Crustal Deformation Studies in the Northern Part of East Java Derived from GPS CORS Data between 2015 and 2018

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Abstract: The tectonic setting of Indonesia is very complex due to its location on the boundaries of several major tectonic plates. The complexity of the tectonics also makes Indonesia prone to natural disasters such as earthquakes, tsunamis, and volcanic eruptions. Crustal deformation caused by the tectonics activities can be monitored using geodetic techniques such as Global Positioning System (GPS) and Interferometry Synthetic Aperture Radar (InSAR). In this research, we analyze the crustal deformation in the northern part of East Java using ten GPS Continuously Operating Reference Stations (CORS) data provided by the Indonesian Geospatial Information Agency from 2015 to 2018. The results showed the horizontal movement toward the southeast for all the stations. The horizontal velocity rates are range between 2.62 cm/yr observed at CPAS site, and 3.173 cm/yr observed at CNGA station. For the vertical displacements, all the sites are subject to subsidence with the rates range from -0.021 cm/yr to -0.4 cm/yr that we suspect related to the geological settings of the study area. However, we found that the vertical annual time series of CMJT stations in 2015 are not consistent; this is because the antenna type was changed on the day of year (doy) 286 in 2015. On the other hand, the strain analyzes in the study area showed considerable compressional strain in the segment formed by three stations, namely CTBN, CSMP and CSBY which are located near to the Kendeng active fault.

Keywords: GPS CORS, crustal deformation, velocity rate, strain analyzes

1. Introduction

Indonesia is located at the confluence of three large tectonic plates namely the Eurasia plate in the north, Indo-Australian plate in the south and the pacific plate in the eastern part of the archipelago, the Philippine sea plate is also included in the tectonic plates that border the Indonesian region [1]. The relative movement of the three mega plates define distinct subduction collision system in Indonesia. In the west, the Australia plate subducts beneath the Eurasia plate along the Java trench while to the east, the continental part of the Australia plate collides with the Banda arc and the Pacific oceanic plate. Frequent earthquakes in Indonesia are caused by the complexity of the tectonics said above. Besides earthquakes, the archipelago is also prone to other natural disasters such as tsunamis and volcanic eruptions. Among these natural disasters, earthquake is a big menace to Indonesia.

The active subduction zone in the south of Java is a boundary between the Indo-Australian and the Eurasian plates [2]. These plates meet at the bottom of the Indian Ocean and move towards the north [3]. East
Java is an area that has lots of seismic activities, especially in the southern part. The earthquake that occurred in East Java was generally caused by subduction zone in the south of Java. According to USGS, more than 180 earthquakes of magnitude between 2.5 and 7 have been recorded in East java from the year 2015 to 2018, and most of the quakes occurred in south part of East Java.

![Image](image.png)

**Figure 1** The distribution of earthquakes in East java from 2015 to 2018. The red lines on the map are active faults provided by the Centre of National Earthquake Studies [6]

The importance of GPS technology in tectonic movement studies recognized last decade. This study has the objective to analyze the movement of GPS stations in the northeastern part of Java Island. The deformation and geodynamics studies in Indonesia have made possible by the establishment of GPS permanent stations that spread all over the Indonesian territories. In this study, we present the deformation parameters derived from GPS CORS in the northeast of Java in the period of four-year, i.e., from 2015 to 2018. It is presumed that the movement of the Indian and the Eurasian plates and the presence of active faults are the leading cause of the displacement in the study area. By means of the Ina-CORS observation stations namely CLMG, CMJT, CNGA, CPAI, CPAS, CSBY, CSIT, CSMN, CSMP, CTBN, this research provide the current information on deformation in the study area and interpreted as the change in position of the stations and the velocity of the shift arising from tectonics and the Kendeng fault activities in the northeast of Java. GPS data from the Ina-CORS observation station processed using scientific software, GAMIT/GLOBK 10.7 [4] and all the results are plotted using GMT (Generic Mapping Tools) [5].

2. Study Area, Data, and Methodology

2.1. Characteristics of The Study Area

This study was conducted in East Java, specifically on its northern part which locates between longitude 111° 30' - 114°30' and at latitude 6°51'. The distribution of GPS CORS stations in the research area is shown in Figure 2. Based on its seismicity history, Java island is dominated by earthquakes related to subduction zone and to the faults [6]. In the past two decades, four earthquakes have occurred around this area and have caused significant damage. These earthquakes are the Mw 7.6 East Java tsunami earthquakes occurred in 1994, the Mw 7.7 and Mw 7.0 West Java earthquakes occurred in 2006 and 2009, and the significant tsunami earthquake with Mw7.5 occurred in 1921. From 2009 to 2015, the seismic activities that still occur in Java island are found around the earthquake location of 1994 to 2006. The tsunami earthquake of 1994 is unique with thrust earthquake mechanism and followed by an aftershock whose most of the mechanisms are normal faults.
2.2. Data Collection

This study is aimed to analyze the deformation in the northeastern part of Java using GPS CORS data from 10 stations namely CLMG, CMJT, CNGA, CPAI, CPAS, CSBY, CSIT, CSMN, CSMP and CTBN located within study area (Figure 2). We also used GPS observation data from 17 IGS stations namely AIRA, ALIC, BAKO, COCO, DARW, IISC, JOG2, KARR, KAT1, MRO1, NAUR, PIMO, SOLO, TOW2, XMIS and YAR2. The observations data of four years, 2015-2016-2017 and 2018 were used together with brdc file that contains precise ephemeris data, precise igs orbits file in igs sp3 format, meteorological file for meteorological modeling, ionospheric file for ionospheric modeling. The rinex observations data for GPS CORS were provided by the Indonesian Geospatial Information Agency while the observation data for IGS stations, navigation data, precise ephemeris data, meteorological and ionospheric data are downloaded from Scripps Orbit and Permanent Array Center (SOPAC) data archives [7]. Besides that, three other relevant data used in the processing are the ocean tide model FES2004 for the removal of contributions from ocean tidal loads at the site locations, the atmospheric modeling data (atmdisp_cm.YYYY) and weather modeling data (vmf1grid.YYYY) downloaded at ftp://everest.mit.edu/pub/GRIDS.

2.3. Data processing

In this study, we used GPS continuous reference stations and GAMIT, version 10.7 to derive the loosely constrained site coordinates. GAMIT is used to produce estimates and an associated covariance matrix of station positions and (by choice) orbital and Earth-rotation parameters which are then input to GLOBK to estimate positions and velocities. The station position estimates and their rates were estimated in ITRF2014 by stabilizing more stable continuous station and core IGS reference stations using GAMIT/GLOBK and GLORG. GPS data processing or network alignment using GAMIT use double-difference technique, here computations are done using the principle of the least-squares calculated weighted parameters. For example, measurements using two points measurement data observations (A) and (B) and two satellites (i) and (j). The distance formed from the two observation points are shown in equations (1) and equation (2).

\[
\rho^h_i = \sqrt{[X^i(t) - X^A]^2 + [Y^i(t) - Y^A]^2 + [Z^i(t) - Z^A]^2}
\]

\[
\rho^i_j = \sqrt{[X^j(t) - X^B]^2 + [Y^j(t) - Y^B]^2 + [Z^j(t) - Z^B]^2}
\]

With the coordinates of the observation point (A) approach is \(X^A, Y^A, Z^A\). After linearization process is carried out, the equations (1) and (2) become equation (3) and (4).

\[
\rho^h_A = \rho^h_0 + cx^i(t)dX_A + cy^i(t)dY_A + cz^i(t)dZ_A
\]

\[
\rho^i_B = \rho^i_0 + cx^j(t)dX_B + cy^j(t)dY_B + cz^j(t)dZ_B
\]
Where $c_x$ is the derivative equation of $dX$, $c_y$ is the derivative equation of $dY$, and $c_z$ is the derivative equation of $dZ$. By substituting the equation in the double difference equation between observers and satellites, the double-difference equation becomes the following [4]:

$$
\Delta \nabla L_{ij}^{ab}(t) = \Delta \nabla P_{ij}^{ab}(t) + \nabla c_x^{ij}(t)dX_A + \nabla c_y^{ij}(t)dY_A + \nabla c_z^{ij}(t)dZ_A + \lambda \Delta N_{ij}^{ab} + \Delta \nabla v_{ij}^{ab}(t)
$$

This double difference equation uses different phase data. Furthermore, do the least-squares of weighted parameters to get the coordinates of the observer (A). The results of observation data processing using GAMIT in the form of a biased solution fixed and bias-free solution. This solution is obtained from a double difference calculation the phase difference data is done twice, which is fixed ambiguity and ambiguity float. Phase ambiguity is caused by the ambiguity of the number of full waves and not full recorded by a GPS receiver.

With GLOBK program that is used to generate the time series from joining the regional and global data, we applied the loose constraints applied to all stations, satellite, and Earth orientation parameters (EOP). The result is a loosely constrained position time series of the observation stations for the entire observation time (2015 to 2018). An adjustment was performed using GLORG to get all station to be in ITRF2014 coordinates system. The velocity was then estimated through a weighted least squares line fit to the daily position time series.

3. Results and Discussions

The first analysis stage concerns the evaluation of the post fit nrms value that is used as a parameter that defines the quality level of results obtained after processing the data, and it indicates whether the data fit the model or not. This value is defined as the chi-square ($\chi^2$) value per degree of freedom, and it indicates the comparison between a posteriori and a priori variants for specific weighted units. The solution is accepted if the post fit nrms value produced by the solution is less than 0.25, in this case, it can be said that the data fit the model and the effect of the cycle slips have been removed. Whenever the solution produces value greater than 0.5, this implies that the cycle slips have not been removed and the results are associated with gross errors parameters, or maybe there is a modeling problem. In this study, the data used in this research are said to fit the model because the solution provide the post fit nrms value less than 0.25, and the fract value less than 10. Figure 3 shows the time series plot of the CMJT station. The significant uncertainty in vertical component occurred in CMJT station is due to the antenna type changes in 2015.

3.1. Velocity Field

The velocities were estimated using a weighted least squares line fit to the daily position time series [7]. The outliers in time series were removed using MATLAB with TSVIEW program. The velocities derived from ten GPS observation stations in the northeast Java are presented in Figure 4. The direction of movement shown that all the stations moved towards the southeast. The horizontal and vertical displacement velocities of all the CORS stations are given in Table 1.

![Figure 3 The coordinates repeatability plot of CMJT station](image)
Table 1 The displacement velocities of all GPS CORS stations in the ITRF2014 reference frame

| Station | Lon  | Lat  | $V_e$ (mm/yr) | $V_n$ (mm/yr) | $V_u$ (mm/yr) | $\delta_e$ (mm/yr) | $\delta_n$ (mm/yr) | $\delta_u$ (mm/yr) |
|---------|------|------|---------------|---------------|---------------|------------------|------------------|------------------|
| CLMG    | 112.3267 | -7.0927 | 27.03         | -9.57         | -3.50         | 0.12             | 0.08             | 0.81             |
| CMJT    | 112.4401 | -7.4653 | 27.44         | -6.67         | -1.15         | 0.10             | 0.09             | 0.29             |
| CPAI    | 113.5302 | -7.7190 | 27.39         | -6.93         | -2.40         | 0.11             | 0.08             | 0.21             |
| CPAS    | 112.9014 | -7.6517 | 26.58         | -4.28         | -2.17         | 0.15             | 0.36             | 0.18             |
| CSBY    | 112.7254 | -7.3348 | 27.37         | -11.22        | -2.23         | 0.11             | 0.14             | 0.19             |
| CSIT    | 114.0136 | -7.7037 | 27.45         | -7.12         | -1.17         | 0.13             | 0.11             | 0.47             |
| CSMN    | 113.8753 | -7.0182 | 26.38         | -9.93         | -2.16         | 0.08             | 0.13             | 0.47             |
| CSMP    | 113.2522 | -7.1955 | 26.08         | -10.67        | -0.21         | 0.08             | 0.08             | 0.34             |
| CNGA    | 111.9103 | -7.6066 | 30.31         | -9.41         | -4.00         | 0.29             | 0.28             | 0.37             |
| CTBN    | 111.9863 | -6.8723 | 25.09         | -9.77         | -0.70         | 0.14             | 0.28             | 0.75             |

As indicated in Table 1, all stations in the study area move toward the southeast and have negative vertical displacements. The station with minimum displacement is CTBN with the horizontal velocity rate of 25.09 mm/yr and the considerable velocity value occurred at CNGA station with the rate of 30.31 mm/yr. The direction of horizontal displacements of all stations are shown in Figure 4. The vertical velocities for all GPS CORS stations are presented in Figure 5. From the figure, it can be seen that all the GPS CORS stations are subject to subsidence.

3.2. Principal Strain

The principal strain in this study was computed using the Delaunay triangulation method [8], the selection of geodetic sites as vertices of convex polygons, leads us to evaluate the strain tensor of the polygon by using the horizontal velocities. These velocities are the horizontal shift values presented by $V_e$ and $V_n$, which is the easting and the northing velocity components results of the ten GPS CORS stations using GAMIT/GLOBK. Three steps to obtain the principal strain are: 1) to get the velocity solutions of the stations in the topocentric coordinates system; 2) triangulate the network (make triangles between CORS stations such that no triangle side is cut by another and no points are contained in any other triangle’s circumscribed circle); 3) computed the strain using the formulas provided by Cai and Grafarend [9] using MATLAB script. The results of principal strain are presented in Table 2.
Table 2 The Principle Strain Values Obtained by Delaunay Triangulation Methods. $\varepsilon_1$ indicates extension, and $\varepsilon_2$ indicates compression.

| No | Triangle segment     | Lon (Degrees) | Lat (Degrees) | $\varepsilon_1$ (µstrain) | $\varepsilon_2$ (µstrain) | $\theta$ (degrees) |
|----|----------------------|---------------|---------------|---------------------------|---------------------------|-------------------|
| 1  | CTBN-CNGA-CLMG       | 112.1122      | -7.3147       | 0.3291                    | -0.2144                   | 54.7137           |
| 2  | CLMG-CNGA-CMJT       | 112.2257      | -7.3882       | 0.8095                    | -0.2788                   | 63.5248           |
| 3  | CMJT-CSBY-CTBN       | 112.3839      | -7.2241       | 0.1217                    | -0.0383                   | -69.2677          |
| 4  | CTBN-CSMP-CSBY       | 112.6546      | -7.1342       | 0.2094                    | -0.4368                   | 72.3900           |
| 5  | CMJT-CNGA-CPAS       | 112.4173      | -7.5745       | 0.3704                    | -0.1243                   | 33.1204           |
| 6  | CSBY-CMJT-CPAS       | 112.6890      | -7.4839       | 0.2099                    | -0.0094                   | -89.7809          |
| 7  | CSBY-CPAS-CSMP       | 112.9597      | -7.394        | 0.1880                    | -0.0173                   | 80.7126           |
| 8  | CPAS-CPAI-CSMP       | 113.2279      | -7.5221       | 0.8881                    | -0.2141                   | -74.2209          |
| 9  | CSMP-CPAI-CSMN       | 113.5526      | -7.3109       | 0.5742                    | -0.0051                   | -86.6646          |
| 10 | CPAI-CSIT-CSMN       | 113.8064      | -7.4803       | 0.3842                    | -0.0327                   | -82.3916          |

To plot the principal strain, the triangle segment file that contains the position (longitude and latitude) of each point in a segment and data containing the observation stations with their position and names are needed. The methods of deriving the two-dimensional geodetic strain rates tensor are introduced and applied to derive the strain rates from the surface residual velocities. Further detailed analysis of the results is also performed in geodynamical aspects. Figure 6 indicates the strain rate values in the area made by the observation stations triangle segments. As can be seen from the figure, the direction of the strain is dominated by east-west for extension principal strain and north-south for compression. Extension is represented by symmetric arrows pointing out, and contraction is represented by symmetric arrows pointing in. Single arrows represent the residual velocities.

![Figure 6](image-url)
Study by Gunawan and Widiyantoro [10] indicates that the Kendang fault is active. The study also identified a considerable compressional strain in the east-west of Madura strait and suggested that the strain is related to the Kendeng fault which is an active fault from the central part of central Java eastward to Madura strait. As indicated on the velocity maps of this research the stations in the east-west of Madura strait are in the Kendeng faults zone, and this study concludes that the deformation in the study area is due to this active fault. In agreement with the study, the results of our study also shown that the strain analysis indicates a considerable compressional strain at the stations near the Kendeng active fault, and we suggest that this region is more active seismically than other regions. The minimum extension is seen at the segment CMJT-CSBY-CTBN with the principal strain value 0.1217 µstrain, and the highest extension value is seen at segment CPAS-CPAI-CSMP with the strain value 0.8881 µstrain. On the other side, the lower compression value occurs at the segment CSBY-CMJT-CPAS with -0.0094 µstrain, and the higher compression value is seen at segment CTBN-CSMP-CSBY with principal strain value of -0.4368 µstrain.

The horizontal velocity rate between 2.692cm/yr observed at CPAS and 3.173cm/yr at CNGA observation sites. The vertical velocities indicate the subsidence in the study area with the values range between 0.021cm/yr observed at CSMP station and 0.4cm/yr at CNGA, we relate this subsidence to the geologic settings of east Java. As can be seen in Figure 7, the northeastern part of java is dominated by alluvium (orange color) ) and almost all observation stations are located in this type of soil. Therefore, we suggest that the subsidence in the study area is associated to the soil type, which is the alluvium. The study by Abidin et al. [11] reported that the northern region of Semarang along the coast exhibits higher rates of subsidence compared to its southern region, and this subsidence is believed to be caused by the combination of natural consolidation of young alluvium soil, groundwater extraction and load of buildings and constructions.

Figure 7 Geology map of East Java and the distribution of GPS CORS stations used in this study

4. Conclusions
From the results, we conclude that the northeastern part of Java, as presented by the GPS CORS stations, moves southeast with subject to subsidence. The horizontal velocities of the stations range between 2.692 cm/yr and 3.173 cm/yr, while the vertical velocities range between -0.021cm/yr and -0.4 cm/yr. We relate the subsidence with the soil type that dominated the northeastern part of Java which is alluvium. Furthermore, a significant horizontal velocities have occurred at CLMG, CMJT, CSBY, CNGA stations because they are located near the Kendeng active fault. Based on the results of the strain computation, a considerable compressional strain with
the value of -0.4368 µstrain is found in the area made of CTBN, CSBY and CSMP are also suspected associated with the Kendeng active fault.

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References
[1] Hamilton, W., 1973. Tectonics of the Indonesian Region, Geol. Soc. Malaysia, vol. 6 pp.3-10
[2] Palupi, I.R., W. Raharjo, S. W. Nurdian, W. S. Giamboro, and A. Santoso, 2016. Geological structure analysis in Central Java using travel time tomography technique of S waves, J. Phys. Conf. Ser., vol. 776, no. 1, pp. 1–7
[3] Kato, T., T. Ito, H. Z. Abidin, and Agustan, 2007. Preliminary report on crustal deformation surveys and tsunami measurements caused by the July 17, 2006, South of Java Island Earthquake and Tsunami, Indonesia, Earth, Planets Sp., vol. 59, no. 9, pp. 1055–1059.
[4] Herring, T.A., R. W. King, and S. C. Mcclusky, 2018. Introduction to GAMIT / GLOBK Release 10.7.
[5] Wessel, P., W. H. F. Smith, R. Scharroo, J. Luis, and F. Wobbe, 2013. Generic Mapping Tools: Improved version released, EOS Trans. AGU, no. 94, pp. 2409-410.
[6] Tim Pusat Studi Gempa Nasional. 2017. Peta Sumber dan Bahaya Gempa Indonesia Tahun 2017. Bandung: Kementrian Pekerjaan Umum dan Perumahan Rakyat.
[7] Nikolaidis, R. 2002. Observation of Geodetic and Seismic Deformation with the Global Positioning System, University of California, San Diego
[8] Turcotte, D.L. and G. Schubert, 2002. Geodynamics 2nd ed. Cambridge University Press
[9] Cai, J. and E. W. Grafarend, 2007. Statistical Analysis of Geodetic Deformation (strain rate) Derived from the Space Geodetic Measurements of BIFROST Project in Fennoscandia, J. Geodyn., vol. 43, no. 2, pp. 214–238
[10] Gunawan, E and S. Widiyantoro, 2019. Active Tectonic Deformation in Java, Indonesia Inferred from a GPS-derived StrainRate, Journal of Geodynamics, vol. 123 pp. 49-54
[11] Abidin, H.Z., H. Andreas, I. Gumilar, T. P. Sidiq, and Y. Fukuda, 2013. Land Subsidence in Coastal City of Semarang (Indonesia): Characteristics, Impacts and Causes, Journal of Geomatics, Natural Hazards, and Risks, vol. 4 issue 3, pp. 226-240.