Study of Macro Earthquake Attenuation Using Q-Factor Coda Waves around Matano Fault

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Abstract. All Several macro earthquakes have occurred at the Matano fault so it is interesting to study how the energy attenuation in the coda wave. Coda wave is a signal that follows a secondary wave on a seismogram recording. Some macro earthquakes can be monitored well by BMKG through LUWI Station at a distance of 200-300 km from the epicenter. The coda Q-factor is analysed using coda waves at range 2-4 Hz and 4-8 Hz frequencies of lapse times at 20 seconds in vertical component. Variation of coda Q-factor is influenced by the rock medium in the Matano Fault. This Matano Fault is very unique because it is a collision of continental and oceanic rocks that extend from western to eastern part. The study area is divided into three zones, namely the western, central, and eastern zones. The objective of this study is to identify vulnerabilities at low or high level in each zones by the Coda Q-factor that will classify hazardous earthquakes. The value of coda Q-factor is obtained 126.27 in the west, 162.80 in the middle, and 181.96 in the eastern part of the fault. The western part is the most vulnerable area because low coda Q-factor is associated with sediments layer. It is formed by metamorphic rocks close to the active Fault of Palu Koro. The highest coda Q-factor is located at the eastern part of the fault which hazardous zone and has the potential to cause a large earthquake. The eastern zone has a composition of ultrabasic rocks with high rock stress. In general, the average value of Q-factor in the Matano Fault is 157.01, where the value indicates that the characteristics of the Matano Fault are seismic active zones.

1. Introduction
Sulawesi Island is a collision of the Sunda Shelf at the western part and the Australian Block at the eastern part. This impact formed an active and complex tectonic zone in the central part of the island surrounding the Matano Fault [1]. Major earthquakes have occurred 6.3 M in 2011 and 5.8 M in 2012 caused hundreds of buildings were damaged and several people were injured in Sorowako City. The damage caused by the earthquake is various effects depending to the strength of the earthquake, the distance to the source, and the rock condition troughed by earthquake vibration. The wave propagation process going through energy decrease or attenuation caused by various factors namely geometrical spreading, intrinsic attenuation, and scattering attenuation [2].

One method that can explain energy reduction in seismic activity is attenuation studies based on coda waves. The vibrations in the Coda wave do not decrease drastically but still exist like a reverberation through by sound vibrations. This attenuation process is inversely proportional by Q-factor. If high level of Q-factor means small attenuation of earthquake wave will be. So that when attenuation is small at earthquake process, then the vibrations felt by more continuous on the medium that is passed by the spread of earthquake waves [3].
The amplitude of the seismic wave decreases due to the distance of the epicenter. Then absorption factor by medium becomes the main variable during the attenuation process. Attenuation of the amplitude of distance is strongly influenced by the geological conditions of the local area (rocks are not homogeneous). There is a logical connection between Coda Q and the local geology condition. The more heterogeneous rocks, the higher the Q value and the smaller attenuation exposed by rocks. So this region has high active seismic [4].

Based on the condition, Matano Fault was defined as an active fault. Previous research shows this fault speed can reach 44 mm per year [5]. The strike-slip movement with the direction from northwest to southeast through Lake Matano and associated with Koro Palu Fault and Sorong Fault [6]. The western geological formation of the Matano fault is dominated by Metamorphic Rock, the eastern part of Ultra Basa, and the middle part is a mixture of Metamorphic and Ultra Basic [7]. Three parts of the Matano fault have different attenuation levels, corresponding to the large earthquake in each zone. This attenuation will be evident that relation the medium and seismic waves, thus giving information vulnerability on the rock zones passed by earthquake waves that have recorded by seismographs. By using the method of attenuation coda Q-factor, this study shall calculate the Q value of the earthquake wave signal that has occurred in the three zones.

By collecting big earthquakes in the area of Matano, the waves of earthquake give us some information from the deepest underground of the area. Among available various information using signal analysis, the most important information are its geological structure, level of solidity and strength of the rock, and vulnerability of the area. This study will focus on identifying the relationship between Q-factor with vulnerability of the region.

2. Theory
Earthquake waves that recorded by seismographs has a unique character. Broadband station records two phase of earthquake waves, namely body and surface waves. The body shape of wave consists of primary and secondary waves, later followed by surface wave. The coda wave occurred shortly after the secondary wave which may became a discussion in this paper. Coda waves are recorded on body waves but are not seen at surface waves. Coda waves are trace from waves be taken out from the source of earthquake. The propagation of waves through several mediums will cause vibrations to attenuate slowly over time. This coda wave is like an echo of gunshot that still resonates within a few moments before the sound energy runs out. Coda waves are a function of the wave distribution formed by the medium between the source and the receiving station [3]. This Coda wave attenuates the amplitude due to energy conversion and internal friction.
Coda waves are part of the secondary wave in a heterogeneous medium. The Q-factor estimation on vertical decrease of amplitude of the coda vibration at the time (frequency) is stated as figure bellow.

![Figure 2. Curve of attenuation at coda wave](image)

Where A is amplitude, (m) gradient, and t time domain. From Figure 2 the coda factor is the gradient / slope (m) of least square fitting $\ln A (f, t)$ to time $t$ stated as follows below

$$Q (f) = \frac{\pi f}{m}$$  \hspace{1cm} (1)

Quality factor ($Q$) is necessary constant equation in seismology to define attenuation. This $Q$ value is inversely proportional to attenuation value. The value of $Q$ will be high in a homogeneous medium, and will decrease in a more heterogeneous medium [8]. This $Q$ value will increase in the deeper layers below the surface of the earth. The high $Q$ value is also associated with large earthquakes as has been studied in Northern Anatolian Turkey [9].

3. Data

The data used for the Coda Wave analysis is macro earthquakes data that occurred in the Matano fault as depict in Table 1. Micro earthquake data on the Matano fault is not well recorded by the BMKG LUWI station because the distance is so far distance. To simplify the research, the earthquake samples taken were in three zones. Zone I is in the western part, Zone II for middle part, and Zone III for eastern part of the Matano Fault with a different geological structure.

| No | Origin time      | Location       | Depth | Magnitude |
|----|------------------|----------------|-------|-----------|
| 1  | 15/05/2013 07:37:07 GMT | 2.26º S - 120.85º E | 5 Km  | 4.3 M     |
| 2  | 15/02/2011 13:33:55 GMT | 2.47º S - 121.55º E | 34 Km | 6.3 M     |
| 3  | 16/04/2012 02:17:51 GMT | 2.62º S - 121.90º E | 22 km | 5.8 M     |

Processing data is using seismic waveforms that sourced from BMKG station records, namely LUWI station at coordinate location 1.04º S and 122.77º E and elevation at 6 m. This station is collaboration between BMKG and GFZ Postdam Germany in Luwuk City, Central Sulawesi. The station was chosen because it has a strategic position and is perpendicular to the Matano Fault and has a more complete data record compared to other seismic stations. The distance between epicenter center samples with stations less than 250 km is still in the ideal range and has implications in calculating local earthquakes [10].
4. Data Processing

This waveform earthquake data has a mini-seed format and then processed using the Dimas software. The stages in coda estimation are as follows [11]:

1. Placement on sets of P and S wave times on vertical components (BHZ) formatted as follows:

   ![Figure 4. Earthquake Records 05-15-2013 07:37:07 GMT 4.3 M at LUWI Station](image)

2. Bandpass filters are performed at a frequency of 2-4 Hz (3 Hz center frequency) and a frequency of 4-8 Hz (6 Hz center frequency).

   ![Figure 5. Butterworth Band Pass filter 2-4 Hz](image)

3. Determination of coda wave by cutting the waveform with the initial time 2 ts (2 X S wave onset) at an interval of 20, 30, and 40 seconds.
4. Envelope process and moving average on coda waves

![Figure 7. Envelope and moving average processes](image)

5. Calculation of Q-factor values from each center frequency and lapse time using equation (3) with the input gradient / slope obtained from the moving average process

5. Results And Discussion

The results of the data processing show that the estimation of Q-factors in each zone has varying values. Variations in Q-factors can be viewed in the following table below.

| Table 2. The value of the Q-factor (bold and italic numbers) in the Matano Fault |
|---------------------------------|---------------------------------|
| **Earthquake 15/05/2013 -2.26° S 120.85° E 07:37:07 GMT 4.3 M depth 10 km** |
| Lapse Time | Band Pass (Frequency Center) | Band Pass (Frequency Center) |
|------------|------------------------------|------------------------------|
| 20 second  | 2 to 4 Hz (3 hertz) | 4 to 8 Hz (6 hertz) |
| 30 second  | 90.69                        | 171.37                        |
| 40 second  | 138.60                        | 207.98                        |

| Earthquake 15/02/2011 -2.47° S 121.55° E 13:33:55 GMT 6.3 M depth 34 km |
|---------------------------------|---------------------------------|
| Lapse Time | Band Pass (Frequency Center) | Band Pass (Frequency Center) |
|------------|------------------------------|------------------------------|
| 20 second  | 2 to 4 Hz (3 hertz) | 4 to 8 Hz (6 hertz) |
| 30 second  | 112.81                       | 198.63                       |
| 40 second  | 138.76                       | 299.62                       |

| Earthquake 16/04/2012 -2.62° S 121.90° E 02:17:51 GMT 5.8 M depth 22 km |
|---------------------------------|---------------------------------|
| Lapse Time | Band Pass (Frequency Center) | Band Pass (Frequency Center) |
|------------|------------------------------|------------------------------|
| 20 second  | 2 to 4 Hz (3 hertz) | 4 to 8 Hz (6 hertz) |
| 30 second  | 93.10                        | 289.43                        |
| 40 second  | 133.49                        | 297.17                        |

![Figure 6. Determination of coda waves](image)
The Q-factors in Table 2 are evaluated in each zone as follows.

![Figure 8. Coda Qc estimation results of each zone (western, middle, and eastern part).](image)

| Zone I (western part) | Zone II (middle part) | Zone III (eastern part) |
|-----------------------|-----------------------|------------------------|
| 126.27                | 162.80                | 181.96                 |

The average value of Q-Factor in the Matano Fault region is 157.01

6. Discussion

Estimation of Q-factors that vary in each of these zones can reveal the seismic characteristics of the Matano Fault. The increase in the value of Q is directly proportional to the time interval at 20, 30 and 40 seconds for coda wave (Figure 6). Therefore, if the time interval is longer, the value of Q-factor shifts into more extent. But not uniform, it caused complexity of the medium at the region. The minimum value of Q-factor in Zone I (western part) with an interval of 20 seconds is 62.69. While the maximum value of Q-factor is 299.62 in Zone II at 40 seconds intervals.

The Q-factor value in Zone I is the lowest, which is 126.27, it can be explained that this zone has the strongest wave attenuation compared to other zones. So that if a strong earthquake occurs, the area around Zone I will take to short direct vibrations because the waves are more quickly attenuated so that the energy will be decreased. However, this zone must be considered because there is a large energy conversion, from vibration energy to other energy, so there is a possibility of causing different vulnerability factors from an earthquake where the effect of the earthquake will be felt more in the area closer to the source of the earthquake. The vulnerability level in Zone I is becomes very high.

The result of low Q-factor for Zone I is associated with high frequency of earthquake similar with Turkey area [12]. Therefore, this area is associated to high frequency of earthquake and geologically it has a composition that is more predominantly metamorphic [13]. The Area with high frequency of earthquakes does not release large earthquakes because the stress of the rocks is low, thus it can be said that as a source of disaster Zone I is no potential for large earthquake.

The Q factor value in Zone II, which is in the middle part of the Matano Fault, has a moderate value of 162.80. Geologically, this zone has a rock composition in the form of a mixture of metamorphic and ultrabasic so that rock medium in this zone can be said to be more heterogeneous compared to other zones. Because the value of Q factor is moderate, the attenuation characteristics are relative, namely between Zone I and Zone III, so it can be concluded that in Zone II it has a moderate level of vulnerability.

The Q factor value in Zone III is the highest, which is 181.96, it can be explained that this zone has the weakest wave attenuation compared to other zones. Geologically, Zone III has a composition that is more predominantly ultrabasic rocks. If a strong earthquake occurs, the vibration is felt long enough because the wave seems to echo and more continuous. Areas that feel vibrations are wide enough so that this zone has the highest level of vulnerability. Highest Q-factor in this zona related low frequency of earthquake, where potentially for release big earthquake. Eastern part is most hazardous than other areas in Matano Fault.
When calculated on average, the overall Q value in this region is 157.01. This value is included in the low Q category. Q values below 200 have active tectonic and seismic implications [4]. In general, the Q factor value in the Matano Fault has an increasing pattern from the west to the east. So that it can be concluded that vulnerability is higher when heading to the east. But the level of vulnerability will be more real if it is supported by other data and methods so that the research is more complete and detailed.

7. Conclusion
The coda Q-factor for three macro earthquake in Matano Fault has examined by the frequency at 2-4 Hz and 4-8 Hz with lapse time 40 s. This region has an average Q value of 157.01 so that it is included in the tectonic and seismic region which is quite active. The western part of the Matano Fault has the lowest average Q value of 126.27, the middle part has a moderate value of 162.80, and in the east has the highest value of 181.96. Western part is the most vulnerable area because the low value of Q-factor has high attenuation. It can be converted seismic wave to other energy such as heat, ground shaking, and deformation. Eastern zone has the highest Q-factor related low frequency of earthquake, where potentially for release big earthquake. Eastern part is most hazardous than other areas in Matano Fault.

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