Pre- and Coseismic Analysis of the Mw7.6 Padang Earthquake 2009 from Geodetic Approach

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Abstract. On September 30, 2009, an Mw7.6 earthquake hit the west coast of Sumatra. This main shock caused the crustal deformation affecting a wide area in the western part of Sumatra. This paper presents the analysis of the deformation recorded by the Sumatran GPS Array (SuGAr) network. More than 40 GPS stations were installed to continuously monitor the deformation in Sumatra, among 12 of them is known to have been deformed by this earthquake. We processed whole data in 2009 to understand the dynamics of western part of Sumatra before, during and after the earthquake. Relative daily position data is obtained from postprocessing with GAMIT/GLOBK software, implementing the DGPS technique to estimate daily position from GPS RINEX data. GPS measurements show that during the earthquake, most stations in Mentawai is deformed toward the southwest direction, varies from 8 – 50 mm, and the stations in mainland Sumatra is deformed toward various direction, varies from 5 – 28 mm. There is no anomaly and strange behaviour before the event as the precursor, and the deformation trend one day after the events seems to return to the preseismic pattern.

1. Introduction

1.1. Geological Setting

Indonesia is located at the boundary of the Indo-Australia, Eurasia, and the Pacific plates. The Indo-Australian oceanic Plate is obliquely subducting the Eurasian Plate, striking N140E at the rate of 50 - 70 mm/yr [10]. The oblique direction is accommodated by the strike-slip fault running parallel to Sumatra Trench, known as the Sumatran Fault or the Semangko Fault [4] and the dip-slip is accommodated by the subduction interface [7]. Sumatran Fault lies along the volcanic line and is a type of dextral-strike-slip fault (Figure 1).

Fore-arc Island Mentawai and Sumatra sits atop Eurasian Plate, and also discovered to have the active fault, Mentawai Backthrust, parallel to the Sunda Fault Zone [2]. This fault is a strike-slip fault corresponds to the fore-arc domain [6]. This mechanism makes the western part of Sumatra and Mentawai prone to the numerous earthquakes from the activity of Sunda Megathrust, Mentawai Backthrust, and Sumatran Fault.
1.2. The 2009 Mw7.6 Padang Earthquake

The 2009 Mw7.6 earthquake shook the low-lying crustal city of Padang and Pariaman and its surrounding area, on 30 September 2009, centered 60 km northwest of the city, on the eastern edge of the locked segment, at the depth of 80-90 km within the oceanic slab of the Indo-Australian Plate [14]. Based on the fault mechanism, the earthquake is more likely an intraslab event rather than on the plate interface.

This earthquake affected a population of 900,000 people in Padang and 80,000 people in Pariaman [3]. [2] and [12] had reported 1.117 deaths from this earthquake together with 135,448 major building damages and more than 60,000 medium to minor damages. This high number of death is related to the time of earthquake occurrence during the office and school hour.

This earthquake was fortunately caused by deep rupture that didn’t generate tsunami, other disaster that Padang is anticipating from. It also caused no effect to the Mentawai segment of Sunda Megathrust, which is believed to have 200 years stress accumulation in Siberut. This accumulation is
projected to have ruptured a large area of Sunda megathrust, causing Mw > 8.5 event with the probability to inundate many cities along the west coast of Sumatra [8].

2. Data and Processing
This study is conducted on the geodetical approach based on the change of position before, during and after the earthquake. This type of data is made possible by the existence of satellite geodetic instrument, GNSS.

GNSS, Global Navigation Satellite System, is commonly known as GPS. GPS is basically one of the satellite system developed by US Navy, stands for Global Positioning System (or formally: NavSTAR-GPS – Navigation System Timing and Ranging – Global Navigation Satellite System). Together with Russian Federation’s GLONASS (Global Navigation Satellite System), Chinese’ BeiDou, India’s IRNSS (Indian Regional Navigation Satellite System), and Japanese QZSS (Quasi-Zenith Satellite System), they provide the GNSS-science monitoring, especially used for Hazard Monitoring [13].

2.1. GNSS Data for Earthquake Monitoring
Satellite geodetic technique e.g., InSAR, GPS have been widely applied in seismotectonic investigation. The low-cost, handy and high-accuracy of GPS measurement, lead to the installation of continuous GPS networks.

GNSS has become an important technology to calculate the crustal deformation and the displacement waves produced by the earthquakes. GPS/GNSS, with its millimeter scale precision, make it possible to accurately measure the change of position of a certain point, make it possible to monitor any change caused by earthquake and other phenomena. This lead the geodynamics study to utilize this instrument and do both temporary and continuous deformation monitoring.

2.1.1. Sumatran GPS Array (SuGAr).
The Sumatran GPS Array (SuGAr) spans more than a thousand kilometers of the convergent plate boundary between Indo-Australian and Asian tectonic plates. This network provides a wealth of information on the Sunda megathrust and the Sumatran fault.

Numerous GPS stations are located on islands that directly overlie the locked sections of the Sunda megathrust: they are very well situated to record interseismic, coseismic and postseismic deformation of the upper part of the subduction zone. SuGAr has provides a great opportunity to understand pre- and post-seismic behaviour of the megathrust by monitoring tectonic deformation above it.

Table 1 shows 12 SuGAr stations available and continuously recorded the position before, during, and after Padang Earthquake. Some sites are located in the Fore-arc Islands of Mentawai, and others are located in the mainland Sumatra (See location in Figure 1).

| Site name | Lon (deg) | Lon (deg) | Height (m) | First Epoch | Last Epoch |
|-----------|-----------|-----------|------------|-------------|------------|
| ABGS      | 99.387    | 0.221     | 236.25     | 2009 08 31  | 2009 12 31 |
| KTET      | 99.841    | -2.363    | 35.20      | 2009 01 02  | 2009 12 31 |
| LAIS      | 102.034   | -3.529    | 20.48      | 2009 01 02  | 2009 12 08 |
| LNNNG     | 101.156   | -2.285    | 40.10      | 2009 01 02  | 2009 10 30 |
| MNNNA     | 102.890   | -4.450    | 28.54      | 2009 01 02  | 2009 12 21 |
| MSAI      | 99.090    | -1.326    | 29.18      | 2009 01 02  | 2009 10 04 |
| NGNG      | 99.268    | -1.780    | 46.28      | 2009 01 02  | 2009 12 29 |
| PKRT      | 99.543    | -2.151    | 31.82      | 2009 01 02  | 2009 12 31 |
| PPNJ      | 99.604    | -1.994    | 34.88      | 2009 01 02  | 2009 12 31 |
| PSKI      | 100.353   | -1.125    | 48.30      | 2009 01 02  | 2009 12 31 |
| TIKU      | 99.944    | -0.399    | 18.79      | 2009 01 02  | 2009 12 31 |
| TLLU      | 99.134    | -1.800    | 97.91      | 2009 01 02  | 2009 12 31 |
2.1.2. RINEX Data Processing and Analysis. All GPS data used in this analysis is in RINEX (Receiver Independent Exchange) format. It is used for calculating the crustal deformation associated with the earthquake by using three dimensional position at 15-second interval data, providing the record of vertical and horizontal position change caused by the earthquake. Beside LIPI’s RINEX data archive, SuGAr’s RINEX data is freely available for download through UNAVCO (University NAVSTAR Consortium), CDDIS (Crustal Dynamics Data Information System), and SOPAC (Scripps Orbit and Permanent Array).

Differential GPS Positioning (DGPS) and Precise Positioning Point (PPP) are the accurate positioning method on GPS [9]. DGPS method requires access to more than one reference station whose coordinates are known, whereas the PPP method works as a single station to get satellite data. This study applied DGPS method using GAMIT (GPS Analysis of Massachusset Institute of Technology) processing software (ver. 10.70) to obtain the daily position data.

Result of GAMIT is processed based on the Kalman Filtering method using GLOBK (Global Kalman Filter VLBI and GPS analysis program). It is a suite of programs designed to combine geodetic results and calculate the GPS coordinates in the ITRF2014 reference frame [5].

GAMIT/GLOBK was developed using the DGPS method or relative positioning, where the position of the station can be obtained and determined based on its distance from other stations as a reference. Each point in DGPS method is measured and defined relative to a reference point. Analyzing SuGAr’s sparse GPS array with GAMIT/GLOBK is quite a challenge, but more precise process could yield more accurate position. Despite its time consuming process, GAMIT/GLOBK require manual preparation which cause the errors to be controlled and corrected beforehand [5]. All factors including ocean tidal, atmospheric, and satellites orbit has been included to reduce the possible errors. Furthermore, stations in Indonesia are still quite far from each other, but with more thorough support, the results are quite good.

The cleaning and filtering mode also make more precise correction, as well as correcting the effect of tropospheric delay during data transmission. GAMIT analysis is followed by the Kalman Filtering for obtaining the GPS coordinate in daily position. This position data timeseries is plotted in three-dimensional plots to show the change in position and its dynamics related to any seismic event. The position data was further analyzed to estimate model of the deformation before, during and after the earthquake and be compared with the observation data. Its curve-fit is the indication for the correct estimation.

2.1.3. Position Data. Continuous GPS data can be used to construct the displacement time series to detect the sudden change in position, and further be used to monitor the energy release after the earthquake.
Figure 2. One year position data from GLOBK which applied Kalman Filtering Method. X-axis is the time of observation, upper figure in Y-axis is the Northward displacement in mm, and lower figure is the Eastward displacement in mm. Dark blue curve shows the observation data with the error bars.

Figure 2 is a time series of one 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 LNNG, PPNJ, PKRT, and ABGS due to the incomplete data, and WRMS < 3 mm for KTET, LAIS, and MNNA. Other three stations: TLLU, MSAI, and NGNG are having the largest WRMS because the calculation included the correction of other earthquake which occurred 47 days before Padang earthquake, and was centered closed to these three sites.

2.1.4. Annual Velocity Map. Velocity map is obtained from glred function in GAMIT/GLOBK which is mainly based on repeatability analysis and combine average position to estimate velocities.

Position data plotted was further processed to obtain annual velocities of all SuGAr stations in default reference frame (ITRF14) (Figure 3). Figure shows that most stations in the the Fore-arc Mentawai is moving northeastward, following the direction of the oblique subduction of the Eurasian
plate. Meanwhile, the stations in the mainland Sumatra is moving as the result of this subduction as well as the dextral strike slip force from Sumatran Fault.

![Figure 3](image-url)

**Figure 3.** Annual Velocity generated from position data in the ITRF14 reference frame, black circle at the tip of arrow is indicating the error ellips with 95 confidence level.

3. **Result**

The results include the post-processing and analysis of position and velocities, and model-to-observation comparative fitting of preseismic trend and coseismic jump.

Preseismic trend was observed and estimated for ~9 months (because of data availability’s first epoch is 2 January for most of stations). The postseismic trend is observed from one day after the earthquake until the latest available data (31 December 2009, for most stations).

3.1. **Seismic Cycle**

Figure 4 shows the result of modeling the earthquake cycle (dark-red curve) compared to the observation data (blue dots). This curve-fit is the indication for the correct estimation. The estimation of whole cycle is used to understand the seismic trend before, during and after the earthquake.
Figure 4. 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, TLLU and NGNG in Siberut. Each point (in dark blue) shows the observation data and the darkred is curve-fit for each observation.

3.1.1. Preseismic Trend. In principle, the preseismic deformation is not of much concern because of its smaller size compared to coseismic. To focus on the prosthesis, it is necessary to enlarge the range on the vertical axis (position).
Figure 5 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. Only LAIS and LNNG in Bengkulu (mainland Sumatra) show the tendency of southwestward movement. Other stations indicate the tendency of shifting towards the northeast.

The displacement before the earthquake occurrence varies for each station. Based on Figure 4, most deformation trends before the earthquake leads to the northeast direction. This is in accordance with [11] which explains that the movement of Fore-arc Islands Mentawai leads to the northeast, following the direction of plate sloping. The stations in the mainland Sumatra is following both oblique subduction from the megathrust and dextral-strike-slip of Sumatran fault. In this process, we found that during the preseismic cycle, both mainland Sumatra and northern Mentawai experienced no change, and there is no anomaly found before the earthquake.

Figure 5. Geological map of the area and measurement points

3.1.2. Coseismic Jump. The coseismic phase is the process by which an earthquake occurs and causes a large deformation. Figure 6 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     |
|-----------|-----------|-----------|-----------|------------|--------------------------|---------------|
| ABGS      | 99.387    | 0.221     | 10.1      | -13.2      | 16.62                    | south-east    |
| KTET      | 99.841    | -2.363    | -4.4      | -6.7       | 8.02                     | south-west    |
| LAIS      | 102.034   | -3.529    | -3.2      | 5.4        | 6.28                     | north-west    |
| LNNG      | 101.156   | -2.285    | -23.9     | 14.0       | 27.70                    | north-west    |
| MNNA      | 102.890   | -4.450    | -4.6      | 3.0        | 5.49                     | north-west    |
| 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    |
| PKRT      | 99.543    | -2.151    | -8.1      | -17.5      | 19.28                    | south-west    |
| PPNJ      | 99.604    | -1.994    | -9.0      | -21.4      | 23.21                    | 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    |
| TLLU      | 99.134    | -1.800    | -20.7     | -27.0      | 34.02                    | south-west    |

Figure 6. Map showing the coseismic jump of Padang Earthquake. Red arrows is indicating the movement of each SuGAr station during the event, and red circle is indicating error ellips with 95 confidence level.
MSAI in northern part of Mentawai seems to have the largest shift of 50.83 mm, while the smallest shift is MNNA which moved 5.49 mm. It can be concluded that in the coseismic phase of the nearer position from the epicenter is much larger in coseismic jump than that of the further ones. The further away the station is from the epicenter, the smaller the shift will be.

3.1.3. Postseismic Trend. For most cases of megathrust earthquakes, the coseismic deformation is followed by high velocity of postseismic movement, which gradually slows down to nearly zero (back to its initial/preseismic velocity). Figure 7 shows for the deformation trend of LNNG station, affected by the 2007 megathrust earthquake and the 2009 intraslab earthquake. The megathrust earthquake is commonly resulting weeks to years of postseismic deformation after its rupture, shown as gradual velocity change from the day of earthquake to two years after. This postseismic trend does not seem to have occurred after the intraslab earthquake, where the deformation rate after the coseismic rupture seems to immediately return to its initial/preseismic rate.

The timeseries of Figure 4 shows the trend of deformation vector before (preseismic) and after the earthquake (postseismic). The comparison of the preseismic and postseismic trend from Figure 4 is indicating that most SuGAr stations has the same deformation pattern on both preseismic and postseismic period. This can be clearly seen from KTET, LNNG, MSAI, PKRT, PPNJ, PSKI, TIKU and TLLU stations. It indicates that there is no postseismic displacement resulted from this intraslab event, giving it the clear distinction from the megathrust event.

![Figure 7](image)

**Figure 7.** Comparison of postseismic deformation, a). The Mw7.6 2009 Padang Earthquake and b). The Mw8.4 2007 Bengkulu earthquake.

4. Conclusion
From the RINEX processing of 12 SuGAr stations in 2009, before the earthquake occurrence, it can be concluded that most stations in the Fore-arc Islands Mentawai is moving toward the northeast, following the subduction trend of the Sunda megathrust, and this trend is also seen after the earthquake. This also support the previous study that the 2009 Mw7.6 Padang earthquake, despite its large size and close epicenter, is not activating the Mentawai segment of Sunda megathrust [8].

For the stations in the west-coast Sumatra, the trend of deformation is supported by the combination of subduction force towards the northeast and the dextral-strike-slip of Sumatran Fault or
Semangko Fault. The same trend of similarities for both preseismic and postseismic is seen in most mainland stations.

This also confirmed that there were no anomalous behaviour before this intraslab earthquake as the precursor to take into account.

This study also require further analysis to model the fault mechanism responsible for the rupture, and understand how wide it was affecting the surrounding area, as well as estimating the impact of this intraslab earthquake to the activation of the ‘silent’ Mentawai Segment.

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DA mainly drafted the manuscripts and all authors contributed in the writing and proofreading process.

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