JOURNAL OF APPLIED GEOSPATIAL INFORMATION

Vol 7 No 1 2023

http://jurnal.polibatam.ac.id/index.php/JAGI
ISSN Online: 2579-3608

1-Dimensional Model of Seismic Velocity after Tarutung Earthquake 1 October 2022 Mw 5.8

Resa Idha [1,2], Endah P. Sari [1,2], Yusran Asnawi [3], Andrean V. H. Simanjuntak [2,4], Syahrul Humaidi [1*], Umar Muksin [4]

[1] Post Graduate Program (Physics), FMIPA, Universitas Sumatera Utara, Medan, Sumatra Utara, Indonesia
[2] Agency of Meteorological Climatology and Geophysical for Indonesia, Medan, Sumatra Utara, Indonesia
[3] Department of Information Technology, Universitas Islam Ar-Raniry, Banda Aceh, Aceh
[4] Tsunami Disaster Mitigation Research Centre (TDMRC), Universitas Syiah Kuala, Banda Aceh, Aceh
*Corresponding author's email: syahrul1@usu.ac.id

Received: February 04, 2023
Accepted: June 27, 2023
Published: June 27, 2023

Abstract

On October 1, 2022, an earthquake with a magnitude (M) of 5.8 occurred in the Tarutung region, Indonesia and was associated with an active fault at a depth of 10 km. The earthquake fault with dextral mechanism is suitable with the pattern of active fault movement in Sumatra in the Northeast - Southwest direction. A total of 170 aftershocks occurred within a week span with magnitude variations of 1.7 – 4.0. In addition, the Tarutung earthquake was felt by the local peoples with an intensity of IV - VI MMI and caused 1 fatality, 25 injuries, and around 900 houses were damaged. Therefore, this study studies the characteristics of seismicity and damage caused by finding an appropriate 1-Dimensional seismic velocity model. The obtained 1-Dimensional speed model has varying values at a depth of 10 km with a speed of ~5.5 km/s and 30 km with a speed of ~7 km/s. The 1-D velocity model obtained has a convergent and unique solution with an RMS value < 1.0. Based on ground motion analysis after relocation, it was found that the high PGA and PGV values were in Tarutung. The PGA results reveal a high percentage value of >10% in Tarutung. This is consistent with the damage data and at the same time confirms that Tarutung is in a seismically active area.

Keywords: Earthquake, Seismic, PGA, PGV, Seismic Velocity, Hypocenter

1. Introduction

On October 1, 2022, a major earthquake with magnitude of M 6.0 occurred in the Tarutung region, Indonesia, which was caused by active fault activity at a shallow depth of 10 km. The solution to the fault mechanism released by the Global Centroid Moment Tensor (GCMT) shows that rupture occurs along the fault moving to the right in the Northeast - Southwest (NE - SW) direction. The Meteorology, Climatology and Geophysics Agency (BMKG) released the epicenter located at coordinates 2.11° N and 98.91° E with a depth of 10 km and is about 15 km to the northwest of the Tarutung area. Tectonically. This earthquake was caused by the activity of the Renun fault which is one of the active fault segments of Sumatra. BMKG recorded 170 aftershocks with variations in magnitude from 1.7 to 4.0 and hypocenter depths in the range of 1 to 10 km.

In addition, the M5.8 Tarutung earthquake was felt by local peoples in the Tarutung and Sipoholon areas with an intensity of VI MMI, Sipahutar V MMI, Singkil IV MMI and Gunung Sitoli III MMI. The National Disaster Management Agency of Indonesia (BNPB) reported the effects of the Tarutung earthquake damage with 1 fatality, 25 injuries, and around 900 houses and buildings were damaged in Tarutung. The Tarutung area is classified as a location prone to earthquakes because of its position near active fault sources, namely the active Renun and Toru faults which move at a shear rate of ~2cm/year in the right direction (Sieh and Natawidjaja, 2000, McCaffrey, 2009)]. Historically, this area has experienced several major earthquakes in 1984, 1987 and 2011 with magnitudes 5 – 6 (Bradley et al., 2017, Pasari et al., 2021, Nurana et al., 2022).

Several studies have been published such as, Koulakov et al. (2009) conducted a tomographic study around the Toba region with seismic wave travel times, Sakaguchi et al. (2006) analyzed the Toba shallow structure by ambient noise tomography and Muksin et al. (2013) formed a seismic tomographic model for the Tarutung pull-apart area. However, no studies have conducted research regarding the 2022 Tarutung earthquake and its implications for seismic hazards. Therefore, this study analyzes the location of the earthquake epicenter by determining the appropriate velocity model so that the location of the hypocenter is more accurate. The accuracy of earthquake parameters is useful for earthquake mitigation efforts and for knowing potential seismic hazards in this region. Determining the location of an earthquake has factors that affect the accuracy of the results obtained, namely determining the arrival time of seismic waves and one-dimensional wave velocity models that are appropriate to local conditions.

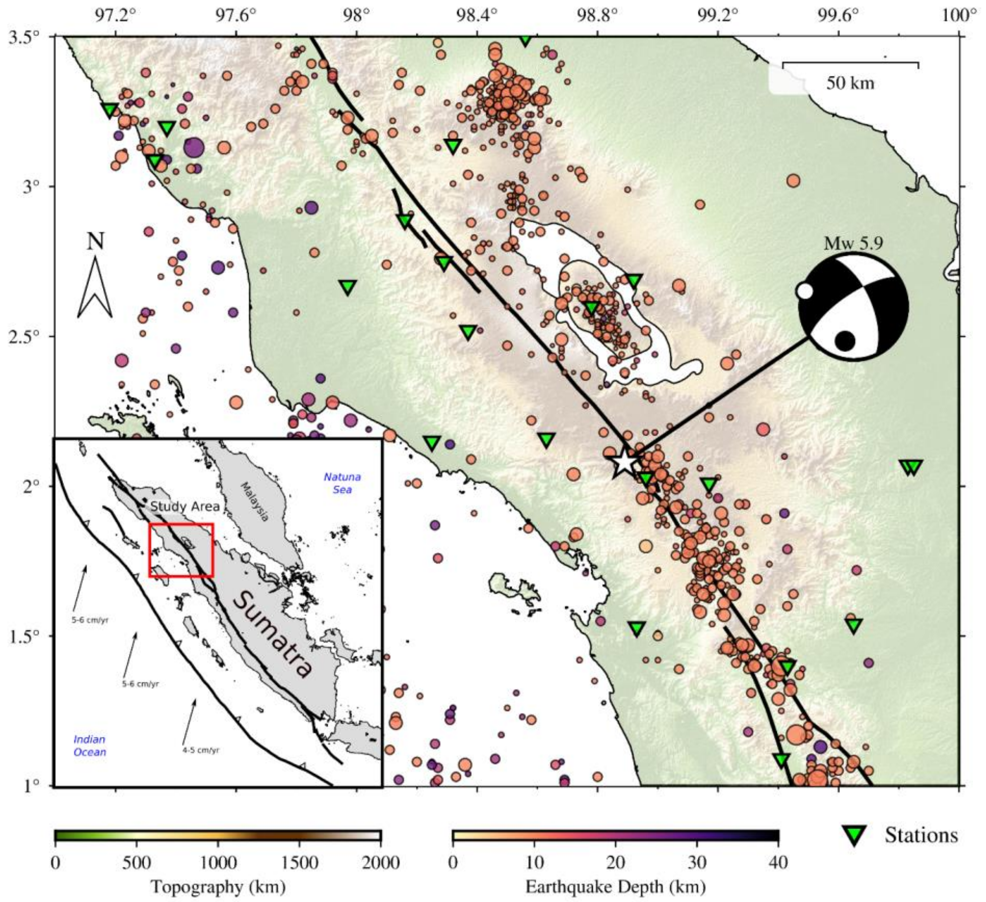

Fig. 1. Seismic map of North Sumatra Province five-year catalog (2017 – 2022) with the Tarutung 2022 Mw 5.8 earthquake (white star with dextral focus mechanism). The black line is the active Sumatran fault while the green triangle is the seismic station of the BMKG network.

2. Section headings

2.1 Geiger Method

Determination of the earthquake location uses the Geiger method based on a linearization approach. The hypocenter parameters and origin time of observation (x_0, y_0, z_0, t_0) is compared with the calculation model and will produce residual travel time. The residual travel time is a correction to get a better hypocenter. These corrections are needed to minimize errors *(Δx, Δy, Δz,* dan *Δt)* which can be calculated by theTaylor series as in equation (1)

$$r = \frac{\partial t_i^{tra}}{\partial x_i}\Delta x + \frac{\partial t_i^{tra}}{\partial y_i}\Delta y + \frac{\partial t_i^{tra}}{\partial z_i}\Delta z + \Delta t \qquad (1)$$

Then, equation (1) can be written in the inversion as in equation (2) and matrix as in equation (3)

$$\mathbf{d} = \mathbf{Gm} \qquad (2)$$

$$\begin{bmatrix} d_1 \\ d_{..} \\ d_n \end{bmatrix} = \begin{bmatrix} \frac{\partial t_i^{tra}}{\partial x_0} & \frac{\partial t_i^{tra}}{\partial y_0} & \frac{\partial t_i^{tra}}{\partial z_0} & 1 \\ \cdots & \cdots & \cdots & 1 \\ \frac{\partial t_i^{tra}}{\partial x_n} & \frac{\partial t_i^{tra}}{\partial y_n} & \frac{\partial t_i^{tra}}{\partial z_n} & 1 \end{bmatrix} \cdot \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \\ \Delta t \end{bmatrix} \qquad (3)$$

Where, *r* is the residual vector, *G* is the partial derivative matrix, and *x* is the correction vector for earthquake location and origin time. The hypocenter and origin time will be corrected simultaneously as *x+Δx, y+Δy, z+ Δz,* and $t_0+\Delta t$. Then, the solution is used in the next iteration stage. The iteration process continues until a predetermined limit or produces a minimum residual (Havskov and Ottemöller, 1999).

2.2 Coupled Hipocenter-Velocity

The method for determining the velocity model as well as relocating the position of the earthquake and correcting the quality of the seismic station uses the Coupled Hypocenter-Velocity method (Kissling, 2002). This method processes simultaneously using a non-linear inversion modeling algorithm with a linear approach as shown in equation (4). In equation (4), t_{obs} is the arrival time of the earthquake at each earthquake sensor, *s* is the origin time, *h* is the hypocenter coordinate that has been obtained, and *m* is the velocity model used.

$$t_{obs} = f\,(s, h, m) \qquad (4)$$

f is a non-linear function of parametersh and m which are not known beforehand. By applying the wave propagation theory using the initial velocity model, the theoretical wave arrival time t_{cal} for each pair of stations can be calculated by equation (5),

$$t_{cal} = f(h_j, m_k) \quad (5)$$

h_j is the theoretical origin time and m_k is the velocity model given. In other hand, t_{cal} needs to be compared with t_{obs} to derive the residual time t_{res} with taylor ekspantion as shown in the proof (6):

$$t_{res} = t_{obs} - t_{cal}$$

$$t_{res} = \sum_{j=1}^{4} \frac{\partial f}{\partial h_j} \Delta h_j + \sum_{k=1}^{n} \frac{\partial f}{\partial m_k} \Delta m_k + e \quad (6)$$

j = total earthquakes;
k = total seismic stations;
Δm_k = parameter model;
Δh_j = parameter hypocenter;

In equation (6), e is the error, this is what is used to be a value in determining the station correction. Several studies have used Velest to determine a 1-Dimensional seismic velocity model, such as Simanjuntak et al. (2022) conducting relocation studies in the Southeast Aceh region and Muksin et al. (2023) conducting an analysis of local tectonic structures in the East Aceh region.

3. Results and Discussion

3.1 Coupled Hipocenter-Velocity

One of the important parameters in determining the accuracy of the hypocenter location of an earthquake is the availability of seismic wave velocity models on a local or regional scale with a high degree of precision. Further analysis is needed to understand it, one of which is hypocenter relocation for. Hypocenter relocation is used to recalculate hypocenter position errors and regain a more accurate position with an appropriate velocity model.

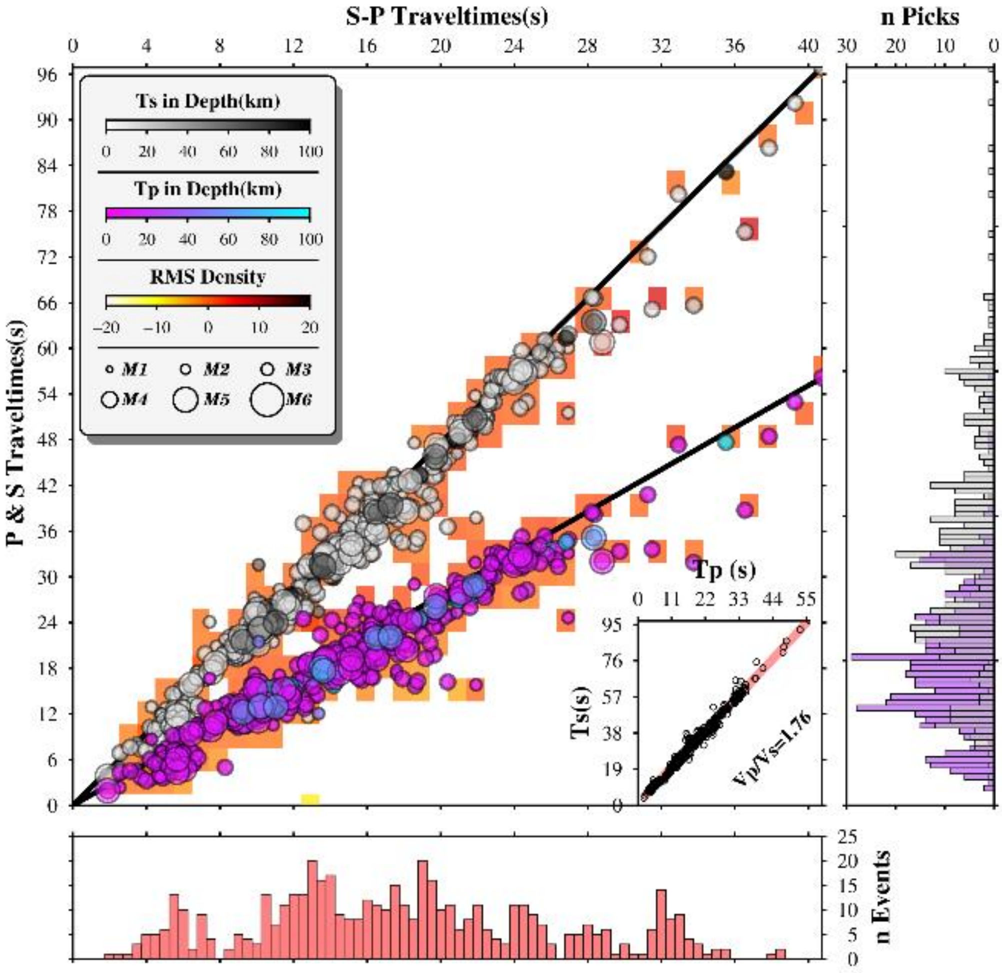

Fig. 2. The relationship between S-P traveltime and the arrival time of the P and S phases is related to the RMS, depth and number of earthquakes and phases and the value of Vp/Vs ~1.76. The difference between the P and S phases is 40 seconds, while the P and S arrival times are 0 – 96 seconds. The accuracy of determining the P and S phases is -5 and 5 seconds.

In this study, the analysis was carried out on 170 earthquake events with magnitudes M 2.0 – 5.8. All events analyzed had 1011 P-phases and 641 S-phases recorded by 24 stations at a ratio V_p/V_s ~1,73 as shown in Fig. 2. The hypocenters of the BMKG catalog still form a lot of solutions that are fixed and trapped at depths of 10 and 33 km. To improve the accuracy of the hypocenter location, it is necessary to find a suitable 1-D model. In this study, 30 a priori models were given to obtain convergent results (RMS < 1.0) with 50 iterations being carried out simultaneously. The convergent model is the most suitable model for the results of initial and final relocation of the hypocenter and for determining the mechanism of the earthquake source as shown in Figure 3. In Figure 3, the results of the model were chosen because it has more data and represents the entire Tarutung area. The velocity models obtained are the velocity of body waves, P waves and S waves as well as the ratio between P and S waves. The RMS value of each model in Figure 3 will decrease with each iteration, because it is through a least-square simultaneous inversion process.

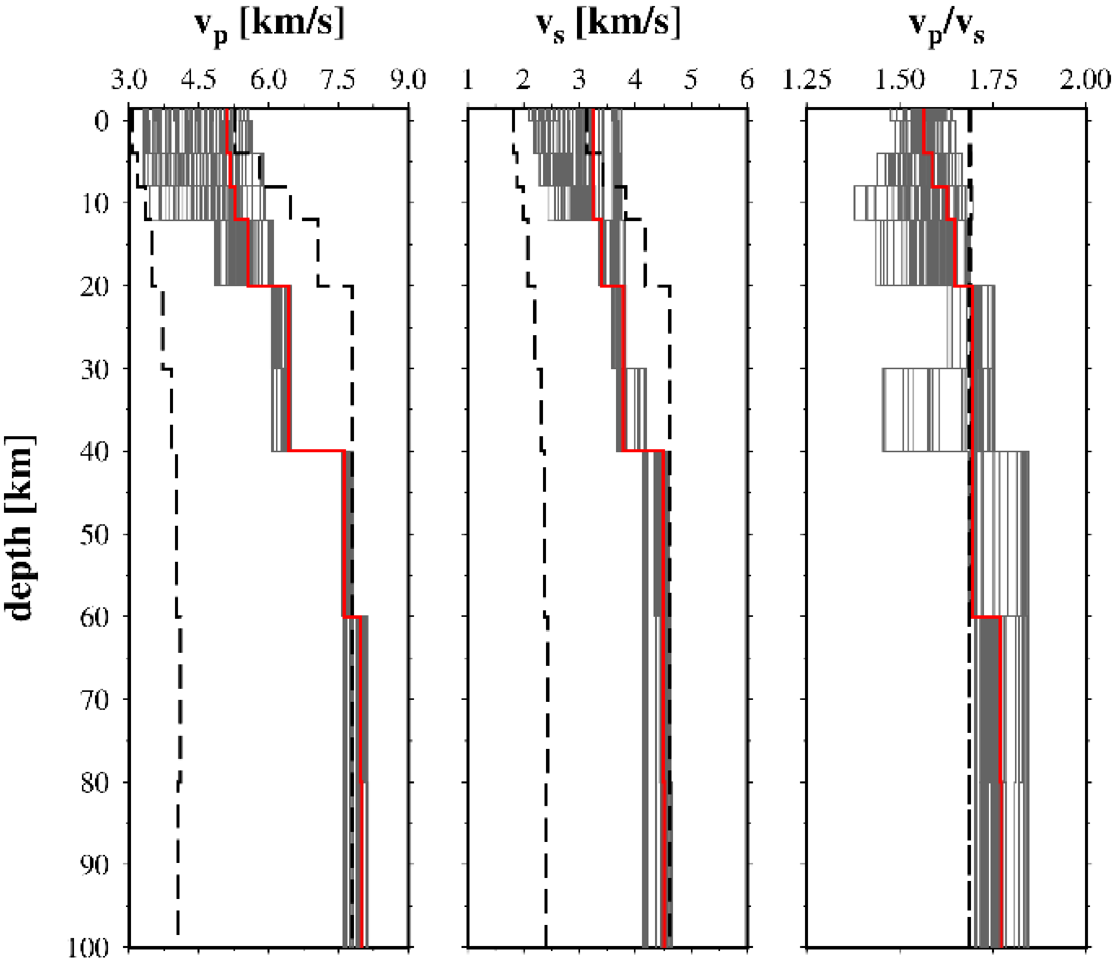

Fig. 3. Final velocity model result (red line) was calculated by simultaneously inversion. Left panel is for P-wave velocity, center panel is S-wave velocity and right panel is for ratio of Vp/Vs.

The RMS value is different because the initial information provided is a priori so it can have low and high values, the optimal RMS is generally < 1.0 s. For relocation with regional stations, the RMS value < 1.0 s is very good, because the stations are far apart. The value of the seismic wave velocity will be greater and directly proportional to depth, because the material that is passed is getting solid and the position of the hypocenter is clearer, as shown in Figure 4. To obtain an appropriate 1-dimensional model, all hypocenters must be selected according to predetermined parameter criteria determined in the inversion process. In this study, the criteria chosen in determining the best model was to have an RMS < 1.0 s while an RMS ≥ 1.0 for 11 earthquakes and for the 1-D model it was obtained with RMS = 0.9 s.

The model with data before relocation has a greater number of hypocenters with better rms than data that has not been relocated. These results have more reliable changes because they are obtained with more data and represent almost all areas. In addition, the change in Vp/Vs after relocation is around 1.73 with a very good correlation between Tp and Ts. The Vp/Vs values using after relocation have minimum misfit values, optimum correlations with small deviations and small distribution of Tp and Ts outliers.

3.1 Ground Motion Model

To find out the scale of the damage caused by the Tarutung earthquake, a ground shaking recalculation was again carried out by taking into account the damage reports obtained from the field survey. From the calculation results, the PGA (Peak Ground Acceleration) and PGV (Peak Ground Velocity) models correspond to the intensity of the earthquake felt by local people in Tarutung with a PGA value of 0 – 15% gal and a PGV with a value of 0 – 8 cm/s^2. The calculation results are consistent with the empirical relationship proposed by Worden et al. (2012). Worden et al. (2012) showed a PGV range of 6 – 9 cm/s can be associated with MMI 6 damage intensity for earthquakes from faults.

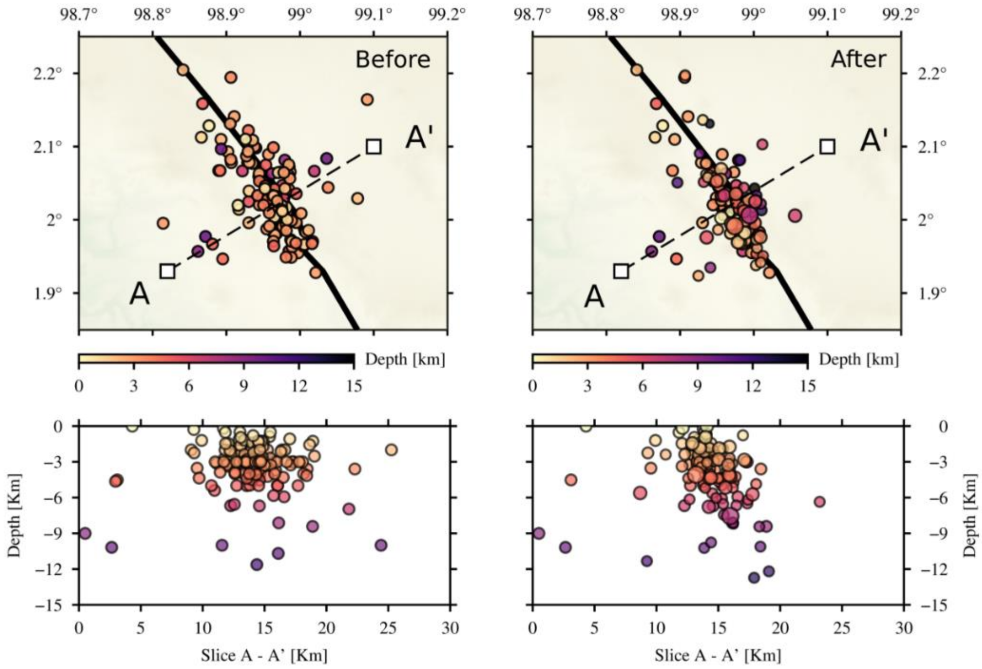

Fig. 4. Relocation of the Tarutung earthquake using Velest. The left is the hypocenter which has not yet been relocated. The right side is the hypocenter which has been relocated properly and produces a 1-Dimensional velocity model that fits the geological and tectonic conditions in the Tarutung area.

In addition, the results obtained are also consistent with a PGA of 10% gal ~110 cm/s^2 as the proposed limit for MMI ~6 [15]. It is noted that the PGA range of 5 – 10 cm/s2 is used globally as a threshold for damaging earthquakes. In general, PGV parameters may have less applicability than globally used parameters such as PGA and PSA. PGV can be included as a ground motion parameter because it is related to the seismic kinetic energy that affects the building structure.

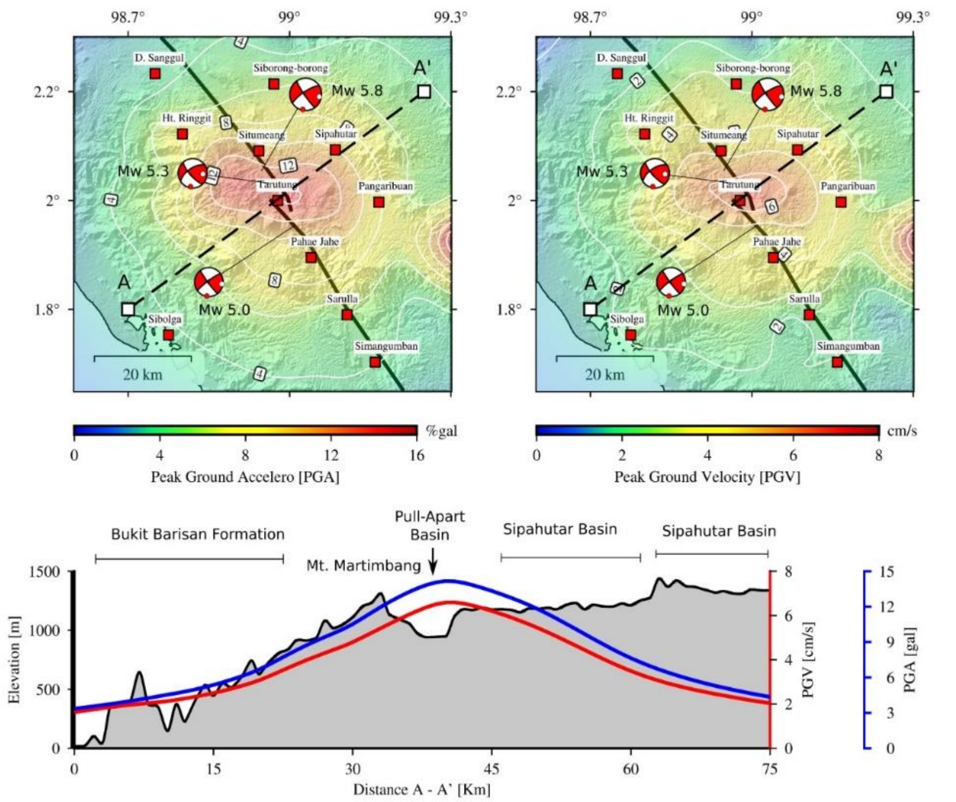

Fig. 5. (a) The spatial distribution of the PGA and PGV of the Tarutung earthquake ranged from 0 – 8 cm/s. (b) Spatial map of PGA ranges from 0% – 15% gal which shows the highest value in the Tarutung area > 10% and corresponds to the damage while PGV 0 – 8 cm/s2 shows the highest value in the Tarutung area with a value of > 6 cm/s2. (c) The profiles of the A – A' slices show massive shaking in the Tarutung area with quite high PGA and PGV values.

Some examples of using PGV include estimating structural strength and damage, evaluating the possibility of liquefaction, and making seismic hazard designs. On the other hand, Atkinson (2020) compared induced and natural earthquakes and showed that PGV has the potential to affect structural damage in the frequency range of 0.5 - 7 Hz, while PGA has a frequency > 5 Hz. PGA generally correlates with the effect felt at low earthquake intensities while PGV at high earthquake intensities. Thus, PGA and PGV are considered as the most effective parameters for measuring building quality.

3.1 Recommendations for the Future Mitigation

Based on research that was conducted on the Tarutung earthquake on October 1, 2022, the following recommendations were obtained:

1. A more detailed earthquake hazard study is needed to increase the preparedness of local governments and communities in dealing with earthquake disasters.
2. A contingency plan for dealing with earthquake disasters is needed at the local BPBD.
3. Evaluate the spatial layout of the Tarutung area by taking into account tectonic conditions and as much as possible avoiding development in soft soil areas.
4. Implementing an appropriate monitoring system in carrying out the construction of buildings, especially vital buildings such as hospitals, government offices, to housing for Tarutung residents.
5. Improving the implementation of education for local governments and local communities to increase understanding and capacity in dealing with earthquake disasters so as to minimize the risks caused by earthquakes.

5. Conclusions

From the results of the research that has been done, some conclusions can be formulated as follows. The one-dimensional local velocity model consists of several layers. Vp at a depth of 10 km is at a speed of ~5.5 km/s. Vp at a depth of 30 km is at a speed of ~7 km/s. The 1-D velocity model obtained has a convergent and unique solution with an RMS value < 1.0. Based on ground motion analysis after relocation, it was found that the high PGA and PGV values were in Tarutung. The PGA results reveal a high percentage value of >10% in Tarutung. This is consistent with previous research and damage data obtained during field surveys, as well as confirming that Tarutung is in a fault area.

Acknowledgements

We thank to Badan Meteorologi Klimatologi dan Geofisika (BMKG) for providing the seismic data. We thank the fruitful discussion with Umar Muksin and Andrean Simanjuntak for their guidance to process the seismic data. We thank also for colleagues of BMKG office in the 1st regional in Medan for the survey report after Tarutung earthquake.

References

Atkinson, G. M. (2020). The Intensity of Ground Motions from Induced Earthquakes with Implications for Damage PotentialThe Intensity of Ground Motions from Induced Earthquakes with Implications for Damage Potential. Bulletin of the Seismological Society of America, 110(5), 2366-2379.

Bradley, K. E., Feng, L., Hill, E. M., Natawidjaja, D. H., & Sieh, K. (2017). Implications of the diffuse deformation of the Indian Ocean lithosphere for slip partitioning of oblique plate convergence in Sumatra. Journal of Geophysical Research: Solid Earth, 122(1), 572-591.

Havskov, J., & Ottemoller, L. (1999). SEISAN earthquake analysis software. Seismol. Res. Lett, 70(5), 532-534.

Kissling, E., U. Kradolfer, and H. Maurer. "Program VELEST user's guide-Short Introduction." Institute of Geophysics, ETH Zurich (1995).

Koulakov, I., Yudistira, T., Luehr, B. G., & Wandono. (2009). P, S velocity and VP/VS ratio beneath the Toba caldera complex (Northern Sumatra) from local earthquake tomography. Geophysical Journal International, 177(3), 1121-1139.

McCaffrey, R. (2009). The tectonic framework of the Sumatran subduction zone. Annual Review of Earth and Planetary Sciences, 37, 345-366.

Muksin, U., Arifullah, A., Simanjuntak, A. V., Asra, N., Muzli, M., Wei, S., ... & Okubo, M. (2023). Secondary fault system in Northern Sumatra, evidenced by recent seismicity and geomorphic structure. Journal of Asian Earth Sciences, 105557.

Muksin, U., Bauer, K., & Haberland, C. (2013). Seismic Vp and Vp/Vs structure of the geothermal area around Tarutung (North Sumatra, Indonesia) derived from local earthquake tomography. Journal of volcanology and geothermal research, 260, 27-42.

Nurana, I., Simanjuntak, A. V. H., Umar, M., Kuncoro, D. C., Syamsidik, S., & Asnawi, Y. (2021). Spatial Temporal Condition of Recent Seismicity In The Northern Part of Sumatra. Elkawnie: Journal of Islamic Science and Technology, 7(1), 131-145.

Pasari, S., Simanjuntak, A. V., Mehta, A., Neha, & Sharma, Y. (2021). A synoptic view of the natural time distribution and contemporary earthquake hazards in Sumatra, Indonesia. Natural Hazards, 108, 309-321.

Sakaguchi, K., Gilbert, H., & Zandt, G. (2006). Converted wave imaging of the Toba Caldera, Indonesia. Geophysical research letters, 33(20).

Sieh, K., & Natawidjaja, D. (2000). Neotectonics of the Sumatran fault, Indonesia. Journal of

Geophysical Research: Solid Earth, 105(B12), 28295-28326.

Simanjuntak, A. V., Kuncoro, D. C., Irwandi, I., & Muksin, U. (2022). Understanding swarm earthquakes in Southeast Aceh, Sumatra. In E3S Web of Conferences (Vol. 339, p. 02011). EDP Sciences.

Simanjuntak, A., Muksin, U., Asnawi, Y., Rizal, S., & Wei, S. (2022). Recent Seismicity and Slab Gap Beneath Toba Caldera (Sumatra) Revealed Using Hypocenter Relocation Methodology. Geomate Journal, 23(99), 82-89.

Worden, C. B., Gerstenberger, M. C., Rhoades, D. A., & Wald, D. J. (2012). Probabilistic relationships between ground-motion parameters and modified Mercalli intensity in California. Bulletin of the Seismological Society of America, 102(1), 204-221.