



Determination of 1-D Seismic Velocity Model in Lombok Island

I Gusti Ketut Satria Bunaga^{1,2}, Mohammad Syamsu Rosid^{1*}, Titi Anggono³, Ardhianto Septiadhi²

¹Physics Department, FMIPA, Universitas Indonesia, Depok, Indonesia.

²Indonesian Agency for Meteorological, Climatological, and Geophysics, Mataram, West Nusa Tenggara, Indonesia.

³Research Center for Geological Disaster, National Research and Innovation Agency (BRIN), Bandung, Indonesia.

Received: October 9, 2023

Revised: November 8, 2023

Accepted: December 25, 2023

Published: December 31, 2023

Corresponding Author:

Mohammad Syamsu Rosid

syamsu.rosid@ui.ac.id

DOI: [10.29303/jppipa.v9i11.6023](https://doi.org/10.29303/jppipa.v9i11.6023)

© 2023 The Authors. This open access article is distributed under a (CC-BY License)



Abstract: The interpretation of local geology structure can be done effectively by using an appropriate local seismic velocity model. It is suitable to implement in Lombok Island that the local fault activity near Mount Rinjani caused the 2019 East Lombok Earthquake. This study determines and updates the 1-D seismic velocity model using the VELEST by applying the Coupled Hypocenter-Velocity method. The 2010-2022 earthquake data from the catalog of BMKG is used for this study. A total of about 166 events ($M \geq 4$) and 20 seismic stations in Lombok and surrounding areas are utilized in this study. The local model (Koulakov) and global (AK-135) are selected as the initial model. The double-difference method is also used to test both velocity models refining the hypocenter location. The results show that the updated Koulakov model has a high relevance in representing the crustal structure of Lombok Island according to the parameters of RMS value, uncertainties hypocenter, and seismic interpretation. It demonstrates not only the local geology condition but also a more reliable seismic velocity model in the region of Lombok Island. This model can be used as a reference for interpreting the better geological structure.

Keywords: Coupled hypocenter-velocity; Double-difference; Earthquake; Lombok

Introduction

By analyzing seismic activity, the structures of active faults can be pinpointed and understood. Ideally, an accurate earthquake location is required, one of which is characterized based on the agreement between the observation and calculation of arrival time at the same seismic station (Lomax et al., 2014). Several factors, such as the network of seismic stations, the number of available phases, the precision of arrival-time readings, and the seismic velocity model, affect the location quality of earthquakes (Gomberg et al., 1990).

An inappropriate determination of the velocity seismic model is crucial, which may result in considerable bias and deviation between observation and calculation in the hypocenter locations, including focal mechanism determination and relocation hypocenter (Michellini & Lomax, 2004; Bormann, 2012). Previous studies presented the global and local seismic velocity model, which were interpreted based on

bathymetric data, active source seismic studies, and inversion (Kissling et al., 1994; Kopp et al., 2009; Laske et al., 2013). There are velocity heterogeneities in the subsurface in each region, so the development of a better seismic velocity model to obtain a more accurate seismic velocity model of the region is needed particularly Lombok Island.

Lombok as an island in the eastern part of the Sunda Arc has complex and dynamic seismotectonics. The subduction of the Indo-Australian plate beneath the Sunda plate, the Flores back-arc thrust, a crustal fault, a volcano, and the appearance of geothermal phenomena are several examples (Bunaga et al., 2022; Irsyam et al., 2017; Puspito & Shimazaki, 1995; Widiyantoro et al., 2011; Zubaidah et al., 2014). The intense tectonic activity in this region causes earthquake activities. Indonesian Meteorological, Climatological, and Geophysical Agency (BMKG) reported that thousands of earthquakes occurred annually from 2018-2022 (BMKG, 2022). The most destructive earthquake occurred in 2018, in which

How to Cite:

Bunaga, I. G. K. S., Rosid, M. S., Anggono, T., & Septiadhi, A. (2023). Determination of 1-D Seismic Velocity Model in Lombok Island. *Jurnal Penelitian Pendidikan IPA*, 9(11), 10663-10670. <https://doi.org/10.29303/jppipa.v9i11.6023>

the significant earthquake sequences (Mw 6.4, Mw 7.0, Mw 5.9, Mw 6.3, and Mw 6.9) damaged 71.962 homes and 460 fatalities (BMKG, 2018; BNPB, 2018).

Previous studies to study seismotectonic in the Lombok region based on hypocenter relocation mostly applied the global seismic velocity model of AK-135 (Bunaga et al., 2015; Taruna & Banyunegoro, 2018; Sasmi et al., 2020; Priyambada et al., 2022). This model is an improvement on the IASP91 model, which is considered one of the best models for a global scale (Hardebeck & Husen, 2010; Havskov & Ottemoller, 2010). However, global-scale models tend to have low resolution. This is intended to provide an overview of large-scale seismotectonic processes, such as subduction zones (Bormann, 2012). In contrast, a local seismic velocity model is required to achieve a more realistic distribution of seismicity with a more detailed representation beneath the surface rather than the global ones (Husen et al., 2011; Muttaqy et al., 2023). In other words, the use of this model can provide information or an understanding of local geological structures. Local seismic velocity models have been successfully applied to several tectonic regions around the world (Husen et al., 1999; Imposa et al., 2009; Muttaqy et al., 2023). This condition is suitable for Lombok Island, which is a complex tectonic region with diverse geological structures (Sarjan et al., 2021; Bunaga et al., 2022). For example, the Mw 5.4 and Mw 5.1 earthquakes occurred in east Lombok Regency on March 17, 2019. The events caused two fatalities and damaged 500 homes, resulting from the local fault activity near Mount Rinjani or Sembalun area (BMKG, 2019; BNPB, 2019). However, the specific characteristics of this local fault are not yet known. Therefore, local velocity models are utilized in this study to obtain accurate hypocenter parameters, allowing for a good interpretation of local geological features. It was also done by Mahesh et al. (2013), Muksin et al. (2014), Sasmi et al. (2020), and Muttaqy et al. (2023) that before determining the precise location of earthquakes and analyzing the seismic distribution patterns, updating the local velocity model is carried out. In this way, earthquake clusters related to crustal structure features can be interpreted.

To have a local model, a seismic velocity model has been determined and improved, which is dependent on the Lombok Island subsurface by using the global model of AK-135 and the local model of Koulakov (Kennett et al., 1995; Koulakov et al., 2009). The Koulakov model was chosen because of the similar characteristics of the research area, which is in a volcanic area, however the study was carried out in the Central Java region (Koulakov et al., 2009).

In this study, both models are evaluated and selected which is more relevant to local conditions of

Lombok Island. Fortunately, starting from 2019, with a dense distribution of BMKG seismic stations, the ability to identify and locate earthquakes in the Lombok region has improved. Under such conditions, it has been used to construct a robust and reliable reference for a local seismic velocity model for Lombok.

Method

A reference seismic velocity model is obtained from the Coupled Velocity-Hypocenter method using the VELEST code (Kissling et al., 1994). VELEST has been applied to local earthquakes from several areas in Central Java, Mamasa, and Bali (Sahara et al., 2021; Rosid, 2022; Muttaqy et al., 2023). This inversion method simultaneously calculates the velocity model, station corrections, and deviations from the initial model. Due to the non-linear of earthquake arrival time and velocity parameters, a first-order Taylor series expansion is used to create a parallel relationship between the travel time residual (t_{res}), adjustments to the hypocentral (Δh_j), and velocity parameters (Δm_k). The relationship is described in the form of a function (f) for the hypocenter parameter (Δh_j) and the velocity model parameter (Δm_k) as on Equation 1. where e is an error in each parameter. The relationship of coupled hypocenter velocity parameters is written as matrix notation as on Equation 2.

$$t_{res} = t_{obs} - t_{cal} = \sum_{j=1}^4 \frac{\partial f}{\partial h_j} \cdot \Delta h_j + \sum_{k=1}^n \frac{\partial f}{\partial m_k} \cdot \Delta m_k + e \quad (1)$$

$$t = H h + M m + e' = A d + e' \quad (2)$$

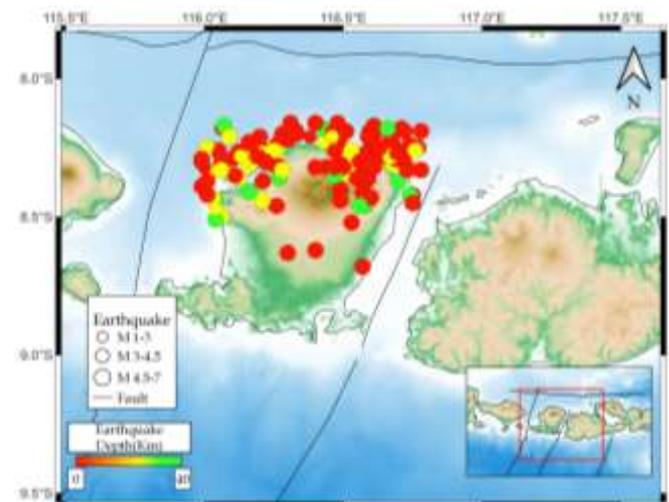


Figure 1. The map of study is the seismicity distribution ($M > 4$) in Lombok and surrounding areas during the time period 2010-2022 (BMKG, 2022). The red line on the inset map denotes the study area. The black lines represent active faults (Irsyam et al., 2017), and the color of earthquakes (circle symbols) denotes the depth of the earthquake as seen in the lower left corner

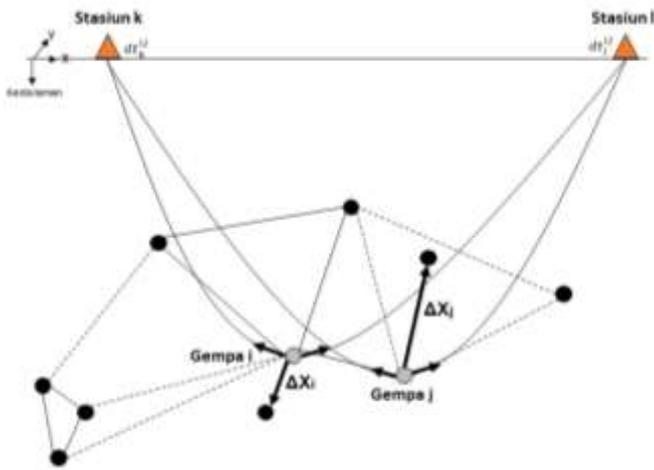


Figure 2. Illustration of double-difference (modified from Waldhauser & Ellsworth, 2000). Grey circles indicate the initial hypocenter (*event i* dan *event j*). Thick black arrows (Δx) illustrate relocation vector of *event i* & *event j* with dt is the travel time difference between *event i* & *event j* at station of *k* and *l*

Where t is a vector of travel time residuals, H and M are matrix of partial derivatives of travel time related to hypocenter and model parameters, respectively. Parameters h and m are a correction matrix (adjustment) of hypocenter and model parameters, respectively. Moreover, e' is a travel time error vector, A is the matrix of partial derivative, and d is a vector of hypocenter and model parameter adjustments. The inversion involves the well-locatable earthquakes (azimuthal gap $\leq 180^\circ$; number of observations ≥ 10). In this study, 166 events ($M \geq 4$) are used that occurred in Lombok and the surrounding area during the period 2010-2022 (BMKG, 2022) (Figure 1). Moreover, the seismic velocity of the Koulakov model and the AK-135 model are chosen as initial reference velocity models.

The double-difference method is applied in HypoDD program (Waldhauser, 2001), which is used to relocate earthquakes using the updated seismic velocity model (Karima et al., 2020; Supendi et al., 2020; Wardani et al., 2021; Priadi et al., 2021). This method is based on the principle that if the hypocenter distance between two earthquakes is shorter than event-station, the ray paths between the source region and a common station are identical (Figure 2).

Arrival time of BMKG catalog is analyzed for the earthquake sequence in March 17 - 18, 2019 or the 2019 East Lombok Earthquake. The catalog consists of arrival time from seismic station observation in Lombok and its surrounding area (BMKG, 2022). A total of 24 events with magnitudes of 2.1 to 5.4 were recorded during this period (Figure 3). All the events have azimuthal gap less than 200° . The steps for updating the 1-D velocity model

and relocating the hypocenter by using the Velest code and hypoDD program can be seen in Figure 4.

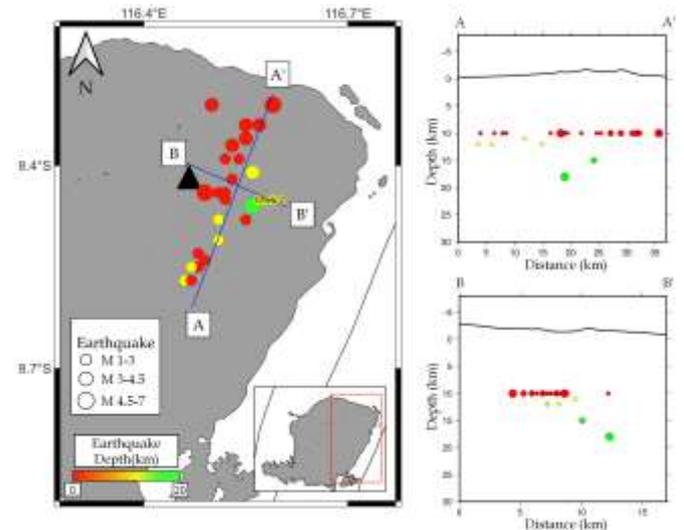


Figure 3. Map of seismic distribution of 2019 east Lombok Earthquake (left panel) with black triangle represents Mount Rinjani. The vertical cross-sections (A-A' and B-B') are shown in the right panel. These distributions are initial hypocenter locations or unrelocated events

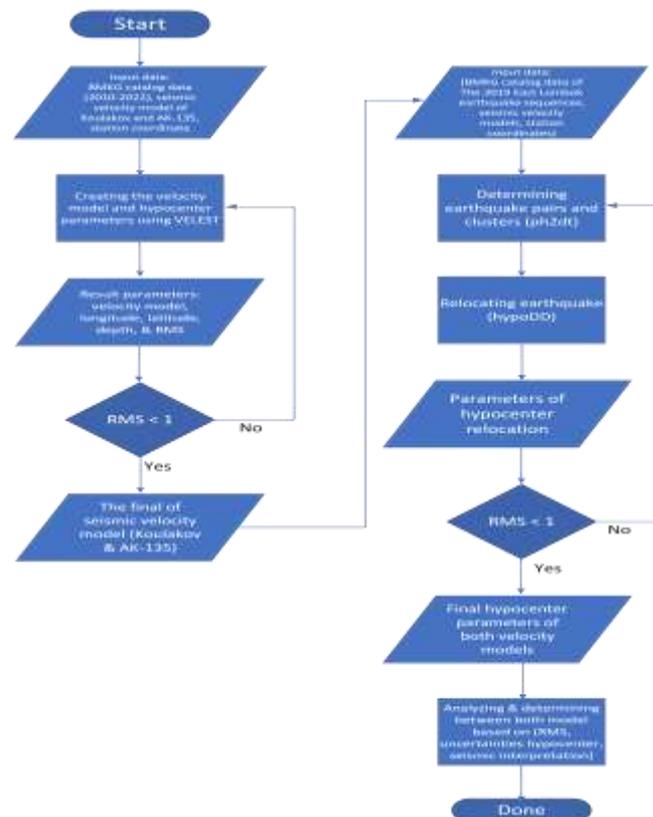


Figure 4. The workflow of this research

Result and Discussion

In the data processing, root mean square (RMS) values from two initial reference velocity models. Based on Grandis (2009), RMS is one of the indicators that demonstrates the similarity between observed and calculated data. In general, travel times residual decrease gradually in each iteration (Figure 5). However, the decline RMS of the Koulakov model is greater than the AK-135 model at 0.62 and 1.16 in the eighth iteration, respectively. In other words, the Koulakov model shows the estimation of earthquake locations that have a higher level of accuracy than another. In detail, the results are displayed in Table 1, Table 2, and Figure 6, which are the comparison between the initial and the updated model.

Table 2 shows a low velocity layer (LVL) in two updated models, including 8-16 km in the Koulakov model and 3.3-10 km in the AK-135 model. According to Ariyanto et al. (2020), the LVL was discovered with depths from 10-20 km, which was controlled by geothermal activities in the north part of Lombok. Therefore, the result obtained from the Koulakov model is closer than the AK-135.

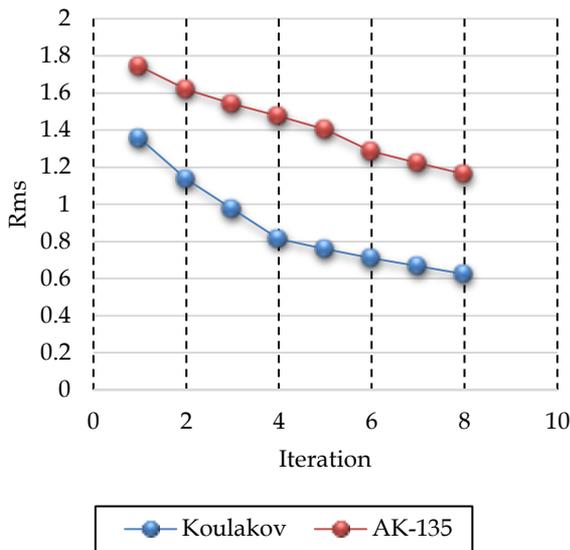


Figure 5. The comparison RMS value between the Koulakov and the AK-135 model according to the VELEST code

Table 1. The Initial Seismic Velocity Model

| Depth (km) | Koulakov Vp (km/s) | Depth (km) | AK-135 Vp (km/s) |
|------------|--------------------|------------|------------------|
| 0 | 4.30 | 0 | 1.45 |
| 3 | 4.90 | 3 | 1.65 |
| 8 | 5.70 | 3.30 | 5.80 |
| 16 | 6.90 | 20 | 6.80 |
| 24 | 7.20 | 28 | 8.03 |
| 77 | 7.80 | 43 | 8.03 |
| 120 | 8.05 | 80 | 8.04 |

Table 2. The updated seismic velocity model.

| Depth (km) | Koulakov Vp (km/s) | Depth (km) | AK-135 Vp (km/s) |
|------------|--------------------|------------|------------------|
| 0 | 4.40 | 0 | 1.50 |
| 3 | 5.20 | 3 | 1.70 |
| 8 | 6.10 | 3.30 | 6.70 |
| 16 | 5.50 | 20 | 6.20 |
| 24 | 7.40 | 28 | 7.50 |
| 77 | 7.80 | 43 | 8.00 |

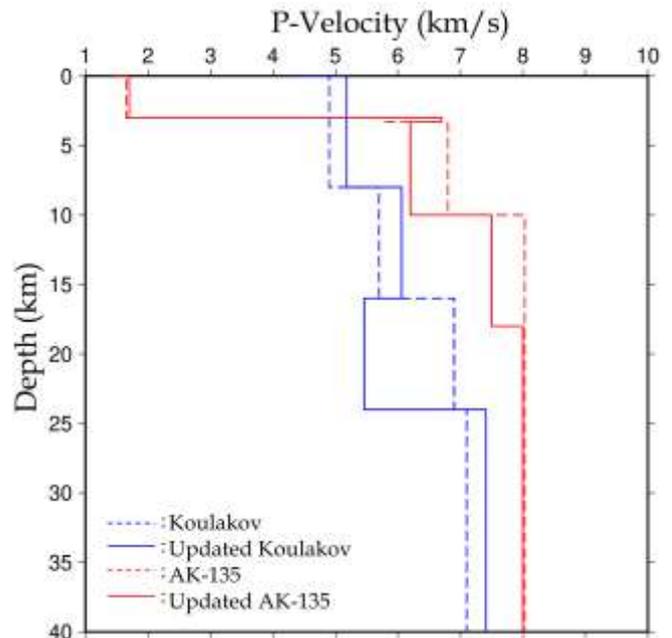


Figure 6. The updated seismic velocity models used in the hypocenter relocation process are shown in bold lines. The dashed lines are references of seismic velocity model taken from Kennett et al. (1995) and Koulakov et al. (2009)

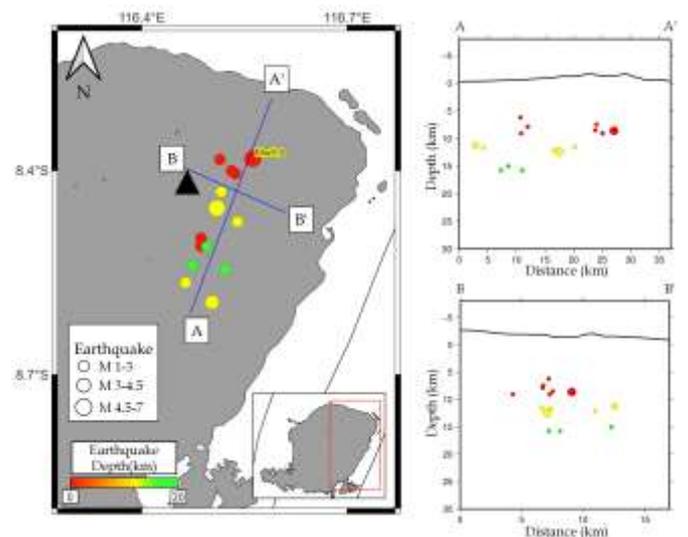


Figure 7. The relocated seismicity of 2019 east Lombok Earthquake using the updated seismic velocity Koulakov model (left panel) with black triangle represent the Mount Rinjani and the vertical cross-sections along A-A' and B-B' directions with the black lines indicated the topography (right panel)

Testing both updated models, the seismic profiles are used for hypocenter relocation process to check their reliability. Figures 7 and 8 depict the map view and vertical profiles after the relocation. The average of the travel time residuals decreases at 0.63 and the average horizontal and vertical mislocations for the Koulakov model are 3.50 km in the east-west, 11.5 km in the north-south, and 4.40 km in the depth directions. However, larger results are obtained for the AK-135 model that have the average residuals of 0.66, including the average horizontal and vertical mislocations with 3.70 km in the east-west, 12.00 km in the north-south, and 4.50 km in the depth directions. The largest error is in the north-south direction because of the azimuthal gap of stations. Such a result can be found in other case, for example, The 2018 Palu earthquake (Suspendi et al., 2019).

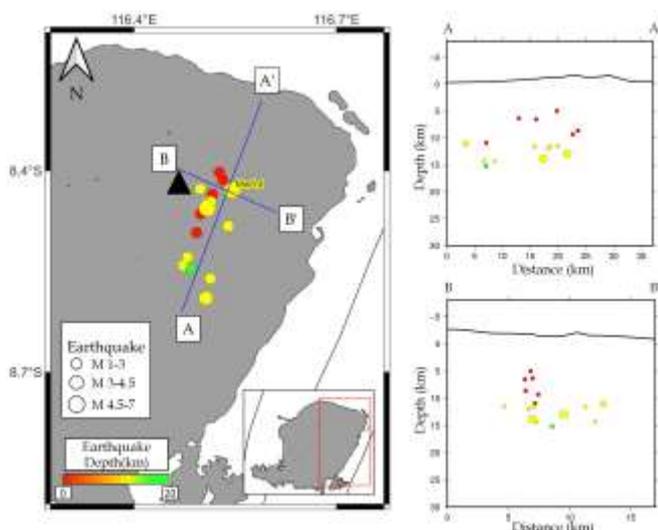


Figure 8. The relocated seismicity of 2019 east Lombok Earthquake using the updated seismic velocity AK-135 model (left panel) with black triangle represent the Mount Rinjani and the vertical cross-sections along A-A' and B-B' directions with the black lines indicated the topography (right panel)

In general, the relocation results of both models (Figure 7 and Figure 8) indicate the similarity of seismicity orientation, which extends from the northeast to the southwest. The biggest change is in depth directions that the events occurred at a fixed depth (10 km) (Figure 3). The similar result was also shown in various cases in Indonesia (Karima et al., 2020; Nugraha et al., 2018; Ramdhan et al., 2021; Syafriani et al., 2023). However, two updated models perform dipping structures with depths ranging from 6.2-15.7 km (the mainshock of Mw 5.4 at 8.6 km) and 5-15.2 km (the mainshock of Mw 5.4 at 13 km) for the Koulakov and the AK-135 model, respectively. Nevertheless, the structure of Koulakov model is more focused and sharper than the AK-135 model making it easier to interpret seismotectonically. These conditions are obtained also

after relocating in other region by Bunaga et al. (2015), Suspendi et al. (2019) Meidji et al. (2023). The mainshock depth determined by the Koulakov model is influenced by the brittle-ductile transition zone's composition in relation to the seismogenic zone in the study area. The earthquake significant occurred above the zone and experienced a high strength effective frictional strength, which requires high friction force to trigger significant magnitude (Scholz, 1988; Behr & Platt, 2014; Lythgoe et al., 2021).

Conclusion

The updated seismic velocity Koulakov model demonstrates the best relevance to represent the crustal structure of Lombok Island according to the parameters of the RMS value (0.62), the uncertainties hypocenter (3.50 km in the east-west, 11.5 km in the north-south, and 4.40 km in the depth directions), and the seismic interpretation. The final model presents a low velocity layer at depth 8-16 km with V_p 6.10 km/s - 5.50 km/s and the seismicity distribution more focused and reveals a dipping fault structure. As a result, the updated model provides a more accurate seismic velocity model of the region beneath Lombok Island than global model of AK-135, and it can be used as a reference seismic velocity model for interpreting the better geology structure.

Acknowledgments

The authors would like to express their profound gratitude to the National Research and Innovation Agency's Degree by Research Program for funding their graduate studies through scholarships. The BMKG is also acknowledged by the authors for providing access to the seismic data catalog that was used in this investigation. Most of the figures are created using the freely available QGIS program, and the elevation data is obtained from <https://tanahair.indonesia.go.id/demnas/#/>. Generic Mapping Tools (GMT) are used to build multiple cross-section maps (Wessel et al., 2013). The publicly available programs are used to compute the following: updating the local velocity, the hypocenter relocation.

Author Contributions

Conceptualization, B.R.A.; methodology, B.R.A.; validation, B.R.A.; formal analysis, B.R.A.; writing — original draft preparation, B; writing — review and editing, R.A; data curation, R.A; supervision, R.A; investigation, S; resources, S. All authors have read and agreed to the published version of the manuscript.

Funding

Research and writing of this article were funded by the first author.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

References

- Ariyanto, P., Ariwibowo, S., Wijaya, A., & Pratama, R. (2020). Crustal Structure Beneath KLNI Station in Lombok Island Based on Teleseismic Receiver Function. *Journal of Physics: Conference Series*, 1491(1), 012055. <https://doi.org/10.1088/1742-6596/1491/1/012055>
- Badan Nasional Penanggulangan Bencana (BNPB) (2019). *Gempa M 5.4 guncang Lombok Timur, 2 orang meninggal dunia dan ratusan rumah rusak*. BNPB. Retrieved from <https://bnpb.go.id/berita/gempa-m-54-guncang-lombok-timur-2-orang-meninggal-dunia-dan-ratusan-rumah-rusak> (last accessed July 2023)
- Badan Nasional Penanggulangan Bencana (BNPB) (2018). *Dampak gempa Lombok: 460 orang meninggal dunia dan kerugian ekonomi 7,45 trilyun rupiah*. Republik Indonesia. Retrieved from <https://bnpb.go.id/berita/dampak-gempa-lombok-460-orang-meninggal-dunia460-dan-kerugian-ekonomi-745-trilyun-rupiah> (last accessed September 2023)
- Badan Meteorologi Klimatologi dan Geofisika (BMKG) (2018). *Earthquake Event*. BMKG.
- Badan Meteorologi Klimatologi dan Geofisika (BMKG) (2022). *Earthquake Event*. BMKG.
- Badan Meteorologi Klimatologi dan Geofisika (BMKG) (2019). *Ulasan Guncangan Tanah Akibat Gempabumi Lombok Timur 2019*. BMKG. Retrieved from <https://www.bmkg.go.id/berita/?p=ulasan-guncangan-tanah-akibat-gempabumi-lombok-timur-17-maret-2019&tag=gempabumi&lang=ID>
- Behr, W. M., & Platt, J. P. (2014). Brittle Faults Are Weak, Yet the Ductile Middle Crust Is Strong: Implications for Lithospheric Mechanics. *Geophysical Research Letters*, 41(22), 8067-8075. <https://doi.org/10.1002/2014GL061349>
- Bormann, P. (2012). *New Manual of Seismological Observatory Practice (NMSOP-2)*. Manual. GeoForschungsZentrum, Potsdam Germany. <https://doi.org/10.2312/GFZ.NMSOP-2>
- Bunaga, I.G.K.S., Purwana, I., And Muzli, M. (2015). Relokasi Parameter Hiposenter Di Wilayah Nusa Tenggara Barat (NTB) Dan Sekitarnya Dengan Menggunakan Metode Double Difference. *Spektra: Jurnal Fisika Dan Aplikasinya*, 16, 6-9. Retrieved from <https://journal.unj.ac.id/unj/index.php/spektra/article/view/5815/4292>
- Bunaga, I. G. K. S., Rosid, M. S., & Anggono, T. (2022). Existence of faults that cause earthquakes on Lombok Island: A critical literature review. *Jurnal Penelitian Pendidikan IPA*, 8(6), 2827-2832. <https://doi.org/10.29303/jppipa.v8i6.2346>
- Gomberg, J. S., Shedlock, K. M., & Roecker, S. W. (1990). The effect of S-wave arrival times on the accuracy of hypocenter estimation. *Bulletin of the Seismological Society of America*, 80(6A), 1605-1628. <https://doi.org/10.1785/BSSA08006A1605>
- Grandis, H. (2009). *Pengantar pemodelan inversi geofisika*. Bandung: CV. Bhumi Printing.
- Hardebeck, J., & Husen, S. (2010). *Earthquake location accuracy*. USA: Community Online Resource for Statistical Seismicity Analysis <https://doi.org/10.5078/CORSSA-55815573>
- Havskov, J., & Ottemoller, L. (2010). *Routine Data Processing in Earthquake Seismology*. Springer Netherlands. <https://doi.org/10.1007/978-90-481-8697-6>
- Husen, S., Kissling, E., & Clinton, J. F. (2011). Local and regional minimum 1D models for earthquake location and data quality assessment in complex tectonic regions: Application to Switzerland. *Swiss Journal of Geosciences*, 104(3), 455-469. <https://doi.org/10.1007/s00015-011-0071-3>
- Husen, S., Kissling, E., Flueh, E., & Asch, G. (1999). Accurate hypocentre determination in the seismogenic zone of the subducting Nazca Plate in northern Chile using a combined on-/offshore network. *Geophysical Journal International*, 138(3), 687-701. <https://doi.org/10.1046/j.1365-246x.1999.00893.x>
- Imposa, S., Fournon, J.-P., Raffaele, R., Scaltrito, A., & Scarfi, L. (2009). Accurate hypocentre locations in the Middle-Durance Fault Zone, South-Eastern France. *Open Geosciences*, 1(4), 416-423. <https://doi.org/10.2478/v10085-009-0030-7>
- Irsyam, M., Widiyantoro, S., Natawidjaja, D. H., Meilano, I., Rudiyanto, A., Hidayati, S., Triyoso, W., Hanifa, N. R., Djarwadi, D., Faizal, L., & Sunarjito. (2017). *Peta sumber dan bahaya gempa Indonesia tahun 2017* (1st ed.). Jakarta: SIMANTU Sistem Manajemen Pengetahuan. Retrieved from <https://simantu.pu.go.id/content/?id=3605>
- Karima, T., Wijaya, S. K., Rosid, M. S., Rohadi, S., & Perdana, Y. H. (2020). Characterization of Lombok Earthquakes on July-August 2018 using focal mechanism analysis. *IOP Conference Series: Materials Science and Engineering*, 854(1). <https://doi.org/10.1088/1757-899X/854/1/012042>
- Kennett, B. L. N., Engdahl, E. R., & Buland, R. (1995). Constraints On Seismic Velocities In The Earth From Traveltimes. *Geophysical Journal International*, 122(1), 108-124. <https://doi.org/10.1111/j.1365-246X.1995.tb03540.x>

- Kissling, E., Ellsworth, W. L., Eberhart-Phillips, D., & Kradolfer, U. (1994). Initial Reference Models In Local Earthquake Tomography. *Journal of Geophysical Research: Solid Earth*, 99(B10), 19635–19646. <https://doi.org/10.1029/93JB03138>
- Kopp, H., Hindle, D., Klaeschen, D., Oncken, O., Reichert, C., & Scholl, D. (2009). Anatomy of the western Java plate interface from depth-migrated seismic images. *Earth and Planetary Science Letters*, 288(3–4), 399–407. <https://doi.org/10.1016/j.epsl.2009.09.043>
- Koulakov, I., Jakovlev, A., & Luehr, B. G. (2009). Anisotropic structure beneath central Java from local earthquake tomography. *Geochemistry, Geophysics, Geosystems*, 10(2), 2008GC002109. <https://doi.org/10.1029/2008GC002109>
- Laske, G., Masters, G., Ma, Z., & Pasyanos, M. (2013). Update on CRUST1.0 – A 1-degree global model of Earth's crust. *Geophysical Research Abstracts*, 15, EGU2013-2658. Retrieved from <https://ui.adsabs.harvard.edu/abs/2013EGUGA.15.2658L/abstract>
- Lomax, A., Michelini, A., & Curtis, A. (2014). Earthquake Location, Direct, Global-Search Methods. In *Encyclopedia of Complexity and Systems Science*, 1–33. https://doi.org/10.1007/978-3-642-27737-5_150-2
- Lythgoe, K., Muzli, M., Bradley, K., Wang, T., Nugraha, A. D., Zulfakriza, Z., Widiyantoro, S., & Wei, S. (2021). Thermal squeezing of the seismogenic zone controlled rupture of the volcano-rooted Flores Thrust. *Science Advances*, 7(5), eabe2348. <https://doi.org/10.1126/sciadv.abe2348>
- Mahesh, P., Rai, S. S., Sivaram, K., Paul, A., Gupta, S., Sarma, R., & Gaur, V. K. (2013). One-dimensional reference velocity model and precise locations of earthquake hypocenters in the Kumaon–Garhwal Himalaya. *Bulletin of the Seismological Society of America*, 103(1), 328–339. <https://doi.org/10.1785/0120110328>
- Meidji, I. U., Jatnika, J., Samatowa, L., Ramadani, A. I. W. S., Ramdhan, M., Efendi, H. A., & Jayadi, H. (2023). Analyzing seismicity pattern of the Gorontalo Region and its surroundings in the form of hypocenter relocation using double difference method. *Jurnal Penelitian Pendidikan IPA*, 9(10), 8581–8587. <https://doi.org/10.29303/jppipa.v9i10.5400>
- Michelini, A., & Lomax, A. (2004). The Effect Of Velocity Structure Errors On Double - Difference Earthquake Location. *Geophysical Research Letters*, 31(9), 2004GL019682. <https://doi.org/10.1029/2004GL019682>
- Muksin, U., Haberland, C., Nukman, M., Bauer, K., & Weber, M. (2014). Detailed Fault Structure Of The Tarutung Pull-Apart Basin In Sumatra, Indonesia, Derived From Local Earthquake data. *Journal of Asian Earth Sciences*, 96, 123–131. <https://doi.org/10.1016/j.jseaes.2014.09.009>
- Muttagy, F., Nugraha, A. D., Puspito, N. T., Sahara, D. P., Zulfakriza, Z., Rohadi, S., & Supendi, P. (2023). Double-Difference Earthquake Relocation Using Waveform Cross-Correlation In Central And East Java, Indonesia. *Geoscience Letters*, 10(1), 5. <https://doi.org/10.1186/s40562-022-00259-2>
- Nugraha, A. D., Supendi, P., Widiyantoro, S., Daryono, & Wiyono, S. (2018). Hypocenter Relocation Of Earthquake Swarm Around Jailolo Volcano, North Molucca, Indonesia Using The BMKG Network Data: Time Periods Of September 27-October. *AIP Conference Proceeding*, 10, 2017. 020093. <https://doi.org/10.1063/1.5047378>
- Priadi, R., Perdana, Y. H., Wijaya, A., & Suardi, I. (2021). Analisis Gempabumi Lombok 2018 berdasarkan mekanisme sumber, distribusi slip, asperity, dan perubahan nilai (Coulomb Stress) pada Bidang Sesar. *Jurnal Geofisika*, 19(01), 1–9. <http://dx.doi.org/10.36435/jgf.v19i1.430>
- Priyambada, F. R., Nugraha, A. D., & Supendi, P. (2022). Hypocenter determination using a non-linear Method in Bali, Lombok, and Nusa Tenggara Regions: Preliminary Result. *Journal of Physics: Conference Series*, 2243(1), 012008. <https://doi.org/10.1088/1742-6596/2243/1/012008>
- Puspito, N. T., & Shimazaki, K. (1995). Mantle Structure And Seismotectonics Of The Sunda And Banda arcs. *Tectonophysics*, 251(1–4), 215–228. [https://doi.org/10.1016/0040-1951\(95\)00063-1](https://doi.org/10.1016/0040-1951(95)00063-1)
- Ramdhan, M., Priyobudi, Mursityanto, A., Palgunadi, K. H., & Daryono. (2021). Analysis Of M 5.3 Sumbawa, Indonesia Earthquake 2020 And Its Aftershocks Based On Hypocenter Relocation From BMKG Seismic Stations. *IOP Conference Series: Earth and Environmental Science*, 873(1), 012070. <https://doi.org/10.1088/1755-1315/873/1/012070>
- Rosid, M. S. (2022). Characterization Of The Mamasa Earthquake Source Based On Hypocenter Relocation And Gravity Derivative Data Analysis. *International Journal of GEOMATE*, 23(97). <https://doi.org/10.21660/2022.97.j2375>
- Sahara, D. P., Rahsetyo, P. P., Nugraha, A. D., Syahbana, D. K., Widiyantoro, S., Zulfakriza, Z., Ardianto, A., Baskara, A. W., Rosalia, S., Martanto, M., & Afif, H. (2021). Use Of Local Seismic Network In Analysis Of Volcano-Tectonic (VT) Events Preceding The 2017 Agung Volcano Eruption (Bali, Indonesia).

- Frontiers in Earth Science*, 9, 619801. <https://doi.org/10.3389/feart.2021.619801>
- Sarjan, A. F. N., Zulfakriza, Z., Nugraha, A. D., Rosalia, S., Wei, S., Widiyantoro, S., Cummins, P. R., Muzli, M., Sahara, D. P., Puspito, N. T., Priyono, A., & Afif, H. (2021). Delineation Of Upper Crustal Structure Beneath The Island Of Lombok, Indonesia, Using Ambient Seismic Noise Tomography. *Frontiers In Earth Science*, 9, 560428. <https://doi.org/10.3389/feart.2021.560428>
- Sasmi, A. T., Nugraha, A. D., Muzli, M., Widiyantoro, S., Zulfakriza, Z., Wei, S., Sahara, D. P., Riyanto, A., Puspito, N. T., Priyono, A., Greenfield, T., Afif, H., Supendi, P., Daryono, D., Ardianto, A., Syahbana, D. K., Husni, Y. M., Prabowo, B. S., & Narotama Sarjan, A. F. (2020). Hypocenter and Magnitude Analysis Of Aftershocks Of The 2018 Lombok, Indonesia, Earthquakes Using Local Seismographic Networks. *Seismological Research Letters*, 91(4), 2152-2162. <https://doi.org/10.1785/0220190348>
- Scholz, C. H. (1988). The brittle-plastic transition and the depth of seismic faulting. *Geologische Rundschau*, 77(1), 319-328. <https://doi.org/10.1007/BF01848693>
- Supendi, P., Nugraha, A. D., Widiyantoro, S., Abdullah, C. I., Puspito, N. T., Palgunadi, K. H., Daryono, D., & Wiyono, S. H. (2019). Hypocenter Relocation Of The Aftershocks Of The Mw 7.5 Palu Earthquake (September 28, 2018) And Swarm Earthquakes Of Mamasa, Sulawesi, Indonesia, Using The BMKG Network Data. *Geoscience Letters*, 6(1), 18. <https://doi.org/10.1186/s40562-019-0148-9>
- Supendi, P., Nugraha, A. D., Widiyantoro, S., Pesicek, J. D., Thurber, C. H., Abdullah, C. I., Daryono, D., Wiyono, S. H., Shiddiqi, H. A., & Rosalia, S. (2020). Relocated Aftershocks And Background Seismicity In Eastern Indonesia Shed Light On The 2018 Lombok And Palu Earthquake Sequences. *Geophysical Journal International*, 221(3), 1845-1855. <https://doi.org/10.1093/gji/ggaa118>
- Syafriani, Raharjo, F. D., Ahadi, S., & Ramdhan, M. (2023). Study of seismicity Based On The Results Of Hypocenter Relocation Using Double Difference (Hypoddd) Method In West Sumatera And Its Surrounding. *Jurnal Penelitian Pendidikan IPA*, 9(7), 5150-5156. <https://doi.org/10.29303/jppipa.v9i7.3792>
- Taruna, R. M., & Banyunegoro, V. H. (2018). Earthquake Relocation using double difference method for 2D modelling of subducting slab and back arc thrust in West Nusa Tenggara. *Jurnal Penelitian Fisika Dan Aplikasinya (JPFA)*, 8(2), 132. <https://doi.org/10.26740/jpfa.v8n2.p132-143>
- Waldhauser, F. (2000). A Double-Difference Earthquake Location Algorithm: Method And Application To The Northern Hayward Fault, California. *Bulletin of the Seismological Society of America*, 90(6), 1353-1368. <https://doi.org/10.1785/0120000006>
- Waldhauser, F. (2001). *hypoDD-A Program to Compute Double-Difference Hypocenter Locations*. US: US Geological Survey
- Wardani, N. N. S. K., Suarbawa, K. N., & Kusnandar, R. (2021). Penentuan Jenis Sesar Pada Gempabumi Lombok Tanggal 1 Juli Sampai 31 Desember 2018 Menggunakan Metode Mekanisme Fokus. *Buletin Fisika*, 22(2), 91-96. Retrieved from <https://ojs.unud.ac.id/index.php/buletinfisika/article/download/67562/38156>
- Wessel, P., Smith, W. H. F., Scharroo, R., Luis, J., & Wobbe, F. (2013). Generic Mapping Tools: Improved Version Released. *Eos, Transactions American Geophysical Union*, 94(45), 409-410. <https://doi.org/10.1002/2013EO450001>
- Widiyantoro, S., Pesicek, J. D., & Thurber, C. H. (2011). Subducting Slab Structure Below The Eastern Sunda Arc Inferred From Non-Linear Seismic Tomographic Imaging. *Geological Society, London, Special Publications*, 355(1), 139-155. <https://doi.org/10.1144/SP355.7>
- Zubaidah, T., Korte, M., Mande, M., & Hamoudi, M. (2014). New insights into regional tectonics of the Sunda-Banda Arcs region from integrated magnetic and gravity modelling. *Journal of Asian Earth Sciences*, 80, 172-184. <https://doi.org/10.1016/j.jseaes.2013.11.013>