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Application of Ensemble Empirical Mode Decomposition The Passive Seismic Signals for Identification of Hydrothermal Activity Signals, Case Study: Mt. Lamongan, East Java - Indonesia

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ABSTRACT

Noise reduction process of non-linear and non-stationary signal was done by dividing the data to obtain linear event called IMF (Intrinsic Mode Function). Noise reduction used the Empirical Mode Decomposition (EMD) method. EMD decomposes seismic signals into a number of components of intrinsic oscillation. Each component of the Intrinsic Mode Function (IMF) has varying frequency according to characteristics of the field. The decomposition is based on the assumption that the data is composed of intrinsic oscillation models. Ensemble empirical mode decomposition (EEMD) method was the development of empirical mode decomposition (EMD) developed by Zhaohua Wu and Norden E. Huang (2009), Jiang and Zhang (2010) to eliminate mode mixing in EMD method. The process of noise reduction was applied to microseismic signals in the geothermal field to determine the estimated position of hydrothermal dynamics in the subsurface. Hydrothermal movement in the pore spaces of rocks causes micro oscillations as a secondary source with high pressure and high temperatures. The recorded primary signal comes from nature considered as ambient noise. The movement of hydrothermal signal has a low frequency between 1 Hz to 5 Hz. As a case study, this research was conducted in the geothermal potential area of Mt. Lamongan, East Java. The microseismic portable device developed by GFZ was used; it can recorded a lot of kinds of signal source, for example: hydrothermal, tectonic earthquake, and local noise around the stations. The results of the research were used to plan long-period microseismic acquisition (Broadband).

1. INTRODUCTION

Microseismic or microtremor is one of the passive seismic methods to record vibration derived from natural sources, such as volcanic activity, waves in the beach, meteorology regional condition, urban (human activity), fluid movement, etc. Microseismic method is used for exploration of development areas in hydrocarbon, geothermal, mining, and geothecnical. The presence of a geothermal system can be identified based on the frequency range from fluid dynamic (hydrothermal) in the pore space of rocks. Hydrothermal movement in the pore space is caused by pressure. The pressure comes from natural pressure in the subsurface or injection activity by injection well in the geothermal exploitation. Natural pressure due to high temperature leasd to increased pore pressure.

Noise is a term used to indicate the ambient vibration of the ground caused by natural sources such as tide, sea water waves on the beach, wind turbulence, wind effects on trees or buildings, industrial machinery, automobiles, trains, traces of human or animal, and so forth. Low frequencies (<1 Hz) are derived from natural ocean and meteorological conditions or large global scale. Intermediate frequencies (1 to 5 Hz) are sourced from local meteorological conditions and urban scales and higher frequencies are associated with the originating natural source e.g. Bonefoy-Clauded (2006). Hydrothermal oscillations in the rock pore spaces due to high pressures and high temperatures have low frequencies <5 Hz. Event duration time is shorter than tectonic events. The time delay between the P and S waves are less than 10 second. It is sometimes very difficult to determine the arrival time of P wave and S wave because the phase difference is not clear.

The spectrum (vertical component) in the reservoir is stronger than in non-reservoir area, e.g. Sanger (2009). To determine the presence of hydrothermal dynamics based on microseismic signals, an anthropogenic noise reduction process becomes very important. Anthropogenic noise is a signal that comes from volcanic activity, urban, waves, meteorology, and storms e.g. Bonnefory-Claudet (2006). The method to separate the desired signal with unwanted signals is Ensemble Empirical Mode Decomposition (EEMD). The EEMD method is a development of Empirical Mode Decomposition (EMD) method by Zhaohua Wu and Norden E. Huang (2009), Jiang and Zhang (2010) to eliminate the mixing mode.

Most of the population in Indonesia is in Java island. The challenge for microseismic acquisition is coherent noise with cultural noise (human activity). The small event or hydrothermal event in the microseismic signal will be difficult to analyse in cases where it has low frequency. Noise reduction of the microseismic signal is very important especially for the station in and around the culture area. In this study, a microseismic portable was used in a preliminary study before microseismic broadband acquisition to determine the possible area for acquisition. The objective was to determine the best location according to signal recording from a preliminary study of microseismic using the portable instrumentation in the short time period. The microseismic portable (DSS Cube) developed by GFZ Helmholtz Center, ICGR, Potsdam, Germany. DSS Cube is a stand-alone 1-channel digital data recorder. The DSS Cube connects to geophone (3 components) with frequency 4.5 Hz. Hydrothermal signal monitoring was installed in the geothermal potential area of Mt. Lamongan, East Java. The five equipment stations around Mt. Lamongan recorded over 4 days, on May 2011. Most of the area is made up of villages and has high urban activity. It will be difficult to look for the hydrothermal signal in the low frequency. EEMDwas applied to determine and determinate the signal characteristic prior to installation of Microseismic broadband sensors.

2. GEOTHERMAL POTENTIAL OF MT. LAMONGAN

Tectonic activity can lead to deformation of rocks (fault, fold, and strike slip). In the volcanic area, the igneous rocks (low porosity and low permeability) can be a good geothermal reservoir while having the fault structure. The fault structure causes the igneous rock to be crushed, then consequently its porosity and permeability is increased. Through the cracks or the fractures thermal fluid (gas and water) move up to the surface of the earth, resulting in geothermal manifestations. In Mt. Lamongan, East Java – Indonesia, there are 2 main faults. Hot water manifestations in the geothermal area appear at the surface caused by main fault in the system. The location of hot springs is between Mt. Lamongan and Mt. Argopuro. The Mt. Lamongan geothermal area have 27 maars, 13 of the maars contain water and, 14 maars are dry. There are a lot of cynder cone or parasite cone in the north part and west part of the mountain. The maars and cynder cones provide evidence of the availability of hydrothermal resources in this area.

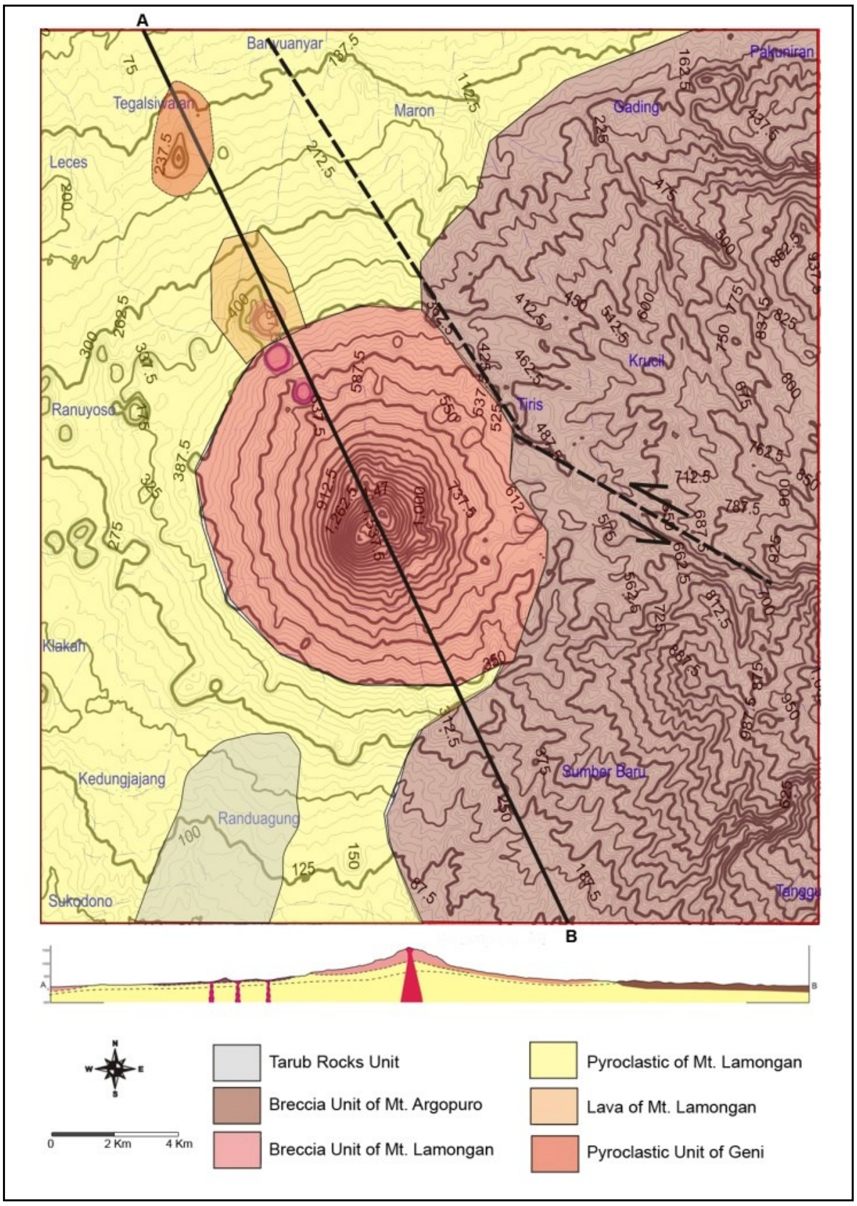


Figure 1: Geological Map of Mt. Lamongan, East Java - Indonesia.

Hot spring discharge is due to the fault structure between Mt. Lamongan and Mt. Argopuro, between breccia of Mt. Agopuro and breccia unit of Mt. Lamongan. The breccia of Mt. Lamongan contains andesite and lava (product of Mt. Lamongan) in the tuff as matrix (coarse grain size), the colour of the Lamongan breccia is grey. The breccia of Mt. Argopuro is exposed in graded bedding with andesite and basalt as fragments in the tuff coarse grain size as the matrix of this rock unit. Members of Geni rock unit are lapilli, tuff, and breccia in holocene periode e.g. Suharsono and Suwarti (1987).

Geothermal manifestations rise through fractures in the andesite breccia rock. The hot springs have temperature range between 37°C to 42°C and the pH range starts from 6.44 to 6.37. Hydro-geochemical studies indicate that 5 hot springs are bicarbonate water or outflow of geothermal system in this area, e.g. Widya Utama (2012). The combination of petrology and geochemistry studies suggest: 1) the relation between sea water and the origin of warm springs; and 2) the existence of a concealed layer responsible for capturing H_2S gas which in turn, accounts for the observed HCO_3 excess of the springs, e.g. Makky Jaya (2013).

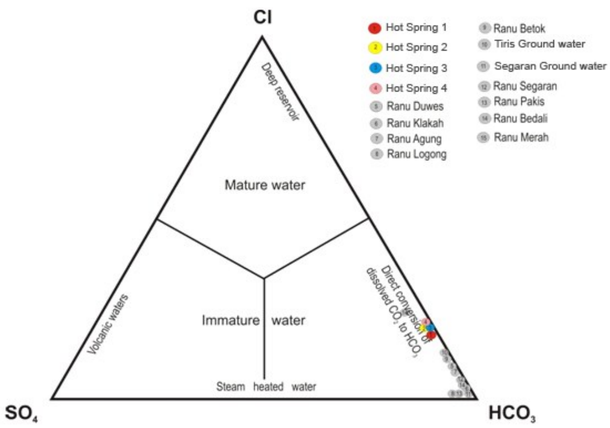


Figure 2: Piper diagram of water samples in the Mt. Lamongan Geothermal Area e.q Widya Utama (2010).

Ranu is the local name of maars around the location. All the water samples are in the bicarbonate category. There is mixing between ground water with hot spring at the location. The water in the maar comes from meteroric water, there is no indication if the water came from ground water according the geochemical analysis and is not connected with the heat source of geothermal system e.g. Widya Utama (2010).

3. ENSEMBLE EMPIRICAL MODE DECOMPOSITION

Random noise reduction is most important for seismic data processing, interpretation, and inversion. Recorded seismic data generally includes secondary signals (which is expected) and noise (the primary source from nature) described by the equation :

$$x(t) = s(t) + n(t) \tag{1}$$

$x(t)$, $s(t)$, and $n(t)$are the recorded signal, the expected signal and noise, all the signal in time domain (t). The noise reduction process to obtain the desired signal is very important in this study. In this study, the EEMD method (Enssemble Empirical Mode Decomposition) was used to reduce noise in the signal data of microseismic.

EMD decomposes the seismic or microseismic signal into some oscillatory components called Instrinsic Mode Function (IMF). Each componen of the IMF has different frequency. The decomposition assumes that the data consist of intrinsic oscillations of various modes. The intrinsic mode (linear or non-linear) will have the same number of extrema, and will be symmetrical against the local average. EMD can not overcome the problems caused by the mixing mode signal interruption, e.g. Huang et al. (2009). To solve this problem, e.q. Huang et al. (2009) superposed the signal with added white noise to avoid mixing mode. This process is known as the Ensemble Empirical Mode Decomposition (EEMD) method.

EEMD method can be described by simple mathematical equations (equation 2). Based on Zhaohua Wu and Norden E. Huang (2009), the steps start analysis with the addition of white noise $w(t)$ in the time domain. White noise $w(t)$ is the random number with zero mean, and standard deviation of a single variant. Here are the steps of the EEMD method :

1. Addition of white noise $w(t)$ to signal.

   $$X(t) = x(t) + w(t)R \tag{2}$$

   R is a standart deviation parameter between amplitude noise added to the data $x(t)$.

2. Data decomposition with addition of white noise to the n component of the IMF. EEMD applied to $X(t)$ to decompose the data $x(t)$ to produce several intrinsic mode function (IMF) start from c_1 until c_n.

3. Repeat step 1 and 2 with addition of white noise $w_j(t)$ to signal $x(t)$, but with different white noise series each time. The process will be stopped when the value of the standard deviation value SD_k is smaller than the limit set by interpreter.

   $$SD_k = \sum_{i=0}^{T} \left[\frac{\left| h_{1(k-1)}(t) - h_{1k}(t) \right|^2}{h_{1(k-1)}(t)^2} \right] \tag{3}$$

4. Obtain the (ensemble) means of correspoinding IMFs of the decompositions as the final result.

   $$c_i = \frac{1}{N} \sum_{j=1}^{N} c_{ij} \tag{4}$$

   $$r_n = \frac{1}{N} \sum_{j=1}^{N} r_{jn} \qquad 5)$$

R value (standard deviation) and N (ensemble number for EEMD) value depend on the interpreter. Wu and Chang (2009) recommend 0.2 for R and a few hundred for N value, for good results in some case. Jeng and Chen (2011) used 0.1 for amplitude noise R and 50 for N value, applied to the GPR and seismic signals, due to the high frequency content of the data and a large amount of data. Jeng (2007) applied 0.5 for R and 100 for N for VLF data processing, a process dominated by low frequency signals.

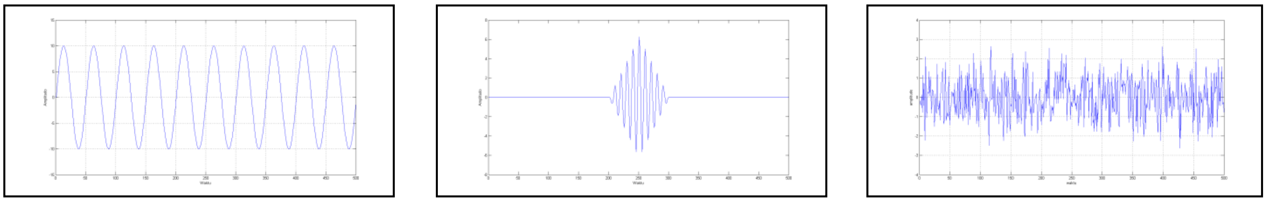
4. DATA SIMULATION

Determining the values of R (standard deviation) and N (ensemble number for EEMD) is very important, according to the type of data. Before applying the EEMD method to microseimic data, a process of simulating data using simple synthetic signal and addition of the synthetic noise signal was used. For synthetic noise signal, we tried using event signal and random noise signal. The event signal is like a spike signal from aurocorrelation of a simple wave equation (sinusoid wave) to know the parameter for smallest signal and the random noise signal to show if the parameter can work for quite noise or high frequency. The synthetic main signal is following :

$$S_1 = 10\sin(2\pi t) \tag{6}$$

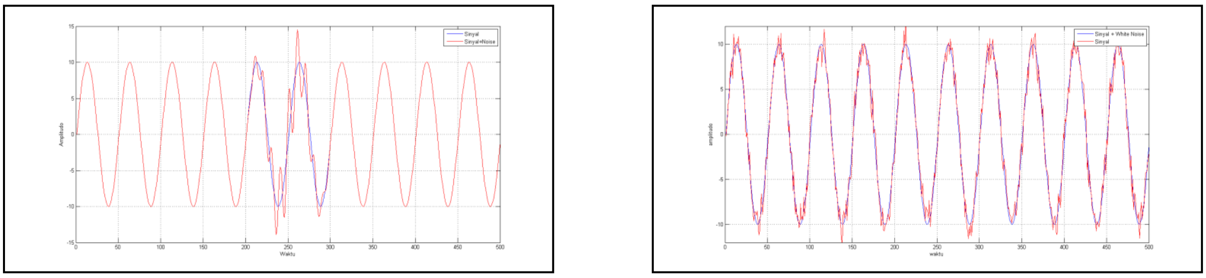
Futhermore, synthetic noise signal (event or spike signal) is autocorrelation of equation 7, it is following :

$$S_2 = 0.5\sin(2\pi t) \tag{7}$$



(a) (b) (c)

Figure 3: (a) Synthetic signal of S_1, (b) Synthetic noise signal (eq. 7), (c) Synthetic noise signal using random noise.



(a) (b)

Figure 4: (a) Mixing signal between Synthetic signal (S_1) and S_2 (eq. 7), (b) Mixing signal between Synthetic signal (S_1) and random noise.

According signal data $x(t)$ illustrated by equation 1, S_1 as $s(t)$ and S_2as $n(t)$. For the simulation, we tried N values of 10, 50, 75, and 100 and for R, we tried 0.1, 0.5, and 0.75. The result when it worked with S_2 as noise is shown in figure 5.

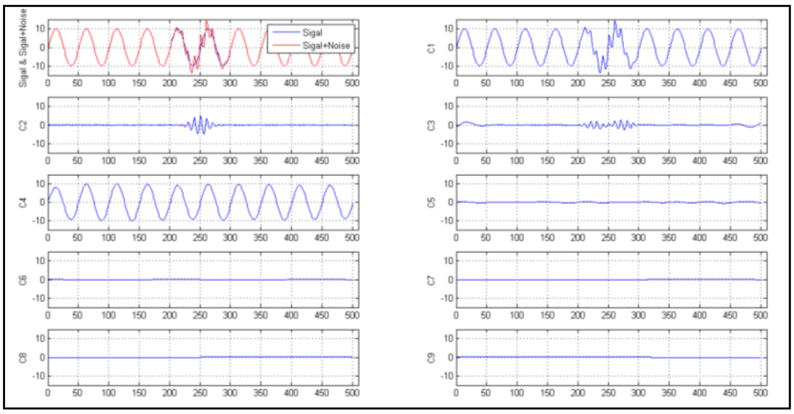


Figure 5: EEMD Simulation using a simple wave signal with parameter value of R = 0.75 and N = 100.

Optimal result from the simulation using S_2 as noise occurred while using parameter R = 0.75 and the value of N = 100. The main signal (S_1) filtered from the noise at IMF-4th of *C4* (4th Component), in figure 4). To clarify the parameters suitable for the EEMD applied to microseismic data, we tried other characteristic noise. We tried using random noise to add to main noise (S_1), equation 6. And also, the main signal S_1 combined with S_2 and random noise to make sure about the parameter and the IMF value of the process.

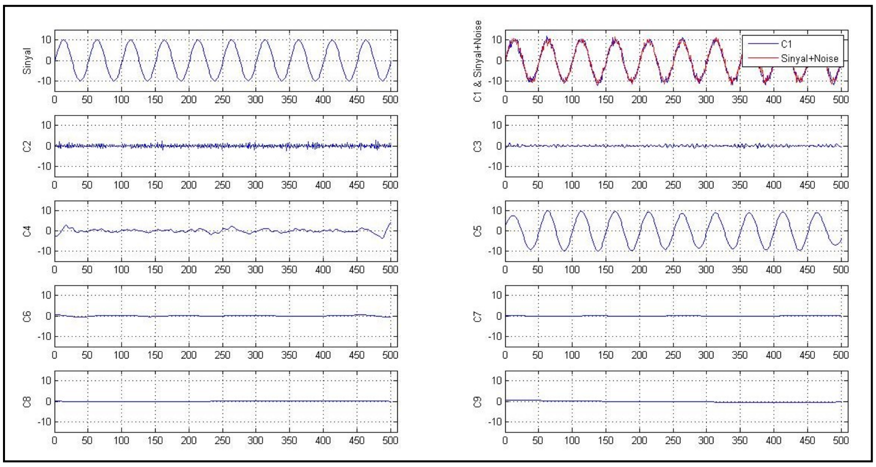


Figure 6: EEMD Simulation using applied for combination signal between $S_1$and random noise with value of *R* = 0.75 and *N* = 100.

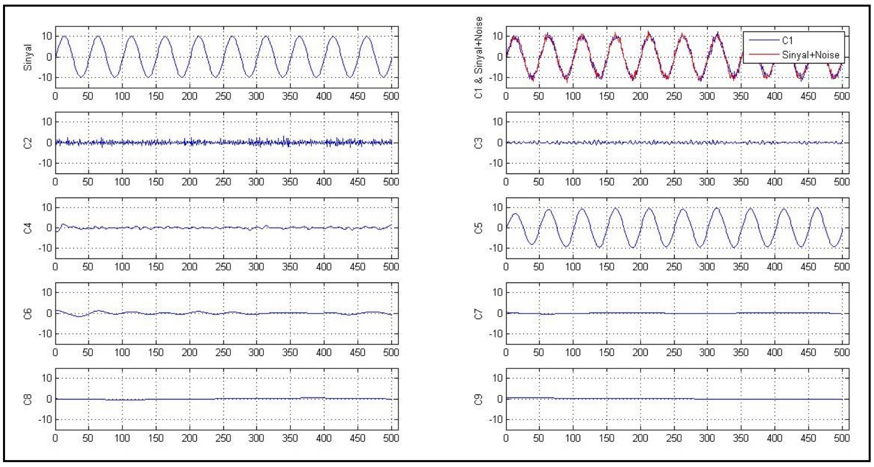


Figure 7: EEMD Simulation using applied for combination signal between S_1, S_2, and random noise with value of *R* = 0.75 and *N* = 100.

Figure 6 and 7 show the result of the EEMD process. They have the same IMF value when the parameter value of *R* and *N* are 0.75 and 100. The signal becomes normal at 5th IMF but it looks different between both of them. At the signal, the addition of random noise and noise (S_2), 5th IMF (fig. 7) approach the main signal as input data. Thus, the parameters R and N used in the noise reduction process are 0.75 and 100. The data to be used hydrothermal events are determined to be the 5th IMF for this simulation. Data used in this study are only the Z component of the signal that can describe the existence of a dynamic event hydrothermal in the subsurface. To determine the IMF value from the process, the signal will be have less noise than previous IMF.

5. ANALYSIS AND DISCUSSION

The signal data (vertical component) from the microseismic portable data were recorded over 24 hours in 4 days. The 5 stations were installed around Mt. Lamongan (figure 8). Recording data performed simultaneously to record movement or vibration of hydrothermal activity in the subsurface. Most of the stations were close to houses, within 1 km to 10 m. The application of EEMD will show the effectiveness to reduce the coherent noise between cultural noise and event of hydrothermal. Noise reduction process used the EEMD method to obtain secondary events derived from hydrothermal vibration in the pore space of rocks in the subsurface. The primary sources are regional earthquake, volcanic activity, the sea waves, and cultural noise. EEMD can show the small event that indicates the hydrothermal activity. EEMD can reduce the high cultural noise around the station.

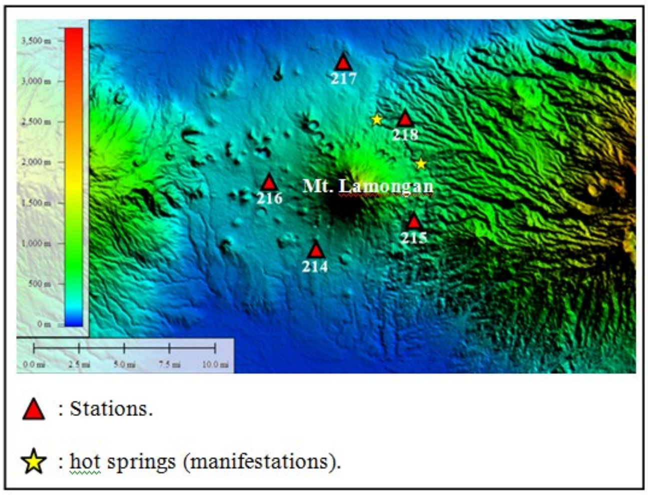


Figure 8: Microseismic portable station installation around Mt. Lamongan.

The EEMD process extracts the input signal data to 16 signals or 16 IMFs (figure 9). 1st IMF or 1st component in the EEMD process is an input data. 2nd IMF to 16th IMF is based on decomposition of the input data. The microseismic event due to micro vibration (small frequency) began to appear in the decomposition process on the 4th IMF until 6th IMF free from anthropogenic noise. The signals have been filtered from noise based on the changing of the phase between previous and next IMF. The chosen signal from EEMD process of the last IMF value before the signal has big changes of phase value.

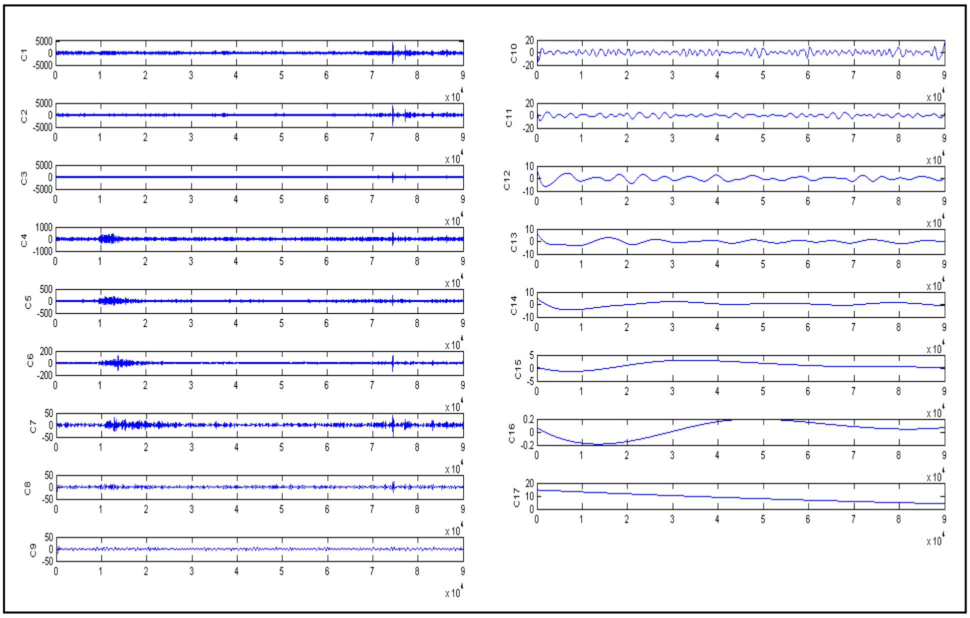
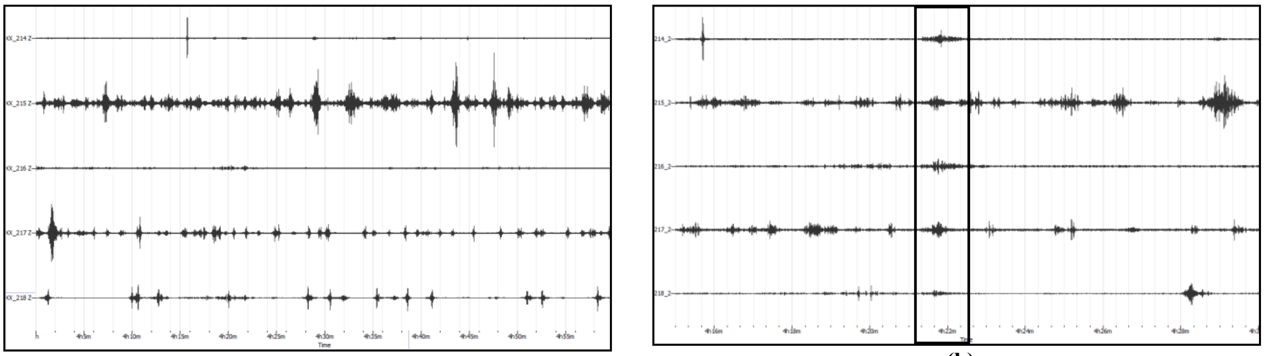


Figure 8: EEMD process decompose the input signal (C1) to IMF components.

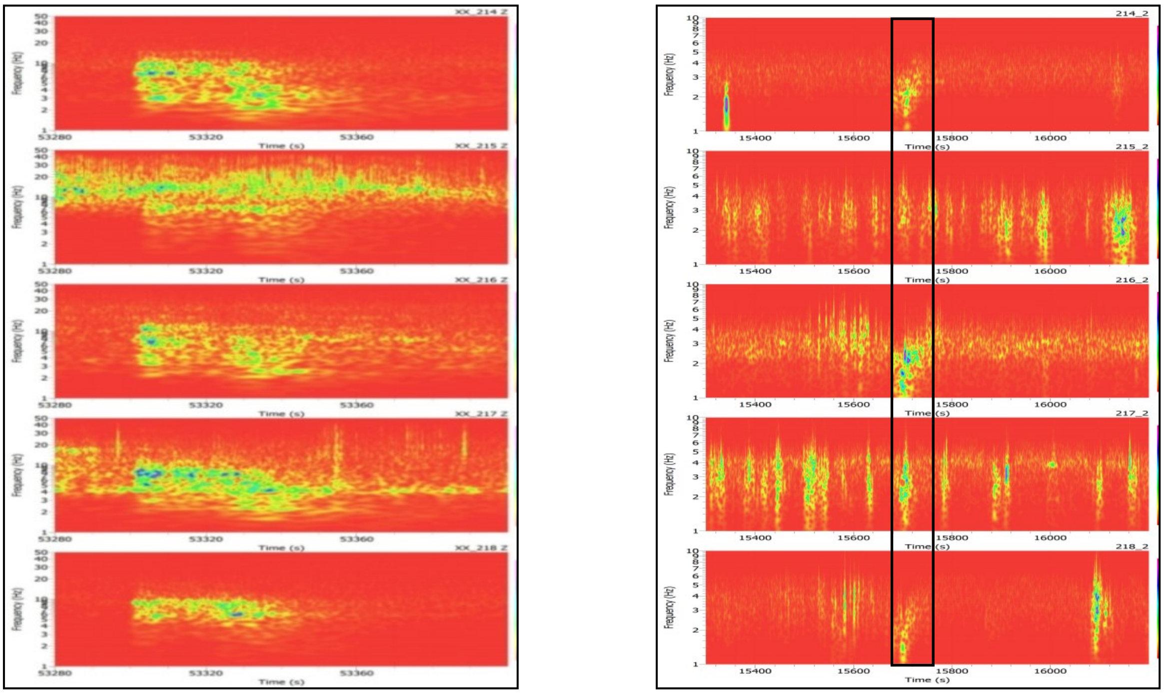
Phase changes happen in the 7th components of IMF. In this case, the signal that has been declared free of the noise are the signal 5th component (C5) or 6th (C6). The 17th component is the residue of the signal decomposition process using EEMD. Signal characteristics from hydrothermal activity have long time duration propagation, and amplitude changes are not significant, so it is difficult to determine S-wave and P-wave arrival time. It is one of the challenges of microseismic processing data. The similarity of time events can be assumed that the tremor originated from fluid (hydrothermal) movement. Another thing that supports that tremor originated from hydrothermal dynamics is the result of amplitude spectrum analysis.



(a) (b)

Figure 9: (a) Raw data of microseismic signal (b) After noise reduction process using EEMD method.

Figure 9 (a) shows the raw data of the microseismic signal. The second station (Station ID : 215) data have a lot more noise than the other station. And also, the station have biggest amplitude compared to the other station. After the signal was processed using EEMD, the small event from hydrothermal activity can shown clearly (figure 9 (b)). Each station has delay time of P-wave around 0.3 to 0.5 second. It caused the distance between the station and the geological condition in the subsurface. The microseismic event has succesive signal type. The impulse signal has very sharp peaks with very short propagation time. While the successive signals have wave propagation travel time longer than the impulse signals.



(a) (b)

Figure 10: Amplitude Spectrum of signal (a) Regional earthquake event (b) Hydrothermal activity event.

During the acquisition, there were 5 regional earthquake recorded by equipment around Indonesia. One of the regional earthquakes happened 2.000 km the north east of the research area with 5.4 magnitude and the epicenter 16 km below sea level. Figure 10 shows the differences between regional earthquake event and hydrothermal event. The regional earthquake was in the frequency range 9.51 to 12.93 Hz based on recorded signal at the research location, shown in figure 10 (a). Figure 10 (b) shows the amplitude specture of the small event of hydrothermal event, the ranges of frequency are 1.66 to 4.85 Hz on below 5 Hz. In 4 days, there were 15 events recorded by the DSS Cube microseismic portable device. It can be called the event if at least 2 station of microsesimic record the signal with the same characteristic of frequency at the same time.

Table 1 : Cumulative event recording data acquisition of microseismic in Mt. Lamongan geothermal prospect area.

Date	P-wave Time Arrival (GMT +7)	Frequency (Hz)				
		Station 214	Station 215	Station 216	Station 217	Station 218
9th May 2011	08:57:43	2.87	2.65	3.21	3.11	3.41
10th May 2011	04:21:15	2.82	3.03	3.30	4.85	1.54
	06:01:33	1.66	2.44	2.38	2.35	1.51
	08:03:49	-	-	2.53	2.38	3.18
	08:10:37	-	2.11	2.59	2.27	2.06
	09:09:31	4.20	4.35	-	4.05	3.98
	10:23:53	-	-	2.44	3.68	2.79
	14:36:05	2.44	-	2.24	2.56	2.50
	15:33:56	2.16	2.19	2.89	1.89	2.04
11th May 2011	07:58:03	2.76	2.56	2.68	2.10	2.55
	08:28:33	3.23	3.09	2.98	2.87	2.78
	17:17:45	2.22	2.13	2.42	2.40	2.32
12th May 2014	02:24:13	3.98	3.54	4.12	3.01	3.16
	16:35:57	2.12	-	1.54	2.29	2.34
	23:20:44	3.11	3.23	3.33	3.65	2.95

The most active areas are in the north and west of Mt. Lamongan or around station 216, 217, and 218 which recorded more intensity than other station. Stations 218 and 217 recorded much more than other stations as they are close to manifestations. Most of the cynder cone and maars give more tremor than the east and north sides of Mt. Lamongan. It can be interpreted if the estimation of hydrothermal activity for this area is caused by the manifestation and parasite cones. Thus, the suggested areas to install the broadband sensor of microseismic equipment are in the North, West, and near the manifestation. The western and northern areas of Mt. Lamongan would be to monitor some parasite cones and maars. For the east side of this area would be to monitor fluid around the manifestation and the fault activity. The sensors place must in the best spot, far away from roads or highways because it can lead to more noise.

6. CONCLUSION

The preliminary study of microseismic acquisition can be applied to know the signal characteristics around the survey location. The characteristic signal can show where is the most activity of low frequency events and to help make acquisition designs correlate with noise source location. The long period recording will be have more sensitive range of frequency and it should be recorded properly. EEMD method (Ensemble empirical mode decomposition) is a noise reduction method that works by dividing the original signal into several IMF components. This method was used for noise reduction on the microseismic signal recording to obtain estimated signal from the reservoir. The EEMD method was applied for noise reduction in the preliminary study of microseismic broadbang acquisition in the Mr. Lamongan area. The preliminary study installed 5 station of microseismic portable (DSS Cube) developed by GFZ Germany. The low frequency events are difficult to intepret from the raw signals because the noise signal is very strong and coherent with the event. The microseismic natural event could come from hydrothermal activity, fault activity, mountain tremor activity, and regional earthquake activity. To extract the hydrothermal activity with low frequency characteristic, the EEMD method can be used to reduce higher event based on ranges of frequency. In this study, the hydrothermal activity is working in frequency ranges 1.66 to 4.85 Hz or below 5 Hz. The most active areas were in the west, north, and around the manifestation. In the western and northern of Mt. Lamongan, the microseismic event could be interpreted as coming from the parasite cone.

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