Tsunami Modeling in The Mentawai Island as A Study Material for Disaster Mitigation (Case Study: Mentawai Earthquake, October 25, 2010)

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Abstract: There was an earthquake in Mentawai on October 25, 2010 which resulted in 509 deaths, 17 people injured, and 11,425 people displaced. Based on this, tsunami modeling was conducted using L-2008 software. This study aims to determine the value of the earthquake source mechanism and conduct tsunami modeling. Tsunami modeling includes earthquake source modeling as a tsunami generator (source modeling), tsunami wave propagation modeling (ocean modeling), and tsunami height modeling (run-up modeling). In this study, bathymetry data and earthquake source mechanism data from the USGS agency were used. The calculation results showed that the Mentawai earthquake had a fault length of 218,78 km, fault width of 45.70 km, and slip of 3.84 m. While the results of tsunami modeling show that the vertical displacemeht value obtained is the maximum value of 1.55 m and the minimum value is -1.55 m. The ocean modeling results show that the tsunami waves reached Sipora Island, North Pagai, and South Pagai at 20 minutes and 50 seconds. While the simulation results of tsunami run up modeling show that the maximum run up is at Sabeugunggu bay with run up value of 6.34 meters. Tsunami run up modeling has an RMSE value of 0.73.

Keywords: Mentawai earthquake; ocean modeling; run-up modeling; source modeling

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I. INTRODUCTION

One of the islands in Indonesia with high seismic intensity is Sumatra [1]. Along the west coast of Sumatra Island, especially the Mentawai Islands, is one of the areas where earthquakes often occur with shallow depths [2]. This is because the Sumatra region located in the western part of Sumatra Island is part of the Eurasian Plate which moves very slowly and relatively to the southeast at a speed of about 0.4 cm / year. In the western part of West Sumatra Province there is also a collision between the Indo-Australian plate which subducts the Eurasian plate at a speed of 5-6 cm/year [3]. The collision between the two plates produces the main structural pattern of Sumatra known as the Sumatra Fault Zone and Mentawai Fault Zone (Fig. 1) [4].

In 2010, the Mentawai Islands experienced a number of earthquakes, namely the M6.8 earthquake on March 5, 2010, followed by M6.5 on May 5, 2010, and finally the M7.8 earthquake on October 25, 2010 which was followed by a tsunami [6]. The Mentawai earthquake that occurred on October 25, 2010 was located in the Mentawai-Pagai segmentation zone [7]. The Mentawai-Pagai segmentation is one of the most active megathrust zones in Indonesia and has the potential to trigger large earthquakes and tsunamis. The megathrust zone is located at the junction of the Eurasian plate and the Indo-Australian plate which has a relatively gentle subduction angle to a depth of 50 km [8]. The Mentawai earthquake

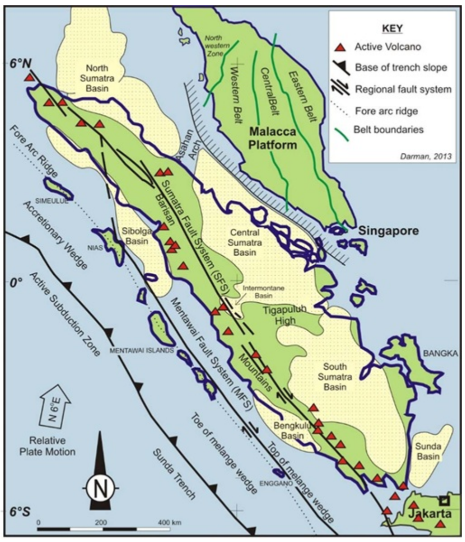

FIG. 1: Tetonics of Sumatra Island [5].

was categorized as a tsunami earthquake because it caused weak tremors with a long duration, but produced large tsunami waves with 2 to 4 wave peaks reaching the shoreline [9]. In the Mentawai earthquake, the seafloor deformation that generated the tsunami was a thrust fault (Fig. 2) [10].

The Mentawai segment is a seismic gap area, which means

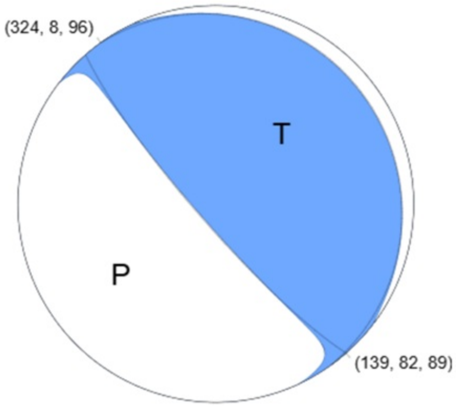

FIG. 2: Focal mechanism of the Mentawai earthquake Oktober 25, 2010 [10].

that this area stores high stress accumulation. High stress accumulation correlates with large earthquake energy [11]. Therefore, the Mentawai region needs to be vigilant because at any time the stored energy (expected energy) can be released in the form of a large earthquake. Based on the analysis of the impact caused by the Mentawai earthquake, the case study used in this research is the Mentawai earthquake that occurred on October 25, 2010. The Mentawai earthquake occurred at 14:42:22 (UTC) with the epicenter located off the southwest coast of Pagai Island with coordinates 3.487° N and 100.082° E with a depth of 11.5 km below the seabed. Based on data from BNPB, the Mentawai earthquake and tsunami on October 25, 2010 resulted in 509 deaths, 17 people injured, and 11,425 people displaced in evacuation sites in South Sipora, South Pagai, North Pagai, and Sikakap [12].

Earthquakes can occur at any time. Vibrations caused by earthquakes can damage everything on the earth's surface such as buildings and other infrastructure so that it can cause casualties and loss of property [13]. Therefore, disaster mitigation studies are needed as an effort to reduce the impact in the event of an earthquake. One of them is this research that aims to determine the value of the earthquake source mechanism through empirical equations and conduct tsunami modeling. Tsunami modeling carried out in this study includes modeling of earthquake sources as tsunami generators (source modeling), modeling of tsunami wave propagation (ocean modeling), and modeling of tsunami height (run-up modeling). Tsunami modeling is carried out by taking into account several factors, namely the shape of the beach, the slope of the beach, vegetation and barrier structures around the beach, the direction of tsunami waves, and the effects of reflection of waves originating from other islands in the vicinity.

Previous research conducted by Wiko Setyonegoro, et al (2015) related to the validation of tsunami modeling based on L-2008 software using USGS, IRIS, CMT, and GFZ earthquake source data with a case study of the March 28, 2005 Nias Tsunami has shown that the results of the data correlation test that are close to the survey are data from the USGS (United States Geological Survey) [14]. Therefore, in this study, the data used is data from the USGS agency. The USGS is a scientific agency of the United States government founded on March 3, 1879 which has four main scientific disciplines namely biology, geography, geology, and water. One of the main programs of the USGS is to monitor earthquake activity around the world including earthquake data in the Mentawai islands provided in the form of datasheets [15]. In this study, the results of tsunami modeling simulations were also compared with the results of field measurements conducted by GITST (German Indonesia Tsunami Survey Team) to determine the validity of the simulation model.

II. METHODOLOGY

This study uses data from the October 25, 2010 Mentawai earthquake from the United States Geological Survey (USGS). The tsunami simulation software used is Tsunami L-2008 software. The input parameters used in this study are earthquake epicenter location, earthquake magnitude, fault length and width, strike, dip, and slip.

Empirically, the length and width of the fault can be calculated using the Well and Coppersmith (1994) equation as in Eq. (1) and (2).

$$M = 5.08 + 1.16 \times LogRL \tag{1}$$

$$M = 4.06 + 2.25 \times LogRW \tag{2}$$

where M = Moment Magnitude, RL = Rupture length (km), and RW = Rupture width (km) [16].

A tsunamigenic earthquake to produce deformation on the seafloor must have a large seismic moment with a shallow epicenter position. Seismic moment calculates the amount of energy released by an earthquake by taking into account the displacement that occurs in the slip along the fault and the surface area of the fault that slips [14]. The relationship between seismic moment and deformation can be seen in Eq. (3).

$$M_\circ = \mu AD \tag{3}$$

where $M_\circ$ = earthquake seismic moment (Nm), μ = rock regidity (Nm^2), A = rupture area (m^2), dan D = deformation (m) [17].

The tsunami modeling input process was conducted using bathymetry data of the area where the earthquake occurred on Mentawai Island on October 25, 2010. The bathymetry data was downloaded from NOAA's GEBCO (The General Bathymetric Chart of the Oceans) world oceanography site.

The tsunami modeling simulation process begins with the collection of earthquake focal mechanism parameter data (Table I) and bathymetry. Then determining the model design or scenario to be carried out (source modeling), creating a grid of the bathymetry values of the simulation area and the design of the tsunami propagation simulation (ocean modeling). Next, model the tsunami wave height (run up modeling). The results of the tsunami run up simulation were then validated with field measurement data conducted by GITST (German Indonesia Tsunami Survey Team) through an accuracy test by calculating the RMSE (Root Mean Square Error) value.

TABLE I: Focal mechanism of the October 25, 2010 Mentawai earthquake from USGS [10].

Parameters	USGS
Lattitude	-3.487
Longitude	100.082
Mw (Richter)	7.8
Strike (Degree)	139
Dip (Degree)	82
Depth (km)	11.5
M0 (Nm)	5.405×10^{20}

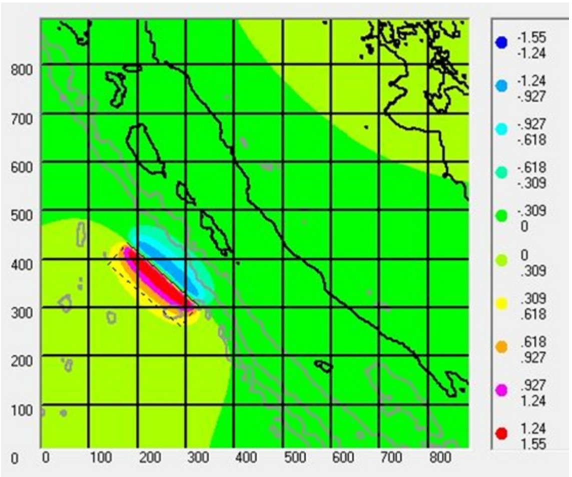

FIG. 3: Vertical displacement of Mentawai earthquake on October 25, 2010.

III. RESULT AND DISCUSSION

A. Source Modeling

The earthquake source parameters used in source modeling are the values of fault length, fault width, and slip obtained from calculations using empirical equations. In addition, the input parameters used for source modeling are the strike and dip values taken from the USGS catalog.

The results of the calculation obtained the value of the length and width of the fault is 218.78 km $\times$ 45.70 km with a slip value of 3.84 m. The results of source modeling in the form of vertical displacement values. Vertical displacement is deformation that occurs on the seabed. The deformation movement of the oceanic crust on the seabed is followed by a shift in the sea surface that follows the deformation of the fault plane.

The vertical movement of the ocean floor up is indicated by the maximum vertical displacement value, while the minimum vertical displacement value indicates the vertical movement of the ocean floor down. The vertical movement of the ocean floor rises and falls rapidly in response to earthquakes and causes seawater to rise and fall. Displacemet movement is an absolute measure of change in particle position. The vertical displacement obtained from this study is the maximum value of 1.55 m and the minimum value is -1.55 m (Fig. 3).

B. Ocean Modeling

Ocean modeling results show the tsunami wave propagation from the source in all directions as shown in Fig. 4. Based on Fig. 4, the tsunami wave propagation from the research results shows that at 16 minutes and 40 seconds the tsunami waves had entered the beach area of Pasangan and Sabenggunggu beach on North Pagai Island and had also entered the beach area of Malacopa and Asahan beach on South Pagai Island. At 20 minutes 50 seconds tsunami waves entered the south coast of Sipora Island, North Pagai Island and South Pagai Island. The tsunami wave propagation time varies in different places, which is influenced by the bathymetry of the sea surface and the slope of the coast in each region.

C. Run Up Modeling

Tsunami run up is the vertical distance between the distance of a tsunami at the coast and the zero point of mean sea level. The run up height and tsunami height depend on the earthquake magnitude, seabed morphology and coastal shape. The increase in tsunami run-up when it reaches shallower seabed has an effect in tsunami propagation simulations. To see the influence of seabed depth on tsunami run-up height, cross-section plots were conducted. In this study, three crosssection plots were conducted, namely on Sipora Island (Fig. 5), North Pagai Island (Fig. 6), and South Pagai Island (Fig. 7).

From the three cross-section plots, it can be seen that the shape of the ocean bottom surface of North Pagai Island for depths of 1000-4000m below sea level looks steeper than South Pagai Island and Sipora Island. While the shape of the ocean bottom surface of South Pagai Island for a depth of 1000m-4000m below sea level looks steeper than Sipora Island. The shape of the ocean bottom surface can affect tsunami wave propagation and tsunami height, where when tsunami waves get closer to land, the waves get higher. This causes the tsunami wave height to be much higher when it reaches the coastal area than the wave height at the initial location of the epicenter.

The results of run up distribution modeling using Tsunami L-2008 software for the Mentawai tsunami modeling on October 25, 2010 were then validated with the run up results from the survey activities conducted by GITST (German-Indonesian Tsunami Survey Team) through an accuracy test by calculating the RMSE value. The RMSE value obtained was 0,73. The RMSE value indicates that the simulation results of the tsunami run-up have a high level of accuracy because the value is close to 0. The comparison value of the Mentawai tsunami run-up simulation with the survey results by GITST can be seen in Table II.

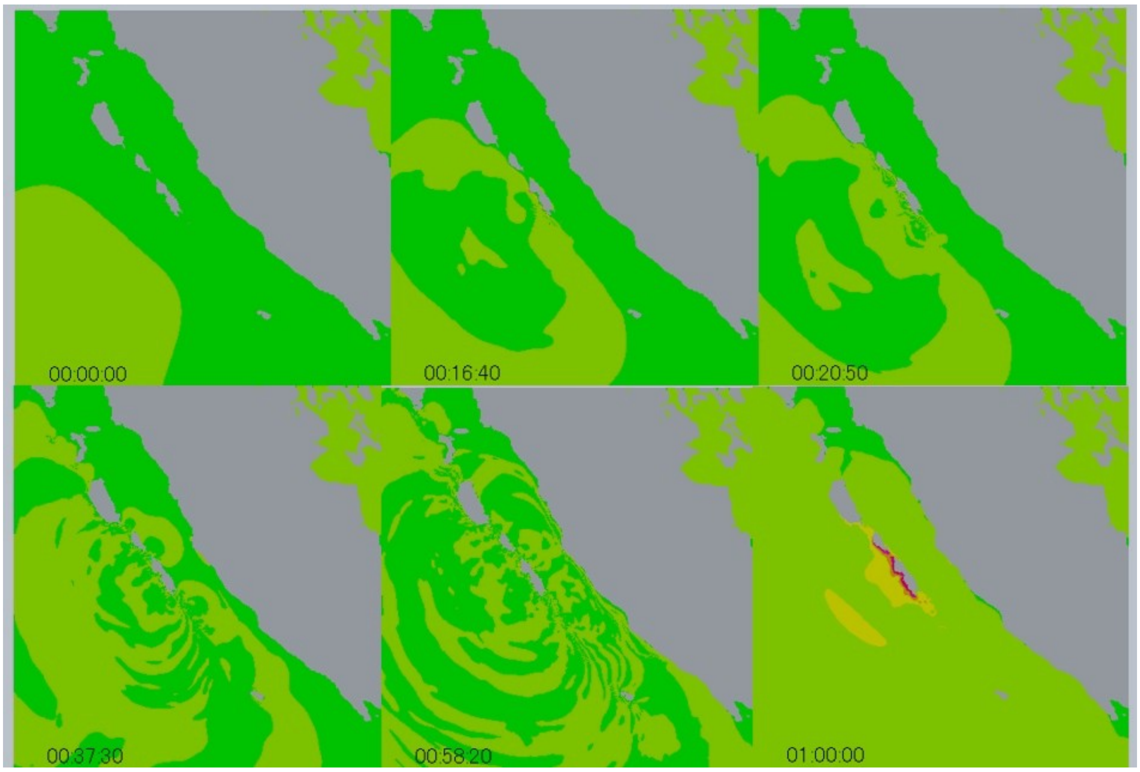

FIG. 4: Tsunami wave propagation of the Mentawai earthquake on October 25, 2010.

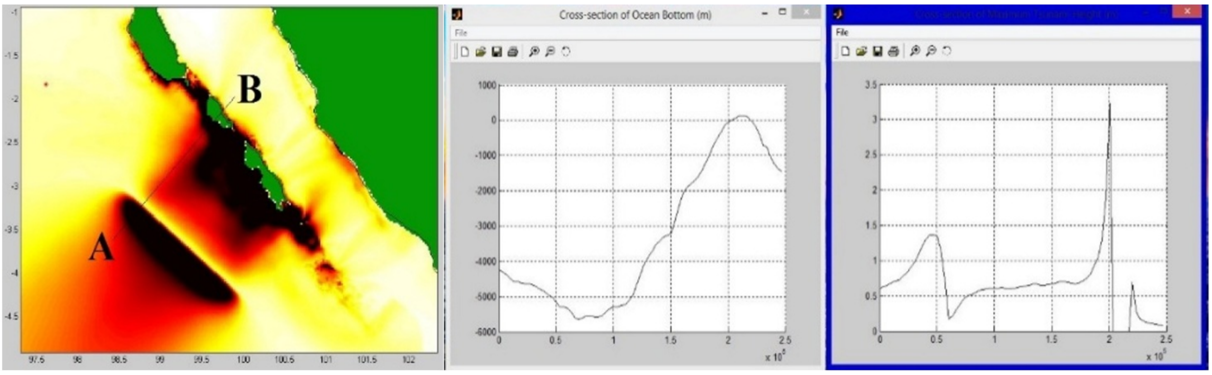

FIG. 5: Cross-section plot of ocean bottom A-B (Sipora island) (distance A to B is 247,3371 km).

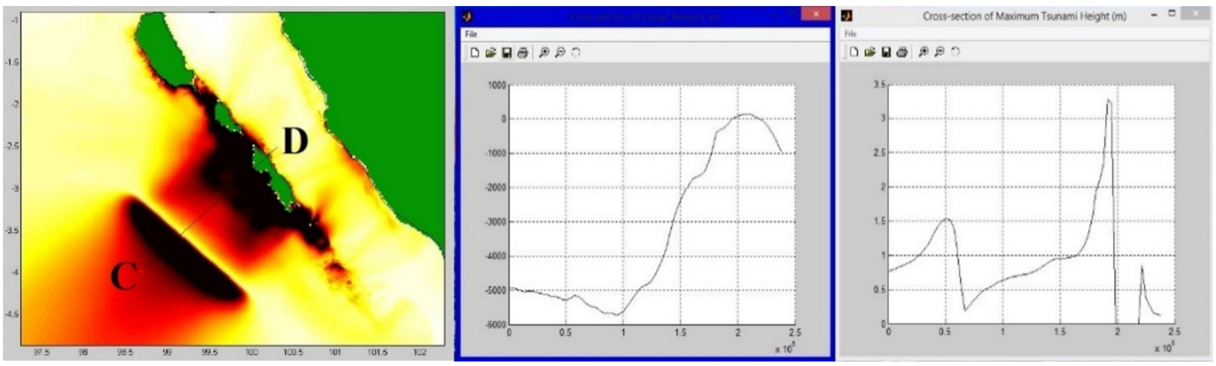

FIG. 6: Cross-section plot of ocean bottom C-D (North Pagai Island) (distance C to D is 238,4714 km).

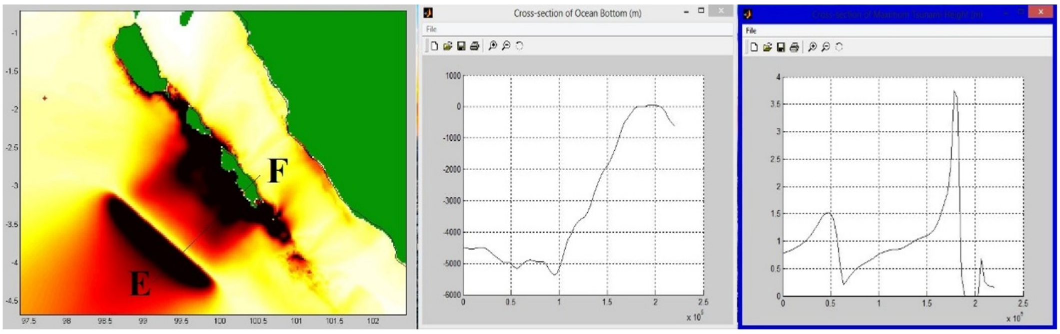

FIG. 7: Cross-section plot of ocean bottom E-F (South Pagai Island) (distance E to F is 220,5039 km).

TABLE II: Comparison of the run up of the Mentawai tsunami of October 25, 2010 from simulation results with survey results by GITST.

Research Area	Run Up (m) Simulation Results	Survey Results
Batimonga Bay	2.43	2.2
Bosua/Ghobi Bay	2.11	1.5
Tumele Bay	4.29	4
Macaroni/pasangan Bay	2.88	2.4
Sabeugunggu Bay	6.34	8
Malacopa Bay	2.94	2.5
Asahan Bay	2.97	2.8

IV. CONCLUSION

Based on the results and discussion of this research, it can be concluded that the Mentawai earthquake of October 25, 2010 had an earthquake source mechanism with fault length of 218.78 km, fault width of 45.70 km, and slip of 3.84 m. While the results of tsunami modeling show that the vertical displacemeht value obtained is the maximum value of 1.55 m and the minimum value is 1.55 m. The ocean modeling results show that the tsunami waves reached Sipora Island, North Pagai, and South Pagai at 20 minutes and 50 seconds. While the simulation results of tsunami run up modeling show that the maximum run up is at Sabeugunggu Beach with a run up value of 6.34 meters. The tsunami run up modeling in this study has an RMSE value of 0.73.

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[1] K. Bima Pramudya, *et al.*, "Analisa Perubahan Kecepatan Pergeseran Titik Akibat Gempa Menggunakan Data SuGar (Sumatran GPS Array)," J. Tek. ITS, vol. 5, no. 2, p. 2301-9271, 2016.
[2] F. Rahma, *et al.*, "Korelasi Tingkat Seismisitas dan Periode Ulang Gempa Bumi di Kepulauan Mentawai dengan Menggunakan Metode Guttenberg-Richter Korelasi Tingkat Seismisitas dan Periode Ulang Gempa Bumi di Kepulauan Mentawai dengan Menggunakan Metode Guttenberg-Richter," J. Fis. Unand, vol. 7, no. Januari, p. 1, 2018, doi: 10.25077/jfu.7.1.84-89.2018.
[3] K. Anton Setyo, "Structural Analysis of The Sumatran Fault Zone Around The Semangka Bay, Lampung South Sumatera," in Proceedings Indonesian Association of Geologists (IAGI) 13th Annual Convention, 1991.
[4] I. Titin, "Mekanisme Fokus Gempa Bumi Mentawai," Universitas Islam Negeri Syarif Hidayatullah Jakarta, 2011.
[5] D. Fitra Harris, *et al.*, "Integrated Seismic Attributes Analysis of Naturally Fractured Basement Reservoir: An Approach to Define Sweet Spot for Optimum Well Location and Trajectory," in Proceedings, Indonesian Petroleum Association, 2017, no. May. doi: 10.29118/IPA.50.17.214.G.
[6] S. Leni, *et al.*, "Analisis Perubahan Ionosfer Akibat Gempa Mentawai Tahun 2010 (Studi Kasus: Kepulauan Mentawai)," J. Tek. ITS, vol. 5, no. 2, p. 11-16, 2016.
[7] D. Cahya, *et al.*, "Pemodelan Segmentasi Mentawai-Pagai: Studi Kasus Gempa Megathrust di Indonesia," J. Geosains dan Remote Sens., vol. 1, no. 2, p. 105-110, 2020, doi: 10.23960/jgrs.2020.v1i2.56.
[8] D. Alifvia, D. Pujiastuti, and T. Anggono, "Studi Bahaya Seismik dengan Metode Probabilistic Seismic Hazard Analysis di Sumatera Barat," J. Fis. Unand, vol. 12, no. 3, p. 445-451, 2023, doi: 10.25077/jfu.12.3.444-450.2023.
[9] R. Eva S., *et al.*, "Rekonstruksi Tsunami Mentawai dengan Menggunakan COMCOT v1.7," Nekton, vol. 2, no. 2, p. 54-62, 2022.
[10] USGS, "M7.8 Kepulauan Mentawai region, Indonesia (BETA)," USGS, 2024. https://earthquake.usgs.gov/ earthquakes/ eventpage/usp000hnj4/focal-mechanism
[11] A. Sabar, "Energi Potensial Gempabumi Di Kawasan Segmen

Mentawai - Sumatera Baratt (0.5 LS 4.0 LS dan 100 BT 104 BT)," PSJ, vol. 2, no. 1, 2014.

[12] BNPB, "Rencana Aksi Rehabilitasi dan Rekonstruksi Pascabencana, serta Percepatan Pembangunan Wilayah Kepulauan Mentawai Provinsi Sumatera Barat Tahun 2011-2013." Sumatera Barat: Badan Nasional Penanggulangan Bencana, 2010.

[13] R. Mudzullah, and Syafriani, "Hazard Seismic Zonation Analysis of West Sumatra Region Using Probabilistic Hazard Seismic Analysis (Phsa) Method," Pillar Phys., vol. 14, no. 1, p. 8-17, 2021, doi: 10.24036/10753171074.

[14] S. Wiko, *et al.*, "Validasi Pemodelan Tsunami Berdasarkan Software L-2008 Menggunakan Data Sumber Gempabumi USGS, IRIS, CMT, dan GFZ Untuk Studi Kasus Tsunami Nias 28 Maret 2005," J. Meteorol. dan Geofis., vol. 16, no. 1, p. 25-36, 2015.

[15] S. Yudi, *et al.*, "Pemetaan Kelompok Sebaran Titik Gempa Bumi Mentawai Dengan Metode K-Medoids Clustering," J. Teknoinfo, vol. 16, no. 1, p. 124, 2022, doi: 10.33365/jti.v16i1.932.

[16] W. Donald L., *et al.*, "New Empirical Relationships among Magnitude , Rupture Length , Rupture Width , Rupture Area , and Surface Displacement," Bull. Seismol. Soc. Am., vol. 84, no. 4, p. 974-1002, 1994.

[17] H. Thomas C., *et al.*, "A Moment Magnitude Scale," J. Geophys. Res., vol. 84, no. B5, 1979.