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Double-Difference Method for Relocating the Hypocenter of Aftershock Earthquakes in Seririt Singaraja

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

A method that does not require a main earthquake (master event) that can be used simultaneously to relocate a very large number of earthquakes with wide hypocenter separation is called the double-difference method. A method used to relocate the aftershocks in Seririt Singaraja on November 14 2019 with coordinate positions 113.478 – 115.181 East Longitude and 8.357 – 7.894 South Latitude. The earthquake data used in this research was accumulated from 85 BMKG seismic stations. Data analysis uses cross-correlation time differences which can increase the accuracy of travel time between the receiving station and the earthquake, thereby reducing errors in calculations. The double difference method used to relocate the earthquake in the Seririt Singaraja area showed that there was a shift in the location of the earthquake hypocenter before

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and after it was relocated. Horizontally and vertically, the distribution of earthquake hypocenters before and after being relocated occurs when there is a collection of location shifts. The results of this research were able to relocate 152 aftershocks properly. The main earthquake after being relocated was at a depth of 17 km, while the distribution of aftershocks was at a depth of around 6-25 km, so that it can more accurately describe the position of the earthquake source and is able to show clearer and easier to interpret structural patterns.

Keywords: Relocation; hypocenter; double-difference; cross-correlation; BMKG.

1. INTRODUCTION

The Indonesian seismic code describes earthquake prone areas and response spectrums for regions in Indonesia. The earthquake map is based on the probabilistic seismic hazard analysis taking into account bedrock condition and active fault distribution [1].

Seririt Singaraja District, Buleleng Regency, located in North Bali, has had a history of earthquakes of large magnitude and claimed many victims. The Seririt Singaraja earthquake occurred on July 14 1976. In a radius of 50 km from the epicenter, 573 people died, 4,755 people were injured, physical damage to 226 houses and schools. An earthquake measuring M 6.5 with an intensity scale of VIII MMI at a hypocenter depth of 36 km shook very strongly [2]. Seririt Singaraja District was again shaken by a tectonic earthquake in 2019, with a magnitude of M 5.1 and was a shallow earthquake due to active fault activity. The most serious physical damage to buildings occurred in Seririt sub-district and had an impact on 4 other sub-districts in Buleleng Regency, namely Sukasada, Banjar, Busungbiu and Gerokgak sub-districts [3].

The results of a local seismicity study in the Bali area carried out by Masturyono [4] to record the local seismic network show that local and shallow earthquake seismicity is an indication of the existence of a thrust fault structure behind the island arc. Meanwhile, seismotectonic studies concluded that there was an extension of the Flores thrust fault to the northeast of Bali and based on the fact that the depth of the hypocenter to the north of the island of Bali is shallower compared to the hypocenter on the mainland of the island of Bali. So it can be stated that the local seismicity of the Bali area provides an indication of the existence of a thrust fault structure behind the island arc [5].

2. METHODS

Research conducted by Waldhauser in 2000 [6] stated that the double-difference method can be used as an algorithm for determining earthquake locations, which is an inversion of the location of the hypocenter of an earthquake group which is connected to the centroid of the earthquake cluster. A method that does not require a main earthquake (master event) so it can be used to relocate a very large number of earthquakes with wide hypocenter separation simultaneously. The main condition needed is that the distance between two earthquakes and the station is further than the distance between the two relocated earthquakes. This method utilizes the fact that if the hypocenter separation between two earthquakes is small compared to event-station distance and the scale length of velocity heterogeneity, then the ray paths between the source region and common station are similar along almost the entire ray path. The bottom line is the difference in travel times for two earthquake events observed in one station can be attributed to the spatial offset between the events with high accuracy [7].

The double-diference method assumes that if there are two earthquakes with hypocenter distance smaller than the distance of the hypocenter to the recording station, ray paths from these earthquakes are considered to propagate through a similar medium. HypoDD minimizes residuals between observed and calculated travel-time diferences in an iterative procedure, and after each iteration, the locations and partial derivatives are updated. This method has been successfully used to relocate earthquakes in Indonesia using the BMKG data [8].

The Geiger method used so far is a speed model which is assumed to be close to the actual situation, but cannot yet be used to determine the actual location. With the velocity model, the location of the hypocenter experiences a shift from its actual position and it is difficult to analyze the structure formed by the distribution of earthquakes, so in determining the actual location of the hypocenter it is necessary to use the double-difference method. The double-difference method can be illustrated as in Fig. 1.

Pesicek in [9] developed the determination of earthquake hypocenter relocation using the teleseismic double-difference algorithm. This method is a development of the original version of the double-difference method [6]. The development of this method is essentially adding ray tracing by considering the round shape of the earth. If the arrival time T, earthquake i, k seismic station can be expressed using ray theory as an integral path along the ray with the formula,

$$T_k^i = \tau^i + \int_i^k u ds \quad (1)$$

where τ is the origin time of the *i*-th event, u is the slowness field, and *ds* is the path length element. Because of the nonlinear relationship between travel time and event location, the Taylor series expansion is a general form for linear equations. The next problem is related to residual travel time. *r*, for an *i*-th event is linearly related to the perturbation. Δm, to the four hypocenter parameters for each *k* observation, namely,

$$\frac{\partial t_k^i}{\partial m} \Delta m^i = r_k^i \quad (2)$$

with $r_k^i = (t^{obs} - t^{cal})_k^i$, t^{obs} is the observation travel time, t^{cal} is the calculated travel time. $\Delta m^i = (\Delta x^i, \Delta y^i, \Delta z^i, \Delta \tau^i)$ in equation (2) is suitable for measuring arrival time. However, the cross-correlation method is used to measure differences in travel time between events. $(t_k^i - t_k^j)^{obs}$, as a result equation (2) cannot be used directly. To obtain the hypocenter parameter equation, relative between two events i and j, with the equation,

$$\frac{\partial t_k^{ij}}{\partial m} \Delta m^{ij} = dr_k^{ij} \quad (3)$$

where $\Delta m^{ij} = (\Delta dx^{ij}, \Delta dy^{ij}, \Delta dz^{ij}, \Delta d\tau^{ij})$ is the change in the relative hypocentral parameter between two events, and the partial derivative *t*, which corresponds to *m* is a component of the light slowness vector that connects the source and receiver [9]. In equation (3) the source is the center of two hypocenters assuming a constant slowness vector for the two events. dr_k^{ij} in equation (3) is the residue between the difference in observed and calculated travel time between two events which is defined as follows,

$$dr_k^{ij} = (t_k^i - t_k^j)^{obs} - (t_k^i - t_k^j)^{cal} \quad (4)$$

where:

t^{obs} = observation travel time (recorded by the receiving station)
t^{cal} = calculation travel time (obtained from ray tracing calculations)
t_k^i = travel time of earthquake i recorded by station k
dr_k^{ij} = residual travel time between earthquake pairs i and j at station k

The double-difference method as defined in equation (4) assumes that the constant slowness vector is valid for every event that is close together, but fails for events that are far away. In general, the equation used in changing the hypocentral distance between two events i and j is from equation (3) which uses the slowness vector and origin time appropriate for each event, as shown in Fig. 1.

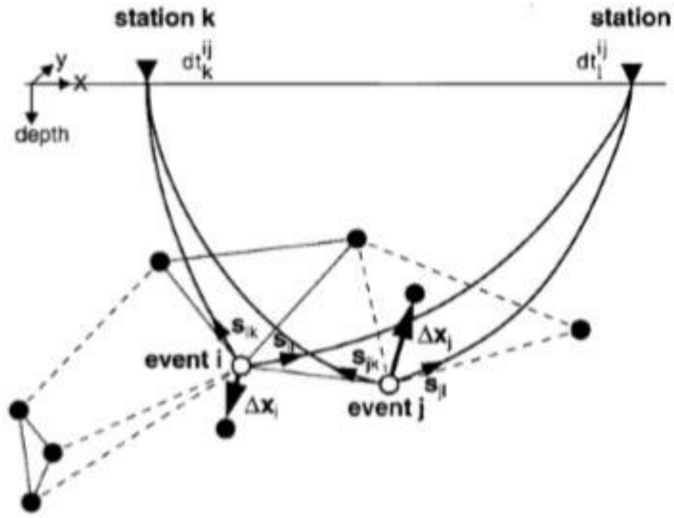


Fig. 1. Illustration of the Double-Difference method [9]

where:

dr_k^{ij} = time difference between earthquake residues *i* and *j* to station k
dr_l^{ij} = time difference between earthquake residues i and *j* to station l
S_{ik} = distance from earthquake *i* to station k
S_{il} = distance from earthquake *i* to station l
S_{jk} = distance from earthquake *j* to station k
S_{jl} = distance from earthquake *j* to station l
Δx^i = earthquake relocation result *i*
Δx^j = earthquake relocation result *j*

This method is effective on travel time data between two earthquakes, with the hypocenter distribution distance between the two earthquakes being very close, compared to the distance between the station and the earthquake, so that the raypath and waveform of the two earthquakes can be considered to be nearly the same. This assumption means that the difference in travel time between two earthquakes recorded at the same station can be considered as a function of the distance between the two hypocenters. In this way the speed model error can be minimized without using station correction [10].

In Fig. 1, *Δx* is the relocation vector for events *i* and *j* obtained from equation (5), and *dt* is the difference in travel time between events *i* and *j* which is observed at stations k and l, namely

$$\frac{\partial t_k^i}{\partial m}\Delta m^i - \frac{\partial t_k^j}{\partial m}\Delta m^j = dr_k^{ij} \tag{5}$$

or in full,

$$\frac{\partial t_k^i}{\partial x}\Delta x^i + \frac{\partial t_k^i}{\partial y}\Delta y^i + \frac{\partial t_k^i}{\partial z}\Delta z^i + \Delta\tau^i - \frac{\partial t_k^j}{\partial x}\Delta x^j - \frac{\partial t_k^j}{\partial y}\Delta y^i - \frac{\partial t_k^j}{\partial z}\Delta z^j - \Delta\tau^j = dr_k^{ij} \tag{6}$$

Equation (6) above was developed by Pesicek et al. [9] to be,

$$r_k^i = \sum_{i=1}^{3}\frac{\partial T_k^i}{\partial T_l^i}\Delta x_l^i + \Delta\tau^i + \sum_{n\in G} W_n^G\delta U_n^G + \sum_{n\in L} W_n^L\delta U_n^L + S_k \tag{7}$$

and

$$dr_k^{ij} = r_k^i - r_k^j \tag{8}$$

where ∂T_k^i is the partial derivative of the arrival time of event *i* to station k with respect to *x*; Δx_l^i (l = 1,2,3) are the components x,y,z: $\Delta\tau^i$ is the origin time of event *i*; $W_n^G\delta U_n^G$ and $W_n^L\delta U_n^L$ are the weighted and slowness ray paths for the global (G) and local (L) models; S_k is the station correction; r_k^i and r_k^j are the residual arrival times of events *i* and *j* at station k, and dr_k^{ij} is the double-difference residual.

3. ANALYSIS AND RESULTS

3.1 Hypocenter Relocation

Earthquake relocation was taken from BMKG Balai 3 Denpasar earthquake catalog data which came from 85 stations with 174 earthquake events. Earthquake relocation using the double-difference method is carried out with the hypoDD program. The hypoDD program has two parts, namely the hypoDD program part for relocating earthquake data and the ph2dt program part for grouping earthquake data.

The RMS (Root Mean Square) value is a value used as a parameter for the accuracy of a method [11]. The smaller the RMS value or the closer it is to zero, the closer the inversion calculation results and observation results are to the same. So it can show that the model parameters prepared through the calculation process are getting closer to the actual model. A comparison of the RMS histogram before and after relocation is shown in Fig. 2, where Fig. 2(a) is before relocation, while Fig. 2(b) is RMS after relocation. In Fig. 2(a) the RMS value ranges from 0.1 to 1.8. it is still not said to be good because the RMS value is still too large. By processing the data in Fig. 2(b), the RMS value changes, namely approaching zero. The residual travel time resulting from relocation using hypoDD is close to zero, indicating that the calculated travel time value is close to the observed travel time. This indicates that the seismic velocity model or structure resulting from the inversion resulting from calculated travel times is close to the actual conditions according to the observation results. So that the model parameters that have been prepared through the calculation process are closer to the actual model.

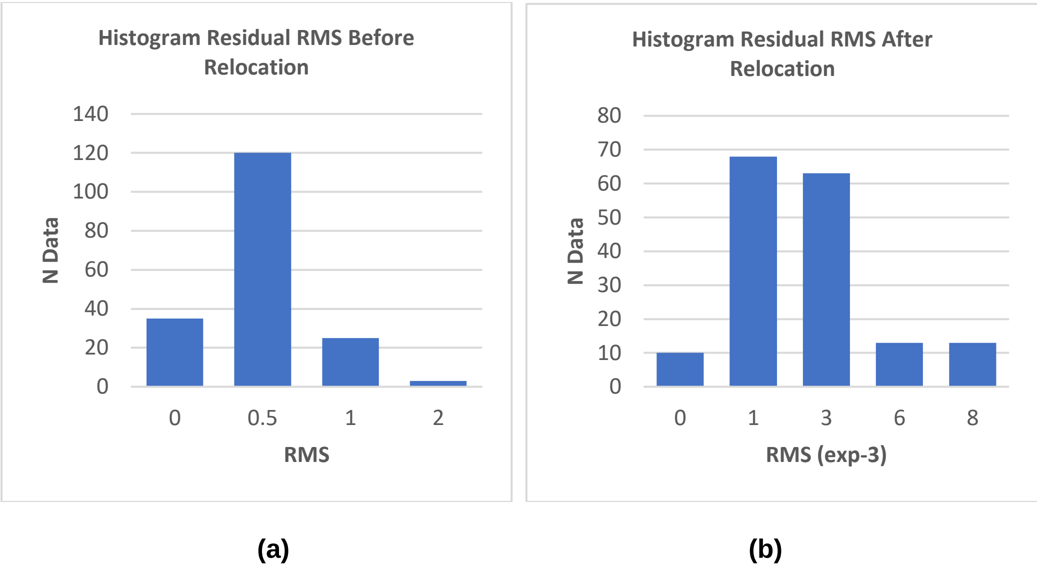


Fig. 2. Histogram of RMS residual time values, (a) before relocation, (b) after relocation

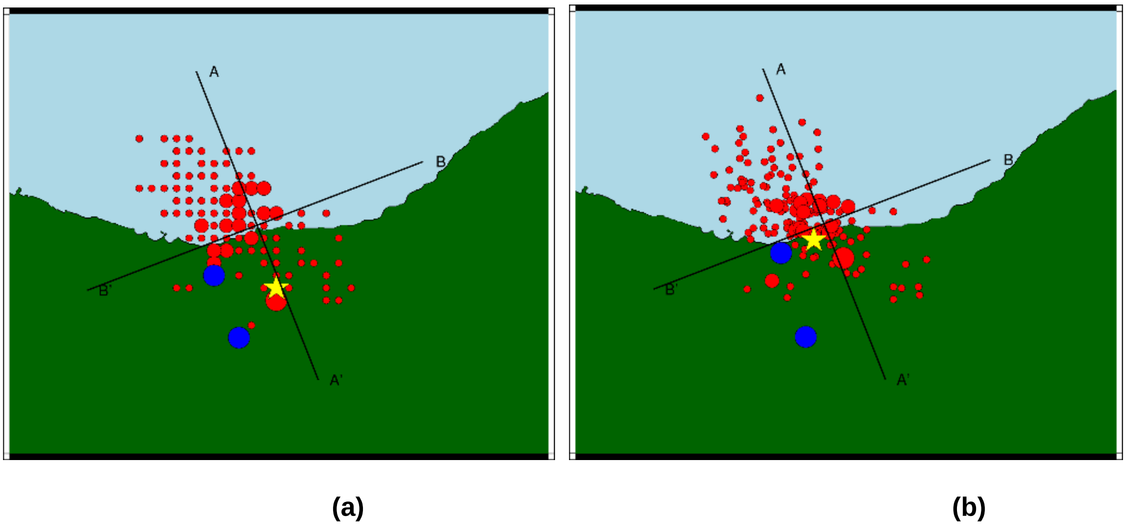
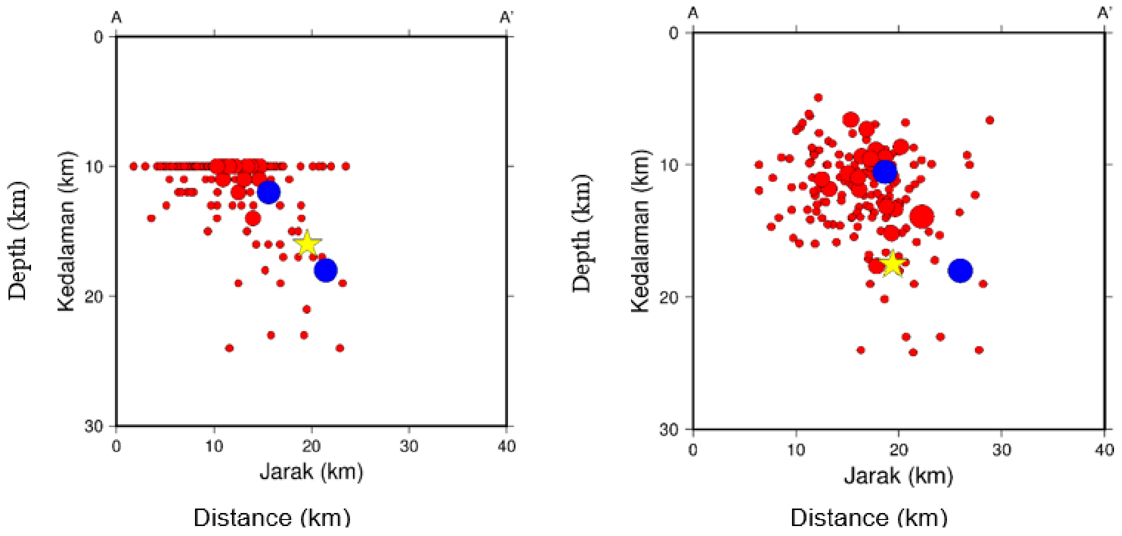


Fig. 3. Results of cross section analysis of areas A-A' and B-B' (a) before relocation (b) after relocation

3.2 Hypocenter Cross Section

The projection of the cross section results illustrated in Fig. 5 is the distribution of earthquake hypocenters. Line A-A' starts from points 114.85569 East Longitude and 8.05601 South Latitude towards points 114.95361 East Longitude and 8.30384 South Latitude with a distance of 31 km, as well as line B-B' which starts from points 115.05672 East Longitude and 8, 11498 South Latitude towards points 114.76970 East Longitude and 8.23324 South Latitude.



(a) **(b)**

Fig. 4. Results of cross section analysis of area A-A' transversely, (a) before relocation (b) after relocation

Fig. 5 shows a cross section in 2 directions, namely vertical (A-A') and horizontal (B-B') which is the earthquake distribution pattern, where the yellow star symbol represents the main earthquake, the blue circle symbol represents the preliminary earthquake, and the red circle symbol represents the main earthquake aftershocks, while the small red circle is an earthquake with a magnitude < 4 and the large red circle is a magnitude > 4.

For the final hypocenters, we replaced the final residuals with samples drawn with replacements from the observed residual distribution and relocated all events with these bootstrap sample data and unit weights to determine the shift in location with the resampled data vector [12].

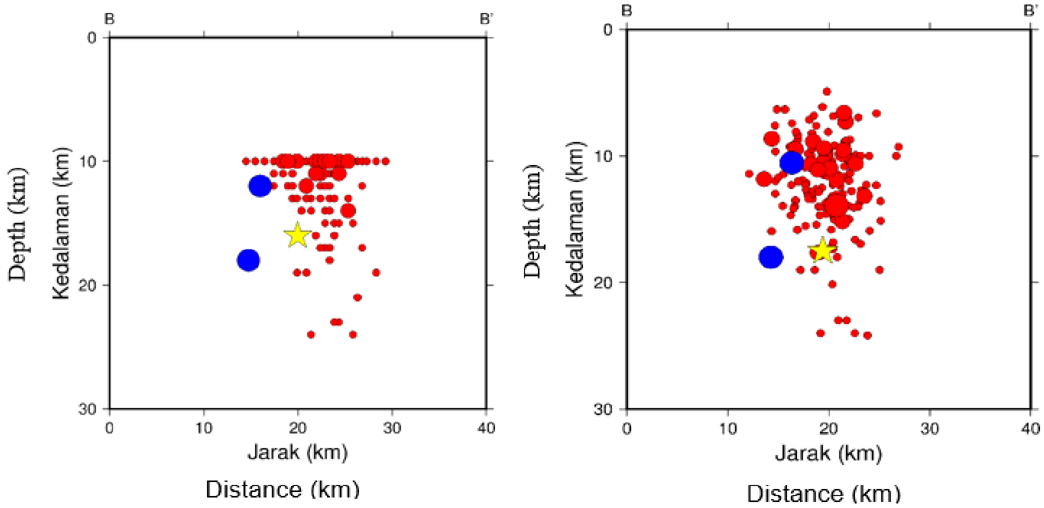
The results of the hypocenter distribution after relocation were obtained from data processing using the double-difference method. The difference in the depth of earthquakes in the A-A' area transversely, before and after relocation is shown in Fig. 4. The distribution of earthquakes before relocation shows the distribution of hypocenters between earthquakes that are close to each other at a depth of 10 to 24 km, while at a depth of 6 to 25 km the distribution of earthquakes After relocation, the distribution of hypocenters between earthquakes is far from each other.

The results of the hypocenter distribution for the B-B' area horizontally, before and after relocation, are shown in Fig. 5. The hypocenter distribution at a depth of 10 to 20 km occurred the most.

After processing the data using the double-difference method, the results of the hypocenter distribution after relocation were obtained. The difference in hypocenter distribution before and after relocation is shown in Fig. 6.

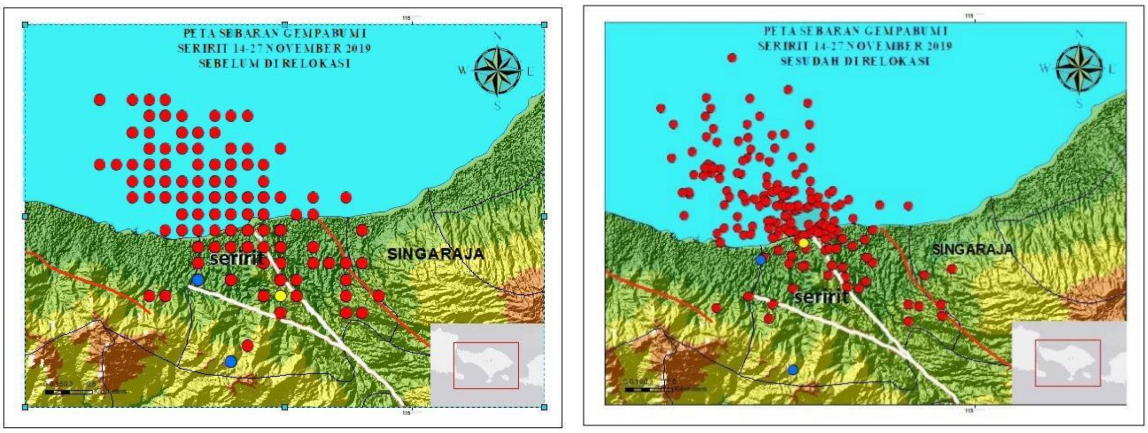
Fig. 6 shows changes in the earthquake location map based on earthquake data on the hypocenter distribution before and after relocation using the double-difference method. Where the position of the hypocenter before relocation is spread out, so it does not show a pattern that corresponds to the main fault, but the distribution of hypocenters after relocation tends to gather to form a group on one line that follows the fault plane. The depth of the hypocenter varies and at a depth of 10 to 20 km the most hypocenters occur.

The relocation results using the double-difference method can be stated to be quite accurate because the validation RMS value produced in this study is close to 0. So the research results show that the data processing carried out is close to the actual situation. The main earthquake in the results of this study was located at a depth of 17 km and the hypocenter distribution of the earthquake was located at a depth of 6 to 25 km below the earth's surface.



(a) (b)

Fig. 5. Results of cross section analysis of the B-B' area horizontally, (a) before relocation (b) after relocation



(a) (b)

Fig. 6. Earthquake distribution map (a) before relocation, (b) after relocation

4. CONCLUSION

The results of the earthquake relocation in Seririt Singaraja District using the double difference method showed that there was a shift in the location of the earthquake hypocenter before and after the relocation. The distribution of earthquake hypocenters before and after in the vertical direction there is a change in the location of the hypocenters which are more clustered to form a group on one line that follows the fault plane. However, in the horizontal direction there is no significant difference. This research succeeded in relocating 152 earthquake aftershocks using the double difference method. The main earthquake after being relocated occurred at a depth of 17 km and the distribution of aftershocks was at a depth of 6 to 25 km, so that it can describe the position of the earthquake source more precisely and show clearer structural patterns for interpretation.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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