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COMPARISON OF EARTHQUAKE HYPOCENTER RELOCATION METHODS IN THE JAVA REGION, INDONESIA

Firman Pratama Putra[1]; Udi Harmoko[2]; Gatot Yuliyanto[3]
[1,2,3]Physics Departement, Diponegoro University, Jl. Prof. Soedarto, SH, Semarang, Indonesia – 50275
[2] udiharmoko@gmail.com

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Abstract— *Java is a frequent island of earthquakes caused by the subduction of the Indo-Australian plate under the Eurasian plate. The mitigation of earthquake disasters is by relocating the hypocenter. Hypocenter relocation was conducted in order to obtain a more accurate earthquake position, which can be used to interpret the structure under the earth's surface. The Modified Joint Hypocenter Determination (MJHD) and Double Difference (DD) methods are required when applying earthquake hypocenter relocation. The objective of research is comparing the relocation results in the Java region with the Modified Joint Hypocenter Determination (MJHD) and Double Difference (DD) Methods for obtaining the distribution of earthquake hypocenters before and after relocation. The study has obtained arrival time data in the form of BMKG catalog data from the period of January 1, 2022 through May 30, 2022 in the Java area with the coordinates of 6.0 LS - 12.0 LS and 106.0 BT - 114.0 BT. The MJHD method compares the travel time difference of a set of data that occurs simultaneously in order to obtain a more accurate hypocenter position, while the DD method compares the hypocenter distance of the two earthquakes with the station distance, so that Ray Path and Waveform are considered equal. The relocation of the initial earthquake has a depth of 10 km, resulting in a shift of shallow earthquakes clustered in the active fault section, while deep earthquakes are clustered in the subduction zone section. The results of relocation with the MJHD method obtained 637 earthquakes.*

Keywords— *mitigation*, MJHD, Double Difference (DD), waveform, Arrival time

INTRODUCTION

Hypocenter relocation is a way to recalculate the hypocenter point of an earthquake to obtain an accurate position. Hypocenter relocation is carried out to see the lineation of the earthquake's hypocenter in order to represent the fault structure below the earth's surface [7]. The Java region is an island that frequently experiences earthquakes, this is caused by activity in the subduction zone between the Indo-Australian plate which is subducting into the Eurasian plate, so that it can form an ocean trench in the region [4]. In general, the Java region is divided into three structural pattern directions, namely the northeast to southwest direction which is called the Meratus pattern, the north to south direction which is called the Sunda pattern and the east to west direction which is called the Javanese pattern [12].

An earthquake is a sudden shift in the structure of rocks in the earth's crust caused by the shifting of tectonic plates [6]. To provide accurate earthquake information, there are several factors, including the magnitude of the seismic waves recorded by the earthquake recording station, the reading of the wave arrival time, and the velocity structure of the seismic waves [10].

To obtain more accurate hypocenter relocation results, research is needed using the Modified Joint Hypocenter Determination (MJHD) method developed by Hurukawa and Imoto in 1990. The Double Difference (DD) method was developed by Felix Waldhauser and Ellsworth in 2000. The aim of this research is to compare relocation results in the form of distribution maps, cross sections and residual histograms in the Java region using the Modified Joint Hypocenter Determination (MJHD) and Double Difference (DD) methods to obtain seismic distribution results before and after relocation.

LITERATURE REVIEW

A. Hypocenter Relocation

Hypocenter relocation is a process of re-determining the hypocenter point of an earthquake to obtain a more accurate position. There are several factors that can increase the accuracy of relocation results, namely

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stations that record waves, arrival time readings, and seismic wave structure speed [3]. The existence of an earthquake can be indicated by the difference in latitude, longitude and depth coordinates which are used to determine the position of the earthquake using the absolute method. Absolute position has a poor level of accuracy. This is caused by the distance of the earthquake to the station point, the number of earthquake recording stations, and the arrival time speed model. The circle method functions to determine the position of the earthquake hypocenter, which is still less accurate because the level of accuracy still depends on the results of drawing a circle. Apart from that, there are relative methods (SED, JHD, and DD) which are the best methods for getting RMS value results [7].

B. Modified Joint Hypocenter Determination (MJHD) Method

The MJHD method is to invert travel time from a set of earthquake data by adding station corrections in the form of azimuth and distance factors, so as to obtain accurate relocation results. This equation functions to determine the position of the hypocenter [5].

$$(O-C)_{ij} = (t_{ij} - To_{ij}) - T_{ij} = \frac{\partial t_{ij}}{\partial x_j} dx_j + \frac{\partial_{ij}}{\partial y_j} dy_j + \frac{\partial t_{ij}}{\partial z_j} dz_j + dTo_j + dS_i \quad (1.a)$$

where O is the observation travel time, C is the calculation travel time, O – C is the residual time of earthquake i to station j, t_{ij} And T_{ij} is the arrival time of earthquake j at station i, To_j is the time the earthquake occurred, dx, dy, dz and dTo are the correction of the hypocenter of the earthquake j, dS_i the station correction for earthquake i.

The MJHD method is divided into two distributions, namely hypocenter distribution and epicenter distribution. The hypocenter distribution, namely changes in stations with distance from the research source, is not related to the selected station, so the following equation is obtained [5].

$$\sum_{i=1}^{n} S_i D_i = 0 \quad (1.b)$$

Epicenter distribution, namely changes in stations, is not related to the azimuth distance between the research source and the selected station, so the following equation is obtained [5].

$$\sum_{i=1}^{n} S_i \cos\theta_i = 0, \sum_{i=1}^{n} S_i \sin\theta_i = 0 \quad (1.c)$$

$$\sum_{i=1}^{n} S_i = 0 \quad (1.d)$$

with S_i is the change in station i, D_i is the distance of station i to the earthquake source, θ_i is the azimuth angle of station i to the earthquake source, n is the total observing stations [5].

C. Double Difference (DD) Method

The DD method assumes that two earthquakes recorded by the same station have a shorter travel time compared to the distance between the station points to each earthquake, so that the raypath and wave form are considered the same [12].

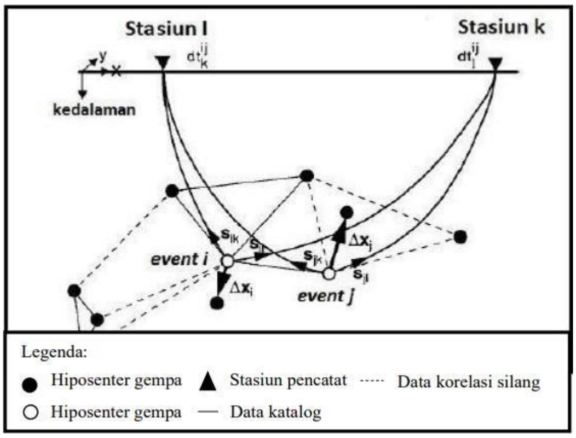

Fig 1. Illustration of the DD method [12].

Figure 1 shows the flow of hypocenter relocation using the DD method, the black and white circles show the distribution of hypocenters associated with earthquakes connected to catalog data (dashed lines) or cross-correlation data (solid lines). Earthquakes i and j indicated by white round symbols were recorded at one station

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(k and l) with a difference in travel timedt_k^{ij}Anddt_l^{ij}, this event causes the raypath to experience similarities and arrows$_{\Delta xi}$AndΔxjdemonstrated earthquake co-relocation [12].

In the Double Difference method there is a residual time between observation and calculation which is defined as the difference between the observation travel time and the calculation travel time for two earthquake events. Observation travel time values are obtained from catalog data, resulting in the following equation:

$$dr_k^{ij} = (T_k^i - T_k^j)^{obs} - (T_k^i - T_k^j)^{cal} \quad (1.e)$$

with$dr_k^{ij}$is the residual travel time from both earthquakes i and j to the initial station k,$(T_k^i - T_k^j)^{obs}$is the residual travel time of earthquakes i and j to receiving station k,$(T_k^i - T_k^j)^{cal}$is the calculated travel time from earthquakes i and j to receiver k, i and j are the two hypocenter points that are close together, k and i are the stations that recorded the earthquake event,$T_k^i$is the travel time of earthquake i to station k,$T_k^j$is the travel time of earthquake j to station k,$T^{obs}$is travel time observed,$T^{cal}$is the calculated travel time.

Based on the two earthquakes i and j, the difference between the observation arrival time and the calculated arrival time is obtained using the slowness vector to obtain the following equation:

$$\frac{\Delta T_k^i}{\partial m}\Delta m^i - \frac{\Delta T_k^j}{\partial m}\Delta m^j = r_k^{ij} \quad (1.f)$$

Complete equation:

$$\frac{\Delta T_k^i}{\partial x}\Delta x^i + \frac{\Delta T_k^j}{\partial y}\Delta y^i + \frac{\Delta T_k^i}{\partial z}\Delta z^i + \Delta\tau^i - \frac{\Delta T_k^j}{\partial x}\Delta x^j - \frac{\Delta T_k^i}{\partial y}\Delta y^j - \frac{\Delta T_k^i}{\partial z}\Delta z^i - \Delta\tau^j = dr_k^{ij} \quad (1.g)$$

Based on equation (1.g), there are changes in four hypocenter parameters that must be calculated. To obtain the hypocenter, you must carry out inversion using the following equation [12]:

$$WGm= Wd \quad (1.h)$$

where d is the M x 4N matrix (M = number of DD observations; N = number of earthquake events; 4 = number of hypocenter parameters), W is the weighting value used to calculate travel time calculations, d is the DD data vector, m is the four parameter matrix hypocenter.

Each equation can be weighted in the form of a diagonal WW matrix, namely a priori weighting which can be seen from the picking quality of each earthquake event having values 0 and 1 with the P and S wave times having the same weight [12].

RESEARCH METHODS

A. Data Acquisition

This research data is in the form of arrival time data from catalog data obtained from Seiscomp3 Class 1 Sleman Geophysical Station on January 1 2022 - May 30 2022. The amount of earthquake data used in the research was 648 earthquake events and 93 earthquake recording stations with a magnitude value of around 5 SR. Research area limits start from 6.0 LS up to 12.0° LS and 106.0°BT to 114.0°BT, which is shown in Figure 2.

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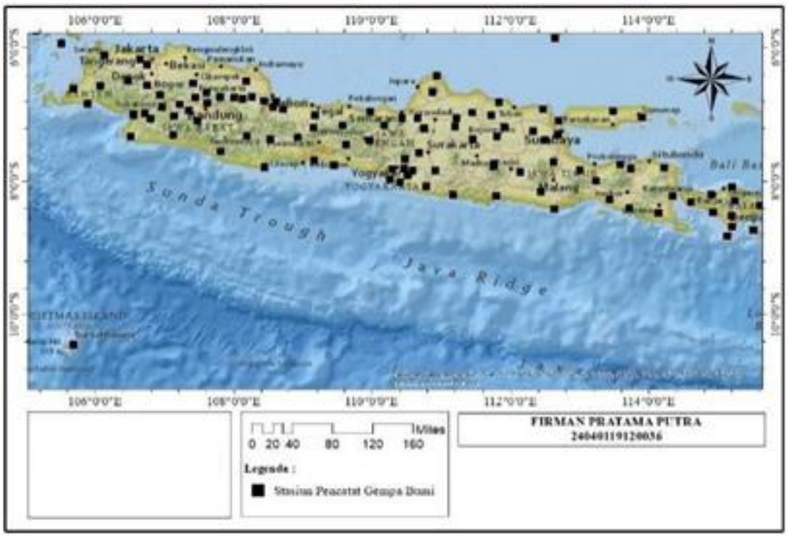

Fig 2. Map of the distribution of earthquake recording stations from BMKG

The tools and materials used in this research are divided into two, namely hardware and software. For hardware such as laptops, while for software such as Windows Subsystem for Linux (WSL), Arcmap, Ph2dt, HypoDD, Fortran, Cygwin, Microsoft Excel, Notepad++.

B. Data *Processing*

For data processing using the MJHD method, data conversion is carried out by preparing input earthquake parameters and earthquake recording station parameters. Then the MEQ and MNST values used are 5. MEQ is the minimum number of earthquakes recorded by one station, while MNST is the minimum number of stations used for one earthquake. After that, we obtained an NST value of 93 stations. Then open the mjhd.inp file by replacing the parameter values from the iteration input, the max-ress values used are 50, 30, 20, 10, 5, 2, 1. The next step is running the program ./mjhd14s and getting the output in the mjhd.out7 file .

The next data processing process using the DD method is data conversion by preparing input earthquake parameters and earthquake recording station parameters. Then determine the boundary values for earthquake pairs in the ph2dt.inp file, in the form of MINWGHT (0), MAXDIST (500 km), MAXSEP (120 km), MAXNGH (6 events), MINLNK (5 events), MINOBS (5 stations), MAXOBS (100 stations). After that, running it gets the output event.dat and dt.ct. Next, the output from ph2dt is copied and pasted into the hypodd program. Then open the hypoDD.inp file to adjust the earthquake parameters. After running, get the output hypoDD.res, hypoDD.reloc.

C. Results Analysis

Output running from the MJHD and DD methods, the position of the earthquake hypocenter can be mapped before and after it is relocated using Arcmap software. Then carry out a validation test using the observed arrival time and calculated arrival time values. If the residual value is > 1 second then the parameters are determined again, whereas if the value is < 1 second then it can be said that the results obtained are accurate. After that, create a residual histogram to determine the accuracy of the relocation results as seen from the number of residual values that collect at the zero point and a cross section to determine the distribution of the depth of the earthquake hypocenter. The next step is to interpret and analyze the results based on the results that have been obtained.

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RESULTS AND DISCUSSION

Figure 3 shows the distribution map of the hypocenter before being relocated, symbolized by the green circle, then the red circle shows the hypocenter after being relocated using the MJHD method. The results of the distribution of the earthquake epicenter, if seen at first glance, do not experience much shift. Therefore, a vertical section A-A' in the Meratus direction was carried out to see the subduction zone which resulted in the position of the earthquake epicenter being correlated with the presence of active fault lines (geological map), so that the distribution was clustered in the area. The results of the A-A' cross section show that earthquakes in the Java region are very complex and have a relatively small distance of around 1 km as many as 2 earthquake events out of 637 earthquake events.

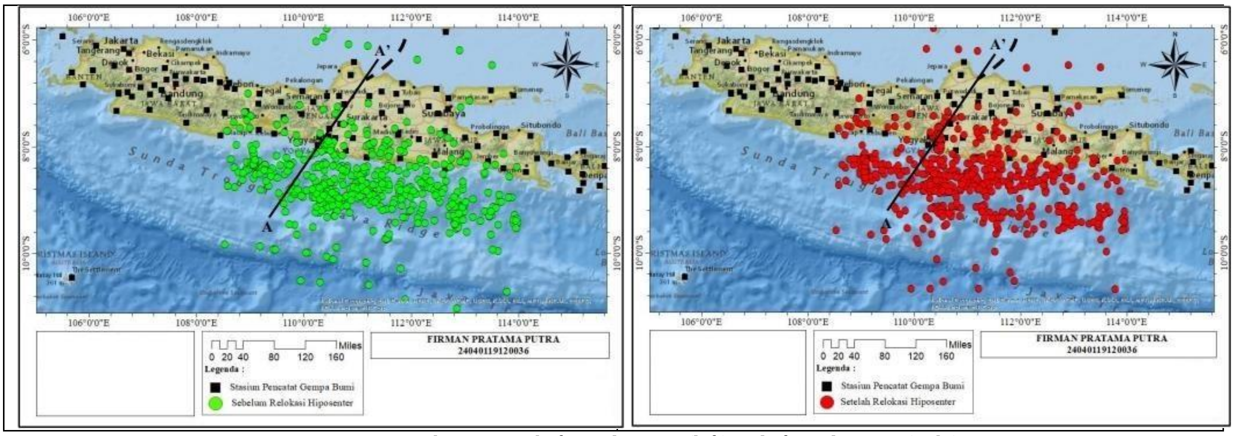

Fig 3 Distribution map before relocation (left) and after relocation (right)

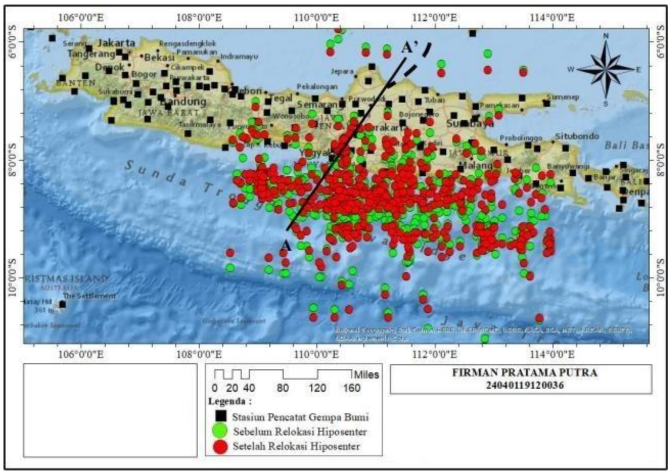

Fig 4 Distribution map before relocation (green) and after relocation (red) by MJHD method

Based on Figure 5, it shows the distribution map of the hypocenter before being relocated, symbolized by the green circle, then the red circle shows the hypocenter after being relocated using the DD method. The results of the distribution of the earthquake epicenter, if seen at first glance, do not experience much shift. Therefore, a vertical section B-B' in the Meratus direction was carried out to see the subduction zone which resulted in the position of the earthquake epicenter being correlated with the presence of active fault lines (geological map), so that the distribution was clustered in the area.

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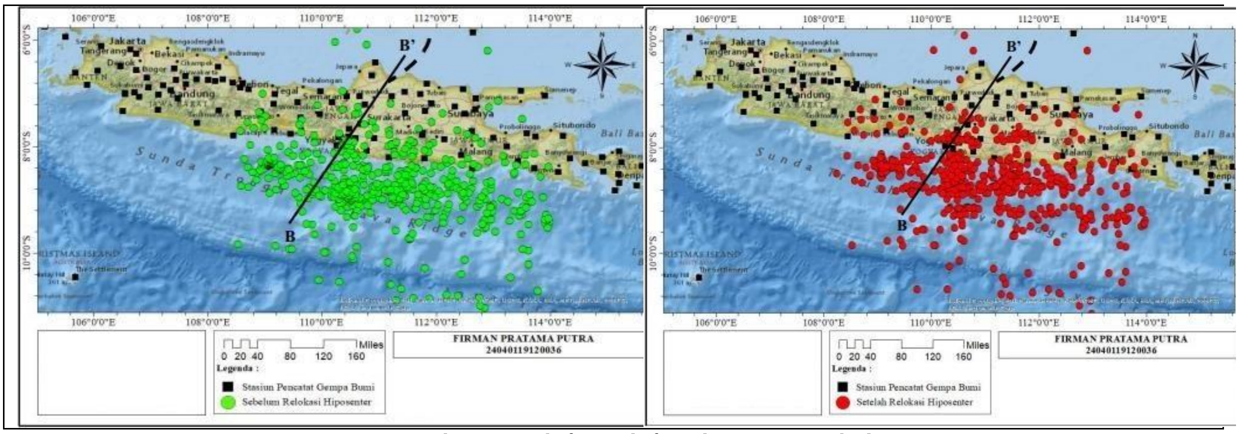
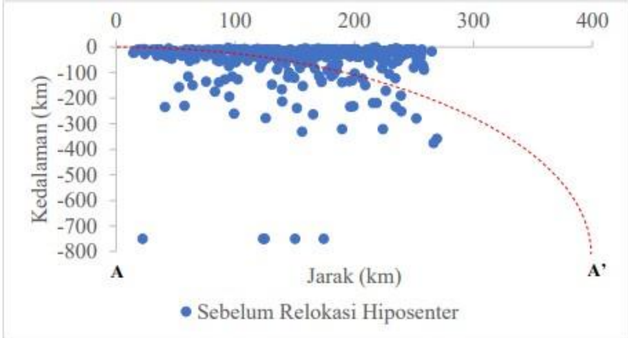


Fig 5. Distribution map before and after relocation DDmethod

Then a cross-section B-B' was carried out showing the results of the distribution of earthquake hypocenters which clustered and formed a continuity of hypocenters related to the tectonic structure in the Java region. The results of the B-B' cross section show that earthquakes in the Java region are very complex and have a relatively small distance of around 1 km as many as 2 earthquake events out of 625 earthquake events.

According to Abercrombie (2001), the distribution of earthquakes before and after relocation using the MJHD and DD methods from sections A-A' and B-B' shows the existence of slab subduction that has been formed hundreds of years below the earth's surface. This is supported by normal faults in the fore-arc zone which have been identified as slab pull forces and slab push forces in the Java region.

Based on Figure 4, it shows the cross section before relocation which is symbolized by a blue circle, then the cross section after relocation is symbolized by an orange circle using the MJHD method. The results of the vertical cross section are by drawing a straight line from A to A' which is directed from the Java Sea to the Indian Ocean. This straight line is drawn in accordance with the direction of the Meratus pattern. The red dotted line from point A-A' shows the slab subduction in the fore-arc zone in the Java region.



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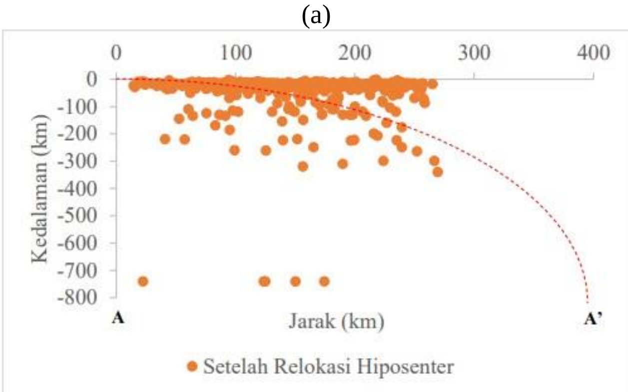

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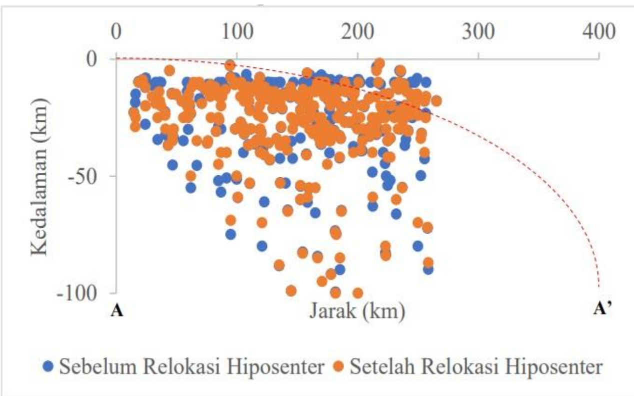
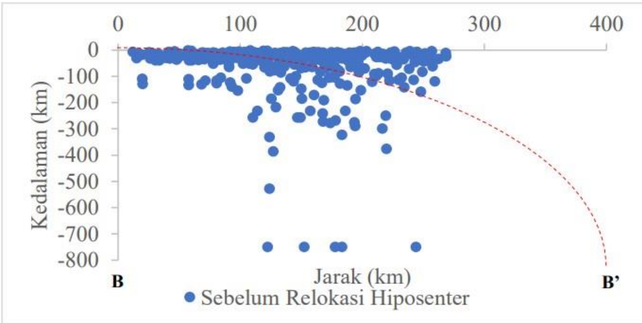


(c)

Fig 6. (a) Cross section before relocation (b) Cross section after relocation (c) Cross section before and after relocation MJHD method

Figure 7 shows the cross section before relocation which is symbolized by a blue circle, then the cross section after relocation is symbolized by an orange circle using the DD method. The results of the vertical cross section are by drawing a straight line from B to B' which is directed from the Java Sea to the Indian Ocean. This straight line is drawn in accordance with the direction of the Meratus pattern. The red dotted line from point B-B' shows the slab subduction in the fore-arc zone in the Java region.



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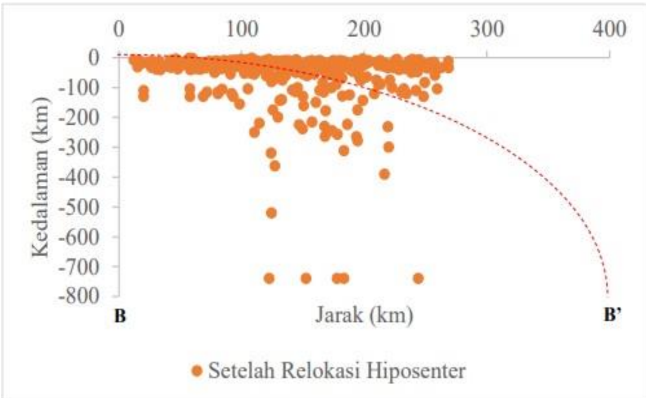

(b)

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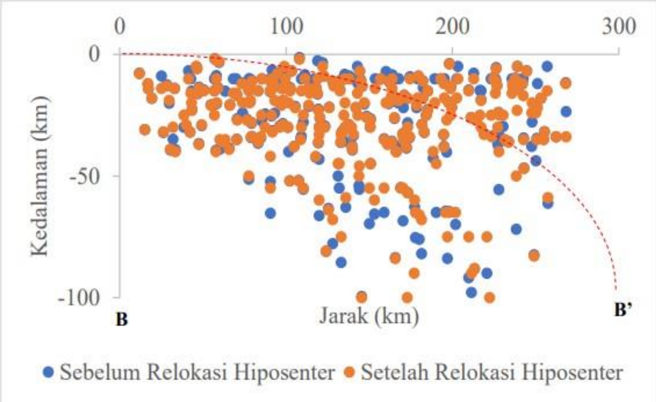


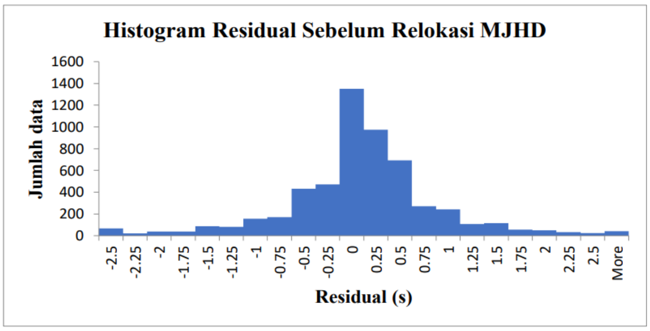
(c)

Fig 7. Cross section before relocation (b) Cross section after relocation (c) Cross section before and after relocation DD method

The distribution of the earthquake's hypocenter before relocation was at a depth of 10 km (fixed depth) which is considered less accurate because it still uses a global 1D velocity model. Then, after being relocated, there was a change in the depth of the earthquake hypocenter, especially at an earthquake depth of less than 50 km, which was included in the megathrust zone and some were at a depth of more than 50 km, which was included in the Benioff zone [2].

Based on the results of the cross section, the earthquake depth of less than 50 km indicates the existence of clusters and continuity related to fault structures in the Java region [9]. Then at a depth of 300-600 km, there are quite a few earthquake hypocenters. This can happen because the rocks in the mantle layer experience melting which is caused by the temperature in the asthenosphere layer being much higher compared to the temperature in the hypocenter rock layer [8].

The residual value is the difference between the observed travel time and the calculated travel time obtained from the MJHD and DD methods. Figure 5 shows the results before relocation. The residual RMS value spreads around -2.5 to 2.5 seconds and collects at the point 0 to 0.5 seconds and the frequency value is close to zero for 1351 data. The residual RMS value before relocation is still not accurate because the RMS value is > 1 second, so it is necessary to relocate the hypocenter using the MJHD method to obtain accurate results. Then the results of the residual RMS values after being relocated using the MJHD method spread between -1.5 to 1.25 seconds and collect at the point 0 to 0.25 seconds and the frequency value is close to zero as many as 1512 data.



(a)

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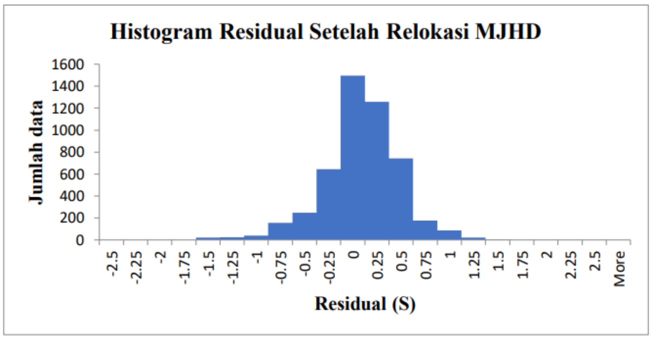
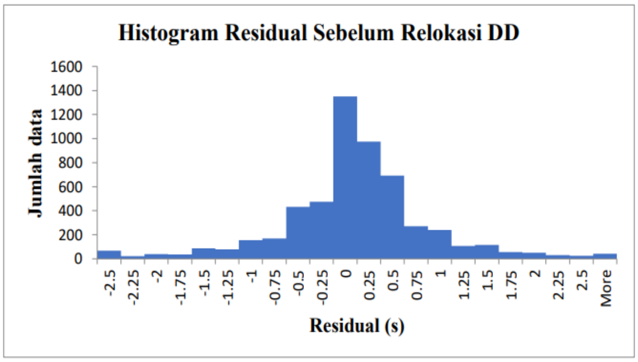


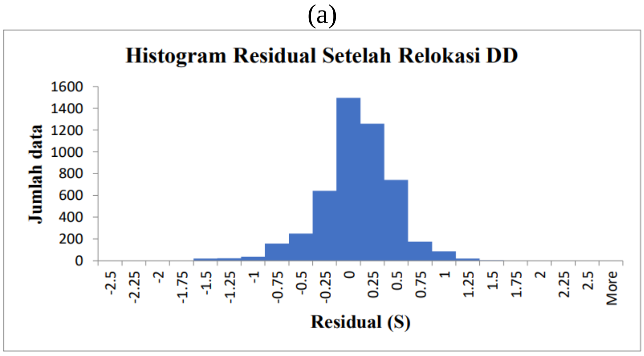
(b)

Fig 8. (a) Residual histogram before relocation and (b) Histogram after relocation MJHD method

Figure 9 shows the results before relocation. The residual RMS value spreads around -2.5 to 2.5 seconds and collects at the point 0 to 0.5 seconds and the frequency value is close to zero for 1351 data. The residual RMS value before relocation is still not accurate because the RMS value is >2 seconds, so it is necessary to relocate the hypocenter using the DD method to obtain accurate results. Then the histogram results after relocation showed an RMS value of around -1.5 to 1.5 seconds and gathered at the point 0 to 0.25 seconds and a frequency value that was close to zero for 1497 data.



(a)



(b)

Fig 9. (a) Residual histogram before relocation and (b) Histogram after relocation DD method

The earthquake that occurred in the Java region was caused by the subduction of the Indo-Australian Plate under the Eurasian Plate. Based on the vertical sections A-A' and B-B', it shows the distribution of earthquakes in the Java region, including the Meratus pattern. Geologically, the Meratus pattern is trending northeast - southwest, where the western part is located on the Cimandiri fault, the outcrop distribution pattern is located in Karangsambung, and the eastern part is located in the Pati basin and Tuban basin. Based on the research results, it shows that the distribution of the dominant hypocenter is spread in the sea area south of Java Island. This is caused by a tectonic structure pattern that trends northeast – southwest. Apart from that, there are active faults and Neogene rocks which have a big influence on the physiography of the island of Java.

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CONCLUSIONS

The results of the distribution of seismicity before relocation using the MJHD and DD methods show that the hypocenter position of the earthquake is mostly spread in the sea area south of the island of Java, whereas after being relocated the position of the hypocenter has shifted and is clustered in the sea south of the island of Java. Apart from that, the cross section results show that the source depth of the earthquake is around 1 km to 100 km, which is included in the Megathrust zone and Benioff zone. Then the RMS value results using the MJHD method collect at an RMS value of 0 to 0.5 seconds and data frequency values that are close to zero as many as 1512 data, while the RMS value results using the DD method collect at an RMS value of 0 to 0.25 seconds and data frequency values that are approaching zero as many as 1497 data.

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