

Estimation of postseismic deformation parameters from continuous GPS data in northern Sumatra after the 2004 Sumatra-Andaman earthquake

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Abstract Continuous global positioning system (GPS) in northern Sumatra detected signal of the ongoing physical process of postseismic deformation after the $M9.2$ 2004 Sumatra-Andaman earthquake. We analyze the characteristics of postseismic deformation of the 2004 earthquake based on GPS networks operated by BIG, and the others named AGNeSS, and SuGAR networks located in northern Sumatra. We use a simple analytical logarithmic and exponential function to evaluate the postseismic deformation parameters of the 2004 earthquake. We find that GPS data in northern Sumatra during time periods of 2005–2012 are fit better using the logarithmic function with τ_{\log} of 104.2 ± 0.1 than using the exponential function. Our result clearly indicates that other physical mechanisms of postseismic deformation should be taken into account rather than a single physical mechanism of afterslip only.

Keywords The 2004 Sumatra-Andaman earthquake · Continuous GPS data · Logarithmic and exponential functions

1 Introduction

Indonesia is surrounded by four major plates; they are Eurasian plate, Indo-Australian plate, Pacific plate, and Philippine plate. This complex tectonic condition may cause earthquakes. These earthquakes possibly occur in the area of subduction zones, such as the 2005 $M8.7$ Nias earthquake (e.g., Kreemer et al. 2006), the 2010 $M7.8$ Mentawai earthquake (e.g., Hill et al. 2012), the 1994 $M7.8$ and 2006 $M7.8$ Java tsunami earthquake (e.g., Bilek and Engdahl 2007), and along the inland faults, such as the 1987 $M6.6$ Toru earthquake (Sieh and Natawidjaja 2000) and the 2013 $M6.1$ Aceh earthquake (Ito et al., manuscript in preparation, 2015). One of the active inland fault zones is the Great Sumatran Fault (GSF). GSF, one of the world's greatest fault zones located inland of Sumatra, consists of 20 segments (Sieh and Natawidjaja 2000) starting from the southern Sumatra with a plate movement of 12 mm/a (Meilano, Susilo and Gunawan, manuscript in preparation, 2015) to the northern Sumatra with the increasingly rapid movements of 20 mm/a (Ito et al. 2012). Historically, magnitude 7 class earthquakes have been occurred along GSF (Sieh and Natawidjaja 2000).

One of the large megathrust earthquakes occurred due to subduction process between Indo-Australian plate and Eurasian plate was the 26 December 2004 $M9.2$ Sumatra-Andaman earthquake (Fig. 1) (e.g., Subarya et al. 2006). According to the geodetic and geological estimation, the continental shelf of Southeast Asia moves independently than Eurasian plate defined as Sundaland block (e.g., Bock et al. 2003). The 2004 Sumatra-Andaman earthquake resulted from devastating tsunami with the lost of more than 280,000 inhabitants (e.g., Sieh 2006). This earthquake is considered as a megathrust earthquake with a longest rupture compared with other earthquakes (Shearer and

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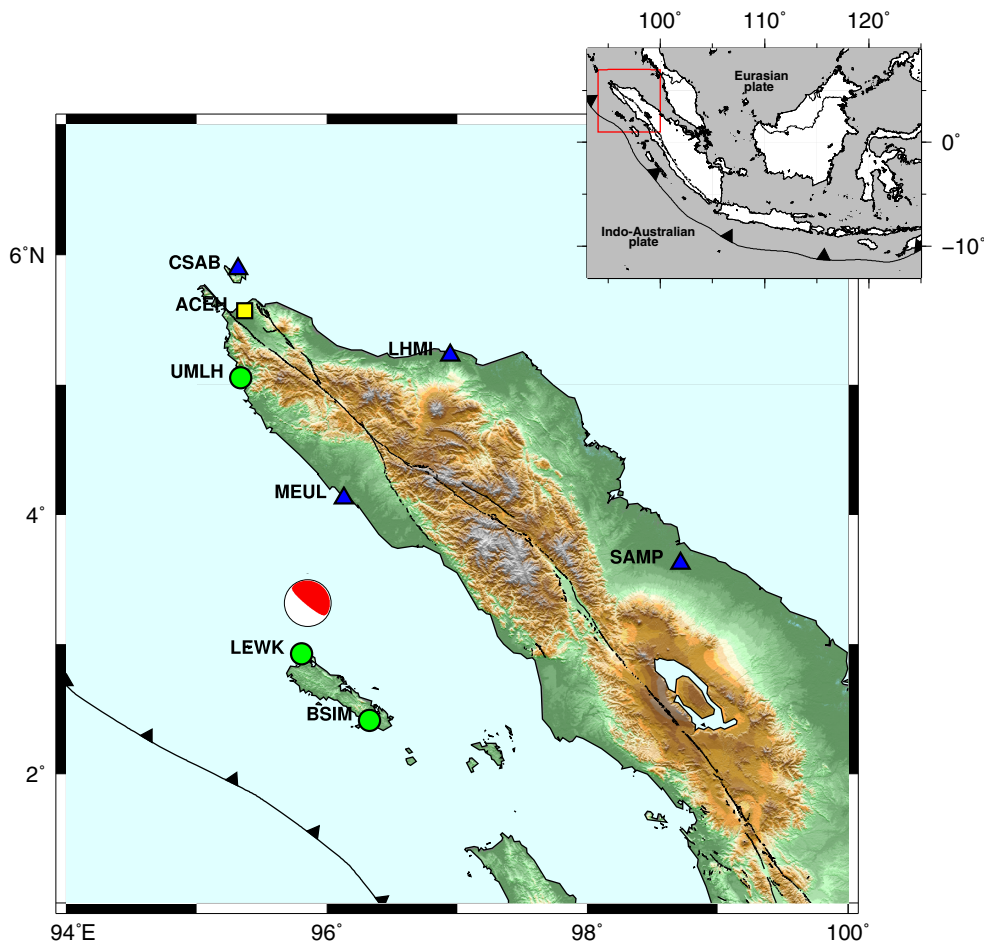


Fig. 1 The distribution of GPS sites used in this study. *Blue triangle* indicates the GPS sites of BIG, while *green circle* denotes the GPS site of SuGAR, and *yellow square* implies the GPS site of AGNeSS. The epicenter of the 2004 Sumatra-Andaman earthquake obtained from USGS catalog. *Black lines* inland of Sumatra show the location of GSF. *Inset* shows larger regional setting

Bürgmann 2010). Rupture along the ~ 1600 km starts from the epicenter near the island of Simeulue (3.3160°N , 95.8540°E) and continuously up to the Andaman Islands with a speed of 1 km/s (Fujii and Satake 2007). That rupture completed within about 10 min and be a source of nuisance of sea water volume in which became a devastating tsunami (Chlieh et al. 2007).

After the 2004 Sumatra-Andaman earthquake, governments and institutions of many countries have collaborated together to understand deeply this earthquake. Many researchers have been trying to understand the characteristics of the 2004 Sumatra-Andaman earthquake so that they might determine the further earthquakes occurrence potential as well as analyze and evaluate the disaster mitigation in northern Sumatra. For instance, the cooperation between the universities from Indonesia and Japan resulted in the project of global positioning system (GPS) observation spread across several regions in northern Sumatra. This GPS network named AGNeSS (Aceh GPS Network

for the Sumatran Fault System) (Ito et al. 2012; Gunawan et al. 2014). Previous studies suggested that there are ongoing postseismic activities due to the 2004 Sumatra-Andaman earthquake with the movement of 5–15 cm per year observed in the Andaman Islands (e.g., Som et al. 2011, 2014), and also in Thailand (e.g., Panet et al. 2010). Furthermore, Gunawan et al. (2014) suggested that post-seismic deformation in the long-term period after earthquake occurrences corresponds to viscous flow in the asthenosphere. They showed that contribution of afterslip during one year periods from end of 2005 to end of 2006 corresponds to $\sim 60\%$ of GPS data displacements.

This study analyzes the continuous GPS data available in northern Sumatra which clearly detect the significant signal of postseismic deformation after the 2004 Sumatra-Andaman earthquake. We use more new continuous GPS data observed by the network that is installed and maintained by Geospatial Information Agency of Indonesia (BIG) in northern Sumatra. This GPS data is very

important because it has never been published by any previous researches before. Additionally, this continuous GPS data may capture the ongoing process of postseismic deformation in northern Sumatra after the 2004 Sumatra-Andaman earthquake. Here, we focus on determining the postseismic deformation parameters of the GPS data time series using simple analytical logarithmic and exponential functions.

2 Data and method

Data used in this study are continuous GPS data observed in northern Sumatra. One GPS network is operated by BIG, and the other GPS networks are named AGNeSS, and SuGAR (Sumatran GPS Array). Figure 1 shows the distribution of GPS sites used in this study.

GPS sites of CSAB, LHMI, MEUL, and SAMP were installed and maintained by BIG. Among these sites, SAMP is the oldest one which has been established since 1997. Then, MEUL was constructed in 2008, followed by LHMI in 2010 and CSAB in 2011. ACEH site is part of AGNeSS, has been installed and maintained since 2005 by the collaboration of Nagoya University, Kochi University, Tohoku University, Bandung Institute of Technology, and Sajah Kuala University (Ito et al. 2012). BSIM, LEWK, and UMLH sites are part of SuGAR installed and maintained since 2005 by Earth Observatory of Singapore (EOS) and Indonesian Institute of Sciences (LIPI) (Feng et al. 2015).

Time series of ACEH was published by previous studies (Ito et al. 2012; Gunawan et al. 2014), so we used their result for further analysis. For other sites, we performed GPS data processing using GAMIT 10.5 to obtain daily solutions (Herring et al. 2010). We used three steps to process the data with GAMIT 10.5. First step is data preparation. It means to prepare raw phase and pseudo-range data in the form of ASCII X-files, station coordinates in the form of L-file, receiver and antenna information for each site, satellite list and scenario, initial conditions for the satellites orbits in a G-file, satellite and station clock values, control files for the analysis, standard tables to provide lunar/solar ephemerides, the Earth's rotation, geodetic datums, and instrumentation information. Second, creating model of each parameter to solve the phase ambiguity to obtain a preliminary coordinate of each site observation. Third, we fix the preliminary coordinate result to IGS sites such as KIT3, HYDE, COCO, DGAR, IISC, KUNM, CUSV, NTUS, BAKO, XMIS, TNML, TWTF, PIMO, DARW, KARR, YAR2, CNMR, GUAM, TOW2, KOUC, and obtain daily solutions in International Reference Frame (ITRF) 2008 (Altamimi et al. 2011).

In order to make the GPS data much more appropriate for tectonics discussion, we need to use the time series data in the Sundaland block reference frame. So after obtaining daily solutions in ITRF2008, we transformed these time series data to obtain daily solutions in the Sundaland block. We use rotation pole proposed by Simons et al. (2007) with parameters of 49.0°N , -94.2°E , $0.336^{\circ}/\text{Ma}$, which is calculated using 28 GPS sites located in South East Asia region. In order to use these parameters correctly, first, we transformed the daily solutions from ITRF2008 into ITRF2000 (Altamimi et al. 2011). Second, we transformed daily solutions from ITRF2000 reference frame into Sundaland block reference frame.

We matched these data based on characteristics of afterslip using logarithmic function (Marone et al. 1991), defined as $u(t) = c + a \ln(1 + t/\tau_{\log})$. We compare the results with other definition of data fit using exponential function (Savage and Prescott 1978), defined as $u(t) = c + a(1 - e^{-t/\tau_{\exp}})$. In these functions, $u(t)$ is horizontal component position, c is data offset and a is amplitudes, while τ_{\log} and τ_{\exp} are decay time of afterslip for logarithmic function and exponential function. We fit the time series horizontal data to these two functions, and search for the unknown parameters of c , a , τ_{\log} , and τ_{\exp} , respectively.

3 Result and discussion

3.1 Time series analysis

The daily solutions of GPS data processing were used to analyze and determine the characteristics of each GPS observation site and the quality of observational data distribution. The displacement characteristics of each observation station were then determined by analyzing the time series of the horizontal components in each GPS site that refer to the Sundaland block reference frame. Figure 2 shows the daily solutions of each GPS site in northern Sumatra.

Previous studies suggested that northern Sumatra experienced significant coseismic and postseismic deformation of the 12 April 2012 $M8.6$ Indian Ocean earthquake (e.g., Yadav et al. 2012; Wei et al. 2013; Hill et al. 2015; Han et al. 2015). In addition, GPS data in Java also experienced crustal deformation due to this earthquake (Gunawan et al., manuscript in preparation, 2015). Since our analysis focused on the 2004 Sumatra-Andaman earthquake, we did not use the GPS data after the 2012 earthquake for further analysis as it was clearly influenced by the 2012 earthquake.

During the period of 2005–2012, there were earthquakes adjacent to this regions detected by GPS time series data. These earthquakes were the 28 March 2005 $M8.7$ Nias

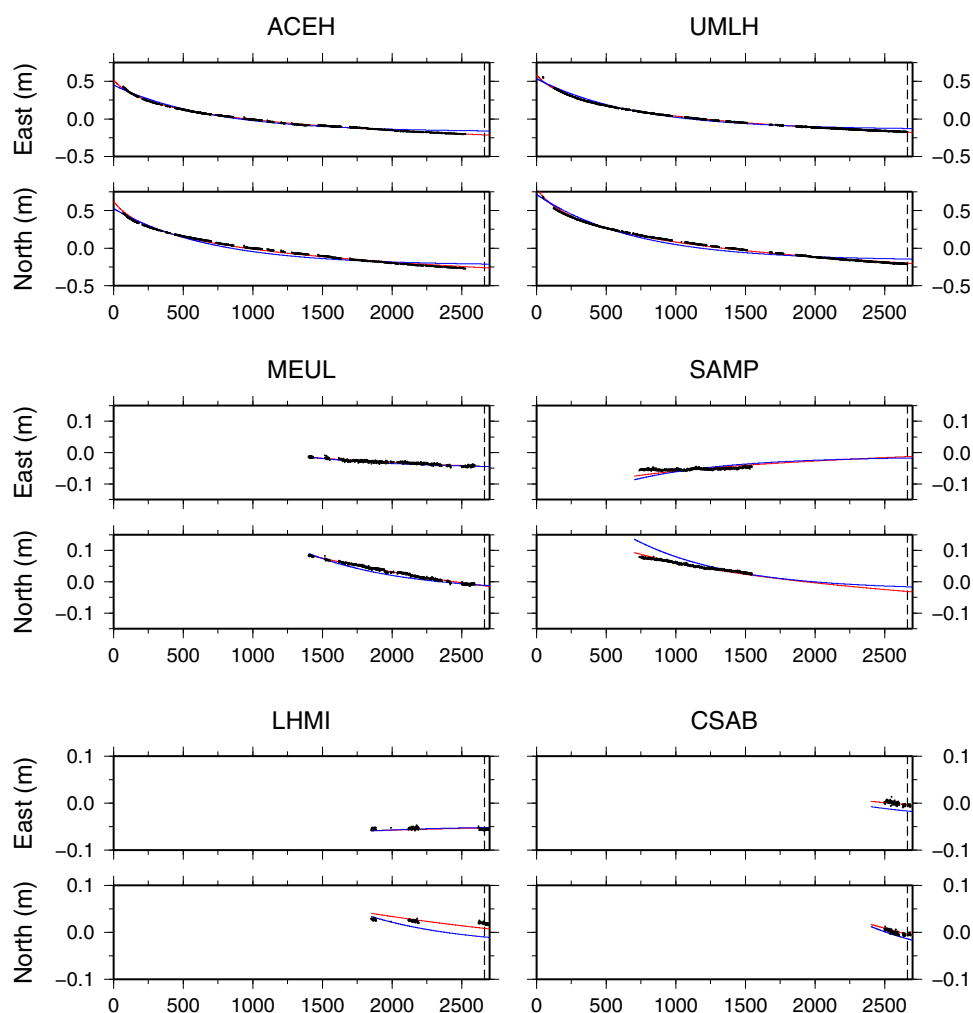


Fig. 2 Time series of GPS sites in northern Sumatra used in this study. *Horizontal axis* indicates days after the 2004 Sumatra-Andaman earthquake, while *vertical axis* implies displacements in meter. *Vertical dashed lines* denote time of the 2012 Indian Ocean earthquake. *Solid red lines* indicate calculated model based on best-fit parameters of logarithmic function, while *solid blue lines* are from exponential functions. *Black dots* represent the GPS time series data

earthquake (e.g., Kreemer et al. 2006), the 20 February 2008 $M7.4$ Simeuleu earthquake (Sladen et al. 2009), and the 6 April 2010 $M7.8$ Northern Sumatra earthquake (https://www.iris.edu/hq/files/programs/education_and_outreach/retm/tm_100406_sumatra/100406_sumatra.pdf, accessed on October 2015).

The significant signal of postseismic deformation of the 2005 Nias earthquake was detected by BSIM and LEWK. Previous studies suggested that significant postseismic deformation of afterslip after the 2005 Nias earthquake occurred at shallow portion of the main rupture at 97°E , 1°N (Hsu et al. 2006; Kreemer et al. 2006). They suggested that afterslip influenced deformation observed by GPS surrounding Nias Island. On the other hand, due to location of GPS sites in northern Sumatra much closer to the rupture of the 2004 Sumatra-Andaman earthquake and much larger magnitude size of this earthquake than the 2005 Nias

earthquake, previous studies suggested that GPS data in northern Sumatra are most significantly influenced by the 2004 earthquake (Subarya et al. 2006; Gunawan et al. 2014). That was why BSIM and LEWK would not be used for further analysis.

Similarly to the cases of the 2008 Simeuleu earthquake and the 2010 Northern Sumatra earthquake, where location of GPS sites in northern Sumatra was much closer to the rupture of the 2004 Sumatra-Andaman earthquake and much larger magnitude size of the 2004 earthquake than those of the 2008 and 2010 earthquakes. So for MEUL site, we removed only the coseismic displacements of the 2010 earthquake with -0.0184 m easting and 0.0385 m northing, as postseismic deformation, was insignificant compared to the 2004 earthquake. We concluded that in this study, we use only GPS data from ACEH, UMLH, CSAB, SAMP, MEUL, and LHMI.

Table 1 Postseismic parameters of logarithmic function

Site	Long (°E)	Lat (°N)	Logarithmic terms				RMS
			c_{east} (mm)	c_{north} (mm)	a_{east} (mm)	a_{north} (mm)	
ACEH	95.36	5.56	514.2 ± 0.6	623.8 ± 3.5	-221.9 ± 0.6	-269.9 ± 3.5	10.4
UMLH	95.33	5.05	586.0 ± 0.4	797.5 ± 2.1	-232.8 ± 0.4	-304.2 ± 2.1	8.1
CSAB	95.31	5.89	228.6 ± 0.9	682.1 ± 4.7	-70.7 ± 0.9	-209.2 ± 4.7	4.0
SAMP	98.71	3.62	-178.3 ± 0.4	298.8 ± 4.6	950.4 ± 0.4	-100.6 ± 4.6	6.2
MEUL	96.13	4.12	113.0 ± 0.1	517.2 ± 2.6	-47.5 ± 0.1	-161.7 ± 2.6	2.4
LHMI	96.94	5.22	-110.9 ± 0.1	360.3 ± 5.6	17.8 ± 0.1	-92.1 ± 5.6	4.6
Average							5.9

Table 2 Postseismic parameters of exponential function

Site	Long (°E)	Lat (°N)	Exponential terms				RMS
			c_{east} (mm)	c_{north} (mm)	a_{east} (mm)	a_{north} (mm)	
ACEH	95.36	5.56	449.8 ± 0.5	217.2 ± 9.5	-623.8 ± 0.5	-754.6 ± 9.5	25.7
UMLH	95.33	5.05	534.8 ± 0.3	713.2 ± 5.1	-678.0 ± 0.3	-879.0 ± 5.1	29.5
CSAB	95.31	5.89	857.8 ± 0.8	246.8 ± 5.4	-895.0 ± 0.8	-253.9 ± 5.4	12.1
SAMP	98.71	3.62	-213.1 ± 0.7	41.2 ± 14.3	200.1 ± 0.7	-438.2 ± 14.3	16.2
MEUL	96.13	4.12	213.1 ± 0.09	858.5 ± 5.0	-263.4 ± 0.09	-890.5 ± 5.05	6.7
LHMI	96.94	5.22	-193.1 ± 0.2	898.5 ± 8.6	144.4 ± 0.2	-878.5 ± 8.6	11.7
Average							16.9

3.2 Postseismic deformation parameters

Using the corrected daily solutions, we matched the GPS data to logarithmic and exponential functions. The post-seismic parameters of logarithmic and exponential functions for each GPS site were shown in Tables 1 and 2. In our calculation, we found that τ_{log} is 104.2 ± 0.1 days while τ_{exp} is 704.5 ± 0.1 days, respectively.

Based on the best matching component of logarithmic and exponential functions above, our results indicated that post-seismic parameters of logarithmic and exponential functions for each GPS site have different results. We found that misfit was obtained for GPS data using the models of logarithmic functions, that was 5.9, smaller than the exponential ones, that was 16.9 (Tables 1, 2). This result indicates that misfit of fitting time series data to logarithmic function obtained ~ 2.8 times smaller than that to the exponential function.

This showed that for 104.2 days after the earthquake, deformation mechanism was dominated by afterslip deformation due to Sumatra-Andaman earthquake in 2004. Since the time series, GPS data captured postseismic deformation for more than 100 days, so the other postseismic mechanisms should be taken into account. This could indicate that the postseismic deformation of the Sumatra-Andaman earthquake was not only caused by a single mechanism of afterslip, but also influenced by the other mechanisms of postseismic deformation, such as viscoelastic relaxation, for GPS data of 100 days forward.

Our finding supported previous research, which suggested that afterslip corresponds to early deformation after earthquake occurrences (Gunawan et al. 2014). In this study, we showed a detail result of postseismic parameters of the 2004 Sumatra-Andaman earthquake. Using a simple analysis model of logarithmic function, we could obtain the ongoing physical mechanisms process after earthquake occurrences exhaustively.

The difference between data fitting to logarithmic and exponential functions was significantly observed and visible during early periods after the 2004 earthquake, especially at ACEH and UMLH sites where early time series data are available (Fig. 2). This indicates that ACEH and UMLH play major role in our analysis. In the longer time series data, discrepancy between logarithmic and exponential functions to fit the data is invisible. Our analysis suggests the importance of maintaining continuous GPS data in prior, during, and after earthquake occurrences for further hazard analysis.

4 Conclusions

We show that GPS sites in northern Sumatra clearly detect significant postseismic deformation after the 2004 Sumatra-Andaman earthquake. We conclude that GPS data in northern Sumatra during the period of 2005–2012 are very well matched using logarithmic function with smaller average misfit of ~ 2.8 times compared to matching using exponential function. The decay time of postseismic

deformation of 104.2 days indicates that other mechanisms of postseismic deformation should be taken into account rather than a single physical mechanism of afterslip only.

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