Characterization of seismic signals at Bledug Kuwu using goodness-of-fit criteria analysis

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Abstract. The Bledug Kuwu is an active mud volcano located in Grobogan, Central Java. The research aims to compare quantitatively between reference signals and event signals using the analysis of goodness-of-fit criteria. The characterization of the seismic signal of Bledug Kuwu is quantitatively based on the seismometer data and video recording into the reference signal type and event signal, and then compares it using Goodness-of-fit criteria analysis. The results of a comparative analysis between the seismic signals and the reference signals using goodness-of-fit have been obtained that the highest level of compatibility with Envelope Goodness-of-Fit (EG) value greater than 6.00 and Phase Goodness-of-Fit (PG) greater than 7.00.

1. Introduction
Mud volcano is one of the natural phenomena that generally occurs along active fault lines in the world, which at the limit of a convergent zone [1]. As an area in the convergent zone, Indonesia has so many phenomena of mud volcanoes; one of them is Bledug Kuwu [2]. The Bledug Kuwu ejects mud material that containing salt accompanied with the release of water and gas to the surface.

The eruptions of mud in Bledug Kuwu can occur several times in a minute with various types of eruptions and causing tremors in the surrounding area [2] [3]. The phenomenon in Bledug Kuwu that produces the vibrations are interesting to do assessment research by using the micro seismic method to study more about the differences of seismic signals characterization resulting from a short period of recording seismometer.

This study is generally aimed to characterize an eruption of event signals Bledug Kuwu from seismic signals data obtained by comparing quantitatively between the eruption event and the reference signals, and then categorize the event signals based on the comparison and match the characteristic form eruption using Goodness of Fit criteria analysis.

2. Basic Theory
2.1. Time-Frequency (TF) Analysis
An instantaneous spectral content of a signal or a time evolution at any frequency of the signal can be obtained by using the TF representation of the signal. The TF representation can be obtained by using
the Continuous Wavelet Transform (CWT). The continuous wavelet transform of signal \( s(t) \) is defined by

\[
\text{CWT}_{(a,b)} \{s(t)\} = \frac{1}{\sqrt{|a|}} \int_{-\infty}^{\infty} s(t) \psi^* \left( \frac{t-b}{a} \right) dt,
\]

where \( t \) being time, \( a \) the scale parameter, \( b \) translational parameter, and \( \psi \) analysing wavelet. Star denotes (*) the complex conjugate function [4] [5] [6].

TFR of signal \( s(t) \) based on the continuous wavelet transform \( W(t,f) \) can be then defined by choosing a relation between the scale parameter \( a \) and frequency \( f \) in the form \( a = \omega_0 / 2\pi f \). because the translational parameter \( b \) corresponds to time and replacing \( b \) by \( t' \). So obtained

\[
W(t,f) = \text{CWT}_{(f,t')} \{s(t)\} = \frac{2\pi |f|}{\omega_0} \int_{-\infty}^{\infty} s(r) \psi^* \left( 2\pi \frac{t-t'}{\omega_0} \right) dr,
\]

where \( W(t,f) \) is a representation of the signal in the TF plane. Having determined the TFR, an envelope \( A(t,f) \) and phase \( \phi(t,f) \) at a given point of the TF plane can be defined.

If there is a signal \( s(t) \) and \( sr(t) \) is a reference signal, then

\[
\Delta A(t,f) = A(t,f) - Ar(t,f) = \left| W(t,f) \right| - \left| Wr(t,f) \right|,
\]

denotes as the difference between two envelopes at each \( (t,f) \) point, and

\[
\Delta \phi(t,f) = \phi(t,f) - \phi r(t,f) = \text{Arg} \left[ W(t,f) \right] - \text{Arg} \left[ Wr(t,f) \right],
\]

denotes the difference between two phases at each \( (t,f) \) point.

2.2. TF Goodness of Fit Criteria

The envelope TF misfits, as described in the previous chapter is to quantify and characterize how much two envelopes differ from each other. If the envelope misfit can attain any value within the range of \((-\infty, \infty)\) or 0 with 0 meaning the two envelopes are agreement. However, if there is a comparison of relatively distant signal envelope, then it can be analyzed using the criteria TF goodness-of-fit. Unlike the misfit criteria, if the results from an analysis of goodness-of-fit criteria approaching ten which means the level of between two signals perfectly.

Criteria TF envelope goodness-of-fit can be defined based on the TF envelope misfit is

\[
EG = A \exp \left\{ \left| EM \right|^k \right\}, \quad A > 0, \ k > 0.
\]

Similarly, the definition of the value of the phase TF criteria of goodness-of-fit equivalent to phase TF misfit criteria

\[
PG = A \exp \left\{ \left| PM \right|^k \right\}.
\]

3. Method

This study was done in the tourism site of Bledug Kuwu, Grobogan, Central Java (figure 1). Geographically located at 07°06'10" - 07°07'40" LS and 111°06'25" - 111°07'45" BT. This research was done on September 29 to October 3, 2013.
Collecting data in the field is done with the monitoring system is the third 3 component seismometer recording device TDV-23S *feedback short period* is placed at three different points, each of which is ± 120m from the source of eruptions. Recording data in the form of seismic signals recorded three components (Vertical Z, North-South *N-S*, East-West *E-W*) that turns against time. In addition to recording vibration on the ground using a seismometers, in the study is done also recording with camcorder to record eruptions of Bledug Kuwu.

Data processing in this study divided into three, first make a selection event signal to the seismic data have been obtained from the recording using software ObsPy 0.9.2 with the Python programming language. The second, choosing a signal reference manually by selecting some signal from event signals that has been obtained from the results of previous processing. The third, doing an analysis of goodness-of-fit criteria also use software ObsPy 0.9.2.

4. Result and Discussion

4.1. Characterize reference signal $SR(t)$

Reference signal is intended as a comparison of the signals of other events to look good quantitative goodness-of-fit between the two signals. In this study, the obtained four reference signals that are distinguished by the characteristic shape of its eruption. Four of the reference signals are as follows.
4.1.1. Type A of Reference Signal
The form of eruption type A of Bledug Kuwu having a characteristic namely the eruption sprayed to the surface in the form of one bubble of material mud that has been mixed with water and gases (figure 2).

![Figure 2](image)

Figure 2. (a) The characteristic form of type A with one bubble eruption; (b) reference signal SR (t) of type A.

4.1.2. Type B of Reference Signal
The form of eruption type B of Bledug Kuwu has a characteristic namely the eruption that sprayed to the surface in the form of two bubbles or double eruption that occurred in the same time (figure 3).

![Figure 3](image)

Figure 3. (a) The characteristic form of type B with two bubbles eruption at the same time; (b) reference signal SR (t) of type B.
4.1.3. Type C of Reference Signal
A signal reference type c has the characteristics of the form of eruption in the form of more than two bubbles sprayed onto the surface. However, this eruption sprayed to the surface is available continuously for approximately 2 seconds (figure 4).

![Figure 4](image1)

Figure 4. (a) The characteristic form of type C with two bubbles eruption at the same time; (b) reference signal SR (t) of type C.

4.1.4. Type D of reference signal
The form of eruption type D of Bledug Kuwu having a characteristic namely eruption’s bubbles that sprayed very large compared to the form of eruption SR (t) type A, B, and C (figure 5). The analysis of the Representation Time-Frequency (TFR) shows differences in the dominant frequency of each signal reference (figure 6).

![Figure 5](image2)

Figure 5. (a) The characteristic form of type D with two bubbles eruption at the same time; (b) reference signal SR (t) of type D.
Figure 6. Analysis of the Representation Time-Frequency (TFR). (a) TFR of reference signal of Type A; (b) TFR of reference signal of Type B; (c) TFR of reference signal of Type C; (d) TFR of reference signal of Type D.

4.2. Analysis of Quantitative Comparison Time-Frequency Goodness-of-Fit Criteria

The level of match two signals from the analysis using the TF goodness-of-fit criteria based on the range of values, quantitative and verbal value that has been researched and developed [6-10] on the Table 1.

| Goodness-of-fit | Quantitative value | Verbal value |
|-----------------|--------------------|--------------|
| 10              | **excellent**      |              |
| 9               |                    |              |
| 8               | **good**           |              |
| 7               |                    |              |
| 6               | **fair**           |              |
| 5               |                    |              |
| 4               | **poor**           |              |
| 3               |                    |              |
| 2               |                    |              |
| 1               |                    |              |
| 0               |                    |              |

The results of the election of an eruption event signal Bledug Kuwu from recording seismometer obtained 155 signals that each compared with four signal references using TF goodness-of-fit criteria. Analysis of the results obtained a few signals from possessing congruity with one of the reference signals being compared (table 2). Compatibility of the signal seen from the quantitative comparison of the two signal values obtained.
Table 2. The result of compatibility signal analysis using TF goodness-of-fit criteria

| Signal Analysis                  | Goodness-of-fit |
|----------------------------------|-----------------|
| Event signals                    | Envelope Phase  |
| Event signal 1                   |                 |
| Type A                           | 6.24 8.62       |
| Type B                           | 4.34 3.00       |
| Type C                           | 6.46 7.16       |
| Type D                           | 4.74 4.15       |
| Event signal 2                   |                 |
| Type A                           | 1.30 3.40       |
| Type B                           | 6.12 8.17       |
| Type C                           | 0.89 4.08       |
| Type D                           | 3.76 1.93       |
| Event signal 3                   |                 |
| Type A                           | 5.75 7.11       |
| Type B                           | 4.61 6.59       |
| Type C                           | 6.60 8.33       |
| Type D                           | 5.13 3.25       |
| Event signal 4                   |                 |
| Type A                           | 4.07 2.78       |
| Type B                           | 5.95 4.19       |
| Type C                           | 3.91 3.83       |
| Type D                           | 6.67 7.02       |

The greyscale colors on the table above shows the suitability of event signals are compared against the reference signal. For example, in the event signal 1 are compared to the existing four reference signal, a signal is obtained that best match is when compared to the reference signal type A are indicated by the great value of the goodness-of-fit obtained. Video recordings also showed similarities between the forms of an eruption by type A with a first event signal, similarly for the other signal.

5. Conclusions

Based on the results of data processing and analysis can be concluded:
1. The results of the seismic signal characterization mudflow based Seismic Data recording and video recording obtained four types of Bledug Kuwu’s eruption namely:
   a. Eruption type A given off one bubble.
   b. Eruption type B given off two bubbles at the same time.
   c. Eruption type C given off more than two bubbles.
   d. Eruption type D given off big bubble of eruption.
2. The results of a comparative analysis between the seismic signals and the reference signals using time-frequency goodness-of-fit obtained that the highest level of compatibility with Envelope Goodness-of-Fit (EG) value greater than 6.00 and Phase Goodness-of-Fit (PG) greater than 7.00.

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