Estimation of Slip Rate and the Opak Fault Geometry Based on GNSS Measurement

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Abstract. GNSS observations are usually used in periodic deformation monitoring. The Opak fault, which was in the Special Region of Yogyakarta, became a concern after the 2006 earthquake. The horizontal velocity values of each observation station are needed to estimate the slip rate and locking depth values of the Opak fault. The magnitude of the velocity vector is computed by the linear least square method, then translated into the Sunda Block reference frame. The creep of fault assumption is used in analyzing the potential for the earthquake in the Opak fault region. The velocity is done by reducing the Sunda Block using the Euler pole method, and it produces a velocity vector value on the east component is -6.08 to 5.25 mm/year while the north component is -3.38 to 5.74 mm/year. Meanwhile, in the northern segment of the Opak fault, the estimated slip rate is around 3.5 to 10.5 mm/year, with the locking depth obtained of 1.1 to 8 km, while in the southern segment of the Opak fault, the estimated slip rate is 4 to 5.5 mm/year, with a locking depth obtained of 0.6 to 1.2 km. The creep of the fault effect is predominantly in the southern segment of the Opak fault. This case indicates that the potential for earthquake hazards is smaller in the south segment than in the north segment.

1. Introduction

One activity that induces earthquake phenomenon in Daerah Istimewa Yogyakarta (DIY), especially the region near the Opak fault, is the tectonic plate movement that through the Indonesia region are Eurasia, Indo-Australian, and Pacific plates [1]. The Opak fault deformation analysis can be performed by the least square method to compute the value of the displacement velocity vector. This value is used as a parameter in estimating the slip rate and depth of the locked fault source. The two values correlate as parameters in determining fault geometry.

The previous study [2] showed that using Global Navigation Satellite System (GNSS) data from 2013 to 2018 with the block motion method, the estimated value of the locking depth has a depth of 22 km in the southern segment of the Opak fault. The distribution of the strike-slip rate in the southern segment of the fault ranges from 0.126 to -9.402 mm/year. The northern segment ranges from -7.689 to 7.549 mm/year [3]. This study performs a simple screw dislocation model using the grid search method to determine the two-parameter values of the Opak fault [4].

In the last decade, the Opak fault became a single fault that identified as a significant active tectonic deformation. There is an indication that a new fault occurred in the northern part of the Opak fault [5]. Therefore, this study focuses on the estimation of locking depth in the north part of the Opak fault.

The results of the estimated slip rate and locking depth can be used as a parameter in determining the value of earthquake strength. This study is expected as a disaster mitigation activity in the DIY region.
2. Data and Method

2.1. Deformation Analysis

An area is said to be deformed if there are any changes or shifts in coordinates at the observation points that are made regularly. The shift is in topocentric coordinates, where the reference point used is the initial observation at each station.

Eighteen GNSS observation stations from 2013 to 2018 were used in the deformation analysis. Three of them are Continuously Operating Reference Station (CORS), which can record the observation data every day for 24 hours continuously. The GNSS data acquisition is carried out by the Geodetic Engineering team of the Universitas Gadjah Mada (UGM). GAMIT/GLOBK is used to get solutions from GNSS observation. Thirteen International GNSS Services (IGS) stations used as reference stations tied with International Terrestrial Reference Frame (ITRF) 2008. This processing scheme is the same as processing the BIG cors station data.

Deformation analysis from shift value can be used to compute the velocity vector. The value is estimated by the least-squares method, where the velocity value is a line gradient of the time series of position changes. From the time series of changes in existing positions can be estimated with linear models by doing the fitting process for all data in a time interval. Mathematically, the linear model is obtained from equation (1), and the results of the velocity value are used to compute the velocity vector by equation (2) [3], [6].

\[
[y] = m[x] + b \quad (1)
\]

\[
Vv = \frac{d}{t2 - t1} \quad (2)
\]

Where \( y \) is a matrix containing shift values (East, North, and Up), \( m \) is the gradient line, \( x \) is epoch matrix observations, \( b \) is a constant, \( Vv \) is velocity vector, \( d \) is displacement each station, \( t2 \) and \( t1 \) is the second and first epochs.

2.2. Sunda Block Reference Frame

The block model is a geodynamic model that usually use to define the relationship between one plate or block of tectonics and another plate or block of tectonics. The movement of these blocks can be represented by Euler’s rotation parameters, which consist of Euler’s latitude and longitude and angular rotational velocity [6].

The Euler pole represents the location of the point traversed by the Euler rotation axis, while the angular rotation velocity represents the magnitude and direction of the relative block velocity [6]. The velocity value resulted from equation (1) uses the Sunda Block respect with the ITRF. For this reason, a transformation is needed for the local Sunda Block. The transformation use equation (3) [6].

\[
\begin{bmatrix}
Vn \\
Ve \\
Vu
\end{bmatrix} = \begin{bmatrix}
-\sin \phi \cos \lambda & -\sin \phi \sin \lambda & \cos \phi & 0 & Z & -Y & \omega X \\
-\sin \phi \cos \lambda & \cos \phi & 0 & -Z & 0 & X & [\omega Y] \\
\cos \phi \cos \lambda & \cos \phi \sin \lambda & \sin \phi & Y & -X & 0 & \omega Z
\end{bmatrix}
\]

Where \( V_{neu} \) is topocentric velocity vector, \( \lambda \) and \( \phi \) are latitude and longitude of Sunda Block, and GNSS station, \( X, Y, \) and \( Z \) are geocentric GNSS coordinates. At the same time, \( \omega \) is the angular velocity of the rotation pole and radius of the earth. Based on the \( X, Y, \) and \( Z \) angular rotation vectors, the value of \( \phi, \lambda, \) and \( \omega \) can be estimated with equations (4), (5), and (6) by [6].

\[
\phi = \tan^{-1} \left( \frac{\omega_z}{2\omega_x^2 + \omega_y^2} \right) \quad (4)
\]

\[
\lambda = \tan^{-1} \left( \frac{\omega_y}{\omega_x} \right) \quad (5)
\]

\[
\omega = \sqrt{\omega_x^2 + \omega_y^2 + \omega_z^2} \quad (6)
\]

2.3. Slip Rate and Locking Depth Estimation

The velocity vector values from GNSS measurements can be used to estimate the strain and moment accumulation rate. The main parameters are the slip rate and the depth of the locked fault source. Slip
rate is one of the characteristics of an earthquake whose value is essential to know to analyze the danger of earthquake shocks on bedrock and surface soil. At the same time, the locking depth is the adequate thickness resulting from the accumulation of the interseismic zone of the active fault [7]. The two values are correlated as parameters in determining fault geometry. To estimate the value of slip rate and locking depth, an equation based on [4] can be seen in equation (7).

\[ V(y) = \frac{V_{slip}}{\pi} \left( \tan^{-1} \left( \frac{X_{gps}}{Z_{lock}} \right) + \frac{\tan^{-1}}{\pi} \left( \frac{X_{gps}}{Z_{lock}} \right) \right) \]  

(7)

Where \( V(y) \) is velocity vector, \( V_{slip} \) is the value of slip rate estimation, \( X_{gps} \) is the parallel distance for every station from The Opak fault, and \( Z_{lock} \) is the depth value of the locked fault source.

The grid search method is used to obtain the most optimum estimation value of slip rate and locking depth. It will create a grid in space in an area that is suspected to be the location of a fault source, which is in the northern part of the Opak fault.

The meshgrid script in visualizing the results of the grid search to produce grids with points that have the same or uniform spacing on the graph. The distance between the grids is used every 0.1° to 0.5° for each component of East and North. Grid search of the slip rate and locking depth are conducted to get the smallest RMS error value based on equation (7). Grid points that have a minimum error value are locations that are suspected as sources of fault [8].

3. Result

3.1. Velocity Vector from Deformation Measurement

The final result of GAMIT/GLOBK processing is a *.pos file containing the coordinates of each doy following the processed rinex data. There are two types of coordinate systems in the *.pos file, namely the geocentric coordinate system and the topocentric coordinate system. The two systems are the position of a point on the surface of the earth but have different zero points. The geocentric coordinate system has zero point at the center of mass of the earth, while topocentric has zero point at one point on the surface of the earth. The coordinate system used to calculate the velocity vectors is a topocentric coordinate system. [6]

The value of velocity vectors from each station can be used to analyze patterns of movement geometrically, both horizontal and vertical components. Table 1 shows the velocity values for each station from the result of linear least square and velocity vectors with respect to Sunda Block. East (E) and North (N) velocity components are shown in VE and VN in units of mm/year, while \( \sigma_E \) and \( \sigma_N \) are their standard deviations in units of mm/year.

There are various values in the vector direction of each station on the E and N components. The negative sign in the N component means the course of the velocity vector to the south from the Opak fault. Otherwise, the positive sign explained that the direction of the velocity vector to the north from the Opak fault. The negative sign in the E component means the direction of the velocity vector is to the west from the Opak fault.

The average standard deviation in the east component is 1.99 mm and the north component is 1.88 mm. This value is relatively small due to the addition of CORS station data in processing the shift velocity. The north component of the CBTL and JOGS stations can even reach a standard deviation of 0.03 mm.

Meanwhile, the velocity vector from the linear least square method on the east and north components are 21.68 to 30.92 mm/year and -7.98 to -14.12 mm/year, respectively. The vector is dominant leads to the southeast from the entire monitoring point of the Opak fault. Each station influenced by the subduction zone of the Java trench due to the convergences of the Sunda Block and Indo-Australian plates.

On the other hand, the reduced velocity value of the Sunda Block in the east component is -6.08 to 5.25 mm/year while in the north component is -3.38 to 5.74 mm/year. These results are very different from the linear least square velocity, which has an average value of around 20mm/year. Figure 1 shows the direction of the velocity vector respect with the Sunda blocks.
The Sunda Block velocity has standard deviation in the east component of 0.47 to 5.44 mm/year with a mean of 2.11 mm/year and the north components of 1.41 to 10.15 mm/year with a mean of 2.55 mm/year. This value is higher than the results of the least square linear velocity due to the reduction process of the two velocity values and combining the standard deviation, which obtain from the standard deviation of the Sunda Block reduction velocity shift. The velocity value can be said to be significant if higher than the standard deviation value [9].

| Station | Longitude (DD) | Latitude (DD) | Velocity with Least Square Method (mm/year) | Velocity with respect to Sunda Block (mm/year) |
|---------|----------------|---------------|---------------------------------------------|-----------------------------------------------|
|         |                |               | VE  | VN  | σE  | σN  | VE  | VN  | σE  | σN  |
| CBTL    | -7.9025        | 110.3350      | 27.2 | -8.42 | 0.06 | 0.03 | 2.28 | 4.20 | 0.47 | 1.41 |
| JOG2    | -7.7738        | 110.3730      | 24.64 | -8.08 | 0.1  | 0.06 | -0.29 | 4.51 | 0.48 | 1.41 |
| JOGS    | -7.8266        | 110.2940      | 26.98 | -8.64 | 0.04 | 0.03 | -2.06 | 3.94 | 0.47 | 1.41 |
| OPK3    | -7.8926        | 110.5492      | 30.17 | -9.96 | 1.6  | 10.05 | 5.25 | 2.75 | 1.67 | 10.15 |
| OPK6    | -7.9619        | 110.5460      | 28.59 | -11.09 | 1.67 | 1.66 | 3.68 | 1.64 | 1.73 | 2.18 |
| OPK7    | -8.0367        | 110.4560      | 24.87 | -14.12 | 4.21 | 2.92 | -0.04 | -1.39 | 4.24 | 3.24 |
| OPK8    | -7.9602        | 110.4049      | 25.59 | -7.98 | 1.52 | 2.56 | 0.68 | 4.69 | 1.59 | 2.92 |
| TGD1    | -7.7686        | 110.4899      | 29.44 | -9.18 | 1.72 | 2.3  | -4.51 | 3.45 | 1.78 | 2.70 |
| TGD2    | -7.8817        | 110.4519      | 31.0  | -8.7  | 1.99 | 2.78 | -6.08 | 3.96 | 2.04 | 3.12 |
| TGD3    | -7.7496        | 110.3692      | 21.68 | -9.81 | 5.42 | 0.55 | -3.25 | 2.76 | 5.44 | 1.51 |
| TGD4    | -7.8543        | 110.3120      | 24.21 | -9.08 | 1.03 | 1.38 | -0.71 | 3.51 | 1.13 | 1.97 |
| TGD5    | -7.7395        | 110.1972      | 22.36 | 11.21 | 4.43 | 2.57 | 2.57 | -1.29 | 4.45 | 2.93 |
| TGD6    | -7.9125        | 110.1964      | 23.98 | -9.32 | 2.17 | 1.2  | -0.94 | 3.25 | 2.22 | 1.85 |
| SGY1    | -7.8815        | 110.4241      | 28.96 | -8.88 | 2.14 | 1.39 | -4.04 | 3.77 | 2.19 | 1.98 |
| SGY2    | -7.9013        | 110.4017      | 27.75 | -10.87 | 1.26 | 1.41 | -2.83 | -1.78 | 1.34 | 1.99 |
| SGY3    | -7.9036        | 110.4249      | 25.29 | -9.28 | 1.31 | 0.92 | -0.37 | -3.38 | 1.39 | 1.68 |
| SGY5    | -7.8570        | 110.4517      | 26.15 | -6.91 | 3.7  | 1.07 | -1.23 | 5.74 | 3.73 | 1.77 |
| SGY6    | -7.8577        | 110.4728      | 30.92 | -10.68 | 1.51 | 1.02 | -6.00 | 1.98 | 1.58 | 1.74 |

Based on Table 1, several observation stations of the Opak fault have insignificant velocity values. The monitoring points of JOG2, OPK7, OPK8, TGD3, TGD4, TGD6, SGY3, and SGY5 have smaller shift velocity values than the standard deviation, in the east component. The monitoring points of OPK6, OPK7, and TGD5 also have a lower shift velocity value than the standard deviation, in the north component. Therefore, these points need to be considered in the slip rate estimation process, especially at OPK7 points, which have insignificant shift velocity values in both components.

In Figure 1, the vector direction from the monitoring point of the Opak fault dominates to the northwest. This direction is different from the results of the linear least square velocity, which leads to the southeast. The loss of influence due to Euler’s polar rotation causes its velocity to be in the local system due to all monitoring points have been successfully reduced from the impact of the Sunda Block.
These results prove that the reduction of the Sunda Block can eliminate the relative influence of tectonic plates and local deformation [2]. The reduction in the impact of the Sunda Block can assume the analysis of the value of the shift velocity that represents the local deformation considering the subduction zone is at the Opak fault. The monitoring stations of OPK7, OPK3, OPK8, TGD6, and TGD 5 are in the opposite direction from the other stations because the location of the monitoring point is quite far compared to other monitoring points on the Opak fault.

**Figure 1.** Velocity vectors for each station respect with local Sunda Block. The blue arrow is the direction of velocity vectors, the red line is the location of the Opak fault, and the triangle symbols are the Opak fault monitoring stations.

3.2. Fault Parallel Velocity and Orthogonal Distance to Fault

**Figure 2.** Graphic of correlation between fault-parallel velocity in mm/yr and orthogonal distance to the Opak fault in km.
According to equation (7), this study considers the perpendicular distance of each observation station to the location of the Opak fault. The fault-parallel velocity value is based on the distance perpendicular to the monitoring point of the Opak fault to the definitive position of the Opak fault. A linear equation calculates the perpendicular station distance from the Opak fault location.

In Figure 2, the circular symbol is the observation stations of the Opak fault with a red scale bar showing the size of the standard deviation. The absis shows the perpendicular distance value in units of kilometers while the ordinate shows the perpendicular-fault velocity vector value in mm/year. The negative sign indicates the north-east direction of the distance value on the Opak fault.

Yellow curves indicate that the perpendicular-fault speed of the Opak fault is relatively rising from north to south. The purple curve also shows an increased value of the perpendicular-fault velocity by assuming the effect of creep of fault in the zero-axis. The distribution of points towards two curves dominantly directed towards the west. Therefore, the Opak fault belongs to the left lateral fault. By observing the spread direction of each station's shift, the Opak fault moves in the left-lateral fault. The correlation between parallel fault velocity and orthogonal distance to fault shown in Figure 2.

### 3.3 Slip rate and locking depth estimation

This research produces two kinds of estimation scenarios, namely assuming a creep and without considering a creep of fault. Estimation of the two values generates by equation (7) with input data on the value of the velocity vectors respect with Sunda Block, according to Table 1. The entire monitoring stations are divided into two segments, namely the north and the south segments.

Estimated values are obtained by selecting the convergence zone of each segment that has the smallest RMSe value. The estimation results are presented in Figure 3, which is the north segment, and Figure 4 is the result of the south segment. The x-axis is the locking depth value in kilometers, while the y-axis is the value of the slip rate in mm/year. The RMSe value show in yellow to dark blue. The more convergent zone is dark blue, the smaller the RMSe value.

In Figure 3, the estimated value of the slip rate from the north segment of the Opak fault ranges from 3.5 to 10.5 mm/year. The locking depth value is 1.1 to 8 km. The results are indicated by the convergence zone of the smallest RMSe amount is ten which visualized as oval shape of a dark blue. The average value of the slip rate, which is relatively large, indicates the creep of fault effect on the segment. The estimated value of the locking depth is different from [3] due to the Opak fault did not remain silent throughout the observation year as well as the addition of continuous observation data that could explain the earthquake events throughout 2013 to 2018.

In Figure 4, the estimated value of the slip rate from the south segment of the Opak fault ranges from 4 to 5.5 mm/year, while the locking depth value is 0.6 to 1.2 km. The convergence zone of the lowest RMSe amount is smaller than the north segment. The range of slip rate values in this segment is smaller than the north segment that indicates the existence of a locked fault.

![Figure 3. Slip rate and locking depth estimation with the grid search method in the north segment of the Opak fault](image-url)
The result of locking depth value is classified as shallow with a value in the south segment of 0.6 km. The result indicates that the south segment does not have the potential to produce large magnitude earthquakes.

For more details, if the entire locking depth region in the southern segment experiences a creep of fault, then it further explains that there is no potential for large magnitude earthquakes. Unlike the north segment, the result of the locking depth value starts from a depth of 1.1 km. The range of locking depth value in the north segment is longer than the north segment of 6.9 km. The result indicates the potential for an earthquake with greater strength than the south segment. The longer the range of locking depth, the bigger potential for an earthquake. The shallow locking depth value still can’t explain the 2006 earthquake of magnitude 6.3 in Yogyakarta. However, this value can explain the shallow earthquakes that occurred throughout the year of observation, according to the USGS earthquake catalog.

By considering the creep effect, the north segment of the Opak fault has a slip rate of 1.8 to 3 mm/year with a locking depth of 0.5 to 3.5 km, while the south segment has a slip rate of 2.1 to 3.5 mm/year with a locking depth of 0.5 to 1.3 km. The result of the creep effect has a much smaller range of values than without assuming creep of fault. These related to the characteristics of fault movement in the zone that occurs creeping that moves slowly. The slip rate value in the south segment is smaller than without the creep assumption. Similar to the north segment, these results are related to the characteristics of fault movements in creeping zones that occur slowly. However, the north segment has greater earthquake potential than the south segment due to not affected by the creep effect significantly.

Figure 4. Slip rate and locking depth estimation with the grid search method in the south segment of The Opak fault

4. Conclusion
Based on the GNSS data, it can produce a shift value for each station and its velocity vector value. The result showed that the velocity vector respect with Sunda Block in the east and north components of 6.08 to 5.25 mm/year and -3.38 to 5.74 mm/year, respectively.

Meanwhile, based on the estimated value of the slip rate and locking depth, the north segment of the Opak fault has greater earthquake potential than the south segment with a greater range of locking depth values. The south segment of the Opak fault is indicated that there is a creep effect that has the potential for shallow earthquakes with less force.
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