Jurnal Fisika Flux: Jurnal Ilmiah Fisika FMIPA Universitas Lambung Mangkurat
Volume 21, Nomor 3, Oktober 2024
1819-796X (p-ISSN); 2541-1713 (e-ISSN)

Hypocenter Analysis of the Bengkulu Earthquake (April 15, 2023) Using 2D and 3D Grid Search Methods

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DOI: https://doi.org/10.20527/flux.v21i3.21112
Submitted: 10 December 2024; *Accepted*: 23 December 2024

ABSTRACT−Earthquakes are one of the natural disasters that can have a significant impact on humans and the environment. This research aims to determine the hypocenter of the earthquake in Enggano, Bengkulu, on April 15 2023, using the 2D and 3D Grid Search method. Based on the analysis results, the earthquake hypocenter was at coordinates 4.50° South Latitude and 76.0340° East Longitude with a depth of 60 km. Meanwhile, data from the United States Geological Survey (USGS) shows the hypocenter at coordinates 4.8305° South Latitude, 77.0454° East Longitude, with a depth of 62.192 km. The difference between the results of this study and USGS data, amounting to 0.3305° in latitude, 1.0114° in longitude, and 2.192 km in depth, indicates that the Grid Search method has a fairly high level of accuracy, although it still requires improvements to get closer to the results. global validation such as USGS. This research emphasizes the importance of further development in the use of the Grid Search method to increase the accuracy of hypocenter estimation, especially through the integration of more detailed seismic wave velocity models and data from more seismic stations. With a relatively short processing speed of 10-15 minutes, this method also has great potential for application in real-time earthquake monitoring systems. The results of this research provide an important contribution to earthquake disaster mitigation, especially in the Bengkulu area which is vulnerable to high seismic activity, such as that affected by the Enggano megathrust segment.

KEYWORD : Bengkulu; Earthquakes; Grid Search; Hypocenter

INTRODUCTION

Megathrust earthquakes are earthquakes that occur due to subduction zones, which are areas where tectonic plates interact, particularly in collision zones (Badrul, 2015; Hermon, 2011; Maulana & Andriansyah, 2024). Subduction zones are the primary source of earthquakes in Indonesia, ranging from Western Sumatra, southern Java, Bali, and Nusa Tenggara, the Banda Sea, Northern Papua, Northern Sulawesi, Eastern North Sulawesi, and up to Western Halmahera (Adiyoso, 2018; Harijoko et al., 2024; Purwasih, 2011). According to Agung Harijoko's "Geology of Earthquakes in Indonesia," there are 13 giant thrust segments and more than 295 active fault segments in Indonesia (Harijoko et al., 2024). One of these is the Enggano megathrust segment located in Bengkulu Province. Bengkulu has two potential seismic segments the Enggano megathrust and the Mentawai-Pagai megathrust segment with a magnitude of 7.9, which directly impacts Mukomuko Regency and North Bengkulu Regency. According to the Bengkulu Meteorological, Climatological, and Geophysical Agency (BMKG), as reported by the Head of the Class III Kepahiang Geophysical Station, BMKG Bengkulu, there have been 95 earthquakes in the Enggano megathrust segment over the past two months or since early 2021. The earthquakes in this segment have magnitudes ranging from 1.5 to 6.3, including two significant quakes that shook Bengkulu (BMKG, 2021).

The Bengkulu Province is situated at the contact zone between the Indo-Australian Plate and the Eurasian Plate, which is a major trigger for the high seismic activity in the region (Hadi, 2023). Bengkulu is also located between two active faults, the Mentawai Fault to the east and the Semangko Fault, which are responsible for earthquakes in the northern Bengkulu region (Aprillo et al., 2019; Litman, n.d.; Utami, 2011; Yulita et al., 2023). This situation makes Bengkulu Province one of the most affected areas by earthquake disasters (Harlianto & Muhamad, 2018). The mechanism of tectonic earthquakes in Bengkulu involves the movement of tectonic plates subducting into one of the subduction plates. The Indo-Australian Plate moves beneath the Eurasian Plate, forming a subduction zone. The interaction of these plates creates cracks and faults in the subduction zone, resulting in seismic vibrations that cause tectonic earthquakes. Based on data from 1900 to 2010, about 95% of tectonic epicenters are located under the Indian Ocean, directly adjacent to Bengkulu Province (Hadi, 2023; Mahendra, 2024)

According to Pujianto (2007), earthquakes are natural phenomena that can be caused by either anthropogenic or natural factors. Identifying the earthquake hypocenter with high precision is crucial for preventing earthquake disasters (Nurmegawati, 2020). High precision is required because the earth materials that seismic waves pass through from the earthquake's epicenter to the recording station are uneven. Therefore, effective methods are needed to accurately determine the earthquake location (Fariha, 2023). The hypocenter is the point within the Earth where the earthquake originates, specified in latitude, longitude, and depth (Aliyah, 2021; Aprillo et al., 2019). In seismology, the hypocenter is the point inside the earth where the earthquake first occurs. The hypocenter is also referred to as the epicenter point of the earthquake and is the source of seismic waves. Numerical computer-based calculations can be used to determine the hypocenter location (Arimuko et al., 2019).

This study aims to determine the hypocenter location of the earthquake in Enggano, Bengkulu on April 15, 2022, using the Grid Search method. In the Grid Search method used by Grandis (2009), calculations at each sample point are based on a grid. The time required for this method is related to the initial parameters in the iteration. The initial range starts from the widest area and is then narrowed down after determining the range with the smallest error value from previous calculations. Calculations will continue until the value of the wide range boundary or the area with the smallest RMS (Root Mean Square) value is found as the best solution (Arimuko et al., 2019).

The use of the grid search method is because it takes advantage of the advantages of other methods, namely in the form of certainty that the best solution among the parameter space to be tested will be found, as long as the optimal parameters are included in the predetermined grid search (Rasimeng et al., 2021; Rasimeng & Yogi, 2020). This provides a good solution compared to other methods that involve manual trial and error which is error-prone and inefficient (Arimuko et al., 2019).

This research uses numerical calculations using 3D and 2D Grid Search methods to determine the hypocenter of the earthquake in Enggano, Bengkulu in 2023 as an effort to mitigate the importance of disaster mitigation in the future. Furthermore, the data in this study was collected from seismic stations located nearby to increase accuracy. Data processing was carried out using Google Collaboratory based on Python and SeisGram2K v7. This research aims to provide accurate information regarding the location of earthquake hypocenters and epicenters, utilizing the latest unprocessed data, and developing more precise methods.

DATA AND METHODOLOGY

This study utilizes data from the earthquake on April 15 2023 in Enggano, Bengkulu. Based on USGS data that can be accessed for free, the location of the earthquake was recorded at 4.8305° South Latitude and 102.9546° East Longitude with a magnitude of 5.5 and a depth of 62,192 km. This research uses earthquake data from a total of six stations: COCO, KAPI, PALK, DAV, MBWA, and NWAO (Table 1), which can be accessed for free on the IRIS page by entering the event date range and minimum magnitude. Earthquake parameters include hypocenter location, time of origin, area and magnitude.

The main software used in this data processing research includes Google Collaboratory and SeisGram2K v7.0.0X10 which can be accessed and used for free. Data processing begins with downloading the earthquake locations recorded by six stations, followed by retrieving the P and S wave phases from the downloaded data using Seismograv software. Origin time (Tobs) is determined from available station data using Wadati diagrams. The wadati diagram is a way to see the results of the arrival times of P and S waves that have previously been picked properly or not by looking at the center of distribution or other data validation, in addition to determining the Vp/Vs ratio (Hurukawa, 2008; Mariyanto et al, 2013; Setiawan, 2017; Rafflesia, 2017; Nurrochman et al., 2020; Sahara., 2021). This method utilizes tp (P wave arrival time) and Ts-Tp (difference in S and P wave arrival times) data from a number of stations. These two data sets are plotted to create Tp and Ts-Tp data intersection points, which serve as an estimate of the time of earthquake origin.

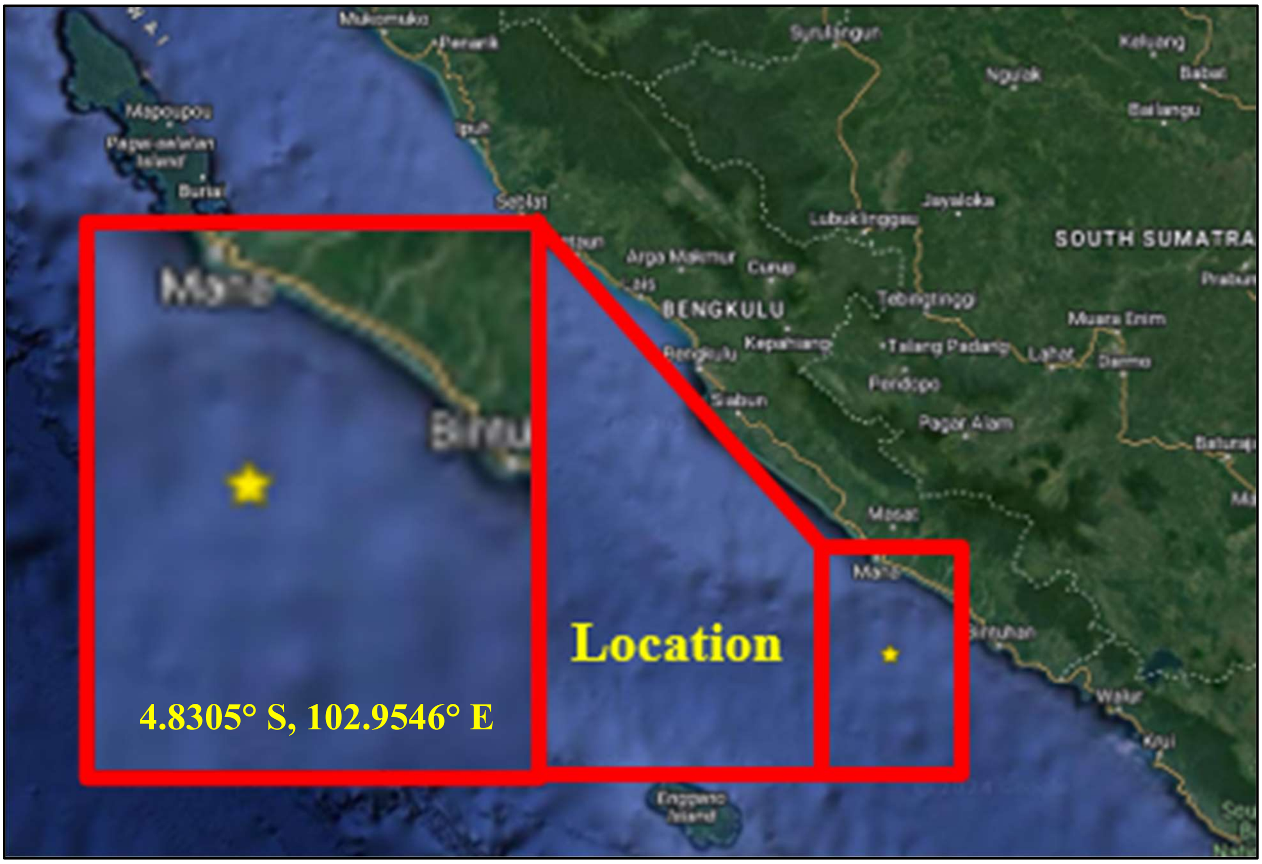

Figure 1 The epicenter location of the earthquake in Enggano, Bengkulu, based on USGS.

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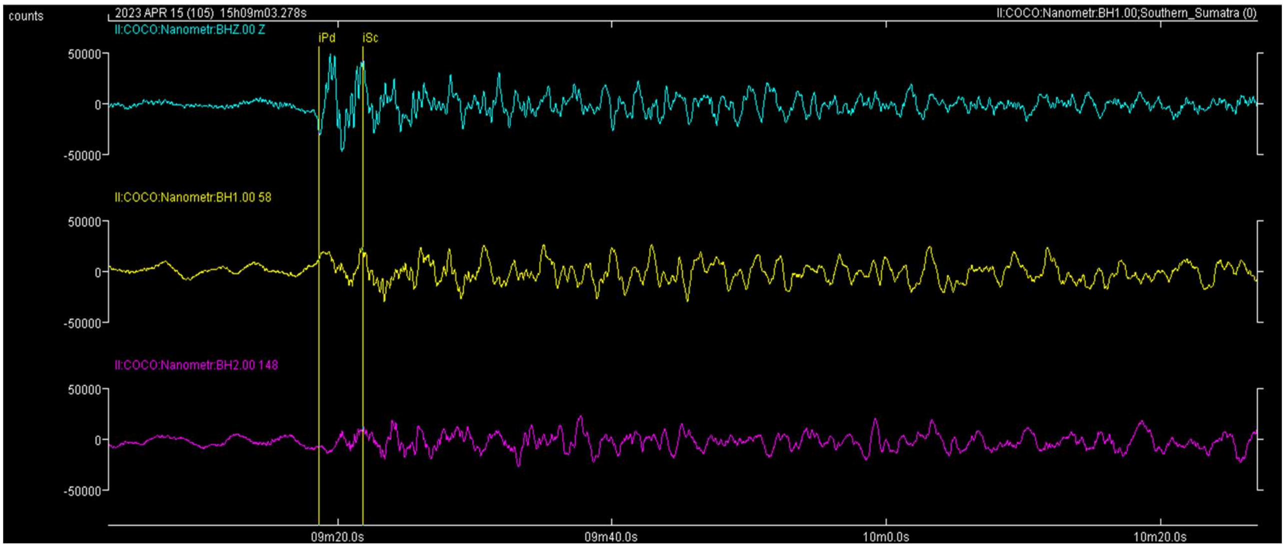

Figure 2 Picking results of P and S waves at COCO station

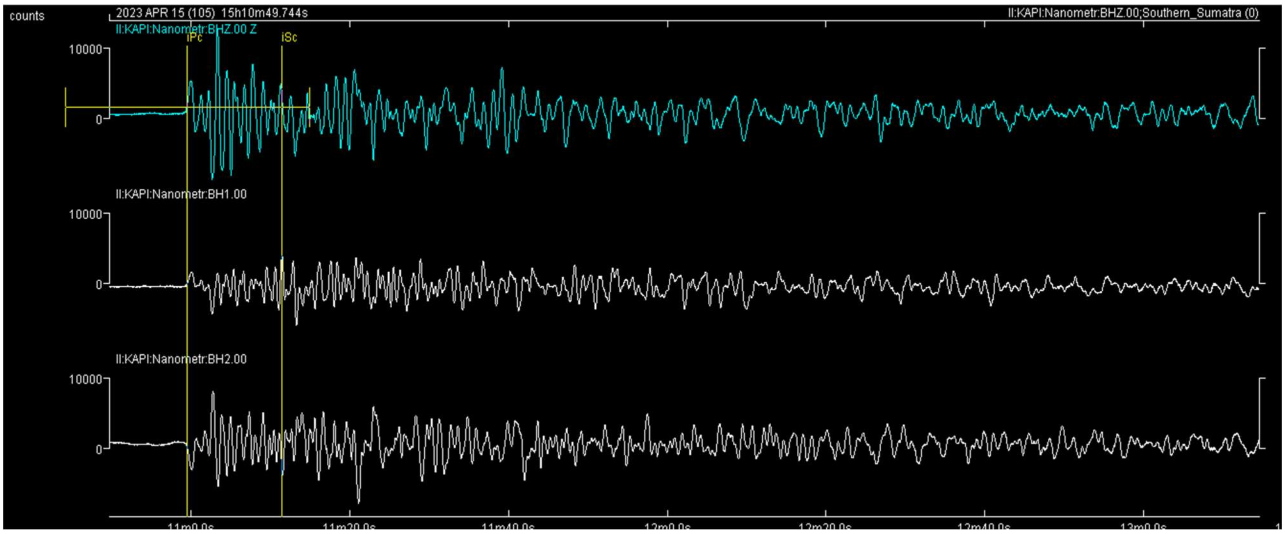

Figure 3 Picking results of P and S waves at KAPI station

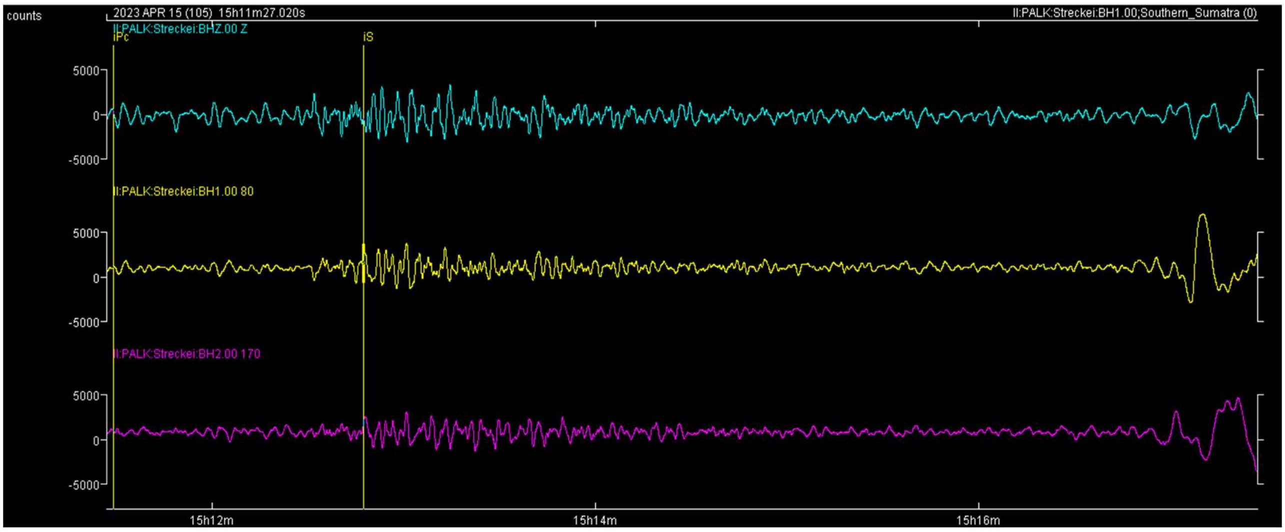

Figure 4 Picking results of P and S waves at PALK station

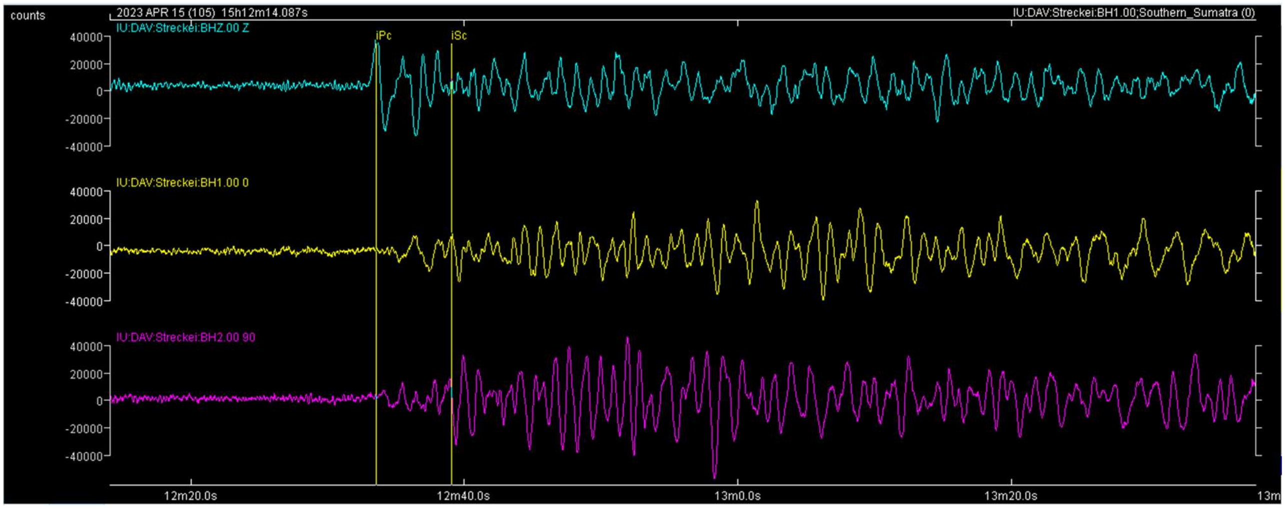

Figure 5 Picking results of P and S waves at DAV station

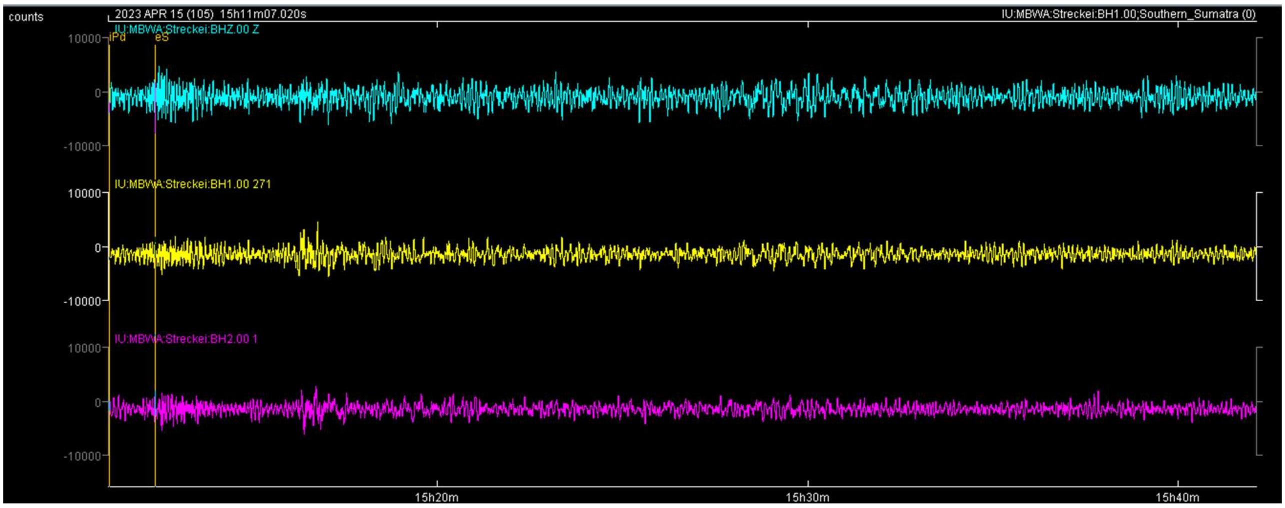

Figure 6 Picking results of P and S waves at MBWA station

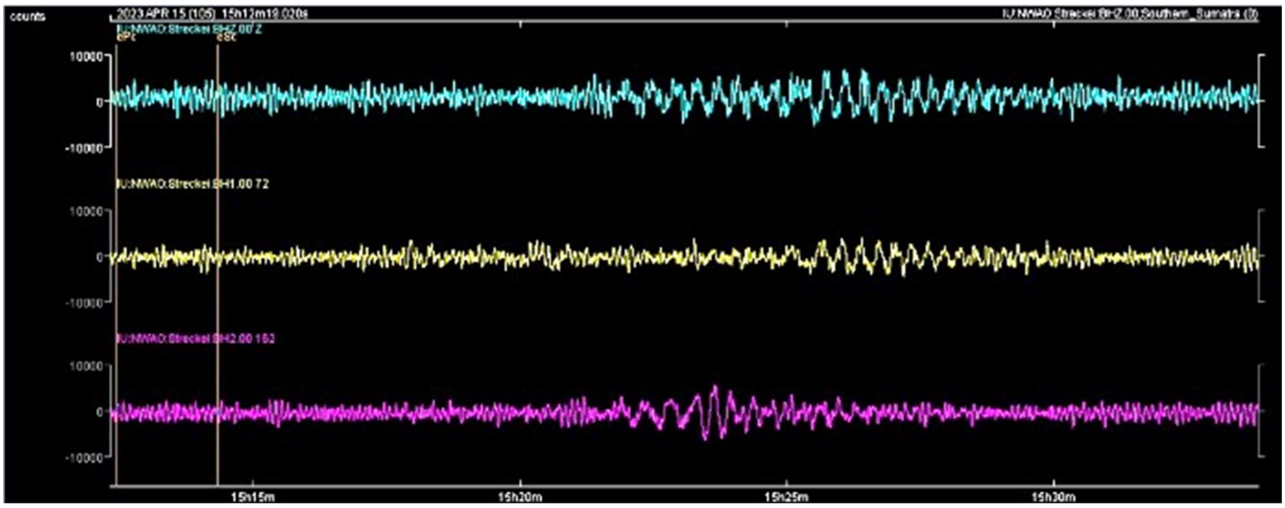

Figure 7 Picking results of P and S waves at NWAO station

Data picking was carried out using SeisGram2K at 6 stations, data picking was intended to determine the arrival of P waves and S waves arriving at each station (COCO, KAPI, PALK, DAV, MBWA, and NWAO). The results of the picking are then processed using the Grid Search method to determine the epicenter and hypocenter of the earthquake.

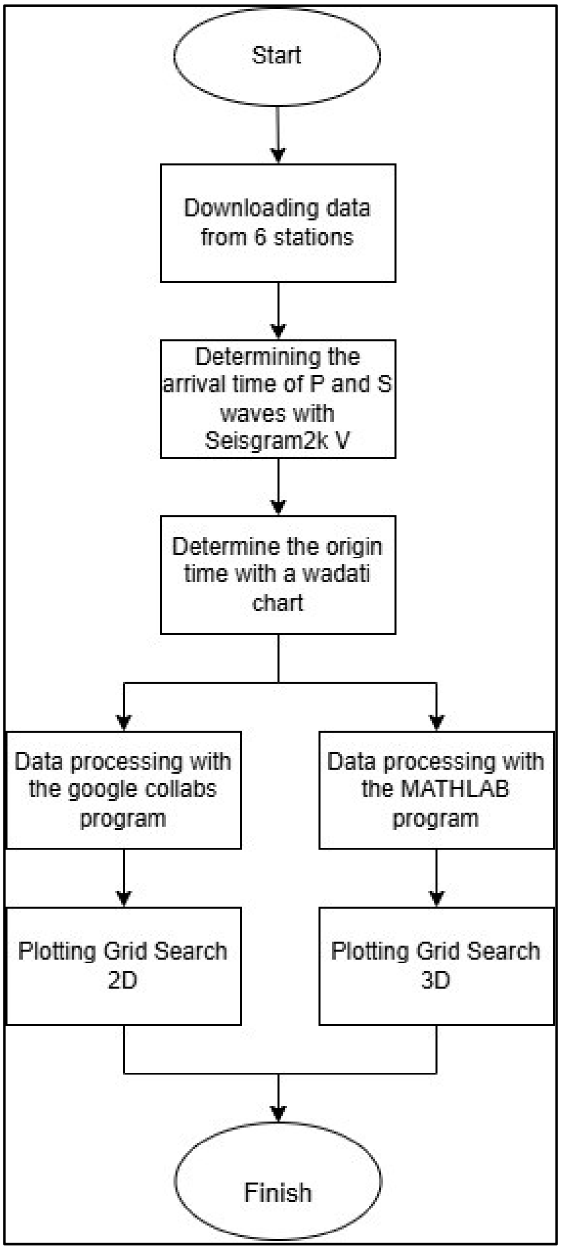

Figure 8 Data processing flowcharts

This method can produce 2D plots to identify epicenters and 3D plots for hypocenters. Grid Search is a technique used to find the best parameters in an iterative process. In Grid Search, each sample point is calculated based on the grid (Grandis, 2009). The time this method takes depends on the initial parameters in the iteration. The search starts from the widest area and is gradually narrowed until finding the area with the smallest error, measured by Root Mean Square (RMS). The method is implemented using software such as Matlab and Python. Tighter grids provide more accurate results but require longer computing time. This method relies on repeated evaluation, where each grid is compared for its error value, and the process continues until the smallest RMS value is found to be the best solution (Rodi & Toksoz, 2000).

RESULT AND DISCUSSION

In determining the earthquake hypocenter, the first step involves picking the arrival times of P-waves and S-waves from each observation station used as a sample. This picking is done using SeisGram software to obtain the arrival times of P-waves (Tp), S-waves (Ts), and the difference between Ts and Tp. The results of this picking serve as the basis for calculating the parameters needed to determine the origin time of the earthquake.

Next, the preliminary origin time (T0) is set to 15:08:00, as this time is a round number that closely approximates the observed arrival times of the waves, making the calculation process easier. Based on the value of T0, the observation time (Tobs) is calculated by subtracting T0 from Tp, as shown in Table 1.

Tabel 1 Arrival time intervals for P-waves and S-waves

Station	Tp	Ts	Ts-Tp
COCO	15:09:14	15:10:22	44.564
KAPI	15:10:49	15:12:48	108.677
PALK	15:12:07	15:14:10	122.715
DAV	15:12:25	15:13:49	84.340
MBWA	15:11:09	15:12:23	74.126
NWAO	15:12:46	15:14:49	119.742

To determine a more accurate origin time, the Wadati Diagram is used by plotting the Tp values on the X-axis and the Ts-Tp differences on the Y-axis, as shown in Figure 9. The Wadati Diagram serves as a graphical method to estimate the earthquake's origin time more precisely (Huda et al., 2021; Hurukawa, 2008; Mariyanto et al., 2013; Miftahul Huda & Sahara, 2021; Nurrochman & Rasimeng, 2020; Raflesia, 2017; Setiawan, 2017)

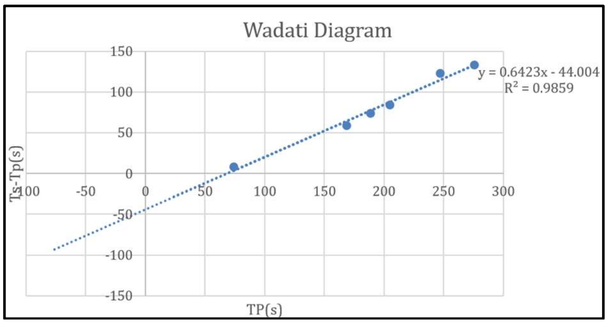

Figure 9 Wadati diagram

Based on Figure 9, the formula Ts-Tp = 0.6423p + 9.2142 is obtained with a coefficient of determination of 0.9859. Thus, the value of parameter x is 12.24153049. To obtain the origin time, the value of T0 is added to x, as shown in Equation (1). Origin Time = T0 + x (2). The resulting Origin Time is 15:08:12.241. The Grid Search method can be used to determine the earthquake's epicenter in two dimensions (2D) and the hypocenter in three dimensions (3D). In this process, the origin time plays a crucial role in detecting the earthquake's location. The 2D Grid Search Method is as shown in Figure 10.

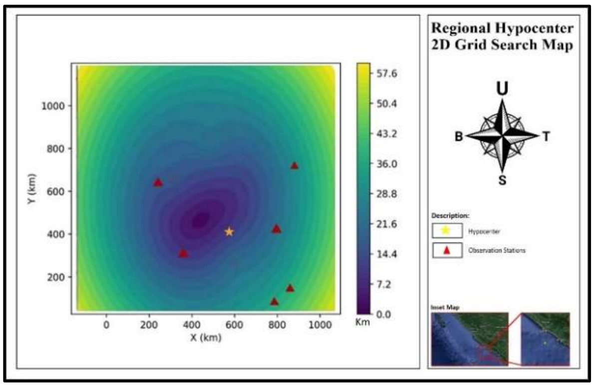

Figure 10 Regional hypocenter position using 2D grid search

From the calculations shown in Figure 10, the hypocenter position is estimated to be on the X-axis (latitude) within the range of 580 to 600 km, and the Y-axis within the range of 400 km with a depth between 21.6 km and 28.8 km, having the smallest RMS error value of 1.97s. The results of the regional hypocenter calculations are not yet sufficient for precise referencing, as the values obtained are still relatively broad. This regional calculation serves as an initial estimate of the hypocenter's position, which can then be refined. The estimated epicenter position, still in kilometers, needs conversion to degrees, resulting in a latitude of 5.39° S and longitude of 3.59° E. This preliminary estimate is not yet adequate for precise determination, so it is combined with the 3D Grid Search method to determine the earthquake's hypocenter. The 3D Grid Search method, using a non-linear inversion approach as shown in Figure 11.

The 3D Grid Search results in Figure 11 show that the X axis (West-East) represents latitude in km, the Y axis (North-South) represents longitude in km, and the Z axis (Depth) represents the depth zone for relocating the hypocenter. The yellow star symbol indicates the hypocenter, and the black triangle indicates the seismic station. The hypocenter is located at a latitude of 500.80 km, a longitude of 8446.23 km, and a depth of 60 km. If converted into degrees, we get a latitude of 4.50° South Latitude and a longitude of 76.0340° East Longitude. The relocated hypocenter is at latitude 4.50° S, longitude 76.0340° E, with a depth of 60 km. The results can be referenced to USGS data for validation. USGS data reports the location of the hypocenter at latitude 4.8305° South Latitude, longitude 77.0454° East Longitude, and a depth of 62,192 km. There is a difference of 0.3305° in latitude and 1.0114° in longitude between relocation calculations and USGS data. Relocation results using the grid search method show increased accuracy because it is closer to the location reported by the USGS. The difference between research results and USGS data in determining the location of the earthquake hypocenter can be caused by several factors. One of the main causes is the difference in the seismic wave velocity models used. The USGS tends to use high-resolution global or regional wave velocity models, whereas local studies often use simpler, area-specific velocity models, which can produce different estimates. Therefore, further refinement is needed to minimize differences.

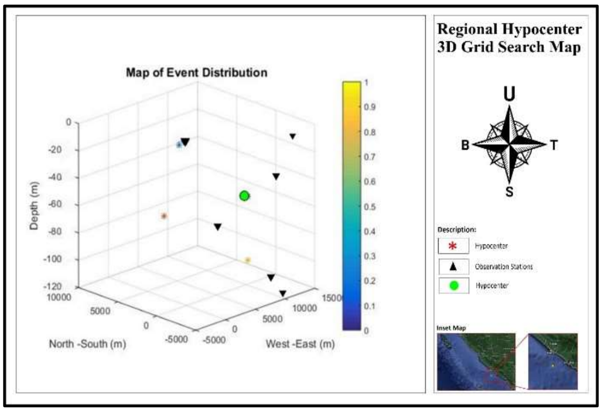

Figure 11 Regional hypocenter position using 3D grid search

The grid search method can be used to relocate the hypocenter position with a 3D structure, providing better results than 2D velocity calculations. The time for relocating the hypocenter position using the grid search method is around 10-15 minutes so it is a feasible method for determining the actual position of the earthquake. So the results of the comparison of USGS and data from the 6 stations in this research have important implications in future earthquake disaster mitigation efforts, especially in the Bengkulu area and its surroundings which are known to have high seismic activity due to the existence of the Enggano megathrust zone. By applying the method Grid Search 2D and 3D, this research has succeeded in providing estimates of the location of the hypocenter with a fairly high level of accuracy.

CONCLUSION

This study aimed to determine the earthquake hypocenter in the Enggano, Bengkulu region on April 15, 2023, using the Grid Search method. Based on the analysis with the 2D and 3D Grid Search approaches, the earthquake hypocenter was located at 4.50° N and 76.0340° W with a depth of 60 km. These results were compared with data from the USGS, which indicated the hypocenter coordinates at 4.8305° N, 77.0454° W, and a depth of 62.192 km, showing differences of 0.3305° in latitude, 1.0114° in longitude, and 2.192 km in depth. These discrepancies indicate that while the Grid Search method provides a close estimation, there are still inaccuracies that need correction. However, this method shows great potential for use in earthquake hypocenter relocation due to its speed and efficiency. With further development, including the use of more detailed 3D velocity structures, it is hoped that relocation results can more closely match validation data, such as that provided by the USGS. In addition, the use of more detailed seismic wave velocity models and integration of data from more seismic stations is expected to reduce differences in results compared to validation data such as USGS.

REFERENCES

Adiyoso, W. (2018). *Manajemen Bencana: Pengantar dan Isu-Isu Strategis*. Jakarta: Bumi Aksara.

Aliyah, S. M. (2021). *Pemetaan Tingkat Resiko Akibat Gempa Bumi di Provinsi Daerah Istimewa Yogyakarta Berdasarkan Pola Percepatan Tanah Maksimum (Studi Kasus Data Gempa Bumi Tahun 1969–2019)*. Doctoral dissertation, Universitas Islam Negeri Maulana Malik Ibrahim.

Aprillo, L. A., Santosa, H., & Hadi, F. (2019). Analisis Total Electron Content (TEC) Menggunakan Continous Wavelet Transform Sebagai Indikator Prekursor Gempa Bumi Di Wilayah Provinsi Bengkulu. *Jurnal Amplifier: Jurnal Ilmiah Bidang Teknik Elektro Dan Komputer*, *9*(2), 27–33. https://doi.org/10.33369/jamplifier.v9i2.15380

Arimuko, D., Wibawa, A. S. W., & Firmansyah, A. (2019). Metode penentuan hiposenter dengan presisi tinggi menggunakan pendekatan Grid Search. *Jurnal Seismologi Dan Kebencanaan*, *9*(2). https://jurnal.unsil.ac.id/index.php/Diffraction/article/view/1290

Badrul, M. (2015). *Penggunaan Data Gempa dan Data Geologi untuk Menganalisa Pola-Pola Sesar di Daratan Pulau Sumatra*. Doctoral dissertation, Universitas Islam Negeri

Maulana Malik Ibrahim Malang.

BMKG. (2021). *Laporan Aktivitas Seismik Segmen Megathrust Enggano*. BMKG Bengkulu.

Fariha, A. N. (2023). *Analisis Zona Kerentanan Bencana Gempa Bumi Berdasarkan Nilai Peak Ground Acceleration (PGA) Menggunakan Metode Fukushima Esteva dan Donovan: Studi kasus Wilayah Malang Raya Periode 1980-2023*. Doctoral dissertation, Universitas Islam Negeri Maulana Malik Ibrahim.

Grandis, H. (2009). *Metode Grid Search Untuk Penentuan Lokasi Gempa*. Bandung: PT. Remaja Rosdakarya.

Hadi, Z. (2023). Mitigasi Bencana Alam Gempa Bumi pada Komunitas Sekolah di Pondok Pesantren Raudatul Jannah Lombok Utara. *Geodika: Jurnal Kajian Ilmu Dan Pendidikan Geografi*, *7*(2), 285–295. https://doi.org/10.29408/geodika.v7i2.24599

Harijoko, A., Anggraini, A., & Setianto, A. (2024). *Geologi Gempa Bumi Indonesia*. Yogyakarta: UGM Press.

Harlianto, Y., & Muhamad, H. (2018). Sesar Aktif dan Potensi Bencana Gempa di Provinsi Bengkulu. *Jurnal Geofisika Indonesia*, *8*(1), 1–10.

Hermon, D. (2011). *Geografi Bencana Alam-Rajawali*. Jakarta: PT. Raj aGrafindo Persada.

Huda, A. M., Sahara, A., & Widyaningrum, Y. (2021). Penggunaan Automated Phase Picking pada Estimasi Hiposenter Gempa Lokal: Studi Kasus Lengan Atas Sulawesi. *Jurnal Riset Fisika Indonesia*, *1*(2), 17–22. https://journal.ubb.ac.id/jrfi/article/view/2206

Hurukawa, N. (2008). *Practical Analyses of Local Earthquakes*. Tsukuba, Japan: Internasional Insitude of Seismology and Earthquake Engineering (IISEE) Building Research Institude.

Litman. (n.d.). Analisis Probilitas Bahaya Kegempaan untuk Pengelolaan Daerah Dalam Mitigasi Bencana Gempa Bumi di Kota. *Naturalis: Jurnal Penelitian Pengelolaan Sumber Daya Alam Dan Lingkungan*, *10*(1), 143–155. https://doi.org/10.31186/naturalis.10.1.181 61

Mahendra, E. F. (2024). *Modifikasi Time History Permukaan untuk Perencanaan Gedung di Provinsi Bengkulu Berdasarkan SNI 8899: 2020*. Universitas Islam Indonesia.

Mariyanto, M., Santosa, B. J., & Bahri, A. S. (2013). Estimasi Poisson's Ratio untuk Analisis Derajat Saturasi Air pada Reservoir Geotermal Menggunakan Data MEQ. *Jurnal Sains Dan Seni ITS*, *2*(2), 63–67. https://doi.org/10.12962/j23373520.v2i2.4155

Maulana, A. T., & Andriansyah, A. (2024). Mitigasi Bencana di Indonesia. *Jurnal Penelitian Dan Pengabdian Masyarakat*, *3*(10), 3996–4012. https://doi.org/10.59141/comserva.v3i10.1213

Miftahul Huda, A. M., & Sahara, A. (2021). Penentuan Sumber Gempa Lokal Berdasarkan Waktu Tiba Gelombang P Dan S: Studi Kasus Lengan Utara Pulau Sulawesi. *Journal of Energy and Technology*, *3*(2), 29–38. https://doi.org/10.58267/petrogas.v3i2.68

Nurmegawati. (2020). Kesesuaian Lahan Tanaman Jeruk (Citrus L) di Kabupaten Kepahiang, Bengkulu. *Agrista: Jurnal Ilmiah Mahasiswa Agribisnis UNS*, *4*(1), 238–250.

Nurrochman, A., & Rasimeng, S. (2020). Perbandingan Penggunaan Matlab dan Python Dalam Penentuan Episenter Gempa; Studi Kasus Gempa Laut Banda 06 Mei 2020. *Jurnal Ilmu Fisika Dan Pembelajarannya*, *4*(2), 77–82. https://doi.org/10.19109/jifp.v4i2.5993

Pujianto, T. (2007). Pentingnya Identifikasi Hiposenter dalam Mitigasi Bencana Gempa Bumi. *Jurnal Kebumian Indonesia*, *3*(1), 1–15.

Purwasih, R. R. I. (2011). *Studi Identifikasi Gempa Bumi Pembangkit Tsunami di Selatan Pulau Jawa Periode 2005-2009*. Universitas Negeri Sebelas Maret.

Raflesia, F. (2017). *Analisis Sebaran Hiposenter Gempa Mikro dan Poisson Ratio di Lapangan Panas Bumi Desert Peak Sebelum dan*

Sesudah Stimulasi Enhanced Geothermal System (EGS). Universitas Lampung.

Rasimeng, S., Dani, I., Wibisono, A. H., Ahadi, R. W., & Al Ghifari, S. (2021). Penentuan Episentrum dan Hiposentrum Gempa Bumi Menggunakan Metode Grid Search di Antelope Valley, California. *Geocelebes*, *5*(2), 173–181. https://doi.org/10.20956/geocelebes.v5i2.14635

Rasimeng, S., & Yogi, I. B. S. (2020). Penentuan Posisi Hiposenter Gempabumi Menggunakan Metode Grid Search, Studi Kasus: Gempa Pada Daerah Sumatera Barat Pada Tahun 2017. *Jurnal MIPA*, *20*(1), 1–8.

Rodi, W., & Toksoz, M. N. (2000). Grid Search Method for Seismic Location. *Journal of Geophysical Research*, *10*(5), 1–10.

Setiawan, A. (2017). Analisis Sebaran Hiposenter Gempa Mikro dan Poisson's Ratio, Studi Kasus: Hydroshearing pada Lapangan Enhanced Geothermal System Newberry, Oregon. *Jurnal Lampung*, *2*(1), 1–10. https://journal.eng.unila.ac.id/index.php/geo/article/view/1045

Utami, M. (2011). *Analisis Mekanisme Pusat Gempa Soroako 15 Februari 2011*. Universitas Islam Negeri Syarif Hidayatullah Jakarta.

Yulita, T., Lubis, C. T., & Hidayat, A. S. E. (2023). Penentuan Premi Murni di Kabupaten Kepahang Provinsi Bengkulu dengan Memperhitungkan Peluang Kejadian Gempa Bumi dan Rasio Kerusakan. *Journal of Statistics and Its Applications*, *5*(2), 147–158. https://doi.org/10.30598/variancevol5iss2page147-158