An analysis of Coulomb stress change and triggering interaction toward seismic activities in the area West Sumatera within January 2000-June 2018

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Abstract. The West Sumatra region is one of the areas prone to earthquake disasters caused by 3 factors. First, namely the Subduction Zone, which is the meeting of two large tectonic plates of the Indian Ocean Plate subducting below the L200 plate of the Eurasian Continent. Second, the existence of the Mentawai Fault which is a horizontal fault due to the sloping subduction process around the Mentawai Islands. Third, the existence of the Sumatran Fault that occurs due to the existence of the Indo-Australian plate which crashes into the western part of the island of Sumatra tilted, resulting in pressure. This study aims to analyze the coulomb displacement of stress and trigger interactions on seismic activity in the West Sumatra region from January 2000 to June 2018 using earthquake data from the United States Geological Survey (USGS) catalog sourced from Global Centroid Tensor Moment Catalog (CMT) earthquake data, United States Geological Survey Catalog (USGS), International Seismological Center Catalog (ISC), ISC-EHB and Meteorology and Geophysics Agency (BMKG), covering the boundaries of -4° SL- 1°NL and 96° - 104°EL. With earthquake magnitude (Mw) ≥7 SR and depth of 1 to 500 km for calculation of Coulomb Stress. Whereas for seismicity later with magnitude Mw ≥ 3.0 up to 9.0 depths of 1 to 500 km. Based on analysis of the earthquake on September 12th, 2007 Mw = 8.5 is a trigger earthquake that triggered all significant earthquakes Mw ≥7 SR, earthquake on September 13th, 2007 Mw = 7.9 is a trigger earthquake that triggered the earthquake that occurred on September 13th, 2007 Mw = 7.0 and February 25th, 2008 Mw = 7.2, the earthquake of February 25th, 2008 and September 30, 2009 was a category of non-trigger earthquakes while the earthquake was significant October 25th, 2010, distribution of stress changes Positive Coulomb is more dominant compared to the negative Coulomb voltage change distribution. This means that after a large earthquake occurred on October 25th, 2010, the Mentawai segment area still has a high accumulation of stress.

1. Introduction

West Sumatra is an earthquake prone area recorded from 2000 to June 2018 West Sumatra has 4,689 earthquake events with magnitudes Mw ≥ 3.0 to 9.0 depths of 1 to 1000 km, in which there are also 6 earthquake events with moment magnitude values (Mw) ≥ 7.0 (USGS and CMT). From the earthquake in 2009 alone, according to Satkorlak PB data, 1,117 people died as a result of this earthquake in 3
cities and 4 districts in West Sumatra, 1,214 people were seriously injured, 1,688 people were slightly injured, 1 person was missing. While 135,448 houses were severely damaged, 65,380 houses were moderately damaged, and 78,604 houses were slightly damaged. [1]

The position of the earthquake-prone area of West Sumatra is caused by 3 factors. First, namely the Subduction Zone, which is the meeting of two large tectonic plates of the Indian Ocean Plate subducting beneath the Eurasian Continent Plate. Second, the existence of the Mentawai Fault which is a horizontal fault due to the sloping subduction process around the Mentawai Islands. Third, the existence of the Sumatran Fault that occurs due to the existence of the Indo-Australian plate which crashes into the western part of Sumatra island tilted, resulting in pressure from this movement.

The movement that occurs is ground movement caused by deformation (fault) because of changes in the shape, dimensions and position of a material. The type of deformation that moves both up, down and sliding in a region can trigger seismic activity so that the previous Researchers studied the relationship between the distribution of Coulomb Stress changes and the triggering process of an earthquake against an earthquake. [2]

Coulomb stress is a way to find out the process of cesarean movement which results in how far the release of core energy and aftershock (relaxation) during an earthquake event, Coulomb Stress is also a method for predicting the next significant earthquake from a significant earthquake trigger [3]

Through this paper the researcher wishes to find out how far the release of core energy and aftershocks during an earthquake event, find out the direction of movement of the fault field and predict the location of the next earthquake energy.

2. Sumatra Tectonic Order

Earthquakes are produced by strains of elastic energy that emit seismic waves. Earthquakes usually occur due to movement of faults or the occurrence of deformation in the upper crust of the earth. Most earthquakes are tectonic earthquakes, namely earthquakes caused by tectonic plate activity. Therefore, the area around the meeting between tectonic plates is an area that often occurs earthquakes.

The theory that explains the mechanism of the occurrence of earthquakes due to magnification is the elastic rebound theory. Basically the elastic theory states that earthquakes occur due to the process of enlarging inside the earth’s crust due to the sudden release of elastic strains that exceed rock strength

![Figure 1](image)

**Figure 1.** Illustration of elastic basic theory (Lowrie, 2007)

Figure 1 shows the sequence of events in the elastic abstract theory. Addition of strain energy is gradually illustrated by developments from a to b. Figure 1a shows in the initial state that parts A and B are compact rocks characterized by lines (which actually do not exist) that connect. Because there is a force acting on the rock then the left side will go up and to the right to the bottom (Figure 1b), so that the rock deforms. The elastic nature of the rock will cause these lines to be carried along by the forces acting on it and bending will occur. Finally, deformed rocks can no longer resist the accumulation of stress that exceeds the elasticity of the rock so that the rock breaks into two parts which are characterized by the presence of non-connecting lines (Figure 1c). The higher strength of rocks in resisting stress, the greater energy released (Lowrie, 2007). In other words, the greater return period of an earthquake the greater earthquake will occur. The greater magnitude of the earthquake, the greater acceleration of the land occurs somewhere [4].
3. Fault of Earthquake

Fault is a gap in the earth's crust at the border between two tectonic plates. Earthquakes are strongly influenced by the movement of rocks and plates in this fault. There are three types of faults that cause earthquakes, namely fault faults, rise faults and shear faults. In addition to the three types of faults, a fault is also known as a combination of a horizontal fault and an up / down fault called the oblique fault. If rocks that support fall down due to supporting rocks on both sides move away from each other, the fault is called a normal fault. If the rocks that support are lifted up due to supporting rocks on both sides moving together, the fault is called a reverse fault. If the two rocks in the moving fault shift horizontally, the fault is called the strike-slip fault [5].

The orientation of the fault field is determined by the parameters of the fault field consisting of strike, dip, and rake.

a) **Strike** (Φ) is an angle formed by a fault move with a north direction. Strike is measured from the north towards the east in a clockwise direction until the fracture stroke (0° ≤ Φ ≤ 360°).

b) **Dip** (δ) is an angle formed by the plane of fault with a horizontal plane and measured in a vertical plane with its direction perpendicular to the fracture (0° ≤ δ ≤ 90°).

c) **Rake** (λ) is the angle formed by the direction of the slip and the fracture stroke. The positive value of the rake on the thrust fault and the negative on the fault down (Normal Fault) (−180° ≤ λ ≤ 180°).

The direction of cesarean movement can generally be divided into 3 types, namely:

1. Dip Slip Movement, which is a movement of faults occurring in a direction parallel to the slope angle of the fault. The dominant movement is the vertical direction.
2. Strike slip Movement is a basic movement that occurs in parallel directions with the fault angle of the fault. The dominant movement is the horizontal direction.
3. The combination of the dip slip movement with the strike slip movement. If strike, dip and rake parameters are known, the type of fault can be determined [6].

4. Data and Method

4.1. Data

Data used is sourced from Global Centroid Tensor Moment Catalog (CMT) earthquake data, United States Geological Survey Catalog (USGS), International Seismological Center Catalog (ISC), ISC-EHB and Meteorology Climatology and Geophysics Agency (BMKG), covering boundaries − 4 SL° up to 1°NL and 96° up to 104°EL, for the observation period namely January 2000 to June 2018. With earthquake magnitude (Mw) ≥7 SR and depth of 1 to 500 km for calculation of Coulomb Stress. Whereas for seismicity the magnitude of Mw ≥ 3.0 to 9.0 is calculated from depths of 1 to 500 km in the period between January 1st, 2000 and June 30th, 2018.

| No | Date          | Latitude | Longitude | Mw (SR) |
|----|---------------|----------|-----------|---------|
| 1  | September 12th, 2007 | -3.78    | 100.99    | 8.5     |
| 2  | September 13th, 2007 | -2.46    | 100.13    | 7.9     |
| 3  | September 13th, 2007 | -2.31    | 99.39     | 7.0     |
| 4  | February 25th, 2008 | -2.6     | 99.95     | 7.2     |
| 5  | September 30th, 2009 | -0.79    | 99.67     | 7.6     |
| 6  | October 25th, 2010 | -3.71    | 99.32     | 7.8     |

4.2. Method

Earthquakes occur when the shear stress of the fault is large enough to exceed normal stress and friction forces that resist the fault from the shift. This equilibrium is characterized by coulomb criteria (King et al., 1994) where coulomb failure stress is expressed by the equation:

\[ \sigma_f = \tau \beta - \mu (\sigma \beta - p) \]  (1)
with:

- $\sigma_f$: Coulomb Stress Change.
- $\tau\beta$: Shear stress on the fault.
- $\mu$: Friction coefficient.
- $\sigma\beta$: Normal Stress
- $p$: Fluid Pore Pressure

The value of $\tau\beta$ in this equation must always be positive, but the process of calculating stress on a fault can be positive or negative depending on the potential slip to the right or to the left.

Stress changes in an earthquake can be estimated through changes in shear stress and normal stress around the fault. So, even though there is no known absolute stress value of a fault, it can be calculated coulomb stress changes using the equation:

$$\Delta\sigma_f = \Delta\tau\beta - \mu (\Delta\sigma\beta - \Delta p)$$  \hspace{1cm} (2)

So that it can be determined whether the fault is triggered (positive stress coulomb changes) or retained (negative stress coulomb changes) for earthquake events. It should be noted that the above calculation is considered to be free from any influence of regional stress or stress from the previous event.

Coulomb stress calculations for cesarean interaction studies are strongly related to changes in fluid pore pressure (pore fluid pressure). Changes in fluid pore pressure are generally assumed to be proportional to normal stress changes and are associated with effective coefficient of friction ($\mu'$), which is expressed by the equation:

$$\mu' = \mu(1 - \beta)$$ \hspace{1cm} (3)

with $\beta$ is the Skempton coefficient which has values varying between 0 and 1. The effective coefficient of friction in the study of changes in coseismic stress varies from 0 to 0.75 with the average value often used is 0.4. With this assumption, coseismic coulomb stress changes are expressed by equations [7].

$$\Delta\sigma_f = \Delta\tau\beta - \mu'\Delta\sigma\beta$$  \hspace{1cm} (4)

If $\Delta\sigma_f > 0$, the slip potential will increase and if $\Delta\sigma_f < 0$, the slip potential decreases. Estimates $\Delta\sigma_f$ caused by earthquakes depend on fault geometry and slip distribution, earthquake magnitude, regional stress orientation and assumption values $\mu$. Uncertainty $\Delta\sigma_f$ in some instances is dominated by uncertainty of slip distribution.

In the field of fault with the orientation of angle $\beta$ with respect to the axis $\sigma_1$ (Figure 4.1) found the stress component equation in the main stress relationship, namely:

$$\sigma\beta = \frac{1}{2}(\sigma_1 + \sigma_3) - \frac{1}{2}(\sigma_1 - \sigma_3) \cos 2\beta$$  \hspace{1cm} (5)

$$\tau\beta = \frac{1}{2}(\sigma_1 - \sigma_3) \sin 2\beta$$  \hspace{1cm} (6)

With $\sigma_1$ is biggest stress dan $\sigma_3$ smallest main stress. Than equation 4 becomes:

$$\sigma_f = \frac{1}{2}(\sigma_1 - \sigma_3)(\sin 2\beta - \mu \cos 2\beta) - \frac{1}{2}\mu(\sigma_1 + \sigma_3) + \mu p$$ \hspace{1cm} (7)

Equation (5) is derived from the $\beta$ function, so the maximum coulomb stress change value is obtained $\sigma_f^{max}$, if:

$$\cot 2\beta = -\frac{1}{\mu}$$ \hspace{1cm} (8)

In the stress axis coordinate system in Figure 2 below, a failure plane is subject to normal stress. Furthermore, the orientation of the fault field with the angle $\beta$ forms $\sigma_1$ as the biggest main stress and $\sigma_3$ as the smallest main stress, with $\tau\beta$ is the shear stress of the fault field. Compression and shear stress reliance on the cesarean section in the image are considered positive. The $\tau\beta$ sign is inverse in the Coulomb calculation stress shear stresses in a specific oriented fault.
Changes in coulomb stress in an optimally oriented plane can be calculated as a result of the main cesarean slips, where aftershocks are thought to occur in the plane of the fault. After an earthquake occurs, the optimum direction is determined not only by changes in stress due to the earthquake $\sigma_{ij}^q$, but also by regional stress $\sigma_{ij}^r$ which gives total stress $\sigma_{ij}^t$ by equation:

$$\sigma_{ij}^t = \sigma_{ij}^q + \sigma_{ij}^r$$  \hspace{1cm} (9)

The main axis orientation resulting from total stress is then derived using:

$$\theta = \frac{1}{2} \tan^{-1}\left(\frac{2\sigma_{xy}^t}{\sigma_{xx}^t - \sigma_{yy}^t}\right)$$  \hspace{1cm} (10)

with $\theta$ is the orientation from one main axis to the x axis as shown in Figure 2, and the other is at $\theta \pm 90^\circ$. From these two orientations, it is necessary to choose the angle with the greatest compression $\theta_1$, thus the optimum fault angle $\psi_0$ is given with $\theta_1 \pm \beta$. Stress changes in the optimum fault area are determined from $\sigma_{ij}^t$, but for normal changes in stress and shear stress in these fields are determined only by changes in stress due to the earthquake $\sigma_{ij}^q$. Then the stress changes in the optimum fault area become:

$$\sigma_{33} = \sigma_{xx}^q \sin^2 \psi_0 - 2\sigma_{xy}^q \sin \psi_0 \cos \psi_0 \cos^2 \psi_0 + \sigma_{yy}^q \cos^2 \psi_0$$  \hspace{1cm} (11)

$$\tau_{13} = \frac{1}{2} (\sigma_{yy}^q - \sigma_{xx}^q) \sin 2\psi_0 + \tau_{xy}^q \cos 2\psi_0$$  \hspace{1cm} (12)

$$\sigma_{f}^{opt} = \tau_{13} - \mu \sigma_{33}$$  \hspace{1cm} (13)

The above equation can be applied to the left-lateral and right-lateral shear faults. It should be emphasized that the calculation of coulomb stress changes is carried out in the optimum field after the earthquake. The optimum field orientation is calculated from the total stress after the earthquake, and coulomb stress changes caused by changes in earthquake stress are resolved in the optimum field. [8].

A positive coulomb stress change can be interpreted that the first fault pushes the second fault so that the stress increases, this increase increases the chance of failure in the second fault. Coulomb stress with a negative value indicates that the first fault has undergone relaxation which causes the chance of failure to become smaller.
5. Result and Discussion

Figure 3. A. Coulomb Stress Change Event Mw=8.5 to Mw=7.9. B. Coulomb Stress Change Event Mw=8.5 to Mw=7.2

Figure 3 Significant Earthquake Cross Section Mw = 8.5 heading to Significant Earthquake Mw = 7.9. The cross section of one positive lobe marked with red is an area of increase in Coulomb voltage with a range of values ranging from 0.2 bar to 2.2 bar with a depth of up to 80 km. This can be interpreted that a significant earthquake Mw = 8.5 can trigger an earthquake significant with Mw = 7.9. These results also correspond to existing theories that an increase in Coulomb voltage can trigger the next earthquake event. Some research also shows similar things, as previous studies conducted by Xie et al. (2010) who examined the pattern of Coulomb stress changes by Ms Wenchuan earthquake = 8.0 and its effect on the occurrence of subsequent earthquakes. The results show that the next event lies in an area of increased stress. As well as the seismic activity shown by more than 90% aftershocks consistent with the Coulomb voltage increase area.

Figure 3.1 B is the result of Significant Earthquake Cross Section Mw = 8.5 heading to Earthquake Significant Mw = 7.2 through reading the area of increase the Coulomb voltage has a range of values ranging from 0.2 bar to 0.4 bar. This is interpreted that a significant earthquake Mw = 8.5 can trigger a significant earthquake with Mw = 7.2

Figure 4. Effect of Coulomb Stress Changes from Earthquake Events 09/12/2007 with Mw = 8.5 on Earthquake Events 09/13/2007 with Mw = 7.0
Figure 4 is describe the area that accumulates voltage ranging from 0.1 bar to 5 bars with a depth of more than 90 km. If returning to the time of a significant earthquake (Research Table 4.1) a significant earthquake with Mw = 7.0 occurs only a few hours range from a significant earthquake Mw = 8.5, so it can be categorized that a significant earthquake Mw = 8.5 triggers a significant earthquake Mw= 7.0.

Figure 5. Effect of Coulomb Stress Changes from Earthquake Events 09/12/2007 with Mw = 8.5 on Earthquake Events 09/30/2009 Mw = 7.6

Figure 6 Effect of Coulomb Stress Changes from Earthquake Events 09/12/2007 with Mw = 8.5 on Earthquake Events 10/25/2010 Mw = 7.8

Figure 5 and Figure 6 have the same effect of the Coulomb Stress Change, which is 0.2 bar, but the difference is in Figure 5 the depth reaches 70 km while in Figure 6 the depth reaches 40 km.

Figure 7. Distribution of Coulomb Stress Changes 10/25/2010 to depth
From Figure 7 it can be seen that Coulomb positive and negative voltage changes work up to a depth of more than 150 km. In general, the positive Coulomb voltage change distribution is more dominant compared to the negative Coulomb voltage change distribution. This means that after a large earthquake occurred on October 25th, 2010, the Mentawai segment area still has a high accumulation of stress. This can indicate that the Mentawai segment area still has a chance of a large earthquake in the future.

6. Conclusion
A significant earthquake with Mw = 8.5 that occurred on September 12th 2007 was the source of the trigger and triggered a significant earthquake on September 13th 2007, February 25th 2008, September 30th 2009 and October 25th 2010. Whereas the earthquake was large on 25 October 2010, within the Mentawai segment still has a high accumulation of stress so that it has the chance of a large earthquake in the future.

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