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Research Article

Earthquake Relocation Using Double Difference Method for 2D Modelling of Subducting Slab and Back Arc Thrust in West Nusa Tenggara

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Abstract

West Nusa Tenggara is classified into earthquake prone zone as it is located between subduction and back arc thrust earthquake sources. Accurate hypocenter determination in this area is necessary for strong motion calculation and earthquake source zone modelling. Earthquake relocation in the region is needed to produce a more accurate hypocenter location and 2D modelling of subduction slab and back arc thrust. A double difference method was employed with earthquake data from 2009-2017. The results show better accuracy in the distribution of the travel-time residual. Subduction slab modelling shows a dip value of about 7-13° from a trench to an arc, 49-55° from an arc to a transition zone, and 60-64° dip at a depth of 300 km. Back arc thrust modelling shows a dip value of about 19-28° at a depth of 15-30 km. The results provide a reliable 2D model for subduction slab and back arc thrust in West Nusa Tenggara. Therefore, the developed models can be used as reference for earthquake zones and seismic hazard assessment in West Nusa Tenggara.

Keywords: *earthquake relocation, double difference method, subduction, back arc thrust*

Relokasi Gempabumi Menggunakan Metode Double Difference untuk Pemodelan 2D Slab Subduksi dan Back Arc Thrust di Nusa Tenggara Barat

Abstrak

Nusa Tenggara Barat merupakan wilayah rawan gempa bumi karena diapit oleh sumber gempa subduksi dan back arc thrust. Penentuan lokasi hiposenter gempa bumi yang akurat di wilayah ini sangat diperlukan dalam perhitungan strong motion dan pemodelan zona sumber gempa. Oleh karena itu, perlu dilakukan relokasi gempa bumi di wilayah Nusa Tenggara Barat untuk memperoleh data gempa bumi yang akurat dan pemodelan 2D slab subduksi dan back arc thrust. Metode yang digunakan adalah metode double difference dengan data gempa periode 2009-2017 di Nusa Tenggara Barat. Hasil-hasil penelitian ini menunjukkan tingkat akurasi lebih baik jika dilihat dari sebaran residual waktu tempuh. Pemodelan slab subduksi menunjukkan nilai dip berkisar antara 7-13° dari palung hingga busur kepulauan, 49-55° dari busur ke zona transisi, dan dip 60-64° pada kedalaman 300 km. Pemodelan back arc thrust menunjukkan nilai dip sekitar 19-28° pada kedalaman sekitar 15-30 km. Hasil-hasil penelitian memberikan model 2D untuk slab subduksi dan back arc thrust yang dapat diandalkan. Oleh karena itu, *model tersebut dapat digunakan sebagai referensi untuk analisis sumber gempa dan prediksi tingkat bahaya gempa di Nusa Tenggara Barat.*

Kata Kunci: *gempa bumi, relokasi, double difference, subduksi, back arc thrust*

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I. INTRODUCTION

Indonesia is undeniably an earthquake prone region. Among several regions in this country, West Nusa Tenggara is one region that has high level of seismicity. West Nusa Tenggara is located between subduction zone to the south and back arc thrust to the north while some faults lie on the land [1].

Seismotectonic spatial distribution indicates the return period of earthquake with M=6 in West Nusa Tenggara is around 5-18 years [2]. The back arc thrust which is located to the northern part of West Nusa Tenggara frequently triggers less than 50-km-depth earthquake with thrust mechanism [3].

The studies related to the earthquake in particular area requires accurate and specific earthquake hypocenter data. The data can be obtained through some methods. The available method to obtain such data is double difference earthquake relocation [4]. During the earthquake striking Padang on 30 September 2009, the earthquake relocation data were used to understand the characteristic and also the source of the earthquake [5]. For complex seismic area, furthermore, the relocation data are needed to differentiate the earthquakes from fault zone, subduction, and volcanoes [6]. In addition, such accurate data are able to lead us to predict peak ground acceleration in particular area [7].

The earthquake relocation data are also utilized to create 2D model of the earthquake source [8]. The earthquake source 2D modeling is essentially needed in calculating the earthquake hazard, either probabilistic or deterministic [1].

It is expected that this research can produce more accurate earthquake hypocenter data and 2D model of subduction and back arc thrust. Therefore, the model can be utilized as main reference for earthquake source analysis and essential requirement for hazard assessment in West Nusa Tenggara.

II. RESEARCH METHOD

Double difference method was employed in this research. In addition, travel-time differences of earthquake pair from catalogue or waveform was also used [9, 10]. The arrival data of body wave were obtained from the catalogues by Center for Meteorology, Climatology, and Geophysics of Indonesia (BMKG) from 2009 to 2017 [11]. In order to achieve better residual errors, only BMKG stations located in West Nusa Tenggara, Bali and East Java were involved [5]. AK135 velocity model was employed for the relocation calculating [12]. The focus of the analysis for West Nusa Tenggara region was limited by coordinate 115.5°E-119.5°E and 7°S-12°S as shown in Figure 1.

Theoretically, the relative residual of arrival time between two nearby hypocenters in a cluster is stated as:

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

wWhere, t_k^i is travel-time of waveform of the earthquake i to station k, and t_k^j is travel-time of waveform of the earthquake j to station k. For the double difference equation can be written into:

$$r_{ij} = dt_i + \frac{\partial T_i}{\partial x_0}dx + \frac{\partial T_i}{\partial y_0}dy + \frac{\partial T_i}{\partial z_0}dz$$
$$-(dt_j + \partial Tj\partial xodx + \partial Tj\partial yody$$
$$+\partial Tj\partial zodz) \quad (2)$$

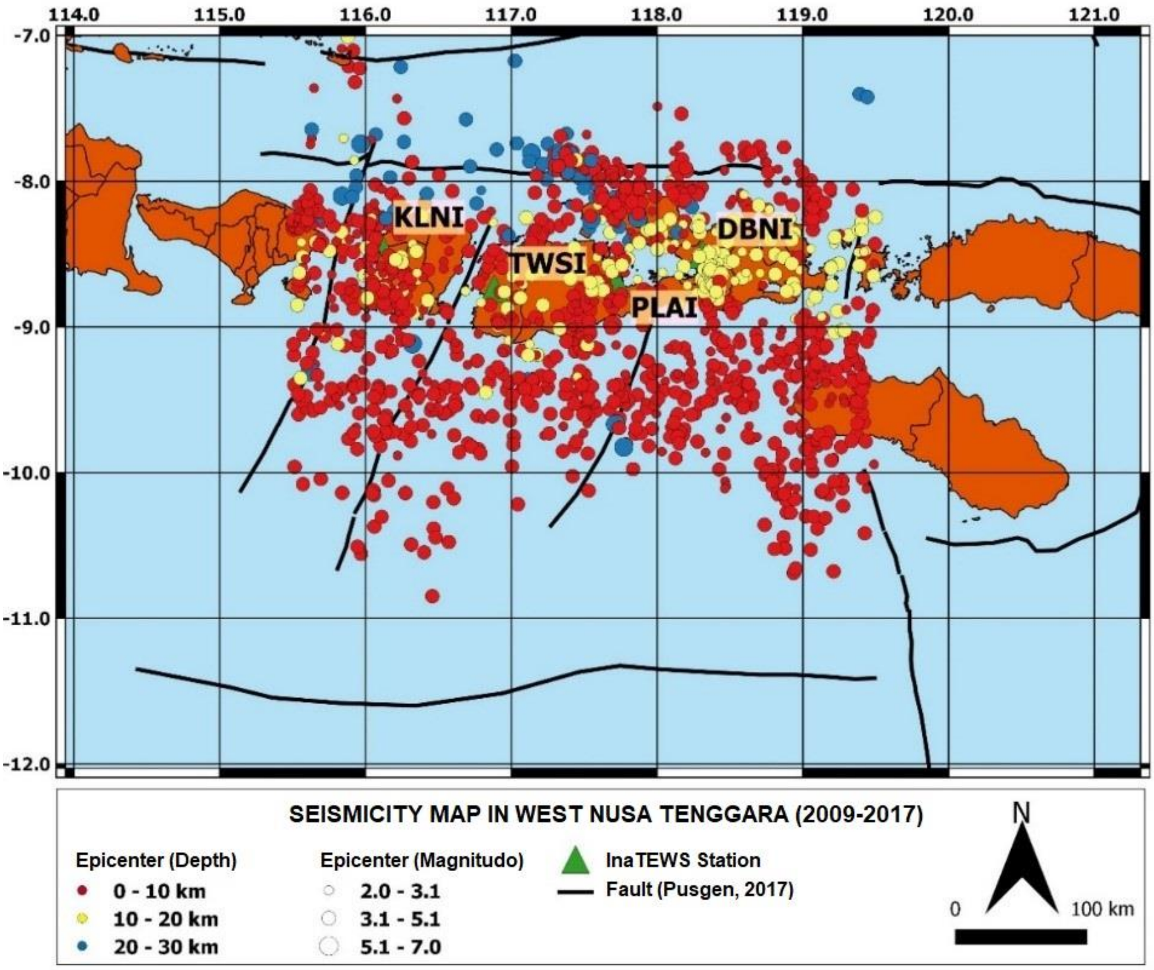


Figure 1. Seismicity Map in West Nusa Tenggara for 2009-2017

Then double difference equation for every station can be expressed using matrix:

$$WGm = Wd \quad (3)$$

where G is matrix of partial derivative of travel-time to hypocenter parameter and sized of M x $4N$.

M is the amount of possible equation formed from every earthquake pair in a cluster and N is the amount of hypocenter in a cluster. m is the vector data of the relative position change between the hypocenter pair and the relative position of the alleged hypocenter in a cluster. While d is double difference residual of all hypocenter pair. W is diagonal matrix for weighting of every station. Matrix W is used because the signal to the value of the ratio is different for each event on each station [13]. The quality of the earthquake relocation can be measured from the travel-time residual between observation and calculation.

The next step to do was to make a vertical slice of the earthquake relocation data to observe the distribution of the earthquakes vertically. Based on regression analysis of earthquake distribution vertically, we can obtain the structure of the slab [8]. Regression analysis that used was linear and polynomial second order as written below:

$$Y = ax + b \tag{4}$$
$$Y = ax^2 + bx + c \tag{5}$$

where, Y is hypocenter depth in km, x is latitude in degree, then a , b , and c are constant.

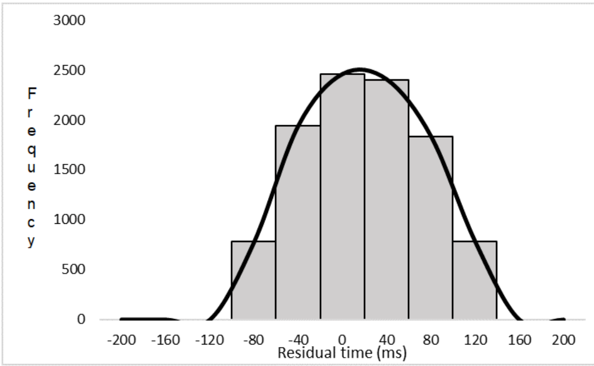
R^2 constant is used to learn data correlation using equation as written below [14]:

$$R^2 = 1 - \frac{RSS}{TSS} \tag{6}$$

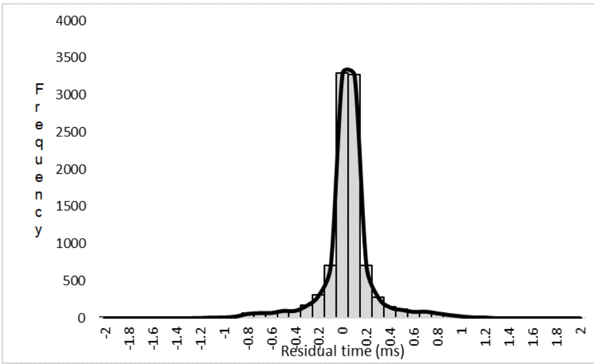
Where R^2 is coefficient of determination, RSS is the sum of the squares and TSS is total sum of squares associated with the response variable. The result of this calculation was then compared with previous model of subduction slab and back arc thrust.

III. RESULTS AND DISCUSSION

The quality of earthquake data was identified through the comparison of histogram of travel-time residual between before and after relocation as shown in Figure 2. The earthquake data that have been relocated can be seen in Figure 3. The earthquake hypocenter after relocation indicates the changes of location and depth. Once it is relocated, the earthquake location becomes closer to the source zone of the earthquake, especially the source of the fault earthquake. In addition, some earthquakes spreading form clusters and indicate lineage. These results are essential for sharp images of seismicity and reveal horizontal lineation of hypocenters that define the narrow regions on the fault, where the stress is released by brittle failure [15]. This happened as the double difference method is quite effective to observe local earthquake relocation. Changes in the depth of the earthquake show a better trend because the depth of some earthquakes caused by subducting plate that lie far from the trend relatively increase.



(a)



(b)

Figure 2. Histogram of Travel-time Residual: (a) Before and (b) After Relocation. Histogram shows a significant residual decrease. Before the relocation, the residual was relatively large up to ±80 ms, whereas after the relocation, residual was ranged between 0 to ± 0.2 ms.

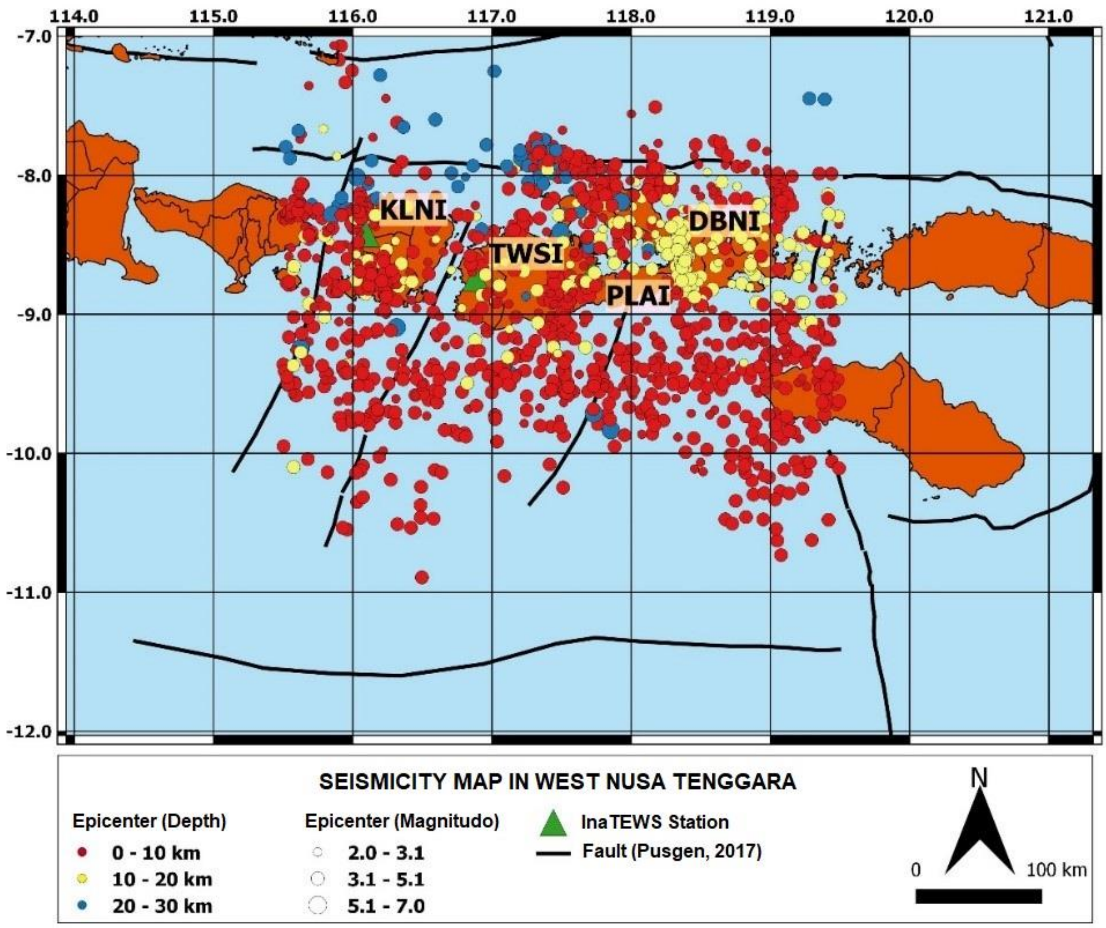


Figure 3. Seismicity Map after Relocation

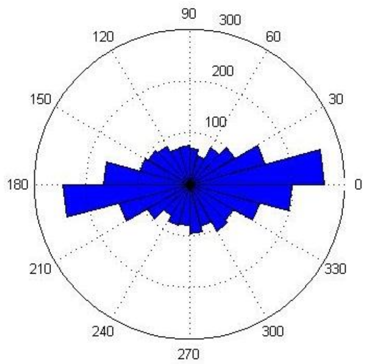


Figure 4. Rose Diagram for Azimuth

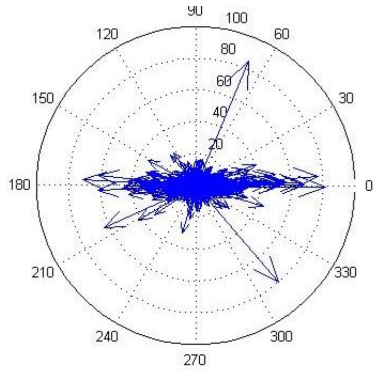


Figure 5. Compass Diagram for Azimuth and Shifting Value

The magnitude of azimuth, location shifts, and depth changes were identified through rose and pass diagrams. The azimuth value was used to determine the direction of the earthquake epicenter shift after being relocated. Figure 4 is a rose diagram that shows the azimuth trends of the analyzed earthquake. Figure 4 shows that most earthquakes shift at azimuth of 0° and 180°.

The compass diagram of distance shift value to the azimuth in Figure 5 shows that most earthquakes shifted as far as 20 km. The same condition is also presented in Figure 6, where the compass diagram of depth change is dominated by the value of 20 km. This shows that the result of double difference relocation did not experience significant epicenter and depth cause, which might be because the earthquake data before relocation already have good quality. However these small shifts are very influential in the calculation of strong motion due to the earthquake [16]. In addition, high accuracy of earthquake data are required in producing earthquake source models.

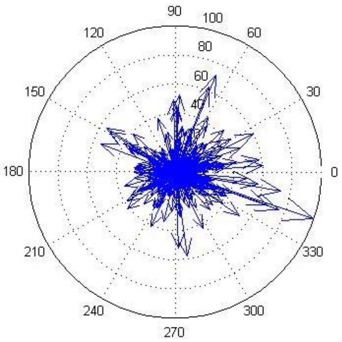


Figure 6. Compass Diagram for Azimuth

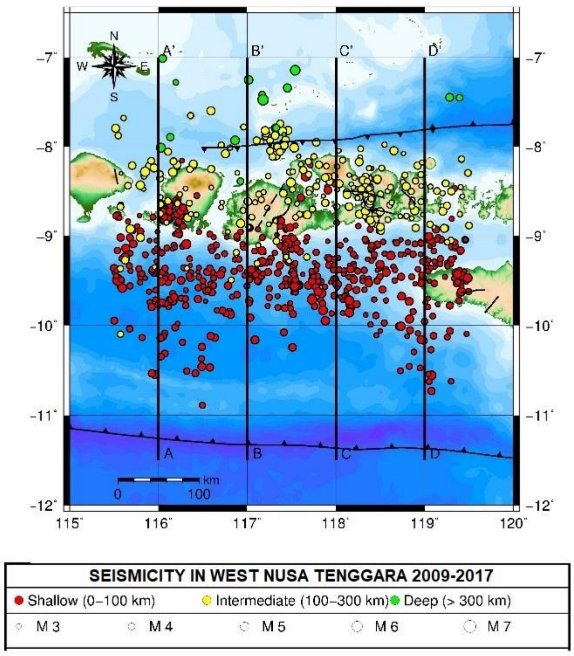
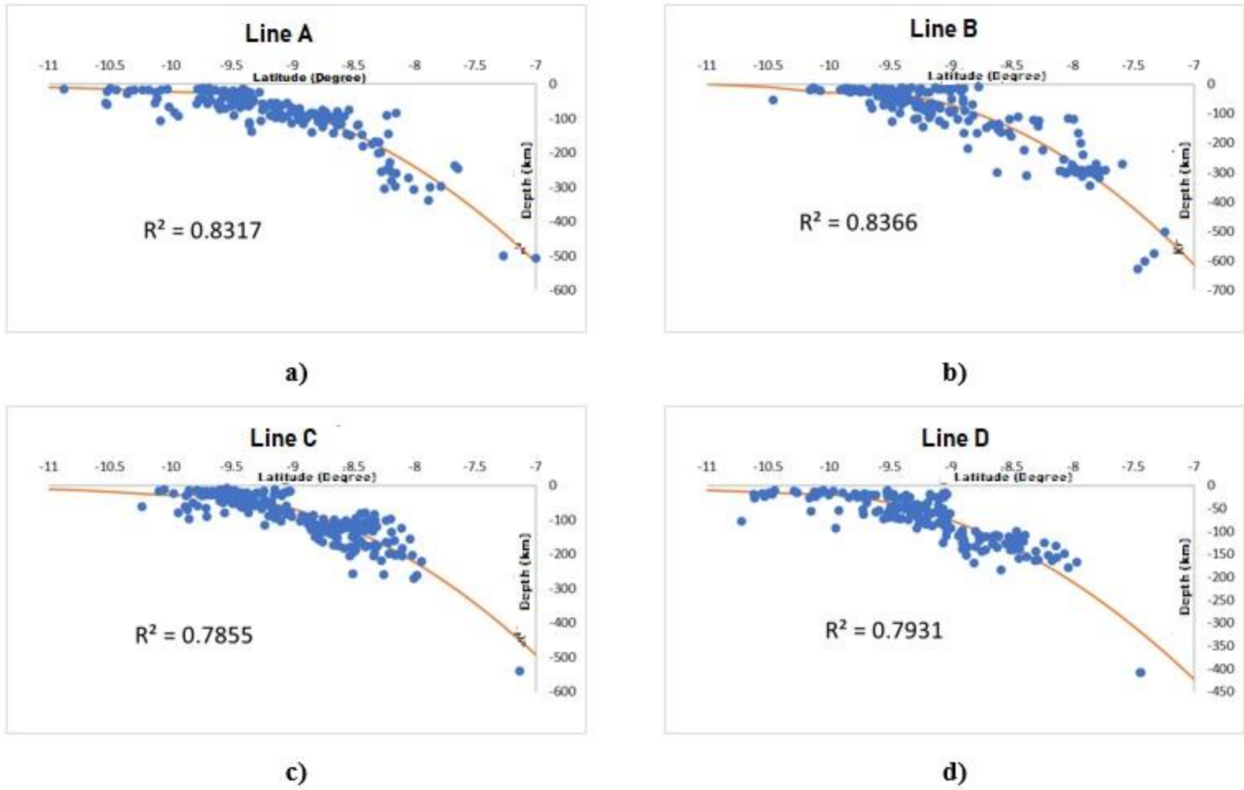


Figure 7. Earthquake and Slices Used for Subduction Slab Analysis

In subduction slab analysis, shallow earthquakes with depth ≤50 km at distances ≥200 km from trench were removed at first. The shallow earthquake is assumed to be derived from fault located in West Nusa Tenggara region. Slab modeling was done on 4 slices with the distance between the slices was 1 degree. The distribution of earthquake data used in the regression analysis and the slices used are shown in Figure 7.

The regression analysis from earthquake relocation data is shown in Figure 8. For subduction slabs close to trench or before arc, linear regression analysis was employed, while for slabs at a distance of approximately 300 km from trench or after arc to transition zone, order 2 polynomial regression analysis was used. Correlation coefficient of each path indicated a good result, as big as 0.78-0.84, so that the model was able to illustrate the trend of the subduction slab well. Validation is done by comparing the slab model in this study with the previous studies on earthquake distribution. In this study, the slab model being proposed is compared with the Hayes and Widyantoro's subduction models [17, 18].

The Hayes' subduction model is one of the subduction models that is often used as a reference in seismic studies globally. The comparison of our subduction model and Hayes is shown in Figure 9, where the red line shows the model by Hayes while the blue line is the proposed model in this study. In general, the model in this study and Hayes' model have relatively similar slope trends. However, on line A, the proposed model in this study is closer to the earthquake cluster located at a depth of 50-150 km and earthquake at a depth of 250-350 km. In the model being proposed in this study, line B looks more superficial than the Hayes' model, but this study illustrates better shallow earthquakes at depths of 50-100 km. The same thing is also observed in the line C, where this study is relatively shallow and able to describe the earthquake clusters that occur at a depth of 100-150 km. Line D shows no significant difference between the model being proposed with Hayes' model.



a) b)

c) d)

Figure 8. Regression Result for Subduction Slab

Next comparison was made between the proposed model in this study and the results of Widyantoro's tomography [18]. Line A to D in this study corresponds to the J-to-M path of the Widyantoro's study. In general, it can be seen that the angle of subduction being proposed is relatively the same as Widyantoro's subduction angle. In Widyantoro's dip of slab, it ranges from 10°-30° from the trench to the arc, and slab dips are steeper, 60°-70° down to the transition zone. However, it appears that the dip changes to nearly vertical at depths of about 400 km below the arc in the eastern Sunda, where the slab is deflected in the transition zone. This study shows the value of dip is 7.2°-13.4° from trench to arc ($\alpha 1$), 49.9°-59.9° from arc to transition zone ($\alpha 2$), and 60.4°-64.8° at the depth of 300 km ($\alpha 3$).

Based on the earthquake spreading, there is an indication of seismic gap seen at is more than 300 km deep. This result is relatively in accordance with Setiadi's research which indicates the existence of seismic gap at the depth of 300-500 km. Seismic gap is a gap in the occurrence of earthquakes recorded at a particular location and depth over a given period. This could have been due to the melting of some rocks in the mantle layer. Melting is a condition where the temperature in the layer of asthenosphere is higher than melting layer rock temperature on the hypocenter. At certain ranges, the rocks on the hypocenter will begin to flex and melt and become frozen again as it passes the temperature limit on the asthenosphere, which is smaller than the melting temperature of the rocks [19].

Modeling was also done for back arc thrust zone in the northern part of West Nusa Tenggara. The earthquake data sourced from back arc thrust were relatively fewer than subduction. Therefore, in this study, only 3 clusters of earthquakes were used and assumed as back arc thrust. Seismicity activities in nothern part of Bali and West

Nusa Tenggara which occurred at shallow crust (less than 50 km depth) were related to back arc thrust fault [20]. Cluster and vertical distribution of the earthquake can be seen in Figure 10.

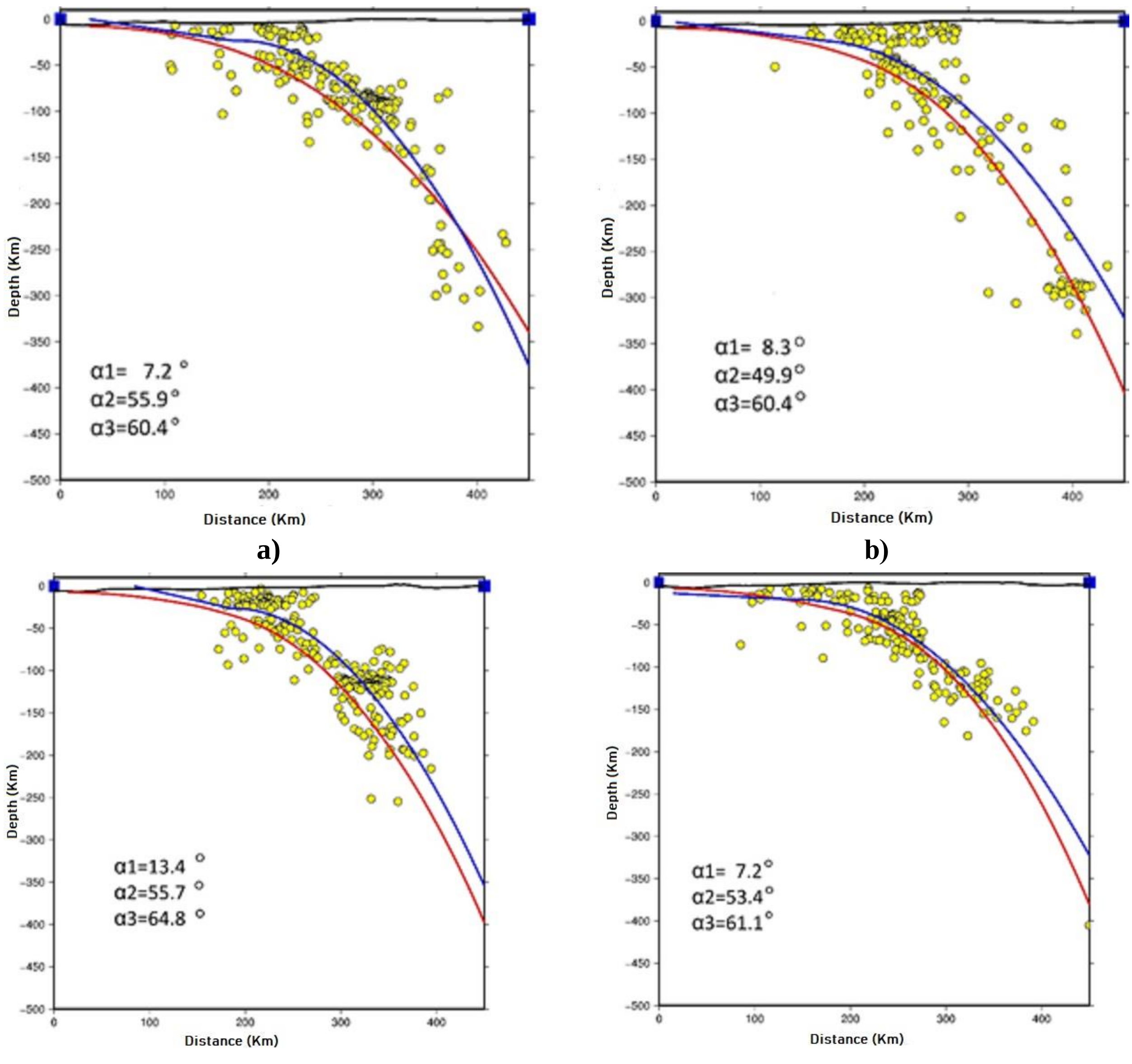


Figure 9. Cross Section of Slice a) A-A', b) B-B', c) C-C', and d) D-D'. Blue lines depict the proposed model in this study and red lines are referred from Hayes' model [17]

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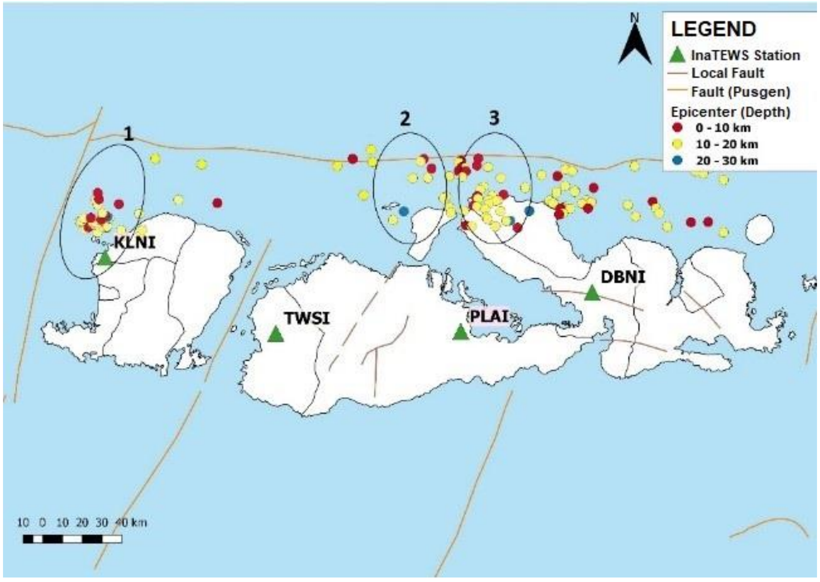
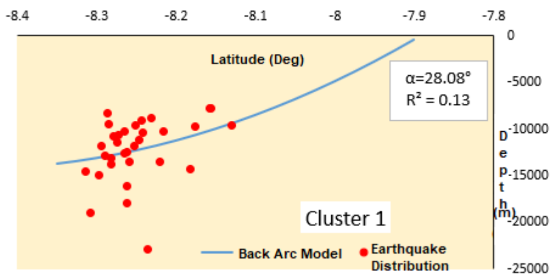
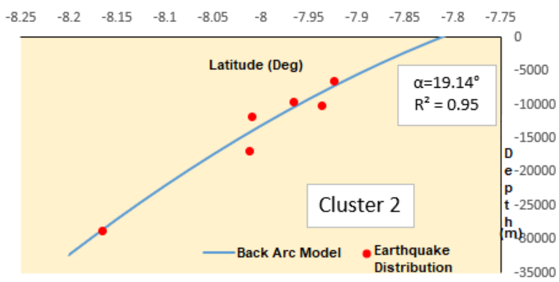
The trend of the back arc thrust show it is getting deeper to the south. Based on the model being proposed, the slope or dip of back arc thrust ranges from 19°-28° with depth 15-30 km. This is corroborated by Widyantoro's research which states that the earthquake in northern Bali to the east has been dominated by shallow earthquakes with the hypo-centrum of less than 50 km [12]. Other research supporting the results of the modeling in this study is the study carried out by Daryono which states that back arc thrust has been dominated by the earthquake with the depths of 16-30 km, 31-45 km, and 0-15 km [14].

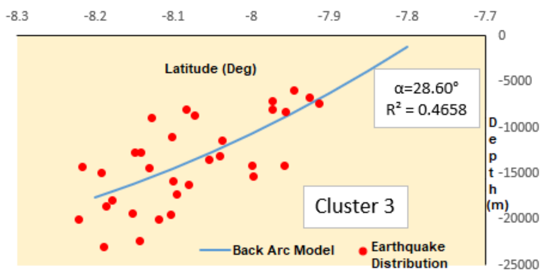


(a)





(b) **(c)**



(d)

Figure 10. (a) Earthquake Data and Clusters for Back Arc Thrust Analysis with cross Section of: (b) Cluster 1; (c) Cluster 2; and (d) Cluster 3

In addition, Daryono also stated that the dip from thrust fault is 20-35 to the south. In addition, the results of the modeling in this study correspond to the calculation of earthquake fault solution on 23 December 1978 in northern part of Flores which had a dip of about 30° [15]. But the weakness of this back arc thrust research is the data that can be used in regression analysis, so the model obtained only describes the occurrence of earthquakes in certain clusters. For that purpose, further study on the source of back arc thrust earthquake needs to be conducted with more data and other supporting methods.

On the other hand, the results in this study can be used as main input for seismic hazard calculation in area. The dip angle, coordinate of fault, and depth of this modeling become the main input in hazard assessment that provides the bases upon which to design maps for building codes and emergency planning [21]. In addition, more recent data were utilized in this modeling which makes this study is more reliable for earthquake source study as the earthquake data for modelling subduction slab and back arc thrust.

IV. CONCLUSION

The distribution of travel-time residual shows an improvement in quality. The relocation results tend to shift to the west and east directions. A relatively well-relocated earthquake represents a local seismic hypocenter from a fault zone or an earthquake from a subduction zone and a back arc thurst. Subduction slab modeling shows low dip values from trench to arc, steep slope from arc to transition zone, and near vertically slope at a depth of 300 km. The model obtained from this study is relatively precise in depicting a 2-dimensional subduction slab. In addition, there is also a seismic gap at a depth of 300-500 km. Back arc thrust in 2-dimensional analysis shows slightly slop model with the depth of less than 30 km. This modeling can be used as the main input for seismic hazard assessment and better understanding of the earthquake sources in West Nusa Tenggara.

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