Determination of Earthquake Hypocenter Distribution using the Modified Joint Hypocenter Determination (MJHD) Method throughout the Palu-Koro Fault (Case Study: August-October, 2018)

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Abstract. The area of Sulawesi, especially along the Palu Koro Fault, is an area that is largely influenced by the confluence and movement of plates as well as regional fault activity pathways with high levels of seismicity. Determining the location of the hypocenter accurately through relocation is required in identifying the detailed tectonic structures in the area. Relocation of the hypocenter using the Modified Joint Hypocenter Determination (MJHD) method using the IASP91 velocity model in the period August to October 2018 with the arrival time data from BMKG catalog. The results of hypocenter relocation using the MJHD method show that from 132 earthquake distribution points to 63 earthquake hypocenter points after the relocation. The change in the location of the hypocenter was much denser along the Palu Koro Fault route than before the relocation as evidenced by the mean value of rms (root mean square) before relocation was 1.31 and after relocation it became smaller (0.61). Changes in parameter values after relocation using the MJHD method caused the distribution of the earthquake hypocenter to be tighter towards the Palu Koro fault than before the relocation, where the distribution had a random and scattered pattern.

Keyword: The Palu Koro Fault; Modified Joint Hypocenter Determination (MJHD); Relocation; Hypocenter; Earthquake

1. Introduction

Sulawesi has two important events that occurred in western Sulawesi at the time kenozoic. The first is rifting and the expansion of the ocean floor in the Strait Makassar in Paleogene, which creates space for the deposition of clastic material originating from Kalimantan. The second is a compressional event started since the Miocene which was influenced by the collision of continents in the west and ofiolite and island arc fragments to the east. Fragments these include the Buton micro-continent, Blacksmith and Baggai Sula. This compression resulting in the West Sulawesi Fold Belt developed in the Early Pliocene. And the effect of the coalition is believed to be the cause of tectonic events in all parts of Sulawesi [1].

In the active regional faults, it is found that the active subduction are still in the Sulawesi area which can trigger activity on large-scale horizontal faults, which are the zone from the source of earthquakes [2]. One of them is along the Palu Koro Fault which is a horizontal fault (strike-slip fault)
because it is close to the collision zone of three plates, namely the Eurasian, Indo-Australian and Pacific plates as well as the Philippine micro plate [3].

There are several techniques are developed for relocating the hypocenter. Modified Joint Hypocenter Determination method has been applied in this research. The Modified Joint Hypocenter Determination (MJHD) method inversing the travel time from the group of earthquakes and the amount of station correction used to obtain a hypocenter location is much better than the initial estimate. So that it can provide improvements of errors due to variations in lateral velocity in the previous method.

The Modified Joint Hypocenter Determination (MJHD) method is a development of the previous method, the Joint Hypocenter Determination (JHD) method. The MJHD method simultaneously inverts the travel time of a group of earthquakes and the magnitude of the station correction to get a better hypocenter location. If the station distribution is uneven and the subsurface medium is very heterogeneous, the solution to overcome this problem is to use the MJHD method. The MJHD method is still more profitable because it does not require a major earthquake. This is very effective, especially in cases where no earthquake is well recorded by all stations [8].

1.1 Geological Setting of Central Sulawesi

The Palu region is one of the most seismically active areas in Sulawesi. With the high level of seismic activity in the region. The zone of collision from the junction of these three plates is convergent and colliding in a relative manner and has resulted in the Central Sulawesi and its surroundings becoming one of the areas with a high level of seismicity [4]. The Palu Koro fault, which is active due to pressure from the Flores Sea in the south and at the northern end through the Makassar Strait which intersects the subduction zone of the Sulawesi Sea plate, extends from north of Palu to the south of Malili and ends in Bone Bay along ± 459 km, moving sinistral to left with an average slip of about 32-45 mm/year, and it is a strike slip fault [5].

1.2 Modified Joint Hypocenter Determination (MJHD) Method

The hypocenter is the epicenter of the earthquake which is inside the earth's surface. Generally, the determination of the location of a hypocenter is generated using the results from the seismic phase observations. These results are recorded by three components, namely N-S, E-W, and up-down at each different station [6]. The determination of the hypocenter for earthquake relocation using the MJHD method was first introduced by [7]. The principle is the development of the JHD method, so the algorithm is almost the same. The only thing that distinguishes it is the added limitation to the final flow of the MJHD method. By adding the station correction price, the travel time residual obtained at station i, namely stasiun can be written as follows:

$$r_{ij} = T_{ij}^{obs} - (T_{ij}^{cal} + s_i)$$

Where $T_{ij}^{obs}$ is the travel time of the seismic waves from the epicenter to the station obtained, $T_{ij}^{cal}$ is the calculated travel time and $s_i$ is the station correction. With the same assumptions as the Geiger method, equation (1) can be linearised using the Taylor first order expansion as follows:

$$r_{ij} = (t_{ij} - T_{oij}) - T_{ij}$$

$$= \frac{\partial r}{\partial xj} \, dxj + \frac{\partial r}{\partial yj} \, dyj + \frac{\partial r}{\partial zj} \, dzj + dT \, Oj + dsi$$

Where $t_{ij}$ dan $T_{ij}$ are arrival times and travel times calculated from the occurrence of an earthquake of j at a station of i. It is known that $i = 1, \ldots, N$ indicates the number of observation stations and $j = 1, \ldots, M$ indicates the number of earthquake occurrences. If equation (2) is arranged into a matrix for all stations, the matrix equation is as follows [8]:

$$\begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1M} \\ r_{21} & r_{22} & \cdots & r_{2M} \\ \vdots & \vdots & \ddots & \vdots \\ r_{N1} & r_{N2} & \cdots & r_{NM} \end{bmatrix} \begin{bmatrix} \frac{\partial r}{\partial x1} \\ \frac{\partial r}{\partial y1} \\ \vdots \\ \frac{\partial r}{\partial xM} \end{bmatrix} = \begin{bmatrix} dT \, O1 \\ dT \, O2 \\ \vdots \\ dT \, OM \end{bmatrix}$$
\[ r_{ij} = A_j dX_j + S_j d_s; j = 1, ..., M \]  

Where \( r_{ij} \) is the residual travel time of each earthquake, \( A_j \) is the N x 4 matrix of partial derivatives calculated at the source, \( dX_j \) is the vector of perturbation or the change in the hypocenter parameter to the predicted (initial) parameter, \( S_j \) is the N x N diagonal matrix with the station recording the earthquake earth and \( d_s \) are station corrections. By adding the station correction price, the travel time residual obtained at station \( i \), namely \( r_{ij} \) can be written as follows:

\[ r_{ij} = t_{ij}^{\text{obs}}(t_{ij}^{\text{cal}} + s_i) \]  

\( t_{ij}^{\text{obs}} \) is the travel time of seismic waves from the epicenter to the station which is obtained from the difference between the arrival time of the earthquake waves and the origin time, \( t_{ij}^{\text{cal}} \) is the calculated travel time and \( s_i \) is the station correction. If equation (2) is arranged into a matrix for all stations, the matrix equation is as follows [8]:

\[ r_{ij} = A_j dX_j + S_j d_s; j = 1, ..., M \]  

Where \( r_{ij} \) is the residual travel time of each earthquake, \( A_j \) is the N x 4 matrix of partial derivatives calculated at the source, \( dX_j \) is the vector of perturbation or the change in the hypocenter parameter to the predicted (initial) parameter, \( S_j \) is the N x N diagonal matrix with the station recording the earthquake earth and \( d_s \) are station corrections. In the iteration of the JHD and MJHD methods, there are 2 ways, the first is calculating the station correction (\( d_s \)), the second is calculating the hypocenter using station corrections from the first method. Earthquake parameters (x, y, z, t) and station corrections obtained from the previous iteration. So that this is what ultimately becomes the initial parameter for the next iteration [8]. To calculate the value \( d_s \):

\[ d_s = \frac{1}{\sum_{j=1}^{M} \sum_{i=1}^{N} w_{ij}^2} \sum_{j=1}^{M} \sum_{i=1}^{N} w_{ij}^2 r_{ij} \]  

In the MJHD method, a limitation is added to improve the stability of the JHD results which implies that the station correction used does not depend on the distance and azimuth angle between the center of the study area and the station used. The limitations used in the MJHD method are:

\[ \sum_{i=1}^{n} S_i D_i = 0 \]  

\[ \sum_{i=1}^{n} S_i \cos \theta_i = 0, \sum_{i=1}^{n} S_i \sin \theta_i = 0, \sum_{i=1}^{n} S_i = 0 \]  

With \( S_i \) is the station correction at the i-th station, \( D \) is the distance between the station and the center of the study area, \( \theta_i \) is the azimuth angle of station i from the regional center and n is the number of observation stations. Determination of the root mean square error (\( E_{RMS} \)) with the following equation [9]:

\[ E_{RMS} = \frac{1}{N} \sqrt{\sum_{i=1}^{N} (t_i^{\text{cal}} - t_i^{\text{obs}})^2} \]  

\( i \) is the station in one earthquake event and \( N \) is the number of stations in one earthquake event. \( E_{RMS} \) does not completely improve the data used, but to find out whether the size of the \( E_{RMS} \) value approaches the research data model or away from the data model with comparisons from the actual data in the field. The Modified Joint Hypocenter Determination (MJHD) method is more profitable because it does not require a major earthquake. This is very effective, especially in cases where there are no earthquakes that are well recorded by all stations used in the study [7].
2. Data and Method

2.1 Research Location Overview
This research is located along the Palu Koro Fault, which is at the boundary coordinates of 2° N - 3° S and 119° - 121° E. The location of this research is bordered by East Kalimantan to the west, Sulawesi Sea to the north, Maluku Sea and Seram Sea to the east, and South and Southeast Sulawesi to the south.

Figure 1 Research Location Map around the Palu Koro Fault, at the coordinates of 2°N-3°LS and 119°E-121°E.

There are 27 total stations used in the calculation and into 21 corrected stations (APSI, BBSI, BKSI, BNSI, BSSI, KMSI, MPSI, MRSI, PMSI, SGKI, SMKI, SMSI, SPSI, SRSI, TMSI, BKB, LUWI, SANI, TOLI2, KAPI, GTOI) after relocation using the MJHD method.
Hypocenter relocation is carried out in several steps, namely taking secondary data from the BMKG earthquake catalog in the form of BMKG arrival time data for the August-October 2018 period to get the final result using the Modified Joint Hypocenter Determination relocation method on Linux with the Fortran programming language. The final results of hypocenter relocation in the form of time correction, longitude latitude correction and RMS were processed using the MJHD method. The final result is then plotted and map making using GMT (Generic Mapping Tools) [10] as interpretation and drawing conclusions.

3. Results and Discussion
The MJHD method is expected to minimize the error value so that the hypocenter position is much more accurate. Earthquake relocation data processing uses the MJHD method using earthquake data from the BMKG catalog, namely arrival time data with the IASP91 velocity model. The MJHD method selects earthquakes based on the parameters of the number of MEQ (minimum number of recorded earthquakes), MNST (minimum number of stations recorded), maximum earthquake depth, and maximum residual value determined at the beginning of relocation, so that not all earthquakes can eventually be relocated. The position of the earthquake distribution generated by the MJHD method is considered to be more accurate and fairly dense compared to the previous position which was random and scattered. This is also supported by changes in the rms value or position after the relocation which tends to be better (figure 3).

Figure 2 Station Distribution Map, there are a total of 27 stations used and ended up being 21 stations that were corrected
In this study, there were a total of 132 earthquake points that were relocated using the MJHD method and turned into 63 earthquake points after relocation with each parameter value used in determining MEQ and MNST being 10. The determination of each parameter value in this study is carried out in stages from the smallest number to obtain a suitable value because these values produce the most ideal and stable results compared to the values before and after the experiment. The relationship between MEQ and MNST with the number of earthquakes relocated is inversely proportional. The greater the MEQ and MNST values, the less earthquakes will be relocated. Because the earthquake was recorded in many stations that will be relocated. Therefore it is necessary to pay attention to the value of MEQ and MNST in order to get ideal results. The ZFIX value or depth is 200 km. The max-ress or residual travel time is set at 2 and the iteration value in 5 consecutive iterations during the MJHD method process is 6, 7, 8, 9 and 10. With the initial distribution of stations in the study amounting to 27 stations and ending up to 21 stations after relocation. The RMS value obtained before and after relocation is 1.31 before relocation and becomes 0.61 after relocation using the MJHD method.

4. Conclusions
The distribution of the earthquake distribution before the relocation was a total of 132 points and became 63 hypocenter points after relocation using the method. The result of the hypocenter points depending on the input parameters in the form of the number of MEQ, MNST, maximum earthquake depth, and maximum residual value determined at the beginning of the relocation.
Figure 4 Comparison of the rms value before and after relocation with the MJHD method

MJHD with the Fortran Linux programming language. Changes in parameter values after relocation are origin time, longitude, latitude, depth, magnitude and rms value. The results of the calculation of relocation before and after the earthquake with the greatest magnitude at the time of the incident in the research time period before relocation have sequential parameter values, namely 10:02:43, 119.85, -0.22, 10 km, 7.48 (Mw) and 0.971. The values after relocation were 10: 02.46, 119.84, -0.17, 12.28 km, 7.4 (Mw) and 0.534. The average rms value before relocation was 1.31 and after relocation it was smaller, namely 0.61.

To get a better relocation value, the local velocity model is used in the study area so that the results obtained will be much more accurate. Because in accordance with the existing speed models in the area. We recommend that the earthquake recording station data and earthquake data be used relatively more so that the results of the relocation are much better and able to describe the seismicity of the research area.

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