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**Gliding and Quasi-harmonic Tremor Behaviour of Raung Volcano:
November 2014 Crisis Period Case Study**

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Abstract - The seismic activity of Raung Volcano was raised on 11 November 2014. As many as 1709 tremors were recorded followed by continuous tremors appearing in late November 2014. Quasi-harmonic and gliding tremors appeared in a spectrogram on 12 November 2014. The quasi-harmonic tremors refer to tremors that have no fully harmonic form in spectrum. The gliding harmonic tremors refer to harmonic tremors that have frequency jumps with either positive or negative increment. After signal restitution processing, the Maximum Entropy Spectral Analysis (MESA) method was applied in Raung recordings resulting the spectrum and the spectrogram of tremors. The quasi-harmonic tremors have the monotonic spectrum in its head and centre segment, and the harmonic one in its tails. There are twenty-four spectrums that show frequency changes between the monotonic and harmonic. The similarity between the fundamental frequency range of the monotonic and harmonic ones suggests that both signals are excited from a common resonator. The alternating of monotonic and harmonic respectively over this period is qualitatively similar with Julian's synthetic time series about the nonlinear oscillator model. It is suggested that Raung Volcano magma pressure is sizeable to make a chaotic vibration. A pressure increasing in Raung magmatic conduit causes the increasing of P-wave velocity and makes a positive gliding frequency.

Keywords: MESA, harmonic, monotonic, nonlinear oscillator model, chaotic vibration

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INTRODUCTION

Raung is a basaltic-andesitic volcano with strombolian-type eruptive activity located in East Java, Indonesia (Figure 1). The first eruption of Raung Volcano was recorded in 1586. Raung has erupted at least fifty-seven times since its earliest recorded eruption. Most eruptions consisted of moderate size explosions (VEI=2). The explosive eruption in 1593 was very large (VEI=5) and caused

fatalities. Paroxysmal eruptions occurred in 1586, 1597, and 1638 killing a lot of people in surrounding villages (PVMBG, 2011). Its strato-volcano summit is truncated by a dramatic steep-walled, a two-km-wide caldera where it always emits gas and often fountain fire. Its caldera has been the site of frequent historical eruptions. Raung is one of the most active volcanoes in the island of Java. The last eruption of Raung occurred in July 2015 after a crisis period that began on 11 November 2014.

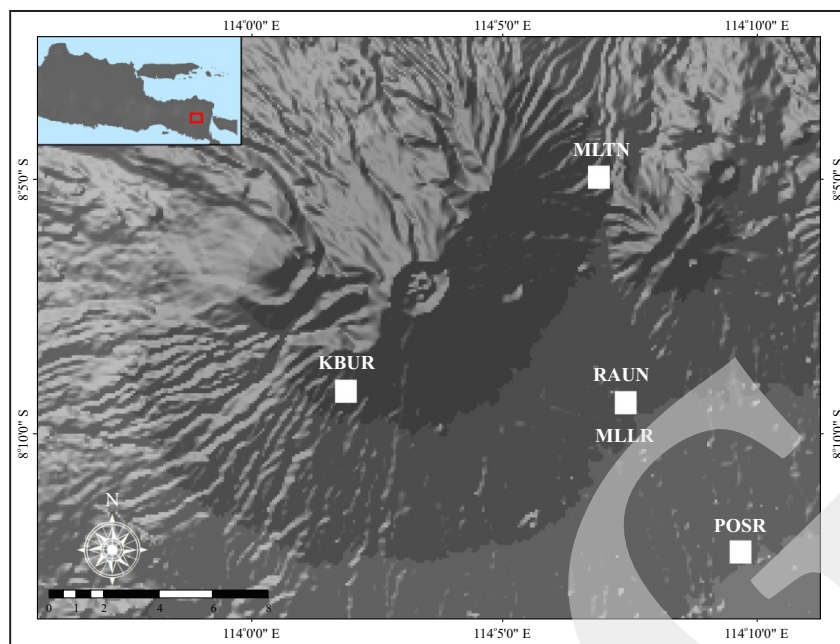


Figure 1. Locations of Raung Volcano and the seismic stations used in this study. White solid squares denote seismic stations.

Tremors appeared on a seismogram at the beginning of the crisis period started at 21 h 9 m 00 s on 11 November 2014. The alert level at Raung Volcano was raised to level II (Waspada) on 13 November 2014 after an increase in its seismic activity. On November 2014, as many as 1709 tremors were recorded followed by continuous tremors appearing in late November 2014. Besides that, harmonic tremors also appeared on November 2014. As many as 27 harmonic tremors appeared on 12 November, twice on 18 November, and three times on 19 November, respectively.

The tremor is one of the volcano earthquake types that occurs near an active volcano and has a long duration started from minutes, hours, to days. In the domain frequency, the harmonic tremors have peak frequencies distributed regularly into even multiples or odd multiples.

Quasi-harmonic and gliding tremors appeared in a spectrogram on 12 November 2014. The quasi-harmonic tremors refer to those that have no fully harmonic form in spectrum. The gliding harmonic tremors refer to those that have frequency jumps with either positive or negative increments (Lessage *et al.*, 2006).

Quasi-harmonic type tremors were reported by Bertin *et al.* (2015) at Cordón Caulle Volcano,

Chili, and by Lees *et al.* (2008) at Reventador Volcano, Ecuador, whereas gliding behaviour in harmonic tremors were notified at Soufrie're Hills Volcano (Jousset *et al.*, 2002), Reventador Volcano (Lees *et al.*, 2008), Arenal Volcano (Lessage *et al.*, 2006), and Redoubt Volcano (Hotovec *et al.*, 2013). The Raung gliding harmonic tremors tend toward the positive gliding type. It means that the frequency jump has the positive increment.

In this paper, a spectral analysis of Raung Volcano tremors is presented, especially the spectral of gliding and quasi-harmonic behaviours. The Maximum Entropy Spectral Analysis (MESA) method was applied to the signal of tremors in order to know both the gliding and quasi-harmonic characteristics. An interpretation was made from these observations for possible causes for gliding and quasi-harmonic behaviours.

METHODS AND MATERIALS

Signal Restitution

Signal restitution was applied to Raung time series for diminishing instrument effect. A seismometer can be considered as a seismic signal

filter. The relationship between input and output seismic signals in the seismometer system can be written in the frequency domain as follows:

$$O(\omega) = T(\omega)I(\omega) \dots\dots\dots(1)$$

where $I(\omega)$ is seismic input signal, $O(\omega)$ is recorded signal (output), and $T(\omega)$ is frequency response function. Thus, the original signal or input can be obtained as:

$$I(\omega) = \frac{O(\omega)}{T(\omega)} \dots\dots\dots(2)$$

The frequency response function can be written in *poles* and *zero* terms (Havskov and Alguacil, 2010):

$$T(\omega) = Y \frac{(i\omega - z_1)(i\omega - z_2)(i\omega - z_3)}{(i\omega - p_1)(i\omega - p_2)(i\omega - p_3)} \dots\dots\dots(3)$$

with p is poles, z is zero, and Y is normalization constant. The poles and zero can usually be found on the instrument manual.

Maximum Entropy Spectral Analysis Method

The MESA method is used to analyze restituted tremor data, and Maximum Entropy Time-Frequency Analysis is used to analyze the tremor spectrogram.

The entropy concept relates to the uncertainty and randomness of a system transmitting information. Entropy H can be written as (Wu, 1997):

$$H = - \int_{-\infty}^{\infty} p(x) \log p(x) dx \dots\dots\dots(4)$$

where $p(\chi)$ denotes the probability density function of time series χ , \int denotes an infinitely dimensional integral, and the integral limits are $-\infty$ to $+\infty$. The derived expression of (4) in the frequency domain is:

$$H = \int \log S(f) df \dots\dots\dots(5)$$

where $S(f)$ denotes the power spectrum density of the time series, f denotes frequency and integral in the whole frequency band. The problem to be solved in (5) is constrained maximization: The quantity to be maximized is the entropy H , and the constraints come from the given partial time series or its autocorrelation function. Usually, this problem is solved using the Lagrange multiplier method. Here, the formula is only presented concerning the explicit solution (Wu, 1997):

$$S(f) = \frac{P_M}{\left| \sum_{k=0}^M a_k \exp(-2\pi i f k) \right|^2} \dots\dots\dots(6)$$

where $i = \sqrt{-1}$, P_M is the power of prediction error, and a_k are the coefficients of the prediction-error filter with $a_0 = 1$. The MESA analysis can be used to estimate power spectra with sharp peaks from short data records.

The principle of Maximum Entropy Time-Frequency Analysis method is the same as the Short Time Fourier Transform (STFT) that divides a signal in time domain to shorter parts, and then analyzes those parts separately, not with the Fourier Transformation, but the MESA method instead. The output of the method is a maximum entropy spectrogram.

Seismic Recordings

Seismic recordings were obtained from the Centre for Volcanology and Geological Hazard Mitigation (CVGHM) seismic stations at the Raung Volcano. CVGHM operates five seismometers at Raung, but only four were available and used in this study. They are the KBUR (located 4 km from the summit crater), MLLR (6 km away), RAUN (6 km away), and POSR (14 km away). The seismometer of MLTN (6 km away) was damaged. The recordings from KBUR were used as the main data for interpreting gliding harmonic tremors, because KBUR recordings

were the clearest ones among the others (Figure 2). Recordings from MLLR, RAUN, and POSR stations were used as comparison data only to distinguish a noise and a signal. Furthermore, the POSR recordings can be used to distinguish a volcanic and a tectonic earthquake. The 1-component L4C seismometers have been installed in KBUR, RAUN, and POSR, whereas the 3-component L22D seismometer has been installed in MLLR.

RESULTS AND DISCUSSION

Raung Tremor Spectral with the MESA Method

The seismo-volcano analysis, interactive Matlab software by Lessage *et al.* (2006) was used for signal restitution and then spectral analyses. Either for spectral or for spectrogram analysis, the MESA method was used with forty numbers of poles. The lengths of windows on the spectrogram analysis were 10.24 s with a 50% overlap. Figures 3a and 3b show that the tremor signal and spectrogram were obtained from 00

h 00 m 00 s to 00 h 40 m 00 s on 12 November 2014. Figure 3c shows the spectrum with the time windows of 50 s shifted by 50 s. For 40 minutes recording, there are twenty-four spectrums that show frequency changes. The harmonic spectrum has a fundamental frequency of 1.5 to 2.2 Hz in range, and the monotonic spectrum also has the dominant frequency of 1.5 to 2.2 Hz. The harmonic and monotonic signal are suggested to be excited from a common resonator, because the similarity of those fundamental frequency. The monotonic tremors are characterized by a pronounced spectral peak and absence of frequency overtones as depicted in 4th, 5th, 11th, 12th, 16th, 17th, 18th, and 24th spectrums in Figure 3c. The 1st, 2nd, 6th, 13th, and 19th spectrums are the harmonic one.

The consistency of Raung tremors to exhibit gliding and quasi-harmonic behaviours continuously are shown in a three-hour spectrogram at 20 h 00 m 00 s to 22 h 00 m 00 s on 12 November 2014 (Figure 4). Furthermore, the Raung spectrum was analyzed separately for four tremor segments; head, centre, early tails, and late tails.

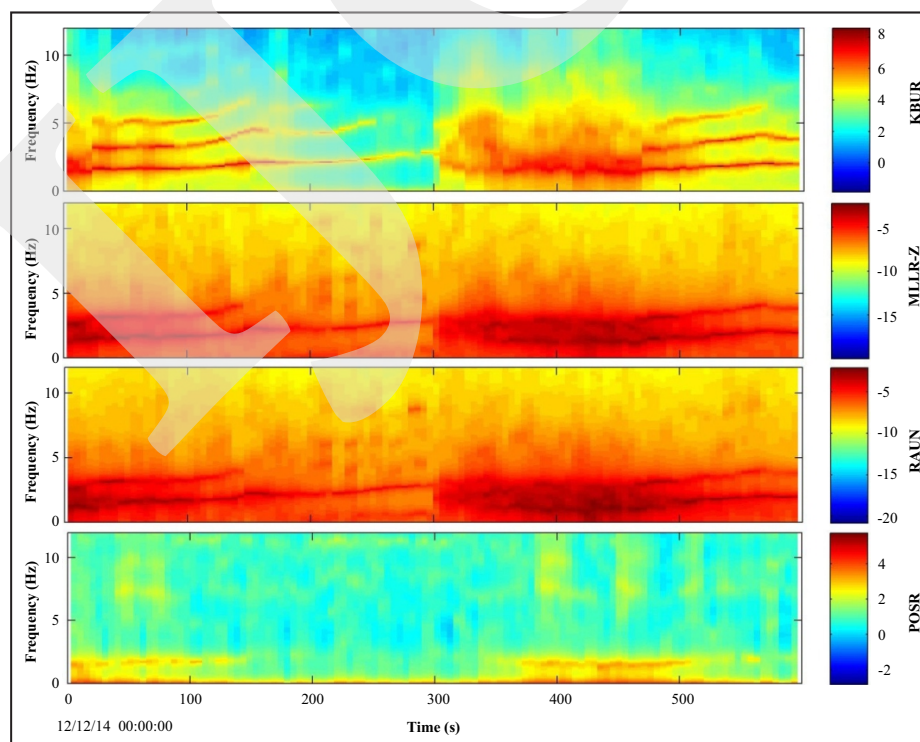


Figure 2. Comparison of spectrograms form Raung seismic stations. KBUR spectrogram appears clearer than the others. The harmonic tremors in KBUR also have more tails compared to the others.

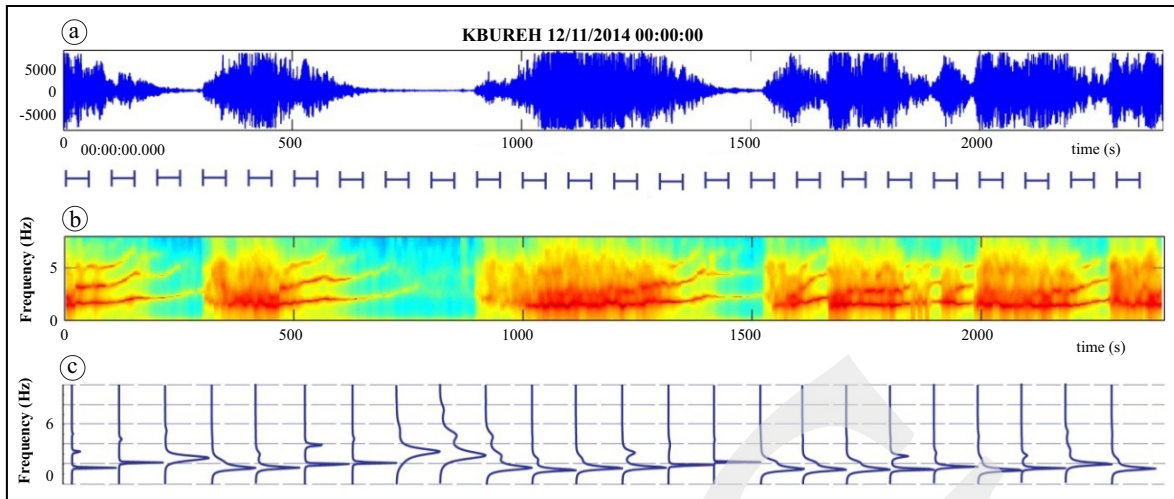


Figure 3. (a) Tremor signals of KBUR from 00 h 00 m 00 s over 40 minutes or 2400 s in 12 November 2014, (b) spectrogram from the same recordings in Figure 3a, (c) a number of tremor spectrums with the time of windows 50 s shifted by 50 s started from 00 h 00 m 00 s over 40 minutes.

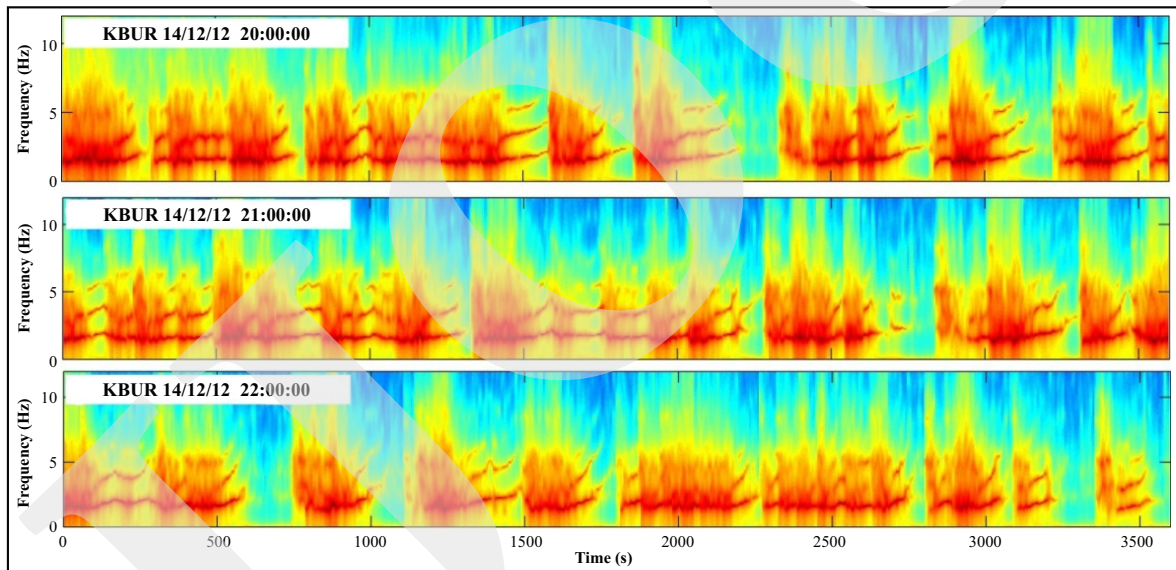


Figure 4. Spectrograms on 12 November 2014 over 3 hours starting from 20 h 00 m 00 s to 22 h 00 m 00 s. The spectrograms show consistent gliding and quasi-harmonic behaviours over those periods. The spectral form of the vibrations abruptly changes and alternates between monotonic and harmonic vibrations.

The results are shown in Figure 5. Either the head or the centre segment shows similar spectrum, but the early and late tails show different values on the harmonic frequency peaks. The frequency peaks of late tails are higher than early tail tremors. A positive gliding occurred in Raung tremor tails.

Harmonic tremors of the 2014 crisis period mostly appeared on November 2014. The uniqueness of harmonic tremors can be seen

after time-frequency spectrogram analyzes. This spectrogram shows that the tremor is harmonic in its tails. In other segments, these are not harmonic ones (Figure 5). Thus, the tremor is not fully harmonics. Therefore, if a tremor is completely analyzed, the spectral could not show clearly that the tremor is a harmonic one. It is because the one is a compound of harmonic and nonharmonic tremors. Thus, it is called the quasi-harmonic tremors. This phenomenon also happens in other

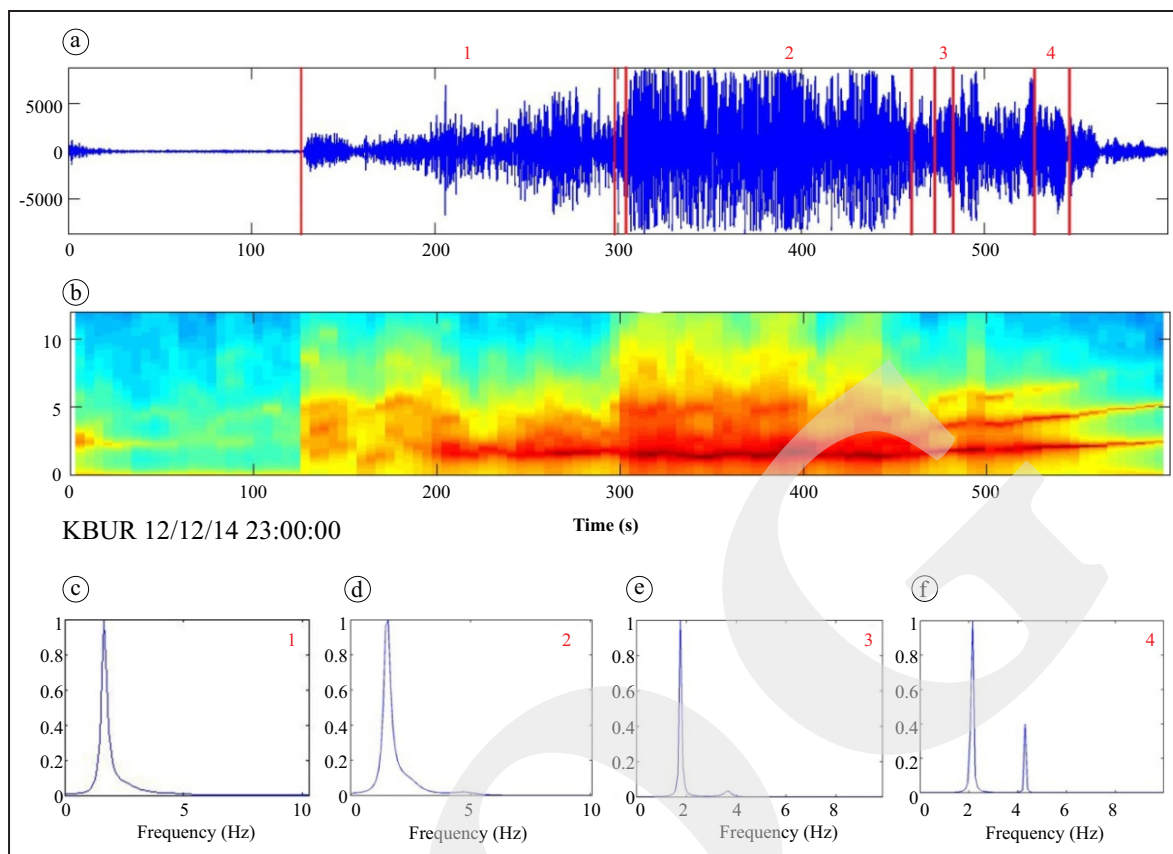


Figure 5. Spectral analysis to some segments bordered with the red borderlines, (a) Tremor of KBUR on 12 November 2014 starting from 23 h 00 m 00 s over 600 s, (b) Spectrogram from the same recordings in Figure 5a, (c) tremor spectrum of range 1 or the head tremor, (d) tremor spectrum of range 2 or the central tremor, (e) tremor spectrum of range 3 or the early tails tremor, (f) tremor spectrum of range 4 or the late tails tremor gliding.

volcanoes as reported by Bertin *et al.* (2015) and Lees *et al.* (2008). The other uniqueness is a gliding on its harmonic frequency (Figure 3b). The fundamental frequency of Raung tremors on this period shows a gradual frequency increase from 1.3 Hz to 2.7 Hz over a period of ± 3.3 minutes.

Possible Causes for Gliding and Quasi-harmonic Tremor

The large variety of seismic signals observed on active volcanoes is closely related to the diversity of processes involved at the sources and to the wide range of physical parameters that characterize the volcanic fluids and solid rocks.

There are lots of explanations of tremor source mechanisms suggested by experts. One of them is the nonlinear oscillator model proposed by Julian (1994). He proposed that tremors were the signal caused by nonlinear vibration

of fluids such as magma flowing inside a dike connecting two reservoirs. The fluid flow is dependent on the pressure differences between the two magma reservoirs and visco-elastic force exerted by elastic wall enclosing the dike. Variations in magma pressure cause the dike wall to open or close. The synthesis tremors made by Julian (1994) show the types of tremor behaviours caused by changes in magma pressure (Figure 6). When the pressure parameter from the lower magma reservoir is 13 MPa, the dike wall vibrates monotonically. If the pressure is increased by just 3 MPa, the vibration changes to a harmonic oscillation with two spectral peaks. Furthermore, at 19 MPa the dike wall exhibits chaotic behaviours, alternating between monotonic and harmonic vibrations (Figure 6).

Figure 4 shows quasi-harmonic tremors repeatedly over 3 hours from 20 h 00 m 00 s. In

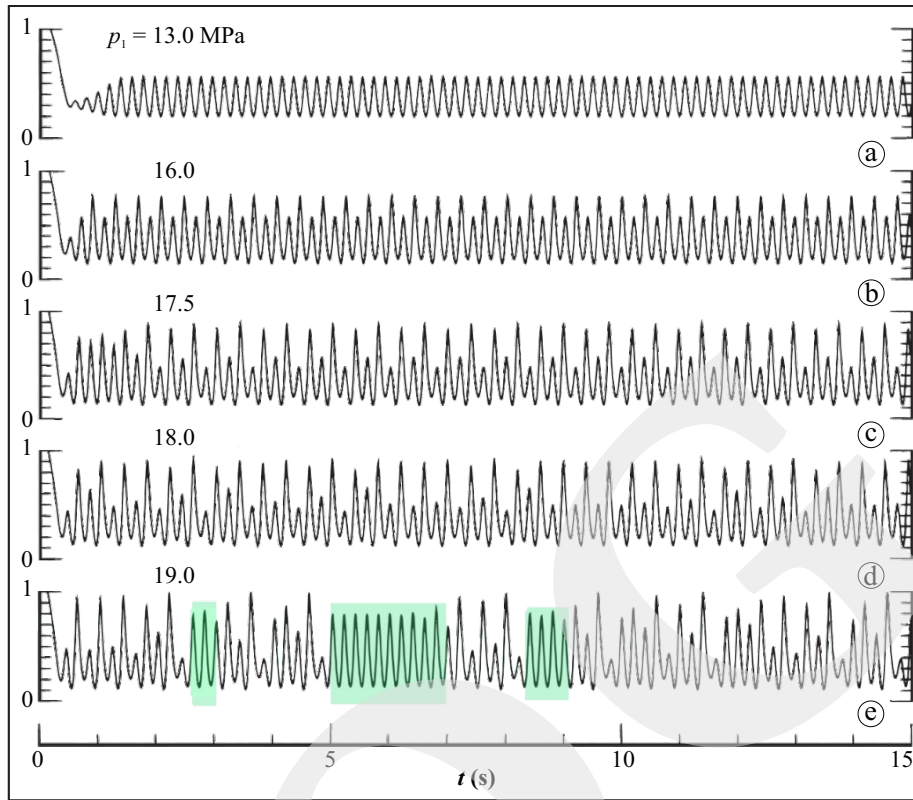


Figure 6. Synthetic tremor time series showing types of behaviour that occur for different values of pressures: P (a) monotonic time series (b) period doubling time series (c) period four (d) chaotic band (e) chaos. The blocked time series is monotonic.

Raung quasi-harmonic tremors, the spectrum of tremor head is monotonic, but the spectrum of tremor tail is harmonic (Figure 5). The alternating of monotonic (tremor head) and harmonic (tremor tail) respectively over this period is qualitatively similar with Julian's synthetic time series (Figure 6). The monotonic time series is depicted in Figure 6a, whereas the alternating between monotonic and harmonic is depicted in Figure 6e. In Figure 6e, the blocked signal with green colour is monotonic and the nonblocked signal is harmonic with several peaks. There is an alternating between monotonic and harmonic.

The same behaviour of the two tremors (synthetic and observed) suggests that the Raung Volcano magma pressure is sizeable to make a chaotic vibration. This suits the conclusion from Wildani *et al.* (2013) about the nonlinear analysis of Raung tremors in the 2012 eruption period. The study suggests that the Raung tremors are chaotic based on the fractal dimension value and the Lyapunov exponent of Raung tremor.

Some researchers try to explain the process of gliding tremors. Hotovec *et al.* (2013) explains the gliding tremor behaviour in Redoubt Volcano is caused by the continuous stick-slip earthquake superposition that the frequency increases. Lees *et al.* (2008) suggests that the gliding tremors are caused by geometry changes in conduit. Jousset *et al.* (2002) proposes the change of magma characteristics that causes P-wave velocity in magma increase, and then this increase causes gliding on tremor frequency. Lessage *et al.* (2006) explains that there is a relationship between gliding tremors and pressure variation in conduit. The pressure modifies gas fraction and velocity wave. If the pressure increases in the bubbly magma, it causes a decrease of gas fraction and an increase in its acoustic velocity that in turn increases the tremor frequency.

A strombolian volcano like Raung is modelled as having rich bubbly magma (James *et al.*, 2012). In the bubbly magma, a pressure decrease induces an increase of gas fraction and a decrease of its

bulk modulus and acoustic velocity that lowers the tremor frequency (Sturton and Neuberg, 2003). In Figure 5, there are gliding frequencies in quasi-harmonic tails from 1.7 Hz to 2.2 Hz for its fundamental frequency. This positive increment in frequency can be interpreted that there is a pressure increasing in Raung magmatic conduit from the magma reservoir. Variations in magma pressure cause the elastic wall to open or close. When the pressure increases, it causes the elastic wall to close then decreases gas fraction in Raung basaltic-andesitic volcano and increases its bulk modulus and P-wave velocity.

CONCLUSIONS

The consistency of Raung tremors were observed to exhibit gliding and quasi-harmonic behaviours continuously on 12 November 2014. The characteristic of gliding and quasi-harmonic tremors in Raung Volcano are summarized as follows:

1. The quasi-harmonic tremors have the monotonic spectrum in its head and centre segment, and the harmonic one in its tails. The harmonic spectrum has a fundamental frequency of 1.5 to 2.2 Hz in range, and the monotonic spectrum also has the dominant frequency of 1.5 to 2.2 Hz. The harmonic and monotonic signals are suggested to be excited from a common resonator because of the similarity of those fundamental frequency.
2. The frequency of fundamental peaks in harmonic tails increases from 1.3 Hz to 2.7 Hz over a period of ± 3.3 minutes, and the gliding frequency was appeared in Raung spectrogram.

The alternating monotonic (tremor head) and harmonic (tremor tail) respectively over this period is qualitatively similar with Julian's synthetic time series about the nonlinear oscillator model. The Raung Volcano magma pressure is suggested to be sizeable to make a chaotic vibration. This positive gliding in frequency can be interpreted that there is a pressure increasing in Raung magmatic conduit from magma reservoir. It decreases gas fraction in Raung basaltic-andesitic

volcano and increases its bulk modulus and P-wave velocity.

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