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HYPOCENTER RELOCATION OF THE YOGYAKARTA AFTERSHOCK 3 JUNE 2006 USING THE DOUBLE DIFFERENCE METHOD

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ABSTRACT

Yogyakarta is one of the regions in Indonesia that is still actively experiencing deformation due to subduction activities of the Indo-Astralian plate and the Eurasian plate. The movement of tectonic plates causes cracks or fractures in rocks beneath the earth's surface. On May 27 2006, an earthquake occurred in Yogyakarta and its surroundings, including Bantul Regency and its surroundings. The cause of the earthquake on land was identified as coming from the Opak Fault and nearby faults which have not yet been identified. Hypocenter relocation is needed to obtain a more accurate hypocenter location, which is important for analyzing seismicity, tectonic conditions, geological structures, or fault zones. In this study, the double difference method was used for hypocenter relocation by utilizing the travel time of earthquake pairs to the station. Tests of several velocity models and damping values were also applied to improve hypocenter relocation results. The best results were obtained using the Koulakov speed model and a damping value of 30, which was then analyzed and validated based on the frequency of residual values. This research shows that the earthquake was influenced by the Ngalang Fault, the southern part of which is connected to the Opak Fault by a newly identified fault called the Oyo Fault.

INTRODUCTION

Yogyakarta is an area in Indonesia that is still actively experiencing deformation due to the subduction activity of the Indo-Australian plate and the Eurasian plate. The movement of these tectonic plates causes fractures or faults in rocks beneath the earth's surface. One of the faults that has formed and been mapped in Yogyakarta is the Opak Fault with a Northeast - Southwest orientation.

According to Natawidjaja (2007), Yogyakarta and its surroundings, especially Bantul, Klaten, Gunung Kidul, and Kulon Progo Regencies, were hit by an earthquake on May 27, 2006, which killed almost 5,000 people. In a later study, Natawidjaja (2016) reported that the United States Geological Survey (USGS) recorded that the earthquake was to the east of the Opak Fault, with a depth of 10 km. He further noted that according to the Incorporated Research Institutions for Seismology (IRIS), the earthquake occurred in the southwest part of the Opak Fault, while the Meteorology, Climatology, and Geophysics Agency (BMKG) reported that the earthquake occurred in the southern sea of Yogyakarta City.

Kayal (2008) states that to get a better and more precise earthquake location, it is necessary to carry out earthquake hypocenter relocation. Hypocenters can be used to detect seismotectonic settings based on the distribution of earthquakes and see the lineation or continuity of hypocenters that describe the fault structure beneath the earth's surface. He further explains that several methods used to determine the hypocenter are the manual method (circle method). This method is less reliable because the quality of its determination depends on the level of accuracy of the circle drawing. Kayal also notes that another method is the relative method (single event determination method, joint hypocenter determination, and Double Difference), which is considered the best method because it provides a solution that can minimize the root mean square (RMS).

Shinta et al., (2020) have conducted research on the relocation of the 2006 Yogyakarta earthquake aftershock hypocenter, by utilizing aftershock waveform data that occurred between June 16 and July 5, 2006, and using the Central Java 1D wave velocity model for the initial velocity model. Their research used the Joint Hypocenter Determination (JHD) relocation method and the Velest program, which aims to identify the distribution of earthquake hypocenters based on aftershock data and obtain a 1D velocity model for the study area. The results of their research indicate that the distribution of earthquake hypocenters forms three clusters parallel to the Opak Fault. One of these fault planes is estimated to be east of the Opak Fault and spreads southward, suspected to be the cause of the 2006 Yogyakarta earthquake. The distribution of earthquake hypocenters is concentrated along the weak zone of the Opak Fault, especially in the eastern part if the observation of the aftershock earthquake is carried out longer.

Based on this research, this research will conduct a Relocation of the Yogyakarta aftershock hypocenter using aftershock data on June 3, 2006. This research was conducted using the Double Difference Method. This method uses more than one earthquake, so that nearby earthquakes can also be used to identify specific earthquake patterns indicated by earthquakes that have similar characteristics. A comparison of the ak135 wave velocity model and the Central Java local velocity model was also carried out (Koulakov, 2009). From the results of this study, we will see the straightness of the earthquake hypocenter distribution pattern with the results of the previous hypocenter study conducted by Shinta (2020) based on different data and will obtain the best velocity model and damping parameters used for hypocenter relocation which have not been carried out in Shinta's (2020) study to support the level of accuracy of the earthquake hypocenter in the blood of this study. From this study, it is expected to provide an effective solution to understand the characteristics of seismicity in the Yogyakarta area and make a significant contribution to earthquake studies, which will help reduce the risk of disasters due to earthquakes in the region.

LITERATURE REVIEW

The Yogyakarta area is located on the Eurasian continental plate, which is close to the subduction zone. According to Rahardjo et al. (1995), this zone was created by the continuous collision of the Eurasian and Indo-Australian plates, which began in the Late Cretaceous Period (about 65 million years ago) and continues to the present day. The Indian Ocean-Australian Plate is shifting north at a rate of about 7 centimeters per year, while the Eurasian Plate is shifting south-southeast at a rate of about 0.4 centimeters per year. The pattern of geological structures, trenches, subduction zones, land basins, volcanic lines (including Mount Merapi), and magmatic lines are the result of this oblique impact. About 256 kilometers from Parangtritis Beach lies the subduction zone located south of Yogyakarta.

Part of the Yogyakarta area is a plain covered with fresh volcanic deposits due to the activity of Mount Merapi, as well as alluvium deposits in other areas. Therefore, the land of Yogyakarta became more productive and rich in water, which caused a surge in population and concentration of people there. This plain turned into hills in the west, precisely Kulon Progo. The highest point in the area is the Jonggrangan plateau, which is approximately 750 meters above sea level. Several waterfalls, each about 30 meters high, adorn the landscape as rivers cut radial valleys across the hills. Karst hills that are part of the Gunung Sewu Karst are located in the eastern part of Wonosari. Rahardjo et al. (1995) further state that the geological formation of Yogyakarta is the result of the collision of the Eurasian and Indian continental plates.

The rocks that make up the Yogyakarta area are generally Quaternary deposits from young volcanic debris and alluvium deposits, as well as Tertiary sedimentary rocks. Volcanic deposits come from volcanic eruptions, especially Mount Merapi, which consist of volcanic ash, tuff, lava, volcanic breccia, andesite breccia, and agglomerate. Other volcanic rocks are also found around Yogyakarta as a result of the eruptions of Mount Tidar, Puser, Balak, Candikukuh, Merbabu, Sumbing, and Merapi. Alluvium deposits consist of loose materials such as gravel, sand, silt, and clay along large rivers and coastal plains. Tertiary sedimentary rocks in Yogyakarta include limestone, coral limestone, calcareous sandstone, marl sandstone, sandstone, conglomerate, tuffaceous marl with glass tuff inserts, which are found in the western (Kulon Progo) and southeastern (Wonosari) parts.

The Opak Fault Line that stretches from northeast to southwest is the main geological feature in Yogyakarta, according to the geological map made by Raharjo et al. (1995). Additional faults are found in the Kulon Progo and Gunung Kidul areas. The Kulon Progo local fold in the Sentolo Formation, a marl sandstone formation, is another geological feature that stretches from east-northwest-southwest.

DATA AND METHODOLOGY

DATA

In this study, the data used are data from previous studies used by Librian et al. (2024) in the Yogyakarta area and its surroundings (7.75^o – 8.25^{o}S and 110.25^o – 110.75^{o}E) using aftershock data recorded by the GTF network. All waveforms from the network consisting of 16 stations were manually and carefully re-evaluated to select the arrival time of P and S waves from June 3 to June 17, 2006 using Seisgram2K software. After determining the arrival time, he determined the hypocenter of the aftershock using a Non-Linear Location method. This study used one day data from Librian et al (2024) that occured on June 3, 2006 with 187 earthquakes (**Figure 1**), and the arrival times of each earthquake that was successfully recorded by the recording station.

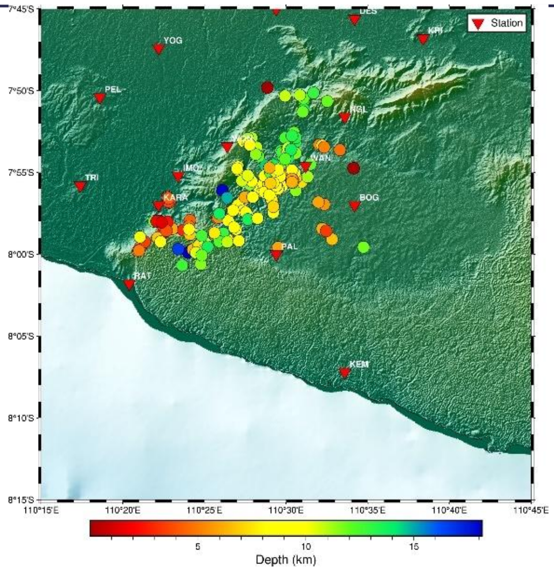


Figure 1. The distribution of the Yogyakarta aftershocks on June 3, 2006 is shown by colored circle symbols based on the depth of the earthquake and triangle symbols indicating the earthquake recording stations.

METHODOLOGY

The Double-Difference method (Waldhauser & Ellsworth, 2000) is an earthquake relocation technique to improve the location of earthquake hypocenters. This method uses the travel time differences between pairs of earthquakes recorded by common stations. that improves the relative accuracy of earthquake hypocenters by using differential travel times between pairs of nearby earthquakes recorded at common stations. This method is effective in minimizing errors when determining the hypocenter that is influenced by the velocity model.

Figure 2 shows the illustration of Double-Difference method. The pair of event i and event j are located nearby, they are recorded by station k and station l. Because the locations are close to each other, the ray paths are assumed to be the same, or the earthquakes are considered to originate from the same source mechanism.

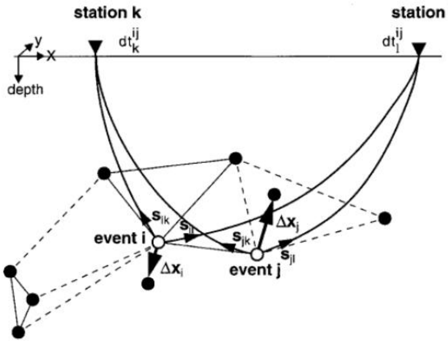


Figure 2. Illustration of the application of the Double Difference method (Waldhauser & Ellsworth, 2000).

HypoDD is a Fortran-based computer program package used for relocating earthquakes with the double-difference (DD) algorithm, developed by Waldhauser and Ellsworth (2000). The HypoDD software is executed using Cygwin terminal.

The hypocenter relocation process is carried out using the HypoDD main program by utilizing the results of the earthquake pair determination process. In this stage, the travel time calculation is carried out for each velocity layer in the velocity model used. In this study, we use two velocity models to compare, which one is the best fit with data. The first model is ak135 with Vp/Vs ratio 1.78. The second model is based on Koulakov et al (2009) with Vp/Vs ratio 1.74 (**Figure 3**).

Data processing for this program is carried out in two steps. First, the data is pre-processed using ph2dt (phase to travel time). Then, the two-step difference method is used to divert the hypocenter through HypoDD. In this study, the MAXDIST parameter is set to 60 km, and the MAXSEP parameter is set to 20 km. The MINOBS and MAXOBS parameters are set to 1 and 16, respectively, according to the minimum and maximum number of stations that can observe the earthquake. For the MAXNGH parameter, the value is 15, which means that each event can have a maximum of 15 neighbors. For the MINLNK parameter, the value is 1, which means that each event must have at least one relationship with another event.

According to Waldhauser (2001), in this process, weighting and damping are used to control hypocenter changes. Damping serves to reduce hypocenter changes that are too large or unstable, with values used ranging from 1 to 100. This damping value is determined by considering the Condition Number (CND), which is the comparison between the largest and smallest eigenvalues, which ranges from 40 to 80. In addition, this study also conducted a damping test to find the value that provides the best results by considering the Condition Number (CND) value limits obtained from each velocity model to ensure that the earthquake relocation results have a high level of accuracy and stability.

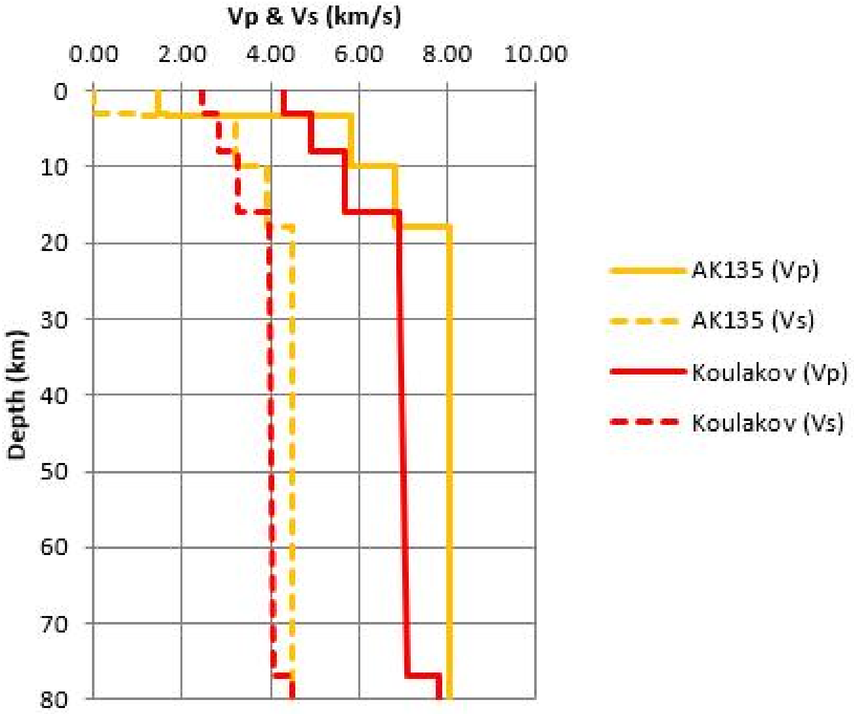
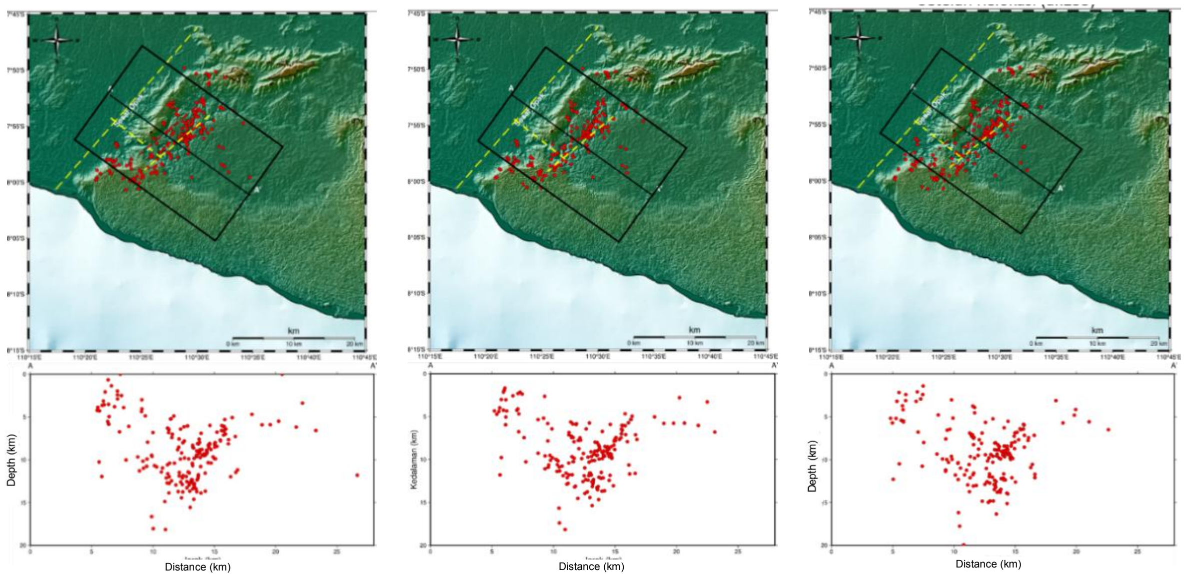


Figure 3. The velocity models used for hypocenter relocations. The red line is based on Koulakov et al (2009), and the yellow line is ak135 velocity model. P-wave velocity is represented by the solid line, S-wave velocity is represented by the dash line.

RESULT

This study analyzes the results of each velocity model produced, with the aim of finding the most effective velocity model parameters to improve the quality of hypocenter relocation results (**Figure 4**). This is because the velocity model affects the travel time of earthquake calculations in each wave layer, so that the velocity value in each layer can affect the calculation of the hypocenter location.



(a) (b) (c)

Figure 4. The cross-section plots from A-A' (SW to NE) of seismicity before relocation (a), after relocation using the Koulakov velocity model (b) and after relocation using the ak135 velocity model (c).

The histogram of residual values before relocation shows the frequency of events approaching zero is only around 1200, indicating many mismatches between the hypocenter location and real conditions (**Figure 5**). After relocation, the histogram shows a range of residual values between -0.5 and 0.5. The frequency of residual values closest to zero after relocation is obtained from the Koulakov velocity model with a frequency count of up to 2000 with an RMS of 0.0246 in **Table 1** while the residual value in the ak135 velocity model with a frequency count of 1600 more. With an RMS of 0.0289 Thus, the hypocenter location after relocation is more accurate than before relocation. In addition, the residual histogram is also straight with the average residual RMS value obtained from each velocity model. Based on the analysis of the results, the Koulakov velocity model is the most appropriate model for use in the relocation of the Yogyakarta earthquake hypocenter.

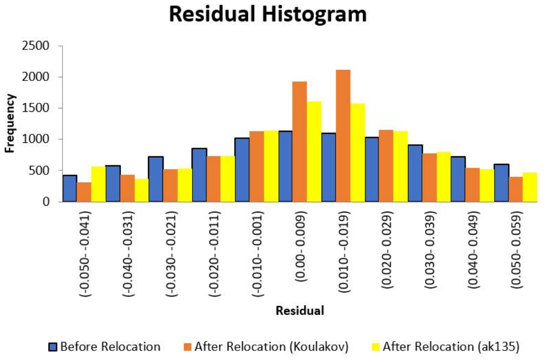


Figure 5. Histogram of residual events before and after relocation of Koulakov velocity model and ak135 velocity model.

Table 1. Number of events, phase and RMS before and after relocation.

Information	Before Relocation	After Relocation (Koulakov)	After Relocation (ak135)
P-phase	9236	9167	9167
S-phase	9218	9098	9098
Event	187	186	185
RMS	0.0414	0.0246	0.0289

Damping is a parameter needed to dampen excessive or unstable hypocenter changes, with a value range between 1 and 100. The goal is to obtain a Conditional Number (CND) in the range of 40 to 80 (**Figure 6**).

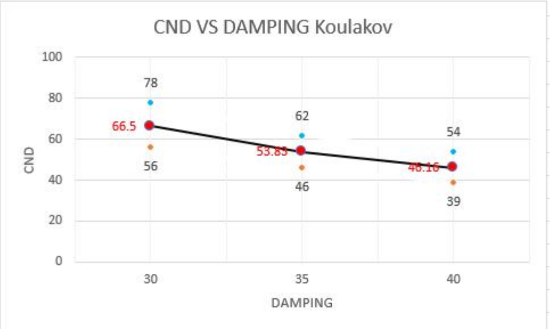


Figure 6. Comparison of the use of damping 30,35 and 40 on the Conditional Number (CND) of the Koulakov velocity model.

The damping value of 30 produces an average Conditional Number (CND) that is within the specified range. Therefore, to ensure that the hypocenter relocation process produces accurate and stable results, the appropriate damping value must be selected.Damping values of 30, 35 and 40 produce an average Conditional Number (CND) that is within the specified range, but a damping value of 40 produces a minimum CND value of 39 which can cause overdamping in the relocation results.

Figure 7 shows the Compass and Rose diagrams of hypocenter relocation results using the Koulakov velocity model. The Compass diagram illustrates the direction of hypocenter shift shown by the arrow on the compass diagram, while the scale of 5 to 25 on the circle shows the distance of each hypocenter shift in km. In the results of hypocenter relocation using the Koulakov velocity model, the furthest shift distance was 20 km, but most hypocenters shifted less than 10 km.

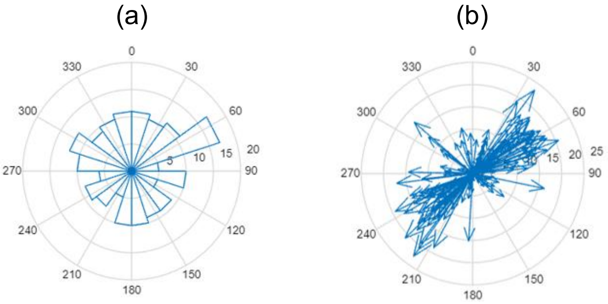
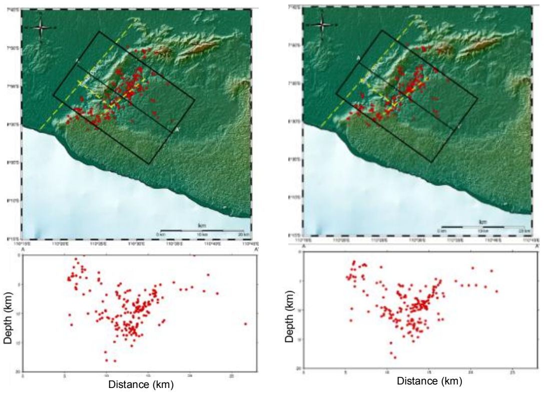


Figure 7. (a) Rose and (b) Compass diagrams of hypocenter relocation results using the Koulakov velocity model.

The long distance shifts are in the northeast and southwest directions, this is because the information on events available mostly comes from earthquake recording stations located on the west and east sides of Yogyakarta. The shift angle and number of events resulting from hypocenter relocation with a scale of 5 to 20 can be seen in the rose diagram. The shift angles of the hypocenter relocation results are spread in all directions, but based on the number of events, the dominant one is in the northeast direction with a shift angle between 60^{o} to 70^{o}, as many as approximately 13 earthquake events.

Figure 8 shows the comparison of the hypocenter distribution before and after relocation using the Koulakov velocity model. The hypocenter distribution looks more scattered and less focused before relocation, indicating that the use of an inappropriate velocity model has caused inaccuracy in determining the location of the hypocenter. This causes the seismicity pattern to be unclear and difficult to determine the presence of geological structures or fault systems. However, after relocation using the Koulakov velocity model, the hypocenters look more focused and concentrated. This neater hypocenter distribution shows an increase in data quality after the application of the Koulakov velocity model, resulting in a more accurate hypocenter location. In addition, after relocation, the hypocenters form a more linear pattern, especially in the circled area. This linear pattern indicates the presence of a more well-defined geological structure or active fault. A clearly visible linear pattern in the hypocenter usually indicates the presence of a fault or fracture zone where the earth's crust shifts.



(a) (b)

Figure 8. Comparison of cross-section A-A' before (a) and after relocation (b) using the Koulakov velocity model.

DISCUSSION

The aftershock data used in this study is different from that used by the previous study by Shinta et al. (2020), Shinta et al. used data from June 16 to July 5, 2006 with a total of 656 earthquake events, while this study used earthquake data from June 3, 2006 with a total of 187 earthquake events. The use of data on that date aims to determine whether the aftershock results that occurred during that period are comparable to the results of previous researchers. The results of this study can be seen in Figure 4. From the figure, it can be observed that the distribution of aftershock relocation in this study shows something similar to the study by Shinta et al. (2020) where Shinta et al. (2020) showed several clusters in the distribution of hypocenters, there are clusters in the eastern and southern parts of the Opak fault (clusters 1 and 2), Clusters 1 and 2 have widely distributed hypocenters, supporting the findings of the study by Tsuji et al. (2009) that the earthquake energy comes from an active fault located about 10 km east of the previously unidentified Opak Fault, which then moves south. The results of this study differ from the findings of previous studies with a few events in cluster 3 compared to the study of Shinta et al. (2020).

Based on the study of Shinta et al. (2020), the RMS value obtained before relocation was 0.122 and after relocation the RMS value approached 0, namely 0.077. While in the study the RMS value before relocation was obtained at 0.0414 and after relocation the RMS value was obtained at 0.0246 as shown in the picture.

Figure 9 shows the comparison between the original (black circle) and the relocated hypocenters (red circle). The seismicity of relocated hypocenters are more nucleated than the original, which features more accurate the fault plane location.

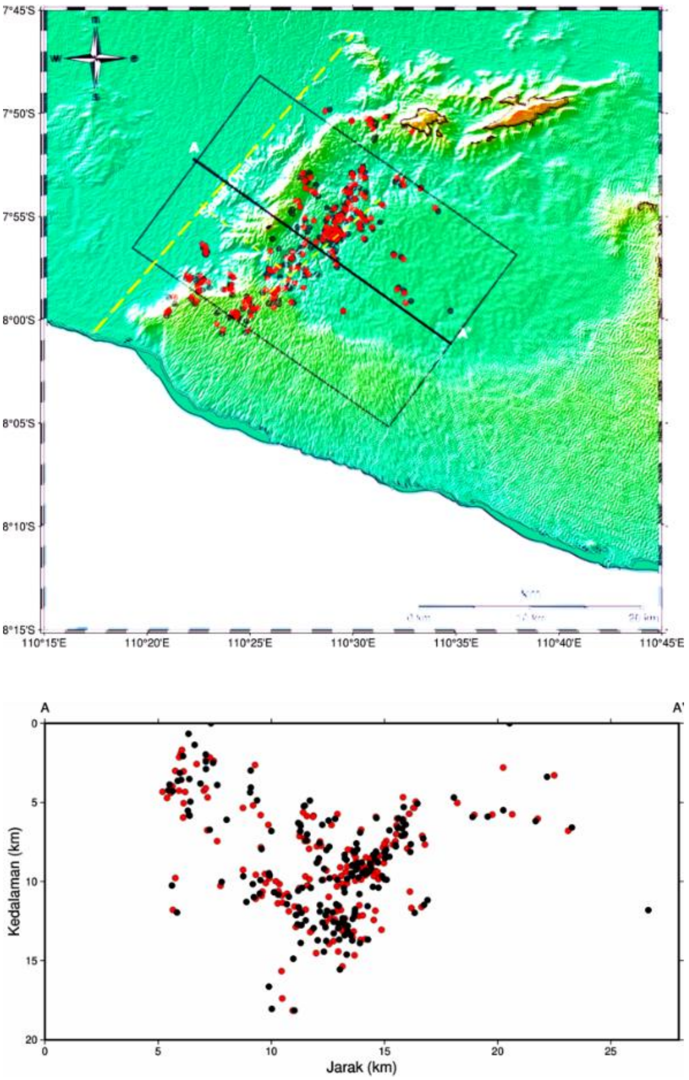


Figure 9. The comparison of original and relocated hypocenters. The black cricle represents the original hypocenters and red circle represents the relocated hypocenters.

Previous study by Shinta et al. (2020) concluded that the 2006 Yogyakarta earthquake was caused by the movement of an active fault to the east of the Opak Fault (**Table 2**). However, the earthquake energy did not only spread southward, but also followed the weak zone along the Opak Fault. Librian et al. (2024) also stated that the 2006 Yogyakarta earthquake was supported by the distribution of aftershocks and the selected source mechanism. Their research suggests that the main earthquake most likely occurred on the Ngalang Fault, the southern part of which is connected to the Opak Fault by a new fault identified as the Oyo Fault. This research strengthens the hypothesis that the 2006 Yogyakarta earthquake was triggered by the movement of an active fault in the eastern part of the Opak Fault, namely the Ngalang Fault, as validated by the findings of Librian et al. (2024).

Table 2. Comparison of RMS Values in this Study and Previous Research by Shinta et al. (2020).

Information	Previous Research		This research	
	Before relocation	After relocation	Before relocation	After relocation
RMS	0.122	0.077	0.0414	0.0246

CONCLUSION

The results of this study show that the Koulakov velocity model produced a smaller RMS value and clearer lineation compared to the ak135 model. By testing three types of damping, a damping value of 30 was found to produce the most accurate results, with a CND value of 40-80. The residual histogram approaching zero indicates that the hypocenter relocation calculation aligns closely with actual conditions, improving the accuracy of the Yogyakarta aftershock relocation on June 3, 2006. The earthquake hypocenters shifted in terms of latitude, longitude, and depth, but remained within the same area, with depths ranging from 0 to 18 km, indicating potential for structural damage.

The Rose diagram shows a hypocenter shift of 5-25 km in a northeast-southwest direction, while the Compass diagram indicates 5-10 relocated events with a shift angle of 60-70 degrees. Based on the results, the earthquake was influenced by the Ngalang Fault, as supported by previous research from Shinta et al. (2020) and Librian et al. (2024), which indicated that the 2006 Yogyakarta Earthquake was triggered by the movement of an active fault to the east of the Opak Fault, likely occurring on the Ngalang Fault and connected to the Opak Fault by the Oyo Fault.

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