Earthquake relocation using HypoDD Method to investigate active fault system in Southeast Aceh

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Abstract. Southeast Aceh is one of the most seismically region in the Aceh Province because the existence of the subduction zone and Sumatra Fault Zone (SFZ). In this paper, we present the active fault system that derived from the seismicity distribution and focal mechanisms of earthquakes which occurring along the fault system. In this case, we studied the earthquakes that occurred around the Tripa segment along the Sumatran Fault. The Tripa fault is a segmented fault of SFZ, actively moving, and recently generating some earthquake, this seismic activity was made by the impact from accumulated stress on rock. We use earthquake catalogues including P and S arrival times which collected by BMKG. The earthquake locations were relocated by using double difference method (HypoDD) and the focal mechanisms were obtained from GFZ-Postdam and global CMT solution. The 70 events was obtained from bmkg catalog, only 40 succeeded to be relocated using local velocity models. The earthquakes relocation by using double difference method finally provides sharper lineation of seismicity consisting of three earthquake clusters in the research area. The relocation results show the value change in location and depth which more reliable than the earthquake data from catalogue. The focal mechanisms of earthquakes indicate the right lateral earthquakes similar to fault plane solution of the Sumatran Fault.

1. Introduction
Seismic study is required in the Southeast Aceh region because of the segmentation of the Sumatran fault and has generated generates devastating earthquakes. The active faults in the region include the Batee segment on the west, Alas and Tripa right through this area. In addition, the Lhokseumawe and Samalanga-Sipopok faults are in the northern and southern parts of the fault. This makes the Southeast Aceh area is surrounded by active faults and becomes vulnerable area to earthquakes.

The Tripa segment is located between Southeast Aceh and Central Aceh where earthquakes occurred in 1990 (GayoLues) with M 6.8 and 1996 (Aceh Tenggara) with M 7.2 from GlobalCMT. BMKG was analysis some medium and felt earthquake in the northern part of the Tripa Segment. The earthquake occurred on July 2, 2013 with M 6.2 around Central Aceh and Bener Meriah, felt quite strongly in Southeast Aceh. Recently, an earthquake with M 5.1 in the north of the Tripa segment occurred on 8 February 2018 and it was felt very strongly in Southeast Aceh.
The Karo Earthquake (1936) was located around 30 km south of Kutacane (Southeast Aceh), with a location north of the Renun fault. The earthquake was quite destructive, because the source distance was close to the population. Although the center is closer to Kutacane, the earthquake was also felt very strongly to the Tanah Karo compared to other areas on the Renun fault line. This is due to Karo plateau topography factor that was surrounded by a series of hills.

In the Figure 1, some epicenters and the focal mechanism of 1996’s earthquake, is not located in the main fault, but in the left and right side. That’s a big question, because the earthquake always generated in the straightness of main fault. We must do a relocation method to solve it and to get better earthquake location because there is no research that really focus on seismicity in this region. If we get the good result, we can know the part of fault which actively produce and make a mitigation program.

The Pidie Jaya earthquake with magnitude of M 6.7 from BMKG catalog is the latest earthquake which occurred along the secondary fault in Aceh province. The Pidie Jaya earthquake could affect the activity of the Tripa Fault because the stress could be transferred to the Tripa Fault (the closest fault). Although the area around the Tripa Fault is very vulnerable, information on the seismic vulnerability index in the region is still very limited. Quantitative and qualitative data on seismic vulnerability becomes very important as that information could be used for the earthquake risk reduction program.
The tectonic pattern of an active fault was obtained from the epicenter distribution and the hypotenter vertical projection result like Figure 1. An accurate hypocenter location is needed to find the fault pattern. However, the location does not fully represent the actual location of the earthquake. This problem is due to the heterogeneity of the medium from the hypocenter to the recording station, the of the recorder station network, the accuracy of the timing readout, and the velocity structural model [1].

We can find that problem from Geophysics Agency result, because the must inform as early a possible the earthquake parameter without using a very local model. So, the relocation method like hypoDD use the local model to relocate and we can compare the best result for earthquake location. Several methods have been developed in order to relocate the seismicity and one of the methods is Double-Difference (DD) method. The method has been widely applied in various places. For example: the Sunda Strait, Java [2], the northern Hayward fracture [3], and central western China [4]. Of all these studies, real earthquake data was used to relocate the main earthquake (mainshock) and aftershocks. Zhao et al. [5] used the Double-Difference method to relocate Wenchuan earthquake aftershock 2008.

**Geological and Tectonic Settings**

The lineation of the Tripa Fault is precisely in the middle of the sediment formation from Plio-Pleistocene era. The Tripa Fault extends from geumpang to the Tanah Karo. The Southeast Aceh lithology is dominated by the similar types of rock which spreads in the Tanah Karo area, like a loop of black shales, clay, quartz sandstone with thin coal insertion.

Geological condition of the Southeast Aceh consists of tertiary sedimentary rocks (Trias) including black shale meta rocks, limestone, silt rocks which interpreted in the precipitate in shallow marine environments. The correlation shows similarities with the Sibaganding rock formations around northern part of Renun Fault [6]. These rock units were intruded by granite forfir and diorite rocks suspected to be Lime-Tertiary. The porphyry granite rocks belong to the ilmenite series granitoid rocks with low susceptibility. The location is not aligned thereon is a rock consisting of a loop of black shales, clay, quartz sandstone with thin coal insertion. This rock formation can be synchronized with the Tanah Karo Formation and the Sibolga Formation which from early tertiary age [6].

### Table 1. Historical earthquake data near Southeast Aceh

| Event      | Date          | Location            | Depth (km) | Mag | MMI |
|------------|---------------|---------------------|------------|-----|-----|
| Kutacane   | -/-/1936      | 30 km South of Kutacane | 10         | 7.2 | VIII |
| Kutacane   | 20 June 1996  | 3.20° N - 96.30° E  | 33         | 6.1 | VII |
| Gayo Lues  | 15 November 1990 | 3.91° N - 97.45° E | 33         | 6.8 | VIII |
| Peurlak    | 22 January 2003 | 4.57° N - 97.54° E | 33         | 5.7 | V   |
| Bener Meriah | 02 July 2013 | 4.60° N - 96.60° E | 10         | 6.2 | VI - VII |
| Gayo Lues  | 29 May 2017   | 4.15° N - 97.20° E  | 10         | 5   | IV - V   |

2. **Data and Method**

This study used 70 earthquake events which obtained from WebDC BMKG (the website, where we can download the continuous seismic waves) during the period of 2008-2018, and only 40 events that have good waveform and well recorded by eight station and 6 events only recorded by one or two sensors. Only 40 events were recorded very well by eight stations in northern Sumatra region.

The first step, The P and S waves from all waveform were picked by using Seismic Analysis Code (SAC) just to obtain the arrival times. Next, The pick arrival results were used as the input for the HypoDD program, which relocates the earthquake by using the double difference method. However, before being processed, the input data is given the deviation of the velocity model to the original
After that, the local model was applied to the arrival time of the P wave of each station by iteration. And the last, we can obtain the very best results with smallest residual.

We use one velocity model from Salsabella et al. [7] and compare it with some velocity model. Then, we use waveform record from eight station to pick arrival time, but for magnitude we use from BMKG’s parameter. We modelling the waveform from event which near to Kutacane City, which have Mw 4.7 and is very good looking waveform. But, the waveform just recorder in six station, two again haven’t record, maybe get a trouble, so the waveform is missed.

Figure 2. (a) Velocity model used for the earthquake relocation obtained from Salsabella et al. [7]. (b) The location of earthquake before relocation, and (c) the waveforms of an earthquake occurred near the Kutacane City and recorded by the BMKG stations.
Double Difference

Double-Difference method is a method to determine a relative parameters of earthquake. The double-difference relocation scheme is based on the measure of the traveltime differences among contiguous seismic events. The main idea of the method is to minimize the errors of earthquake locations caused by the lack of structure knowledge by using a relative relocation method.

If the distance between two events recorded by the same station is much smaller than the source-receiver distance and the size of velocity heterogeneity then the ray-paths of those two events could be considered to be identical. Figure 3 shows two earthquakes \( i \) and \( j \) which recorded in the same recording station (\( k \) and \( l \)) with a shorter hypocenter distance than the earthquake distance to the station, so that the second raypath of the earthquake is considered to be similar [3].

![Figure 3. The Illustration of Double-Difference with black-white circle shows the hypocenter distribution with its relocation vectors which recorded in the same two stations (k, l) [3].](image)

The Double-Difference method was developed from Geiger equations to determine the earthquake location. The residual between time difference calculation and observation of two earthquakes at the recorder station is related to the position of the earthquake hypocenter through the partial derivative of each earthquake travel time from both the catalog data and the waveform cross correlation data. In this case, the residual between the time difference of the calculation by observing two near earthquakes, is defined as follows:

\[
d_{ij}^{tk} = (t_{ij}^{obs} - t_{ij}^{cat})
\]

(1)

With \( t_{ij}^{tk} \) is the travel time of the waveform to station \( k \) and \( t_{ij}^{tk} \) is the travel time of the waveform \( j \) to station \( k \). For the distance residuals of the earthquake hypopcenter between two distant earthquakes \( i \) and \( j \), defined as follows:

\[
\frac{\partial t_{ij}^{t_k}}{\partial m} \Delta m^t - \frac{\partial t_{ij}^{t_k}}{\partial m} \Delta m^j = \Delta d
\]

(2)

Therefore it is described as follows:
\[
\frac{\partial t_k^i}{\partial x} \Delta x^i + \frac{\partial t_k^i}{\partial y} \Delta y^i + \frac{\partial t_k^i}{\partial z} \Delta z^i + \Delta \tau^i = \frac{\partial t_k^j}{\partial x} \Delta x^j - \frac{\partial t_k^j}{\partial y} \Delta y^j - \frac{\partial t_k^j}{\partial z} \Delta z^j = \Delta d
\]  

By combining the above equations of all earthquake hypocenter pairs at each station, will form a linear system equation:

\[W G m = W d\]  

With \(G\) is a matrix with \(M \times 4N\) dimension (\(M\), number of observations of Double-Difference; \(N\), number of earthquakes), \(d\) is a data matrix, \(\Delta d\) in dimension equations \(M \times 1\), \(m\) is a parameter of hypocenter change (\(\Delta m\)), and \(W\) is the weighting applied in the diagonal matrix [3]. Calculation of the relative location of the hypocenter of the earthquake will continue iterated until the residual between observation and calculation of travel time is close to zero, with that the hypocenter position changes will get better.

3. Results and Discussion
Figure 4. The relocated events resulted from HypoDD relocation by a local velocity model from Salsabella et al. [7] and one global velocity (IASP-91) model which used by BMKG.

Blue color shows the distribution of earthquake source before relocation and red color shows the distribution of earthquake source after relocated using HypoDD. Distribution before and after relocation has almost the same pattern, but after relocation the depth of earthquake source tends to located deeper and more precise follow the structure.

The distribution of earthquake sources to the collecting depths forms two clusters on the left and right sections of the Sumatran fault. The displayed graph illustrates the clustered area are changed. The determination of the hypocenter location can be quite good, which is calculated from the timing of the earthquake and the surrounding earthquakes to the receiving station based on the velocity model of Salsabella et al. [7].

Figure 5. The location of earthquakes obtained from BMKG compared to the relocated hypocenters after relocation.

Figure 5 shows us the parameters change of the location and depth, which the depth commonly used by BMKG produced by global speed model. That result make focus of the earthquake trapped at a certain depth between 10 and 33 km. That result is not able to present a local fault activity, which have variations value in shallow depths. From the graph above, we can see the Tripa segment generates an earthquake generally at a depth of 0 - 15 km.
The result is very important for further analysis, because the contact plane that occurs in the strike slip interacts in each depth, and simply explains that the tripa fault produces stress at every depth. The location change also shows the earthquake epicentre is grouped on one cluster and is in the alignment of the Tripa segment in Figure 6.

The location change can be used too as a new reference to explain which part is active and not. For the inactive part, the rock maybe is locked or the friction coefficient is so large and should be aware because it may be broken anytime following the release of accumulated stress. The result can be used as a mitigation program in the Kutacane region, because some research does not yet exist.

Figure 6. The location of earthquakes obtained from BMKG compared to the relocated hypocenters after relocation, and relocation map result between BMKG and HypoDD.

Figure 6 show us the strike direction of the focal mechanism which obtained from Global-CMT follows the distribution of earthquake relocation. Thus, we can see that the left and right sections of the main fault are earthquake clusters that must be further investigated. This study is the beginning of the analysis in order to explain that there is a fault on the left and right hand side of the Sumatran fault. One of the fault had generated a devastating earthquake in 1996.

4. Conclusion
The double difference method provides the result and shows a cluster solution which consisting three earthquake zone. The hypocenters depth is more diverse and describe a particular structure as tectonic condition and only 40 events has been successfully relocated which using local speed models for 70 events was obtained from bmkg’s catalog. The relocation results show the value of parameters change in location and depth that is more reliable than before. Waveform cross-correlation data can be added in the hypocenter relocation method to obtain a better hypocenter solution. It is better to use the appropriate local velocity model searched for 1-D relocation.

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References
[1] Pavlis, G L 1986 Bulletin of the Seismological Society of America 76 1699
[2] Ramdhan, M, Widiyantoro S, Nugraha, A. D, Métaxian, J P, Saepuloh, A, Kristyawan, S, Fahmi, A A 2017 Earthquake Science 30 67
[3] Waldhauser F, Ellsworth W L 2000 Bulletin of the Seismological Society of America 90 1353
[4] Yang Z X, Waldhauser F, Chen, Y T, Richards P G 2005 Journal of Seismology 9 241
[5] Zhao B, Shi Y, Gao Y 2011. Earthquake Science 24 107
[6] Cameron N R, Clarke M C G, Aldiss D T, Aspden J A, Djunuddin A 1980 9th Annual Convention Proceedings
[7] Salsabella Y 2014 Inovasi Fisika Indonesia 02 89