Seismic cycle before the main earthquake and the end of time after shocks in West Sumatra

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Abstract. Indonesian archipelago is one of the areas that often experiences earthquakes, this is because Indonesia is located between four plates that move together. One area in Indonesia that is prone to earthquakes is West Sumatra, because West Sumatra is in the vicinity of the active zone. The earthquake that occurred in West Sumatra in the period 2000-2019 had the smallest magnitude of 4.5 SR and the largest magnitude was 7.6 SR. The earthquake in West Sumatra has a Mainshock-Aftershock seismic cycle, an earthquake that begins with a preliminary earthquake and is followed by aftershocks. The suitable method to estimate the end time of aftershocks in West Sumatra is the Utsu method.

1. Introduction

Indonesian archipelago is one of the regions that frequently experiences earthquakes, this is because Indonesia is located between four mutually moving plates namely the Eurasian plate, the Indo-Australian plate, the Pacific plate and the Philippine plate. As a result of the movement of the plate form a fault or fault that will cause an earthquake. Areas that have faults or faults that have the potential to experience earthquakes are called active seismic regions [1]. West Sumatra is one of the areas on the island of Sumatra that has a fairly high seismic levels, this is because West Sumatra is in the active asymmetrical zone. West Sumatra is in the vicinity of three active seismic zones, which are around the subduction zone, Mentawai fault, and the Sumatra fault [2].

The Province of West Sumatra has experienced frequent earthquakes, both, medium and large earthquakes. In addition to earthquakes that occur in West Sumatra due to active seismic zone activities, West Sumatra also has active segments which are also one of the causes of earthquakes. Some earthquakes that have occurred in West Sumatra, namely; March 08 1977 earthquake (M = 5.5 SR), April 11, 1994 (M = 6.5 SR) earthquake, April 1, 1998 (M = 6.9 SR), February 22, 2004 earthquake (M = 6 SR), April 10 earthquake 2005 (M = 6.7 SR), February 25, 2008 earthquake (M = 7.2 SR), September 30, 2009 earthquake (M = 7.6 SR), earthquake, September 14, 2012 earthquake (M = 6.2 SR), earthquake 31 August 2017 (M = 6.3 SR), and earthquake February 2, 2019 (M = 6 SR) [3]. The main earthquake events that have occurred in West Sumatra were followed by aftershocks that occurred at certain intervals.

Earthquakes consist of large earthquakes and small earthquakes, large earthquakes are usually referred to as major earthquakes. Earthquakes are said to be major earthquakes or large earthquakes, namely earthquakes that have a magnitude of 6 SR-8 SR. The major earthquakes that occur will usually be
followed by aftershocks that occur after the main earthquake. The main earthquake has a smaller magnitude compared to the main earthquake. Aftershocks can occur because there is still energy left due to the release of energy from the main earthquake, aftershocks occur during a certain time until finally the aftershocks end. This aftershock will cause damage that occurred after the main earthquake occurred. Aftershocks are caused by the same movement of faults or faults caused by the main earthquake. Aftershocks do not always occur on the same fault or fault but usually occur within the fault area that surrounds the main earthquake [4].

Earthquakes have different seismic cycles including earthquakes that occur preceded by a preliminary earthquake followed by a major earthquake and aftershocks, there are also earthquakes that occur without being traversed by major earthquakes but followed by aftershocks. Aftershocks occur around the location of the main earthquake, the location of the spread of aftershocks is related to the area of the main earthquake fault [5]. The occurrence of aftershocks occurring is considered as a mechanism to achieve equilibrium after the release of energy with a short time in the main earthquake. Aftershocks that occur after this major earthquake last for a certain period of time. The expiration of aftershocks can be known using the Omori method and the Utsu method.

2. Methods
The data used in this study are data obtained from BMKG Padang Panjang and the USGS website, the data used is earthquake data with magnitude ≥ 4.5 SR. The earthquake that will be studied is an earthquake that occurred in West Sumatra in the period 2000-2019. The research method used in this study is the least square method that is used to determine the earthquake cycle before the main earthquake and the Omori and Utsu methods used to determine the end time of the subsequent earthquake that occurred. The Omori and Utsu methods can be used after knowing the frequency of aftershocks that occur [6]. The equation for Omori method that can be used to obtain estimates of the expiry of other earthquakes that:

\[ n(t) = \frac{k}{t + c} \]  

Where \( n(t) \) is the earthquake frequency (SR), \( t \) is the time interval (days), and \( c \) is a constant. In addition to the Omori method which can be used to estimate the end of the earthquake time, another method that can be used is the Utsu method. The equation that can be used to estimate the end time of aftershocks can be used as follows:

\[ n(t) = \frac{a}{(t + c)^b} \]  

Where \( n(t) \) is the frequency of aftershocks (SR), \( t \) is the time interval (days) and \( a, b, c \) are constants. Both methods can be used to estimate the end of aftershocks, after the results of the two methods are obtained, then the correlation coefficient values are seen using the following equation:

\[ r = \frac{(n \Sigma xy - \Sigma x \Sigma y)}{\sqrt{(n \Sigma x^2 - (\Sigma x)^2)(n \Sigma y^2 - (\Sigma y)^2)}} \]  

Where \( r \) is the correlation coefficient, \( n \) is a lot of data, \( \Sigma xy \) is the amount of data on variables \( x \) and \( y \), \( \Sigma x \) is the amount of data in variable \( x \), \( \Sigma y \) is the amount of data in the variable \( y \). The results of the values found from each method are seen as the correlation coefficient value, if the results obtained are close to 1 or -1 then the method is suitable but if the amount of values obtained from each test show the value of 1 or -1, the method is not suitable to estimate the end of the earthquake earth aftershocks [7].
3. Result and Discussion
Aftershocks that occurred in West Sumatra in the period 2000-2019 which had a magnitude of $\geq 4.5$ SR occurred as many as 1152 earthquake events shown in Figure 1.

![Figure 1. Map of the Seismicity of the West Sumatra Earthquake Period 2000-2019.](image)

Based on Figure 1, the earthquake in West Sumatra had the lowest magnitude of 4.5 SR and a high magnitude of 7.6 SR. The main earthquake that occurred in West Sumatra was followed by aftershocks. The main earthquakes that occur during this period include the following:

- Earthquake of February 10, 2008
  The earthquake that occurred on April 10, 2005 with a magnitude of 6.7 SR occurred in the Mentawai Islands region. This earthquake has a seismic cycle that begins with a preliminary earthquake that occurred on April 9, 2009 with a magnitude of 4.8 SR and followed by aftershocks such as in Figure 2.
Figure 2. Earthquake Cycle April 10, 2005

The aftershocks that occurred after the April 10, 2005 earthquake based on the Omori method were estimated to last when the aftershocks ended on the 41st day after the main earthquake event while based on the Utsu method, it was estimated that the aftershocks ended on the 63rd day after the main earthquake.

- Earthquake of February 25, 2008
  The earthquake that occurred on February 25, 2008 with a magnitude of 7.2 SR occurred in the Mentawai Islands region. This earthquake has a seismic cycle that begins with a preliminary earthquake that occurred on February 24, 2008 with a magnitude of 6.5 SR and followed by aftershocks such as in Figure 3 below:

Figure 3. Earthquake Cycle February 25, 2008

The aftershocks that occurred after the February 25, 2008 earthquake based on the Omori method have been estimated to last when the aftershocks ended on the 53rd day after the main earthquake event and based on the Utsu method, it was estimated that the aftershocks ended on the 26th day after the main earthquake.

- Earthquake of September 30, 2009
  The earthquake that occurred on September 30, 2009 with a magnitude 7.6 magnitude occurred in the Padang area. This earthquake has a seismic cycle that begins with a preliminary earthquake that occurred on September 25, 2009 with a magnitude of 4.9 SR and followed by aftershocks such as in Figure 4 below:
Figure 4. Earthquake Cycle September 30, 2009

The aftershock that occurred after the February 25, 2008 earthquake based on the Omori method had the final estimate when the aftershocks ended on day 102 after the main earthquake event, while based on the Utsu method, it was estimated that the aftershocks ended on the 90th after the main earthquake.

- Earthquake of September 14, 2012
  The earthquake that occurred on September 14, 2012 with a magnitude of 6.2 SR occurred in the Mentawai Islands region. This earthquake has a seismic cycle that begins with a preliminary earthquake that occurred on August 28, 2012 with a magnitude of 4.6 SR and followed by aftershocks such as in Figure 5 below:

Figure 5. Earthquake Cycle September 14, 2012

The aftershocks that occurred after the events of the September 14, 2012 earthquake based on the Omori method were estimated to last when the aftershocks ended on the 68th day after the main earthquake event, and based on the Utsu method, it was estimated that the end of the earthquake ended on the 6th day after the main earthquake.

- Earthquake of February 02, 2019
  The earthquake that occurred on September 14, 2012 with a magnitude of 6 SR occurred in the Mentawai Islands region. This earthquake has a seismic cycle that begins with a preliminary earthquake that occurred on February 02 with a magnitude of 5.2 SR and followed by aftershocks such as in Figure 5 below:
The aftershocks that occurred after the February 2, 2019 earthquake based on the Omori method were estimated to last when the aftershocks ended on the 40th day after the main earthquake, while based on the Utsu method, it was estimated that the end of the aftershocks ended on the 5th day after the main earthquake.

Based on the results obtained, namely the earthquake that occurred in West Sumatra in the period 2000-2019 it is known that the seismic cycle possessed by the earthquake in West Sumatra is the mainshock-aftershock cycle, where before the occurrence of the main earthquake there is a preliminary earthquake and after an earthquake the main is followed by aftershocks. The suitable method used to estimate the end time of aftershocks in West Sumatra is the Utsu method, because the result of the correlation coefficient produced in the Utsu method is close to a value of 1 or -1. One of the aftershocks that has a correlation coefficient value close to -1 is a subsequent earthquake that occurred on September 30, 2009 where the correlation coefficient obtained is equal to -0.93. The September 30 earthquake is estimated to end the time of aftershocks, namely on the 80th day after the main earthquake event [8]. While the results obtained using the Utsu method were estimated that the aftershocks that occurred as a result of the 30 September 2009 earthquake ended on the 86th day after the occurrence of the main earthquake.

4. Conclusion
Based on the results of the earthquake cycle and the estimated end of aftershock earthquake, it can be concluded that the seismicity that occurs in West Sumatra has a mainshock-aftershock earthquake cycle where all major earthquakes that occur in West Sumatra occur after the introduction of an earthquake and are followed by aftershocks and a suitable method to use for estimating the end time of aftershocks are the Utsu method. This is because the results of processing using the Utsu method are close to the estimated results from BMKG.

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