Crustal deformation of Eastern Indonesia regions derived from 2010-2018 GNSS Data

Suchi Rahmadani¹,², Irwan Meilano¹,², Dina A. Sarsito¹,², Susilo³

¹ Geodesy and Geomatics Engineering, Faculty of Earth Sciences and Technology, Institut Teknologi Bandung, Jalan Ganesha No. 10, Bandung, Indonesia
² Center of Earthquake Science and Technology, Institut Teknologi Bandung, Jalan Ganesha No. 10, Bandung, Indonesia
³ Indonesian Geospatial Information Agency (BIG), Jalan Raya Bogor Km. 46, Nanggewer Mekar, Cibinong, Indonesia

E-mail: suchi.rahmadani18@gmail.com

Abstract. Eastern Indonesia lies in a complex tectonic region due to the interaction of four major tectonic plates: the Australian Plate, Pacific Plate, Philippine Sea Plate, and Sunda Block. Therefore, this region hosted some destructive seismic activities as well as tectonic deformation, such as the Mw 7.5 Palu Earthquake, the sequences of the 2018 Lombok Earthquake, and the Mw 6.5 Ambon Earthquake in 2019. Our work proposes a recent study on crustal deformation in Eastern Indonesia inferred from Global Positioning System (GPS) velocity field. We used GPS data from the observations of 49 permanent and 61 campaign stations from 2010 to 2018. Here, our velocity field result represents long-term tectonic deformation regions in Eastern Indonesia continuously, from Bali in the west to Papua in the east, demonstrated both in the ITRF 2008 and the Sunda reference frames. The spatial pattern of velocity field map collected from this research will give an initial insight into the present-day tectonic condition in Eastern Indonesia and then can be used to improve our ability to assess this area's earthquake potential.

1. Introduction

Eastern Indonesia is the region with the most complex tectonic configuration in Indonesia. This region is formed by the convergence of four active plates, namely the Australian Plate, Pacific Plate, Philippine Sea Plate, and Sunda Block [1]. The convergence of the Australian Plate and Sunda Block has partitioned between a megathrust and a continuous zone of back-arc thrusting extending over 2000 km started from east Java to northern Timor [2]. Meanwhile, from the geological study, the Banda Arc itself was formed by a single slab subduction of the Australian plate [3].

This complex tectonic setting has contributed significantly to most of earthquakes happened in Eastern Indonesia. Some of them are the destructive earthquakes, such as the Mw 7.9 1992 Flores earthquake [4], the Mw 7.5 Palu Earthquake which followed by a tsunami [5], the sequences of the 2018 Lombok Earthquake [6, 7], and the Mw 6.5 Ambon Earthquake in 2019 [8], which followed by thousands of aftershocks. Figure 1 shows the historical earthquakes (Mw >5) from 1900 to 2015 in Eastern Indonesia based on the catalog of the National Center for Earthquake Studies (PuSGeN) [9].
Figure 1. Tectonic setting of Eastern Indonesia. The black lines are active faults, and the colored circles are seismicity data [10]. The color bar shows the depth of the earthquakes. The grey arrow represents the plates velocity with respect to Sunda Block [11].

The previous geodetic studies in Eastern Indonesia focused on the part of the Banda Arc and Sulawesi with lack of GPS observations distribution [10, 12, 13]. This study will be the first one in the last decade of conducting the continuous velocity field in the vast area of Eastern Indonesia. This study area spread from Bali in the west to Papua in the east, with a denser and longer time of Global Positioning System (GPS) observation data. GPS could provide precise three-dimensional relative position up to millimeters fraction over a baseline range of hundreds of meters to thousands of kilometers [14]. Therefore, this technology is very suitable for geodynamics study.

2. Data and Method

We used GPS data from 110 stations provided by the Indonesian Geospatial Information Agency (BIG). The data consist of 49 continuous and 61 campaign stations (Figure 2). The data covered a nine-year time span from 2010 to 2018, although some covered shorter times. But in this study, we only directly processed the GPS data of 31 continuous stations using the GAMIT/GLOBK 10.7 software [15] to get daily time-series, while the rest of the GPS velocities that we used (18 permanent and 61 campaign stations) were from Susilo (2018) [16]. We also incorporated 16 IGS (International GNSS Service) stations (ALIC, AUCK, BAKO, CEDU, COCO, CUSV, DARW, GUUG, HYDE, IISC, KARR, PIMO, TOW2, TWTF, XMIS, and YAR2) into our processing to connect our regional network to the global GPS network, to get better daily solutions. To estimate the linear horizontal velocity, we removed outliers and seasonal variations and corrected for offsets in the time-series [17].

Since our velocity results were discrete, to effectively portray the velocity field throughout Eastern Indonesia, we used the spline interpolation with a tension algorithm suggested by Sandwell and Wessel (1998) to determine the continuous velocity field. After several testing, we implemented the interpolation within a square-based grid of the east and north velocity components with a grid size of 0.3° and applied a 0.3 tension factor, as recommended for topographic interpolation [18].
Figure 2. Map of Eastern Indonesia GPS stations used in our analysis. Red and blue circles represent permanent and campaign stations used in this study, respectively. The hollow squares are the GPS sites of the previous study [2]. The brown lines are faults.

3. Result and Discussion

The first result of our study is the interpolated velocity field based on our GPS observations with respect to the 2008 International Terrestrial Reference Frame (ITRF 2008) [19], which is shown in Figure 3. The velocity rates surely indicates that the velocities increase significantly from west to east with a range of ~0.8-72 mm/year. A significant value difference was demonstrated between west and east of Banda Arc (around Tanimbar trough), implying that this area's deformation is characterized mainly by crustal shortening due to the collision of Australian Plate. The velocity field also demonstrates a clear counterclockwise rotation from west to east and up to the north. The vectors have changed the direction from SE in the southern of Papua to NW in the northern of Papua, with magnitude ~50-70 mm/year.

For more analysis, we tied our GPS velocity to the Sunda reference frame [20]. The result (Figure 4) shows that the west part of Eastern Indonesia (Kalimantan, West Sulawesi, Bali, and Lombok) has minimal velocities compared to the velocity rates with relative to the ITRF 2008 reference frame. It suggests that the west part of the study area is part of Sunda Block and others block different from the east part of Eastern Indonesia [2, 20, 21, 22]. The northern part of Papua reflects higher velocity rates (~95 mm/year) value than the result in Figure 3 and tends to move towards the NW; this is due to the Pacific Plate's convergence to the Papua. While velocities in the southern part of Papua tend to move northward as the result of the Australian Plate. The pattern of the velocity field in Papua has separated around the Jayawijaya mountains, as there is a major fault mechanism in there called Papuan fold belt [15].
4. Conclusions

Our denser velocity field result represents long-term tectonic deformation regions in Eastern Indonesia continuously, from Bali in the west to Papua in the east, demonstrated in the ITRF 2008 and Sunda Block reference frame. The results clearly show that the deformation pattern in Eastern Indonesia has partitioned into several blocks that have to be detailed with a comprehensive strain and block modeling in the future study. The pattern of velocity field map produced from this research will provide insight...
into the recent tectonic condition of Eastern Indonesia and then can be used to improve our knowledge to assess the earthquake potential of this area.

Acknowledgments
We are grateful to BIG for providing the GPS data. Figures were generated using GMT software [23]. This research was funded by the 2020 PMDSU research scheme of the Ministry of Research and Technology.

References
[1] Hamilton W B 1979 Tectonics of the Indonesian region. Tech. Rep 1078 U.S. Govt. Print. Off., Wash.
[2] Koulali A, Susilo S, McClusky S, Meilano I, Cummins P, Tregoning P, Lister G, Efendi J and Syafi’i M A 2016 Crustal strain partitioning and the associated earthquake hazard in the eastern Sunda-Banda Arc Geophys. Res. Lett. 43 (5) pp 1943-1949
[3] Spakman W and Hall R 2010 Surface deformation and slab–mantle interaction during Banda arc subduction rollback Nat. Geosci.
[4] Pranantyo I R, Cummins P R 2019 Multi-Data-Type Source Estimation for the 1992 Flores Earthquake and Tsunami Pure Appl. Geophys. 176 2969–2983
[5] Soequet A, Hollingsworth J, Pathier E, and Bouchon M 2019 Evidence of supershear during the 2018 magnitude 7.5 Palu earthquake from space geodesy Nat. Geosci. 12 192–199
[6] Salman R, Lindsey E O, Lythgoe K H, et al 2020 Cascading Partial Rupture of the Flores Thrust during the 2018 Lombok Earthquake Sequence, Indonesia Seismol. Res. Lett. 91 pp 2141–2151
[7] Supendi P, Nugraha A D, Widiyantoro S, Pesicek J D, Thurber C H, Abdullah C I, Daryono D, Wiyono S H, Shiddiqi H A, Rosalia S 2020 Relocated aftershocks and background seismicity in eastern Indonesia shed light on the 2018 Lombok and Palu earthquake sequences Geophys. J. Int. 221 pp 1845–1855
[8] Sahara D P, Nugraha A D, Muhari A, et al 2021 Source mechanism and triggered large aftershocks of the Mw 6.5 Ambon, Indonesia earthquake Tectonophysics 799 228709
[9] National Center for Earthquake Studies 2017 Peta Sumber dan Bahaya Gempa Indonesia Tahun 2017. Pusat Litbang Perumahan dan Perumukman, Badan Penelitian dan Pengembangan, Kementerian Pekerjaan Umum dan Perumahan Rakyat, Bandung
[10] Nugroho H, Harris R, Lestariya A W, Maruf B 2009 Plate boundary reorganization in the active Banda Arc-continent collision: Insights from new GPS measurements Tectonophysics 479 (1-2) pp 52-65
[11] DeMets C, Gordon R G, and Argus D F 2010 Geologically current plate motions Geophys. J. Int. V 181 no 1 pp 1-80
[12] Herawati Y A, Meilano I, Sarsito D A, Efendi J 2017 Strain analysis in Banda Sea using grid strain based on GPS observation AIP Conf. Proc. 1857 4987075
[13] Pradipta G C, Meilano I, Gunawan E, Efendi J 2017 Deformation analysis in the east nusa tenggara and banda islands based on GPS observation from 2010-2015 AIP Conf. Proc. 1857 4987076
[14] Segall P and Davis J L 1997 GPS applications for geodynamics and earthquake studies Annu. Rev. Earth Planet. Sci 1997 pp 301–36
[15] Herring T A, King RW and McClusky S C 2018 Introduction to GAMIT/GLOBK, Release 10.7. Cambridge: Massachusetts Institute of Technology
[16] Susilo 2018 Realisasi Model Deformasi Geodeetik Untuk Datum Semidinamik di Indonesia Academic Dissertation, Institut Teknologi Bandung
[17] Nikolaidis R 2002 Observation of Geodetic and Seismic Deformation with the Global Positioning System Academic Dissertation, Univeristy of California
[18] Wessel P and Bercovici D 1998 Interpolation with splines in tension: a Green’s function approach
Math. Geol. 30 77–93
[19] Altamimi Z, Métivier L and Collilieux X 2012 ITRF2008 plate motion model J. Geophys. Res.-Sol. Ea. 117
[20] Yong C Z, Denys P H, and Pearson C 2017 Present-day kinematics of the Sundaland plate J. Appl. Geodesy 11 169–177
[21] Bock Y, Prawirodirdjo L, Genrich J F, Stevens C W, McCaffrey R, Subarya C, Puntodewo S S O and Calais E 2003 Crustal motion in Indonesia from Global Positioning System measurements J. Geophys. Res. 108 2367
[22] Simons W J F, Socquet A, Vigny C, Ambrosius B A C, Haji Abu S, Promthong C, Subarya, C, Sarsito D A, Matheussen S, Morgan P and Spakman W 2007 A decade of GPS in Southeast Asia: resolving sundaland motion and boundaries J. Geophys. Res. 112 B06420
[23] Wessel P and Smith W H 1998 New, improved version of generic mapping tools released. Eos Trans. Am. Geophys. Union 79 pp 579-579