Hypocenter relocation using 2006 aftershock data and the current seismic activity in the Yogyakarta region, Indonesia

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Abstract. On May 27, 2006, a significant earthquake Mw 6.4 struck Yogyakarta Area, Indonesia. In this study, we analyzed aftershocks waveform data from 16 temporary network stations of Geo Forschungs Zentrum (GFZ) located around the Yogyakarta Area. We determined the P- and S-wave arrival times manually, with the criteria recorded at least five stations starting from June 3 to July 5, 2006. We successfully relocated 1228 events consisting of 8122 P-and S-wave phases, respectively, and update the 1-D velocity model simultaneously using the Joint Hypocenter Determination Method. To confirm the aftershock distribution, we also analyze the seismic activity around the Yogyakarta Area starting from 2006 until 2019. Our results show that the aftershocks are divided into 2 clusters; cluster located in the southern part of Opak Fault and 10-20 km east of the Opak Fault. We proposed that the main fault rupture of the 2006 Yogyakarta earthquake located in the east of Opak Fault, where this zone is still seismically active until 2015. We conclude that the main fault rupture zone and the Opak Fault are joined in the same fault complex. However, further studies of this complex fault zone are still needed; hence, we will use the results of this study as input in conducting three-dimensional velocity and attenuation inversion.

1. Introduction
The Yogyakarta Area located in the southern part of Java Island near the subduction zone between Indo-Australian Plate and Eurasian Plate, hence the potential for earthquakes in the Yogyakarta area is quite high. In addition, the potential of the earthquakes is also caused by the activity of several local faults on the land formed by the pressure of plates in the southern part of Java Island [1]. The major fault that is around the Yogyakarta area is Opak Fault, which extends along the Opak River from the southern part of Java around the west coast of Parangtritis extends to the north-east direction to Prambanan area [2], [3]. Based on historical records of seismicity between 1840 and 2010 in the Sunda Arc [4], the area of Yogyakarta and its surroundings experienced a devastating earthquake more than 13 times. One destructive earthquake in Yogyakarta occurred on May 27, 2006, with a magnitude of Mw 6.4 [5]. As a result of the earthquake, more than 5,700 people died, and 37,000 were injured, and more than 156,000 houses and other public facilities were totally destroyed with economic losses.
of more than Rp. 29.1 T [6]. The tremendous impact is due to the Yogyakarta area has a dense population and building structures that are not yet resistant to earthquakes.

Observations from the National Earthquake Information Center (NEIC) and the National Research Institute for Earth Science and Disaster Resilience - Japan (NIED) show that the hypocenter position is on the Opak Fault line which indicates the Opak Fault activity caused the Yogyakarta earthquake. However, the United States Geological Survey (USGS) and Ministry of Energy and Mineral Resource Indonesia (ESDM) showed that the mainshock earthquake was east of the Opak Fault, so the idea emerged the cause of the Yogyakarta Earthquake was not associated with Opak Fault activities. The idea was supported by the distribution of earthquake aftershock by Walter et al., (2008), which is relatively clustered at a distance of 10-20 km east of the Opak Fault. Therefore, Walter et al., (2008) suggested that the cause of the 2006 Yogyakarta earthquake was not associated with the Opak Fault, but with a fault around 10-20 km east of the Opak fault identified as an unknown fault.

Taking advantage that Walter et al., (2008) only uses about 10% of the recorded aftershock data, this study aims to conduct seismicity analysis with a higher amount of data and a longer observation time. In this study, we use a non-linear approach that can simultaneously relocate the hypocenter and update the 1-D velocity model. We also observed the current seismic activity from 2006 to 2019 based on cataloged data to determine which zones are still active until today. This research aims to determine the aftershocks distribution after the 2006 earthquake in long-duration so that we can confirm the relationship between the unknown fault and the Opak Fault. Furthermore, we aim to use the results of this study as an initial model for further seismic data processing, including three-dimensional velocity and attenuation tomography.

2. Regional Geology

Yogyakarta is a basin that adjacent to Mount Merapi in the north, the Indian Ocean in the south, The Southern Mountains in the east, and the Kulon Progo Mountain in the west (figure 1). This basin is a depression filled with Quaternary deposits, most of the volcanic product of Merapi (Qv). Morphological differences are seen very clearly between Yogyakarta depression with Wonosari High, which interpreted as the existence of Opak Fault striking northeast-southwest along the Opak river [3].

Stratigraphically, The Late Cretaceous basement of the studied area is exposed to the northeast that consists of low-grade metamorphic rocks (KTm) (Surono et al., 1992). The younger formation includes The Kebobutak Formation (Tmok), Semilir Formation (Tmse), Nglanggran Formation (Tmn), and Sambipitu Formation belong to sedimentary and interbedded volcanic rock containing basaltic – andesitic – pyroclastic rocks that are spread in the eastern part of the form's forms Wonosari Highland. Limestone unit with an approximate thickness of 960 m belong to the Sentolo Formation (Tmps) that exposed in western of the study area, Oyo Formation (Tmo), Wonosari Formation (Tmwl) and the Kepek Formation (Tmpk) that exposed at the southwest of study area overly the older volcanic formations (Rahardjo et al., 1995). On the top overlay surficial deposit Alluvium (Qa), Colluvium (Qe) that distributed in the southwest, and young volcanic deposits of Merapi Volcano (Qmi) that covered half of the study area and filled Yogyakarta's depression [3].

Yogyakarta is an area that has varied tectonic settings. Not only volcanic products and earthquakes caused by subduction zones and plate tectonics activity, but Yogyakarta is also prone to earthquake effects due to the presence of local faults on land. Some active local faults around Yogyakarta are Opak Fault, Oya Fault, Dengkeng Fault, Progo Fault. The Opak Fault became a considered fault that was thought to have primary control over the 2006 Yogyakarta earthquake [8]–[10]. The Opak Fault is a geological structure developed from Prambanan-Depok beach estuary striking northeast-southwest along the Opak River that has an orientation N 235 °E / 80° [10]. The Opak Fault is a strike-slip fault where the east block is relatively moved towards the north, and the west block is moved towards the south [3].
3. Data and Method
In this study, we used waveform data from 14 Geo Forschungs Zentrum (GFZ) temporary station networks around the Yogyakarta area, starting from June 3 to July 5, 2006, to conduct aftershock earthquake analysis. To analyze the current seismic activity, we used earthquake catalog data from the USGS and International Seismological Center (ISC) around the Yogyakarta area from 2006-2019 obtained from the Incorporated Research Institutions for Seismology (IRIS) website (http://ds.iris.edu/wilber3/find_event). The initial 1-D velocity model used to analyze the aftershocks data based on the previous study by Koulakov et al., (2007) around Merapi Volcano.

3.1. Determining P- and S-waves Arrival Time
We use Seisgram2Kv.7. Program to pick the P- and S-waves arrival time. The vertical component of the waveform (BHZ) is used to determine the P-wave arrival time, and the horizontal component (BHE or BHN) is used to determine the S-wave arrival time (figure 2). To control the quality of the arrival time picking, we use the Wadati diagram for each event by plotting between the P-wave arrival time and the difference between the P- and S-wave arrival time (figure 2). Good picking quality can be seen from the gradient of the Wadati diagram, which approaches the value ((Vp/Vs)-1) around 0.73. Data obtained from the determination of arrival time for one month was 1228 events consisting of 8122 phases of the P wave and S waves, respectively, recorded at least by five stations.
Figure 2. Example P- and S-wave arrival time determination using Seisgram2Kv.7. on June 3, 2006, at 14:33. Wadati diagram shows that the picking quality is quite good with Vp/Vs ratio is around 1.7341.

3.2. Determining Initial Location and Origin Time

The initial location and origin time are determined using the Single Event Determination (SED) method using the Geiger Adaptive Damping program [13]. The Geiger method's principle is to intensively compare observed arrival time and calculated arrival time using least square optimization to minimize residual errors from calculations. The P- and S-waves arrival time obtained from the previous process, station coordinates, and initial 1-D velocity model [12] are needed as input in SED. The Wadati diagram of the entire event using the origin time obtained from SED shows a good trend without any outlier events (figure 3).

Figure 3. Wadati diagram for all events using origin time from GAD with Vp/Vs ratio 1.7341.
3.3. Hypocenter Relocation and Update 1-D Velocity Model

An accurate 1-D velocity model and hypocenter location are needed to conduct seismicity analysis. We applied the Joint Hypocenter Determination (JHD) method using the Velest program by [14] to evaluate the 1-D velocity model and relocate the hypocenter simultaneously. The observed arrival time \( t_{obs} \) is a non-linear function of the coordinate station \( (s) \), hypocenter parameters \( (h) \), and velocity \( (m) \) as in equation (1) that cannot be solved directly because hypocenter parameters and velocity structures are unknown.

\[
t_{obs} = f(s, h, m)
\]  

(1)

The Joint Hypocenter Determination method inverses the travel time of several events simultaneously to obtain a more precise location of the hypocenter accompanied by station correction of the velocity error model used. [15] used the first order of Taylor series expansion to obtain the relationship between residual travel time \( t_{res} \) and adjustment to the hypocenter and velocity parameters:

\[
t_{res} = t_{obs} - t_{cal} = \sum_{k=1}^{4} \frac{\partial f}{\partial h_k} \Delta h_k + \sum_{l=1}^{n} \frac{\partial f}{\partial m_l} \Delta m_l + e
\]  

(2)

In the inversion process using the Velest program, the calculated arrival time \( t_{cal} \) is obtained from forward modeling using ray tracing from the hypocenter to the station based on the a priori 1-D velocity model with the addition of damping factors as:

\[
f = [A^TA + L]
\]  

(3)

Where \( A \), \( A^T \), and \( L \) are the Jacobi matrix, the transpose Jacobi matrix, and the damping matrix. The use of damping value significantly affects the perturbation value of the model \( \Delta m \). Workflow to relocate the hypocenter and update the 1-D velocity model using the Velest program can be seen in figure 4.

![Workflow Joint Hypocenter Determination using Velest program (Kissling, 1994)](image)

**Figure 4.** Workflow Joint Hypocenter Determination using Velest program (Kissling, 1994)
A comparison between the initial 1-D velocity model and the 1-D velocity model update can be seen in table 1. Changes in the velocity model only occur at a depth of -3 km to 16 km because the position of the deepest hypocenter is only up to a depth of 20 km; hence no ray path passes through layers at deeper depths.

| Depth (km) | Initial Vp | Initial Vs | Update Vp | Update Vs |
|------------|------------|------------|-----------|-----------|
| -3         | 4.30       | 2.48       | 3.10      | 1.99      |
| 0          | 4.60       | 2.65       | 4.63      | 2.66      |
| 3          | 4.90       | 2.83       | 4.91      | 2.84      |
| 8          | 5.70       | 3.29       | 5.73      | 3.31      |
| 16         | 6.90       | 3.98       | 6.94      | 4.01      |
| 24         | 7.10       | 4.10       | 7.10      | 4.10      |
| 77         | 7.80       | 4.50       | 7.80      | 4.50      |
| 120        | 8.05       | 4.65       | 8.05      | 4.65      |
| 165        | 8.17       | 4.72       | 8.17      | 4.72      |
| 210        | 8.30       | 4.79       | 8.30      | 4.79      |

4. Result and Discussion
We successfully determined the hypocenter of 1228 events starting from July 3 until June 5, 2006 (figure 5). This study shows that the aftershocks distribution is divided into two clusters shown by red dashed rectangles in figure 5. Cluster A follows the southern Opak Fault along 13 km, while cluster B is 10-20 km east of the Opak fault along 25 km. In cluster A and cluster B, aftershock distribution shows a relatively vertical distribution that supports the strike-slip fault mechanism.

![Figure 5](image_url)
Compared with the previous study by Walter et al., (2008), our result revealed a significant difference in the number of aftershock events in cluster A, where our results show that aftershocks in cluster A turned out to be quite a lot. Aftershocks in cluster A indicate that the southern Opak Fault zone is also active during the earthquake period. The aftershocks distribution in cluster A is not continuous into the northern Opak Fault zone because the Opak Fault is divided into two different segments and only the southern segment that seismically active during the 2006 earthquake. The segmentation of Opak Fault is supported by the existence of a strike-slip fault around the Segoroyoso Area based on the geological map by [3]. The depth of aftershocks in cluster A is less than 10 km, which suggests that the weak zone of the Opak Fault may only reach depths of less than 10 km.

In cluster B, the aftershock distribution is at a deeper depth between 8 km to 16 km. Aftershock distribution in cluster B is following the mainshock position of USGS and ESDM. Seismic activities from 2006 to 2019 with magnitudes ranging from 2.5 Mw to 4.8 Mw are also concentrated in this cluster (figure 6), hence we suggest that the mainshock nucleate from this area. Seismic activity is still active in this area until 2015, marked by red, yellow, and green dots (figure 6). However, seismic activity from 2016 to 2020 significantly decreased as indicated by orange dots (figure 6). We suggest that until 2015, there will still be a release of energy left over from the 2006 earthquake so that the zone in the eastern part of the Opak Fault is still seismically active.

![Figure 6](image6.png)

**Figure 6.** The current seismicity around Yogyakarta Area starting from 2006 until 2009. Yellow stars show the mainshock epicenter from several institutions. Red, yellow, green, and orange dots show the earthquake category that occurred in 2006-2009, 2010-2012, 2013-2015, and 2016-2020. The dashed lines denote the fault based on the geological map of [3].

Although we divided the aftershocks distribution into 2 clusters, the 3-D distribution reveal that clusters A and B are linked to each other in the south by an earthquake at a depth of about 10 km correspond with the Oya Strike-slip Fault with the NW-SE direction indicated by red dashed rectangle in figure 7. Therefore, we proposed that the fault rupture in the east of Opak Fault is part of the Opak Fault zone. We also identify the aseismic zone to the north of the Oya Fault which limits clusters A and B. The existence of this aseismic zone is probably due to the fact that this zone is composed of relatively harsher volcanic breccia.
5. Conclusion

We successfully determine the 1228 aftershock event from the 2006 Yogyakarta earthquake recorded within one month. Based on our results, we conclude that the aftershock distribution of the 2006 Yogyakarta earthquake is divided into two clusters along the southern Opak Fault and at a distance of 10-20 km east of the Opak Fault. We supported the idea that the main fault rupture of the 2006 earthquake was located in 10-20 km east of the Opak Fault based on the Aftershock clustering and the current seismic activity. We suggest that the fault in 10-20 east of the Opak Fault and the Opak Fault are the same fault zone. We also noted the aseismic zone that terminates the cluster A and cluster B associated with the volcanic breccia layer. However, further studies are needed to confirm the fault complex's geometry in this zone; hence, we will use this result as input for three-dimensional velocity and attenuation inversion.

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