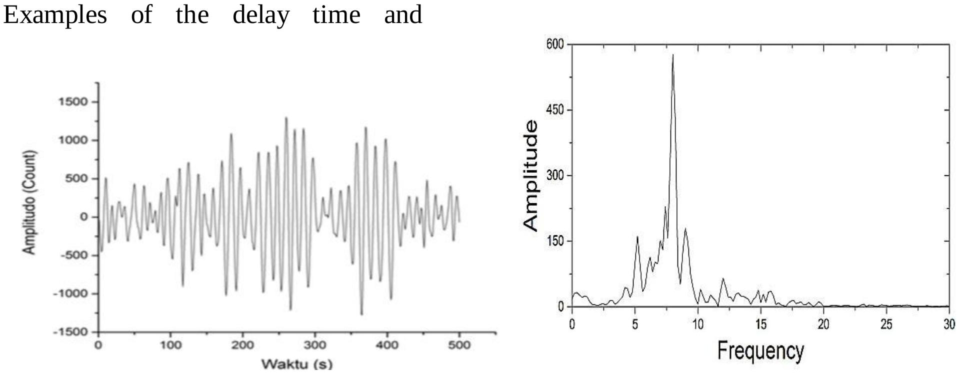


Figure 3. Examples of the waveform and spectral of a seismic event at Cangar on May 30, 2018 at 01:25:00 Western Indonesian Time.

November-December 2019
ISSN: 0193-4120 Page No. 1638 – 1645

Fig. 4 shows the attractor diagram which form from delay time at 0,01 s; 0,02 s; 0,03 s; dan 0,04 s. It can be seen that when τ = 0,01 s, the coordinates of m at each point correlate strongly to form an ellipse close to the diagonal of the phase space. But when τ is raised, the points on the attractor start to diverge in no time and form a strange attractor (see when τ = 0,03 s). This form of attractor indicates that the hydrothermal system in the Cangar area is chaotic.

The number of points generated from the attractor diagram (N) then plotted with a stretching factor (S) to obtain the LE value. From the 25 seismic events analyzed, LE has a positive value range from 0,0154 to 0,0316. When the LE value is positive, this indicates that the particles in the system separated very fast exponentially due to sensitive dependence on initial conditions. This positive LE value also means that changes in particle direction occur randomly and cannot be predicted after passing through the initial conditions. In terms of nonlinear dynamics, this is called chaotic behavior and the system is deterministic. This deterministic nature shows that chaotic behavior originates from nonlinear systems and not due to random or noisy inputs [24, 25].

Chaotic behavior in the Cangar Arjuno-Welirang complex perhaps occurs due to the complexity of subsurface conditions in the area. Faust & Mercer (1977) said that the complexity of the hydrothermal system is because this system has a reservoir containing fluid, where this fluid can be a single-phase (water dominant or steam dominant) or 2 phases (water and steam), thus to describe that system should consider the behavior of these phases and their heat transport [26]. Surely, the transportation of hot fluid from the reservoir to the surface is also very complex due to the inhomogeneous geological conditions below the surface.

In geothermal areas, nonlinear systems and shown by the appearance of seismic events can occur due to several reasons, such as diffusive heat discharges, continuous heat discharges, or intermittent heat discharges [11]. In this case, the geothermal system in the Cangar area, Arjuno-Welirang complex is included in the continuous heat discharges through convection in hot springs and steam (fumaroles in the Arjuno-Welirang crater). Zobin (2013) said that the existence of geothermal systems in active volcanoes is a response to the circulation of hydrothermal fluid convection [11].

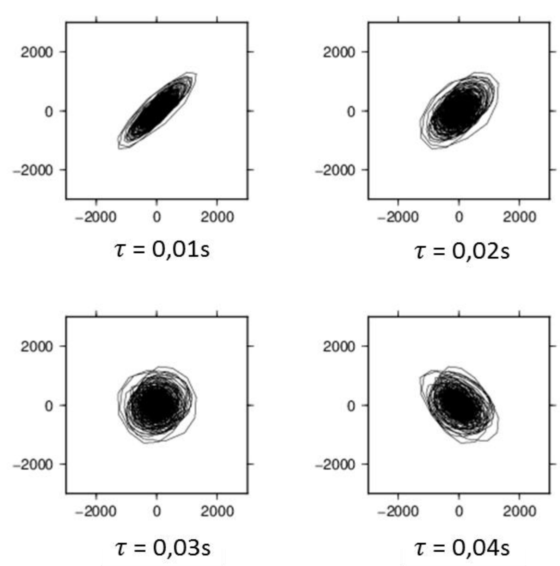


Figure 4. Attractor diagram of a seismic event on May 29, 2018 at 23:26:00 Western Indonesian Time. In the Fig. above, the correct attractor diagram as described by Perwita (2013) [22] is shown in the diagram with a value τ = 0,03 s and indicates that the system has stabilized from interference.

The non-stationarity of seismic events autocorrelation in the Cangar hydrothermal area (Fig. 2a) is probably due to the process of partial condensation of steam in hot water from below to the surface [27]. As geothermal water rising to the surface, there will be changes in pressure and temperature, then due to the open structures (fractures, cracks) it causing degassing or gas release process [28], forming a bubble, similar to the water in the pot when it starts to boil. The formation of bubbles in degassing process has led to the emergence of seismic events, especially microtremors in the study area. This degassing

TEST Engineering & Management

November-December 2019
ISSN: 0193-4120 Page No. 01 – 08

process is also strengthened by the fluid conditions in Cangar hot spring which have bicarbonate water type, a product of gas condensation (mainly CO_2) mixed with meteoric water [29]. In addition, chaotic processes also can be due to medium properties [30]. When the fluid passes through the fracture structure or crack, the possibility of a small shock due to the friction of fluid and rocks around the fracture/crack will cause the appearance of short distinct seismic.

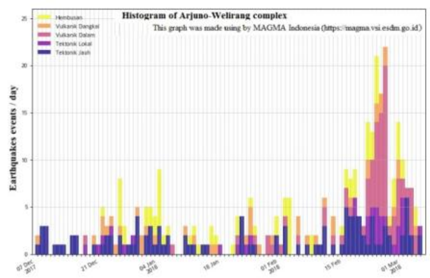


Figure 5. Seismic activity (a) at Arjuno-Welirang complex

Furthermore, based on seismic method, epicenter and hypocenter have been estimated and the results there were about 11 epi-hypocenter with depth between 22-94 meters near the surface manifestation [12, 13]. Microearthquakes activity at these areas had increased. It could be caused by daily activities of Welirang and Kelud volcanoes increased significantly (Fig. 5). Visually, we observe the Arjuno Welirang activity and noted in 7th of February 2018, there were supposed to be a new crack in another side [4]. It is similar to the VSI record that shows an increase volcanic activity in Arjuno Welirang started from early February and getting more in the end of February. At that time, the occurrence of A-type volcanic earthquake used as precursor of an increase volcanic activity due to magma inside the volcano begins to move to upper part of the conduit. VTA was getting more up to 20 events in the end of February. VTB (B-type volcanic earthquake) also recorded more than 20 events. VTB represents that the earthquake is already in the shallow part ranging from the crater surface to several hundred meters in depth. [6]

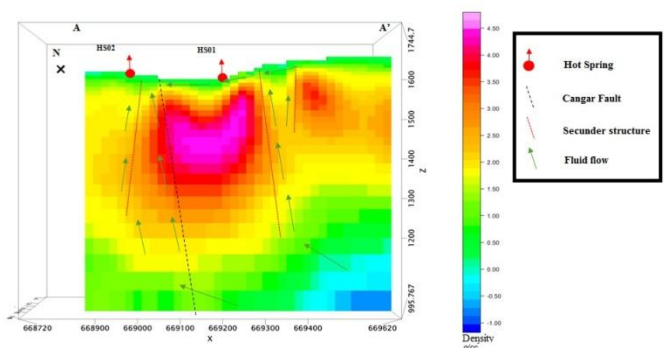


FIGURE 1. Model of hydrothermal system based on non-seismic method (gravity method)

Some geophysical researches had been conducted in Cangar geothermal area to investigate subsurface condition, such as Self Potential (SP), magnetics, gravity, geoelectric, seismic, magnetotelluric, etc [6]. Since this area is volcano hosted geothermal complex, so it is needed to conduct geophysical research continuously especially seismic to monitor Arjuno Welirang volcano activity whether it is related to Cangar hydrothermal activity and volcano hazard mitigation. Less of information about seismic acitivity in this area. Most of the research investigated the geothermal potential and subsurface structure.

IV.CONCLUSION

Positive Lyapunov Exponent values from the calculation by using the attractor diagram in phase space has a range of 0.0154 to 0.0316. This positive LE value provides information that the hydrothermal system at Cangar hot spring is a chaotic system and deterministic. The seismic events in this area perhaps due to the forming of bubbles in degassing process or due to the friction between rocks and hot water when the hot water passing through the fractures or cracks.

V. ACKNOWLEDGEMENT

Authors thank to Brawijaya Volcanology and Geothermal Research Center, Faculty of Mathematics and Natural Sciences University of Brawijaya for partially financially supporting this research and the members of Brawijaya Volcanology and Geothermal Research Center for their help during the data acquisition. This research was also partially funded by Professors and Doctors Research Grants by contract number 25/UN10.F10/PN/2019, University of Brawijaya accordance by Rector Regulation Number 15/2019.

REFERENCES

[1] Geothermal Directorate, *Geothermal Potential in Indonesia*, 1st ed. Jakarta: Geothermal Directorate, Ministry of Energy and Natural Resources, 2017.

[2] A. Wardana, J. O'Sullivan, and M. O'Sullivan, "Natural state and future production modelling of Arjuno-Welirang geothermal field, Indonesia," in *Proceedings 38th New Zealand Geothermal Workshop*, 2016, p. 9.

[3] A. P. Utama, A. Dwinanto, J. Situmorang, M. Hikmi, and R. Irsamukhti, "Green Field Geothermal Systems in Java, Indonesia," in *Proceedings of 1st ITB Geothermal Workshop, Bandung, Indonesia*, 2012.

[4] Sunaryo, "Identification of Arjuno-Welirang Volcano-Geothermal Energy Zone By Means of Density and Susceptibility Contrast Parameters," *Int. J. Civ. Environ. Eng.*, vol. 12, no. 1, pp. 9–20, 2012.

[5] A. Harijoko, H. W. Utama, and S. Husein, "Volcanism and Structural Geology on Geothermal Area of the Arjuno Welirang Volcanic Complex , East Java," in *Proceedings The 5th Indonesia International Geothermal Convention & Exhibition 2017*, 2017, pp. 1–9.

[6] S. Maryanto, "Geo Techno Park Potential at Arjuno-Welirang Volcano Hosted Geothermal Area , Batu , East Java , Indonesia (Multi Geophysical Approach)," in *AIP Conference Proceedings*, 2017, pp. 1–12.

[7] Y. Daud, F. Fahmi, W. A. Nuqramadha, D. M. Heditama, S. A. Pratama, and E. Suhanto, "3-Dimensional Inversion of MT Data over the Arjuno-Welirang Volcanic Geothermal System , East Java (Indonesia)," in *World Geothermal Congress 2015*, 2015, no. l, p. 6.

[8] D. Y. U. Nuha, S. Maryanto, and D. R. Santoso, "Determination of the direction of hot fluid flow in cangar area, arjuno-welirang volcano complex, east java using self potential method," *J. Penelit. Fis. dan Apl.*, vol. 07, no. 02, pp. 123–132, 2017.

[9] F. Rakhmanto, S. Maryanto, and A. Susilo, "Geoelectric Tomography in Cangar Hot Spring, Batu, Arjuno-Welirang Complex," *Nat. B*, vol. 1, no. 2, pp. 188–195, 2011.

[10] R. Rahmawati, S. Maryanto, and A. Susilo, "Identification of Geothermal System in Cangar, East Java Using Magnetotelluric Method," *JPSE (Journal Phys. Sci. Eng.*, vol. 2, no. 2, pp. 72–82, 2017.

[11] V. M. Zobin, "Seismic Signals Associated With Geothermal Activity Within Volcanic Environment," in *Complex Monitoring of Volcanic Activity*, V. Zobin, Ed. New York, USA: Nova Science Publishers, 2013, pp. 171–188.

[12] R. Uluwiyah, S. Maryanto, and Abdurrouf, "Spatio-Temporal Changes on Spectra of Hydrothermal System at Arjuno-Welirang Volcano Complex , Indonesia," *J. Res. Environ. Earth Sci.*, vol. 5, no. 1, pp. 10–15, 2019.

[13] A. L. Liaw and T. V. McEvilly, "Microseisms in geothermal exploration—studies in Grass Valley, Nevada," *Geophysics*, vol. 44, no. 6, pp. 1097–1115, 1979.

[14] H. R. Nicholls and J. S. Rinehart, "Geophysical study of geyser action in Yellowstone National Park," *J. Geophys. Res.*, vol. 72, no. 18, pp. 4651–4663, 1967.

[15] S. Maryanto, "Preliminary investigation of volcano hosted geothermal area at Kasinan-Songgoriti-Cangar, Batu city, based on gravity-seismic methods," *AIP Conf. Proc.*, vol. 2021, pp. 1–6, 2018.

[16] J. Zhang, K. C. Lam, W. J. Yan, H. Gao, and Y. Li, "Time series prediction using Lyapunov exponents in embedding phase space," *Comput. Electr. Eng.*, vol. 30, no. 1, pp. 1–15, 2004.

[17] M. J. Nicholl, S. W. Wheatcraft, S. W. Tyler, and B. Berkowitz, "Is Old Faithful a strange attractor?," *J. Geophys. Res.*, vol. 99, no. B3, pp. 4495–4503, 1994.

[18] F. L. Aderemi and O. I. Popoola, "Computation of Lyapunov Exponent for Characterizing the Dynamics of Earthquake," *Int. J. Recent Adv. Phys.*, vol. 5, no. 3/4, pp. 09–15, 2016.

[19] K. I. Konstantinou and C. H. Lin, "Nonlinear time series analysis of volcanic

tremor events recorded at Sangay volcano, Ecuador," *Pure Appl. Geophys.*, vol. 161, no. 1, pp. 145–163, 2004.

[20] K. I. Konstantinou, C. A. Perwita, S. Maryanto, Surono, A. Budianto, and M. Hendrasto, "Maximal Lyapunov exponent variations of volcanic tremor recorded during explosive and effusive activity at Mt Semeru volcano, Indonesia," *Nonlinear Process. Geophys.*, vol. 20, no. 6, pp. 1137–1145, 2013.

[21] S. Maryanto, D. R. Santosa, I. Mulyana, and M. Hendrasto, "Fractal and Chaos Properties of Explosion Earthquakes Followed by Harmonic Tremor at Semeru Volcano, East Java, Indonesia," *Int. J. Sci. Eng. Res.*, vol. 2, no. 7, pp. 1–7, 2011.

[22] Perwita, C.A. 2013. Analysis of Nonlinear Dynamical Properties of Volcanic Tremor Recorded at Semeru Volcano. Unpublished thesis in partial fulfillment of the requirements for the degree of Master of Science, University of Brawijaya, Malang, Indonesia.

[23] M. T. Rosenstein, J. J. Collins, and C. J. De Luca, "A practical method for calculating largest Lyapunov exponents from small data sets," *Phys. D*, vol. 65, pp. 117–134, 1993.

[24] S. H. Strogatz, *Nonlinear dynamics and chaos: with applications to physics, biology and chemistry*. New York: Perseus Book Publishing, 1994.

[25] G. Boeing, "Visual Analysis of Nonlinear Dynamical Systems: Chaos, Fractals, Self-Similarity and the Limits of Prediction," *Systems*, vol. 4, no. 37, p. 18, 2016.

[26] C. R. Faust and J. W. Mercer, "Theoretical analysis of fluid flow and energy transport in hydrothermal systems," Virginia, 1977.

[27] M. M. Ramazanov, D. A. Alkhasova, and G. M. Abasov, "Flows and heat exchange in a geothermal bed in the process of extraction of a vapor–water mixture from it," *J. Eng. Phys. Thermophys.*, vol. 90, no. 3, pp. 606–614, 2017.

[28] A. K. Houseal, "Facies Model of Hot Springs The Hot Springs Facies Model - Background," 2000.

[29] V. Martadiastuti, A. Harijoko, I. W. Warmada, and K. Yonezu, "Hydrogeochemical Characterization of Geothermal Water in Arjuno-Welirang, East Java, Indonesia," *J. Appl. Geol.*, vol. 2, no. 2, pp. 59–69, 2017.

[30] M. Urquizú and A. M. Correig, "Analysis of seismic dynamical systems," *J. Seismol.*, vol. 2, no. 2, pp. 159–171, 1998.