Estimation of Deformation Parameters to Separate Postseismic Effect After The 2006 Yogyakarta Earthquake Based on Geodetic Observation

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Abstract. The 2006 Yogyakarta earthquake with a magnitude of 6.3 happened with presumption due to activity from the Opak fault. After the earthquake, the activity of the Opak fault continued to be monitored by using Global Positioning System (GPS) technology. GPS data can be used to see the characteristics of deformation, which happened until present after the Yogyakarta earthquake in 2006. The characteristics of the deformation caused by the earthquake can be either afterslip or viscoelastic relaxation, where each of them can be approached by using a logarithmic and exponential function. The results show the data from continuous stations shows better results compilation approached with an exponential function, which means the deformation of the Opak Fault depends on the interseismic phase with still potential as viscoelastic relaxation of material which lies on the lower crust. Then, the results of the exponential parameters are used to correct the velocity for all GPS stations. The statistical result shows that only the velocity of the continuous stations is significantly different from the velocity before being corrected.

1. Introduction
The 2006 Yogyakarta earthquake that struck Bantul and surrounding areas, including Yogyakarta City, Sleman, and Klaten, occurred on May 27, 2006, at 05.54.01 WIB with a strength of 6.3 Mw. The epicenter of this earthquake was in coordinates 7.961 °S; 110.446 °E with a depth of about 10 – 17 km. The existence of an active fault Opak which is a shear fracture is thought to be one of the causes of the 2006 earthquake with a slip rate of 4 to 6 mm/year based on the results of research conducted by Abidin after the 2006 earthquake (Abidin, 2009). The 2006 earthquake that occurred due to the activity of the Opak Fault caused deformation of the surrounding crust, both horizontally and vertically. One of the deformation observations that occur in the Opak Fault can be detected through continuous geodetic observation by using the GPS satellite technology, which is deployed in the Special Region of Yogyakarta.

After the 2006 earthquake, it is thought that there was still residual energy that was released slowly until it returned to its original condition or was in the postseismic phase. But until now, the characteristics of postseismic deformation that occur in the Opak Fault are still unknown. Geodynamic studies are needed to analyze the strains that arise during the earthquake cycle, especially in this research in the postseismic phase (Anugrah et al., 2015). This continuous GPS
observation can be explained to estimate the mechanism of the physical process that occurs in the deformation of the Opak Fault after the 2006 Yogyakarta earthquake using the least square calculation method of the three mathematical functions approach. Three mathematical functions that are used as a representation of the physical process mechanism that occurs in the deformation of the Opak Fault after the 2006 Yogyakarta earthquake are linear functions and a combination of linear functions and non-linear functions (logarithmic and exponential).

Figure 1. Location of epicenter the 2006 Yogyakarta Earthquake and distribution of 18 GPS Stasions. The black triangle indicates the monitoring stations, the red line indicates fault line, and beach ball indicates the epicenter of the 2006 Yogyakarta earthquake

2. Data and Method
The data used in this study are four GPS Continous Observation Reference Stations (CORS), where three of them are managed by Badan Informasi Geospasial (BIG), namely CBTL, CPTS, JOGS, and one is led by Universitas Gadjah Mada in collaboration with Geo Forschungs Zentrum (GFZ), namely JOG2 with observation period varying from 2009 to 2019. Besides continuous data, there are Opak Fault monitoring Stations, which are measured periodically from 2013 to 2018 which are managed Department of Geodetic Engineering, Universitas Gadjah Mada. Processing to obtain a daily solution using GAMIT/GLOBK software by reference to the 2008 ITRF reference framework (Herring et al., 2015).

The GPS data has been processed by using GAMIT software. The processing used three steps of processing. The first step is data preparation for raw phase and pseudorange data, station initial coordinate, receiver and antenna information for each site, satellite orbits information and earth rotation parameters. Second, each parameter was modeled to solve phase ambiguity for the baseline vector estimation. Finally, daily positioning solution in terms of geocentric Cartesian coordinate (X, Y, Z) was determined for each continuous and periodic stations by connecting the network to the ITRF 2008 (Altamimi et al., 2011; Aris et al., 2016). To this end, the minimum constraint approach
was performed by using thirteen International GNSS Service (IGS) stations globally distributed on the earth surface.

There are two mathematical functions that can describe the mechanism of the physical process, which is happened around the Opak Fault presently. We use these functions to fit the time series data at the four continuous stations, first (1), with the effect of afterslip (Marone et al., 1991) and second (2), with the effect of the viscoelastic relaxation (Savage dan Prescott, 1978). The equation of each can be written as follows:

\[ u(t) = a + b \ln (1 + \frac{t}{\tau_{log}}) + vt \] (1)

\[ u(t) = a + c \ln (1 - e^{-\frac{t}{\tau_{exp}}}) + vt \] (2)

Where \( u \) is the shift for each observation \( t \), \( a \) is the coseismic offset, \( b \), and \( c \) are logarithmic and exponential constants respectively, and \( v \) is the secular velocity. We use the fourth of the CORS time series above to search for unknown parameters, namely \( a \), \( b \), \( c \), \( \tau_{log} \), and \( \tau_{exp} \) for each station. Then we use the parameters of estimation to correct the velocity for 18 of GPS stations and compared the result against velocity without postseismic correction.

A good mathematical function has a minimum RMSE value or is getting close to zero, which indicates that the function has the best similarity. Furthermore, to verify the significance of the difference between the velocity before and after the postseismic correction, a significance test of the two parameters was performed. Mathematical equations (3) and testing criteria correspond to equations written as follows (Ghilani 2010):

\[ t = \left| \frac{x_1 - x_2}{\sqrt{\sigma^2 x_1 + \sigma^2 x_2}} \right| \] (3)

Where \( x_1 \) and \( x_2 \) are velocity before and after postseismic correction respectively. While \( \sigma^2 x_1 \) and \( \sigma^2 x_2 \) are standard deviations for each velocity respectively. The rejection of the null hypothesis (Ho) at the value of \( t < t_{df, \frac{\alpha}{2}} \) with \( t_{df, \frac{\alpha}{2}} \) is the value of \( t \) distribution in the \( t \)-student table with an interval of confidence of \( \alpha \). Acceptance of Ho indicates the two parameters are not significantly different, while rejection Ho shows the two parameters are statistically different.

3. Result and Discussion

3.1. Timeseries Analysis

Timeseries data in the form of daily solutions are used to see the characteristics of deformation, which occurred from each continuous observation station. There are four CORS data available stations generated from 2009 to 2019. Unfortunately, the existing CORS data did not go through 2006 so that it could not to be seen how the postseismic process was exactly after the earthquake. The results of the daily solution plotting on the graph show a similarity to the shift of the trend for the
east-west and north-south components. With observations beginning quite long from the earthquake, it is estimated that the Opak Fault is now entering the interseismic phase. The mathematical function fittings can see whether, in this interseismic phase, there are still process mechanisms that influence or were entirely released.

![Postseismic Model of JOG2](image)

**Figure 2.** An example of fitting of mathematical function to time series data. The blue scatter indicates time series coordinate while the yellow line indicates the mathematical function.

### 3.2. Postseismic Deformation Parameter

The results of the four continuous stations daily solution data are then fused with two mathematical functions. The results of RMS error values can be seen in Table 1 and Table 2 respectively. The RMS error values of each component at each observation station to see the average RMS error values. Based on the calculation of the results of the two mathematical functions for four continuous stations, the exponential function has the smallest total RMS value compared to the logarithmic function with a value of 0.2 mm for The East-West component and 0.29 mm for The North-South component. The results indicated that postseismic parameters for each GPS site have different goodness-of-fit results. The postseismic signal captured in the GPS signal is not too inclined towards one of the Functions, which can be seen by the RMS error value, where the difference very small and not too significant. This happened because the existing GPS observation data just started a few years after the earthquake happened.

During the calculation process, the determination of estimates uses continuous data because it’s able to explain the physical process with a longer epoch of observation period, so we find that the average logarithmic value is 1.08 years and Exponential 4.64 years. Meanwhile, the estimated coseismic offsets and postseismic amplitudes for the earthquake range between stations from several centimeters to millimeters with the continuous station respectively. The RMS value of the exponential function were smaller than the logarithmic function shows the physical process mechanism which happened in the Opak Fault, which has entered the interseismic phase, which is still dominated by the influence of viscoelastic relaxation of material on the lower crust after the
Yogyakarta earthquake in 2006. Then we use the exponential function to correct the velocity for all stations.

### Table 1. Parameters of logarithmic function

| Site | Long (°E) | Lat (°N) | αEast | αNorth | βEast | βNorth | RMSEast | RMSSouth |
|------|-----------|----------|-------|--------|-------|--------|---------|---------|
| CBTL | 110.34    | -7.89    | -61.38| 25.65  | 20.01 | 2.48   | 8.96    | 4.54    |
| CPTS | 110.30    | -8.01    | -219.8| 172.9  | -16.08| -200.4 | 6.8     | 5.19    |
| JOGS | 110.29    | -7.82    | -27.69| 11.89  | -2.43 | -0.85  | 7.18    | 4.94    |
| JOG2 | 110.37    | -7.76    | 81.64 | -159.8 | -45.11| 139.2  | 7.38    | 4.19    |
| Average |          |          |       |        |       |        | 7.58    | 4.72    |

The afterslip effect described by the logarithmic function appears to be gone because the decay time is quite short from the moment of the earthquake, while the exponential function can see a quite long postseismic process. The depth of the 2006 earthquake predicted by several references is about 10 to 17 km could be suspected that there is the material which is relaxed at the bottom of the earth's crust (Pollitz, et al., 2017). Therefore, to calculate or find the deformation value of a place that is in the area around the Opak Fault should be considered in the postseismic effect phase so that the value obtained deformation free from postseismic effects.

### Table 2. Parameters of an exponential function

| Site | Long (°E) | Lat (°N) | αEast | αNorth | βEast | βNorth | RMSEast | RMSSouth |
|------|-----------|----------|-------|--------|-------|--------|---------|---------|
| CBTL | 110.34    | -7.89    | -52.03| -102.1 | -73.58| 139.5  | 8.96    | 4.54    |
| CPTS | 110.30    | -8.01    | -211.4| 155.7  | -74.5 | -313.8 | 6.79    | 5.19    |
| JOGS | 110.29    | -7.82    | -29.56| 33.38  | -5.47 | -25.64 | 7.17    | 4.93    |
| JOG2 | 110.37    | -7.76    | 240   | -42.73 | -424.1| 294.8  | 6.71    | 4.18    |
| Average |          |          |       |        |       |        | 7.41    | 4.71    |

3.3. **Velocity Analysis**

The results of the horizontal velocity of 18 monitoring stations before and after postseismic correction with an exponential function produce values in millimeter fractions. Table 3 shows the value of the velocity with the accuracy of 18 monitoring stations on the North (N) and East (E) components. The velocity before correction uses linear mathematical function fitting and the velocity after correction uses the results of the exponential function fitting.
Table 3. The velocity of 18 GPS stations before and after postseismic correction

| No | Site  | $V_x$ (mm/year) | $V_y$ (mm/year) | $\sigma_{V_x}$ (mm) | $\sigma_{V_y}$ (mm) |
|----|-------|----------------|----------------|---------------------|---------------------|
|    |       | Lin      | Exp      | Lin      | Exp      | Lin     | Exp     |
| 1  | CBTL  | -8.42    | -10.58   | 27.20    | 25.27    | 0.03    | 0.01    | 0.06    | 0.01    |
| 2  | CPTS  | -11.20   | -12.51   | 28.03    | 26.92    | 0.11    | 0.02    | 0.02    | 0.01    |
| 3  | JOG2  | -8.08    | -9.92    | 24.64    | 23.45    | 0.06    | 0.10    | 0.10    | 0.02    |
| 4  | JOGS  | -8.64    | -11.07   | 26.98    | 24.61    | 0.03    | 0.02    | 0.04    | 0.01    |
| 5  | OPK3  | -9.96    | -8.90    | 30.17    | 28.90    | 10.05   | 1.69    | 1.60    | 6.04    |
| 6  | OPK6  | -11.09   | -10.74   | 28.59    | 27.37    | 1.66    | 1.73    | 1.67    | 1.90    |
| 7  | OPK7  | -14.12   | -14.67   | 24.87    | 23.79    | 2.92    | 4.30    | 4.21    | 3.00    |
| 8  | OPK8  | -7.98    | -10.36   | 25.59    | 24.20    | 2.56    | 1.49    | 1.52    | 2.74    |
| 9  | SGY1  | -9.18    | -9.97    | 29.44    | 28.18    | 2.30    | 1.75    | 1.72    | 2.46    |
| 10 | SGY2  | -8.70    | -12.66   | 31.00    | 28.76    | 2.78    | 1.98    | 1.99    | 1.63    |
| 11 | SGY3  | -9.81    | -11.17   | 21.68    | 20.25    | 0.55    | 5.97    | 5.42    | 0.63    |
| 12 | SGY5  | -9.08    | -10.58   | 24.21    | 23.20    | 1.38    | 1.05    | 1.03    | 1.50    |
| 13 | SGY6  | 2.57     | -7.06    | 22.36    | 23.06    | 11.21   | 2.22    | 4.43    | 1.33    |
| 14 | TGD1  | -9.32    | -10.83   | 23.98    | 22.95    | 1.20    | 2.39    | 2.17    | 1.24    |
| 15 | TGD2  | -8.88    | -11.26   | 28.96    | 26.74    | 1.39    | 2.11    | 2.14    | 1.42    |
| 16 | TGD3  | -10.87   | -13.05   | 27.75    | 26.14    | 1.41    | 1.27    | 1.26    | 1.45    |
| 17 | TGD4  | -9.28    | -9.79    | 25.29    | 23.90    | 0.92    | 1.32    | 1.31    | 1.00    |
| 18 | TGD6  | -10.68   | -12.04   | 30.92    | 29.26    | 1.02    | 1.53    | 1.51    | 1.05    |

Figure 3. Velocity comparison before and after postseismic correction
We show in Figure 3 the results of the comparison between horizontal velocity before and after postseismic correction with the standard deviation. Red lines describe the location of the Opak Fault based on research (Widjajanti et al., 2020). Blue arrows indicate velocity results before correction, and magenta arrows indicate velocity results after postseismic correction.

| No | Site | Ve | Vn | Ve | Vn |
|----|------|----|----|----|----|
| 1  | CBTL | 29.54 | 61.79 | Significant | Significant |
| 2  | CPTS | 37.55 | 11.56 | Significant | Significant |
| 3  | JOG2 | 8.37 | 27.39 | Significant | Significant |
| 4  | JOGS | 46.44 | 76.92 | Significant | Significant |
| 5  | OPK3 | 0.55 | 0.09 | Not Significant | Not Significant |
| 6  | OPK6 | 0.51 | 0.14 | Not Significant | Not Significant |
| 7  | OPK7 | 0.18 | 0.13 | Not Significant | Not Significant |
| 8  | OPK8 | 0.65 | 0.64 | Not Significant | Not Significant |
| 9  | SGY1 | 0.52 | 0.24 | Not Significant | Not Significant |
| 10 | SGY2 | 0.80 | 1.23 | Not Significant | Not Significant |
| 11 | SGY3 | 0.18 | 1.62 | Not Significant | Not Significant |
| 12 | SGY5 | 0.69 | 0.74 | Not Significant | Not Significant |
| 13 | SGY6 | 0.14 | 0.85 | Not Significant | Not Significant |
| 14 | TGD1 | 0.32 | 0.88 | Not Significant | Not Significant |
| 15 | TGD2 | 0.74 | 1.20 | Not Significant | Not Significant |
| 16 | TGD3 | 0.90 | 1.07 | Not Significant | Not Significant |
| 17 | TGD4 | 0.75 | 0.38 | Not Significant | Not Significant |
| 18 | TGD6 | 0.77 | 0.93 | Not Significant | Not Significant |

Based on the test results of the significance between two different parameters in Table 4, we obtained that the velocity before and after the postseismic correction results are different significantly only at continuous stations, while for periodic stations, here was no significant difference. Our study supported previous research there is an affect of viscoelastic mechanism after almost 14 years. Then the statistical test revealed that postseismic correction has a significant effect on the estimated velocity motion of continuous stations. This happened due to the lack of data on periodic observations so that the estimated results of postseismic corrections using continuous data have no significant effect on the results of the periodic station.

4. Conclusion
We show that GPS stations in Yogyakarta, mainly CORS (CBTL, CPTS, JOGS, and JOG2) can explain this fault movement in the interseismic phase, but it is still a postseismic energy effect. We conclude that GPS data in the Yogyakarta region over the period 2009-2019 are more suitable using the combination of linear and exponential functions with an average mismatch ~ 0.96 times smaller than using logarithmic functions. There are still other mechanism of the postseismic deformation that should be taken into account in determining deformation value in Yogyakarta.
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