Analysis of Kaligarang Fault Deformation with GNSS Survey in 2016-2018

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Abstract. The GNSS Survey has been conducted for the deformation of Kaligarang Fault in 2016 and 2018. Active fault activity can be shown by the value of slip rate and locking depth. The magnitude of the slip rate cannot be measured directly, but the displacement on the surface of the earth data could be obtained from GNSS measurements. Then the slip rate could be calculated by inversion techniques from the displacement data form GNSS survey. We have done the slip rate modeling using the displacement data using the value of locking depth 5, 10, 15 and 15 km. But the position of the observation station point cannot converge to a single slip rate line at all locking depth values. Therefore this research has not been able to infer the optimal slip rate for Kaligarang fault.

Keywords: Kaligarang fault, slip rate, GNSS

1. Introduction

The Government of the Republic of Indonesia in this case the National Agency for Disaster Management is currently trying to make earthquake mitigation efforts by creating a National Earthquake Hazard Map Indonesia. The map is used as the basis for the preparation of Indonesian National Building Standards as well as Earthquake Disaster Risk Assessment. Making Indonesia Earthquake Hazard Map one of them requires data of seismic activity of earth crust either in the form of subduction activity and fault activity.

Kaligarang fault that divides the city of Semarang in the north - south has experienced a long history of activities. The Kaligarang Fault Zone has been formed since Tertiary with the horizontal shift mechanism to the left. After that the Plio-Pliocene undergoes reactivation with horizontal shift. The result of geological study with morphometric and morphotectonic approaches shows that the Kaligarang Fault Zone is an Active Fault [1].

An indication that Kaligarang Fault is an Active Fault shows that the area of Semarang City has the potential for seismic activity. But the status of active faults cannot be used for data input making Detailed Earthquake Hazard Map, because it still requires data slip rate of the fault. Fault activity that expressed with slip rate will cause the displacement on the surface of the earth. The magnitude of the slip rate can not be measured directly, but the displacement on the surface of the earth data could be obtained from GNSS measurements. Then the slip rate could be calculated by inversion techniques from the displacement data [2].
Therefore this research was conducted to calculate slip rate of Kaligarang fault by measuring GNSS, so that shear rate data of Kaligarang Fault can be used as input for making Indonesia Earthquake Hazard Map.

2. Kaligarang Fault

In the Tertiary era, the Kaligarang Fault is a right lateral fault. This fault displacement was caused by the tectonics of that era which had the greatest major stretch of northeast-southwest direction. In the Quaternary era this fault was reactivated as a left lateral fault. The reactivation of this fault is caused by the largest mainline of the relative direction of the northwest-southeast direction [3].

Kaligarang Fault area has seven formations composed of rocks of seeds, volcanic rocks, and igneous rock intrusions. The oldest rocks are the late Miocene plutonic igneous rocks in the form of andesite intrusive rocks. Then marine sedimentary rocks to land ash formation Kerek, Kalibeng Formation, Kaligetas Formation, and Damar Formation. Volcanic activity occurred at the beginning of Pliocene until Holocene form Kaligesik Formation and Gajah Mungkur Formation [1].

At Plio-Pliocene, a Kaligarang Fault Zone is formed with movements of the left lateral faults and the folds in the Kerek Formation and Kalibeng with the NEE-SWW fold axis. The direction of tectonic deformation in this phase is the NWW-SSE with its regional tension N 1550 E direction.

In the Holocene, the Kaligarang Fault zone still has displacement of left lateral fault and the folds of the Damar, Kaligetas, Gadjah Mungkur and Kaligesik Formations with E-W fold axis. This zone continues to grow until now so that the development of restraining and realising. The development of restraining is controlled by the transoressional process in Patemon and Pakintelan.

Danescwara et al has conducted a preliminary survey of GPS Observation in Kaligarang Fault area. The GNSS measurements were made once in September 2016 [4].

3. Slip Rate Model

Fault is one of the fractures of the rock layers that cause a layer to move relatively down or up, or move right or left to another layer of rock. Earthquakes can occur in active fault. This earthquake occurs when there is release of energy in the fault plane. It is characterized by suddenly movements of both fault areas either moving in horizontal or vertical directions [5].

The fault plane have a crack which is termed the slip rate. The slip rate indicates the level / rate of adhesiveness to the surface contact area of the fault plane. The contact surface that is experiencing adhesiveness, when koseismik will slip or in other words the liberated energy accumulated during the interseismic process. Active fault activity can be shown by the value of slip rate and locking depth.

Slip rate and locking depth estimation can be calculated by modeling the level of fault activity. The modeling of slip rate can be formulated mathematically as follows [6–9].

\[ S(y) = \frac{D}{\pi} \text{Atan} \left( \frac{Y}{W} \right) \]  

\( S(y) \) : Slip of point observation due to fault activity  
\( D \) : Slip rate (m/year)  
\( Y \) : Perpendicular distance of point observation to fault (km)  
\( W \) : Locking depth (km)

4. Data and Method

Observation of GNSS Station carried out along the Kaligarang river but is limited by two segments: the Old Kradenan segment and Tinjomoyo segment. The data used are: 2016 and 2018 GNSS RINEX data observation of Kaligarang Fault, GNSS RINEX data of IGS Station as a reference point and support data for GPS processing on GAMIT software.

GNSS Measurement at stations of deformation observation of Kaligarang Fault was done in two sessions, namely in April and June 2018. GPS data processing was done using GAMIT software. GNSS
measurement data in 2016 obtained from Daneswara et al in 2016. We can see the GNSS Kaligarang Fault observation stations in Table 1.

### Table 1. The DOY (Day of Year) of the GNSS Kaligarang Fault observation stations

| Station | The DOY   |
|---------|-----------|
|         | | October 2016 | April 2018 | June 2018 |
| TK01    | 279       | 95         | 176       |
| TK02    | 279       | 95         | 176       |
| TK03    | 280       | 95         | 176       |
| TK04    | 280       | 96         | 177       |
| TK05    | 285       | 96         | 177       |
| TK07    | 286       | 96         | 177       |
| TK08    | 286       | 97         | 179       |
| TK09    | 287       | 97         | 178       |

#### 4.1. GNSS data processing

The RINEX data of GNSS observation were checked by TEQC software to get the value of MP1 and MP2. MP values obtained ranged from 0.5 s.d. 2.3. We used GAMIT/GLOBK software to process the GNSS data. The reference coordinate system was established by connecting to the nearby IGS stations. We used seven IGS stations as reference station. The results of the GNSS data processing are the geocentric coordinates of each station. The topocentric coordinates on 2016 observation of each station serve as the origin of the topocentric coordinate system of each respective station. Hence each station has its topocentric coordinate system.

#### 4.2. The displacement of Kaligarang Fault observation stations

We used the linear curve fitting method to get the velocity rate of the observation stations from the topocentric coordinates of each station.

### Table 2. The velocity rate of the GNSS Kaligarang Fault observation stations

| Station | The velocity rate (m/year) |
|---------|---------------------------|
|         | Ve | Vn | Vhor |
| TK01    | 0.0144 | 0.0004 | 0.0144 |
| TK02    | 0.1048 | 0.0623 | 0.1219 |
| TK03    | 0.0157 | -0.0089 | 0.0180 |
| TK04    | -0.0035 | -0.0035 | 0.0049 |
| TK05    | 0.0159 | -0.0106 | 0.0191 |
| TK07    | 0.0356 | -0.0133 | 0.0380 |
| TK08    | 0.0337 | -0.0069 | 0.0344 |
| TK09    | 0.0213 | 0.0013 | 0.0213 |

The velocity rate (Table 2) still be affected by displacement due to the rotation of the Sunda block. We should eliminate the effect of rotation of the Sunda block. So the velocity rate that resulted is reduced by the velocity rate of the observation stations due to Sunda block rotation.
The velocity rate of observation station due to Sunda Block rotation was calculated using a euler pole model in ITRF 2008. This model has origin of rotation at -85.899º of longitude and 46.202º of latitude and angular velocity 0.370 deg/Myr [10].

Table 3. The velocity rate of the GNSS Kaligarang Fault observation stations after elimination the Effect of the Sunda Block rotation

| Station | The velocity rate (m/year) |  |  |
|---------|---------------------------|---|---|
|         | Vc                        | Vn | Vhor|
| TK01    | -0.0118                   | 0.0084 | 0.0144 |
| TK02    | 0.0786                    | 0.0703 | 0.1054 |
| TK03    | -0.0105                   | -0.0009 | 0.0105 |
| TK04    | -0.0296                   | 0.0045 | 0.0300 |
| TK05    | -0.0102                   | -0.0026 | 0.0106 |
| TK07    | 0.0095                    | -0.0053 | 0.0109 |
| TK08    | 0.0075                    | 0.0011 | 0.0076 |
| TK09    | -0.0049                   | 0.0093 | 0.0105 |

Then, we calculated the slip of point observation due to fault activity (S(y)) and the perpendicular distance of point observation to fault (Y) in equation (1). The values of S(y) an Y can be seen in Table 4.

Table 4. The slip of point observation due to Kaligarang fault activity (S(y)) and the perpendicular distance of point observation to fault (Y)

| Station | S(y) (m) | Y (km) |
|---------|----------|--------|
| TK01    | 0.0099   | 7.15   |
| TK02    | 0.0591   | 4.90   |
| TK03    | 0.0005   | 3.44   |
| TK04    | 0.0084   | 2.44   |
| TK05    | -0.0012  | 1.39   |
| TK07    | -0.0066  | 2.49   |
| TK08    | 0.0000   | 4.11   |
| TK09    | 0.0099   | 6.20   |

4.3 Slip rate modeling
Using S(y) and Y values, we have done the slip rate modeling in equation (1). We determined the value of locking depth 5, 10, 15 and 15 km. For each locking depth value, we make a fault model with a slip rate of 0 to 30 mm with a 2 mm interval.
5. Result and Discussion
The result of slip rate model of Kaligarang Fault can be seen in Figure 1.

![Figure 1](image-url)

**Figure 1.** The slip rate model of Kaligarang Fault. The figure (a) using 5 km locking depth (b) 10 km (c) 15 km and (d) 20 km

From Figure 1, we can see the value of slip rate model ranged 0 to 30 mm with 2 mm intervals symbolized by colored lines. Slip rate Modeling is done by determining the value of locking depth at 5 km in figure 1a, 10 km in figure 2a, 15 km in figure 1c and 20 km in figure 1d. The circle points in the picture show the observation station. The X axis shows the value of Y while the Y axis shows the value of S(y).

In the figure, the position of the observation station point can not converge to a single slip rate line at all locking depth values. Therefore this research has not been able to infer the optimal slip rate for Kaligarang fault. Some things that may cause the value of slip rate can not be obtained is as follows.

RINEX GNSS data quality can be seen from its MP value. The MP value for GNSS RINEX data should be less than 0.5. All existing RINEX GNSS data were greater than 0.5. That were due to the condition of the location of the measurement that many trees are tall which caused a lot of multipath.

All observation station still use campaign type not continuous station. These conditions lead to the possibility of error in tooling centering large enough. The error can reach the order of mm or cm. In addition, observation data are still three sessions so that the deformation trend in the observation station can not be seen. To get the deformation pattern still needed some more observation sessions.
6. **Acknowledgments**

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