Deformation analysis for Padang earthquake using GPS data

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Abstract. On September 30, 2009, an Mw 7.6 earthquake occurred off the coast of Sumatra. This earthquake caused deformation in the area around the center of the earthquake. Surface deformation in the area around the epicenter was analyzed using GPS data from the SuGAr (Sumatran GPS Array) network. The observed SuGAr stations were TIKU, PSKI, NGNG and MSAI. Data processing used GAMIT / GLOBK software. GPS data were observed for 100 days before and after the main earthquake occurrence. The measurement results indicate that the MSAI and NGNG stations in Mentawai deformed towards the south-west direction, varies between 38 - 50 mm, and TIKU and PSKI stations on the mainland of Sumatra were deformed in north-west directions, varies from 5 - 12 mm. This indicates that this Earthquake deformed the area of Western Sumatra and nearby Mentawai regions, in Siberut Island.

1. Introduction

West Sumatra Province is a province where earthquakes often occur. This region includes part of the Eurasian plate and the Indian Ocean plate which moves slowly following its direction. The province of West Sumatra is located in the western part of Sumatra Island, which is part of the Eurasia Plate and Indian Ocean which moves very slowly and is relative to the southeast and north with speed about 0.4 - 7 cm/year[1]. This region also has faults, namely the Sumatra Fault and the Mentawai Fault. The Sumatra Fault System moves across the island of Sumatra while the Mentawai Fault Zone an ascending fault around the Mentawai islands [2]. This causes West Sumatra Province to have a high level of seismicity. One of the earthquakes with a high seismic level occurred on September 30, 2009 in West Sumatra.

The earthquake that occurred had a high enough magnitude, causing severe damage to several areas in West Sumatra. Earthquakes occur due to vibrations and shaking on the surface due to the release of seismic wave energy in the earth's crust. This energy respiration causes deformation of tectonic plates in the earth's crust[3]. This large earthquake has a strength of Mw 7.6 at a depth of 80 km in West Sumatra[4]. Several areas in West Sumatra major building damage, where 135,448 houses with severe damage, 65,380 houses with moderate damage, and 78,604 houses with minor damage[5]. The large amount of damage to infrastructure and other material losses was caused by the earthquake.

The movement of deformation changes can be done with a geodetic approach, namely using InSAR technology (Interferometry Synthetic Aperture Radar) and GPS (Global Positioning System) technology. The suitable technology for measuring deformation due to seismicity is GPS, because it
has a higher order precision compared to InSAR[6]. GPS technology can provide vector values for the deformation of the earth's crust in three dimensions, meaning that GPS can provide deformation information in horizontal and vertical directions with a degree of precision up to the order of millimeters and good consistency[7]. The islands of Sumatra and the Mentawai Islands have GPS stations that are used to store tectonic plates, namely the SuGAr (Sumatran GPS Array) station. The SuGAr used is installed and operated by the Earth Observatory of Singapore (EOS) and the Indonesian Institute of Sciences (LIPI)[8]. SuGAr works by recording the position of the station every time interval (15 minutes) to find out the value of the shift or movement of the earth's tectonic plates in the lithosphere layer. Based on the research that has been done, there is still little that discusses the estimation of deformation changes due to earthquakes using GPS data.

![Figure 1. Geological map of the study area. The darkgreen circle shows the location of the SuGAr station used in the deformation analysis. Black beach-call shows Mw7.6 earthquakes that occurred 30 September 2009. Plate boundaries for megathrust were plotted based on Bird 2003 with additional plot for the Sumatran Fault and Mentawai Back Thrust[9].](image)

2. Data and Methods
This research was be observed in a span of 100 days before (Preseismic), during (coseismic), and after (pascaseismic) an earthquake occurred using GPS technology, also known as GNSS (Global Navigation Satellite System) through the SuGAr station, Sumatran GPS Array (SuGAr) is GPS stations spread along 1300 km along the west coast of Sumatra Island. SuGAr was initiated by Professor Kerry Sieh, et al., from the California Institute of Technology (CalTech) Tectonics Observatory (TO) in collaboration with the Indonesian Institute of Sciences (LIPI) in 2002. The total number of SuGAr stations installed is 58 stations on Sumatra Island. The SuGAr station directly sends data to the central server located on the LIPI Bandung and EOS Singapore campus. There are four SuGAr stations used in this study, namely TIKU, PSKI, MSAI and NGNG.
Table 1. Location of Station SuGAr used for analysis

| No | Station Name | Location | Coordinate | First Epoch | Last Epoch |
|----|--------------|----------|------------|-------------|------------|
| 1  | PSKI         | Sikuai Island | -1.1247, 100.3530 | 2009 01 02 | 2009 12 31 |
| 2  | TIKU         | Tiku     | -0.3991, 99.9442 | 2009 01 02 | 2009 12 31 |
| 3  | MSAI         | Muara Saibi, Siberut Island | -1.3264, 99.0895 | 2009 01 02 | 2009 10 04 |
| 4  | NGNG         | Nyang-Nyang, Siberut Island | -1.7996, 99.2683 | 2009 01 02 | 2009 12 29 |

The form of data used in deformation analysis via GPS is in the RINEX (Independent Exchange Receiver) format. The RINEX format is used to calculate the deformation associated with an earthquake by using the changes in each point caused by the earthquake. This research was assisted by using the GAMIT / GLOBK (GPS Analysis of Massachusetts Institute of Technology) software (ver. 10.70) to obtain daily position data. GAMIT results were processed based on the Kalman Filtering method using the program GLOBK (Global Kalman Filter VLBI and GPS analysis)\(^{[10]}\). Determination of the Size and Shift Direction of the SuGAr Station. SuGAr observation data for 2009 which were processed using GAMIT / GLOBK, resulted in data in the form of changes in the daily coordinate position of the SuGAr station, namely the latitude and longitude positions\(^{[11]}\).

Figure 2. Position data from GLOBK which applied Kalman Filtering Method. Each point (in dark blue) shows the observation data with the error bars.
Figure 2 is a time series of 1 year position data from GLOBK which applied Kalman Filtering Method. The error bars and NRMS value indicate the error level of the calculation, which seems quite significant (WRMS = 5 mm) in TIKU due to the incomplete data, and WRMS < 3 mm for PSKI. Other two stations: MSAI and NGNG are having largest WRMS because the calculation included the correction of other earthquake occurred 47 days before Padang earthquake, and was centered closed to this three sites.

The data on the change in position of each SuGAr station can be seen using the deformation shift vector at each SuGAr station point calculated in the coordinate system using the equation:

\[
\begin{align*}
    dE_{12} &= (E_2 - E_1) \times 111320m \\
    dN_{12} &= (N_2 - N_1) \times 111320m
\end{align*}
\]  

Where :

- \(dE_{12}\) = Deformed of SuGAr Station to the east
- \(dN_{12}\) = Deformed of SuGAr Station to the north
- \(E_1\) = Longitude position at the start of the SuGAr station
- \(E_2\) = Longitude position at the last of the SuGAr station
- \(N_1\) = Latitude position at the start of the SuGAr station
- \(N_2\) = Latitude position at the last of the SuGAr station

1 degree (latitude or longitude) = 111320m

The value \(dE_{12}\) and \(dN_{12}\) obtained are still coordinates in degrees. To convert coordinates to distance in meters is to multiply by the value 111320 m. The direction and magnitude of the displacement of the SuGAr station can be determined by calculating the resultant shift vector of the SuGAr station. The resultant amount is calculated using the equation:

\[
R = \sqrt{(dE_{12})^2 + (dN_{12})^2 + 2dE_{12}dN_{12}\cos\theta} \tag{3}
\]

Where :

- \(R\) = Resultant deformed SuGAr station
- \(\theta\) = The Angle formed \(dE_{12}\) and \(dN_{12}\)

Resultant direction is calculated using:

\[
\tan \theta = \frac{dN_{12}}{dE_{12}}
\]

\[
\theta = \arctan \left(\frac{dN_{12}}{dE_{12}}\right) \tag{4}
\]

Based on the results of processing assisted by GAMIT / GLOBK software, the value of the deformation shift of the four observed stations is obtained:
Figure 3. Timeseries including seismic cycle (Pre-, Co-, and Post-seismic) recorded by SuGAr. Green dashed vertical line is the epoch of Padang earthquake, and the grey dashed line is other earthquake in Mentawai recorded by MSAI and NGNG in Siberut. Each point (in dark blue) shows the observation data and and darkred is curve-fit for each observation.

Figure 4. Geological map of the area and measurement points
Figure 4 shows the SuGAr horizontal deformation vector in the preseismic phase from the first available epoch (2009 01 02) to a day before the jump. It can be seen that SuGAr stations have different horizontal shift directions but all indicated stable movement before the earthquake[9].

The coseismic phase is the process by which an earthquake occurs and causes a large deformation. Figure 5 shows the vector displacement of the SuGAr station during the September 30, 2009 Padang earthquake. Table 2 shows that SuGAr stations have various movement direction and opposite to the preseismic direction.

Table 2: Coseismic Jump recorded on SuGAr stations

| Site name | Lon (deg) | Lon (deg) | East (mm) | North (mm) | Horizontal Movement (mm) | Direction |
|-----------|-----------|-----------|-----------|------------|------------------------|-----------|
| MSAI      | 99.090    | -1.326    | -40.2     | -31.1      | 50.83                  | south-west |
| NGNG      | 99.268    | -1.780    | -22.3     | -30.8      | 38.03                  | south-west |
| PSKI      | 100.353   | -1.125    | -3.6      | 4.7        | 5.92                   | north-west |
| TIKU      | 99.944    | -0.399    | 4.6       | 10.5       | 11.46                  | north-east |

Figure 5. Map showing the coseismic jump of Padang Earthquake. Yellow arrows is indicating the movement of each SuGAr station during the event, and red circle is indicating error ellips with 95 confidence level[9].

3. Conclusions
From the RINEX processing of 4 SuGAr stations in 2009, before the earthquake occurrence, it can be concluded that most stations in the Forearc Islands Mentawai is moving toward the south-west, following the subduction trend of the Sunda megathrust, and this trend is also seen after the earthquake.
For the of stations in the northeast Sumatra, the trend of deformation is supported by the combination of subduction force towards the northeast and the dextral-strike-slip fault of Sumatran Fault or Semangko Fault. Where, the measurement results indicate that the MSAI and NGNG stations in Mentawai were moved south-west ward, varying between 38 - 50 mm, and TIKU and PSKI stations on the mainland of Sumatra were deformed in north-west directions, varying from 5 - 12 mm. The same trend of similarities for both preseismic and postseismic is seen in most mainland stations. In this condition there is also no anomalous behavior prior to this intraslab earthquake as a precursor to be taken into account. This study also requires further analysis to model faults affecting the surrounding area.

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