Analysis of Earthquake Hazard-Prone Areas Using Peak Ground Acceleration (PGA) Values in Enggano Island, Bengkulu

Hangga Novian Adi Putra[1]*

[1]Department of Physics, Faculty of Mathematics and Natural Sciences, Universitas Udayana, Badung, Bali, Indonesia 80361

Email: *hangga@unud.ac.id

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Abstract – *Enggano Island is one of the oceanic islands located on the outermost edge of Bengkulu Province, which makes it highly vulnerable to tectonic earthquake hazards. This study aims to analyze the level of earthquake hazard vulnerability in the Enggano Island region of Bengkulu Province by utilizing Peak Ground Acceleration (PGA) values as the main indicator for assessing earthquake hazard potential. This study was conducted using 37 earthquake events data that occurred in the vicinity of Enggano Island within the time span from 1990 to 2025. The earthquake data used in this analysis focused on events with a magnitude of 4 Mw or higher and depth less than 50 km. Based on the disaster vulnerability analysis in the Enggano Island area, the regions with the highest earthquake hazard levels are Banjar Sari, Meok, Malakoni, and also a portion of Apoho, which have a PGA range of 106 gal to 114 gal and VI MMI scale. The moderate hazard levels are upper parts of Banjar Sari, Meok, Apoho, and Malakoni, as well as the southern portions of Kaana and Kahyapu, which have a PGA range of 94 gal to 104 gal and VI MMI scale. In contrast, the areas with lower hazard levels are found in the northern parts of Kaana and Kahyapu, where the PGA ranges from 78 to 92 gal and corresponds to intensity level V on the MMI scale. This study indicates that Enggano Island falls within a moderate earthquake hazard category.*

Keywords: *Earthquake; Enggano; PGA; Mitigation*

1. Introduction

An earthquake is a natural event that occurs as a result of the sudden release of energy from within the Earth's crust. This released energy generates seismic waves that cause vibrations and shaking on the Earth's surface [1]. Earthquakes can have significant impacts on the environment, infrastructure, and human safety, depending on the magnitude and depth of the earthquake source.

Earthquakes are natural events that can be triggered by various factors. Some of the main causes include tectonic activity, which involves the movement of rock layers within the Earth's crust that collide or shift against each other. In addition, earthquakes can also be caused by volcanic activity, the impact of extraterrestrial objects such as large meteors striking the Earth's surface, landslides on land or under the sea, and human activities such as underground bomb testing. However, among these causes, tectonic activity remains the most common factor responsible for earthquakes, especially in regions located along the boundaries of Earth's tectonic plates [2].

The threat of earthquakes extends across nearly all regions of the Indonesian Archipelago, ranging from minor tremors to major quakes capable of causing significant damage. This high level of seismic hazard is closely related to Indonesia's geographic setting as an archipelagic country located at the convergence of three major tectonic plates, namely the Eurasian Plate, the Indo-Australian Plate, and the Pacific Plate [3]. The only area relatively safe from earthquake sources is most of Kalimantan Island, particularly the western, central, and southern parts. Nevertheless, this region can still experience tremors originating from earthquake epicenters located in the Java Sea and Makassar Strait. Geographically, earthquake-prone areas in Indonesia include the provinces of Aceh, North Sumatra, West Sumatra, Bengkulu, Lampung, West Java, the Special Region of Yogyakarta, Central Java, East Java, and the eastern regions such as Bali, Nusa Tenggara, Sulawesi, the Maluku Islands, North Maluku, and Papua [4].

Enggano Island is located within the administrative region of Bengkulu Province, specifically in North Bengkulu Regency. The island covers an area of approximately 400.6 km² and consists of six villages:

Banjarsari, Apoho, Meok, Malakoni, Kahyapu, and Kaana [5]. These six villages form part of the local community inhabiting the island, which is characterized by its unique geographical features and relatively remote location.

Geographically, Enggano Island has a coastline length of approximately 126.71 km, stretching about 35.60 km from the northwest to the southeast, from Teluk Berhau to Tanjung Kahoubi. The island spans a width of around 12.95 km from the northeast to the southwest, specifically from Malakoni Harbor to Tanjung Kioyo. Enggano Island is separated from Sumatra Island by the Indian Ocean, making access to the island relatively limited and requiring a considerable sea journey. The distance from Enggano Island to Pulau Baai Port, Bengkulu is 156 km [6].

Administratively, the territorial division and geographical location of Enggano Island can be seen more clearly in Figure 1, which displays the island's administrative map along with the boundaries of its existing villages. This information is essential as a basis for research planning, disaster risk mapping, and sustainable regional development.

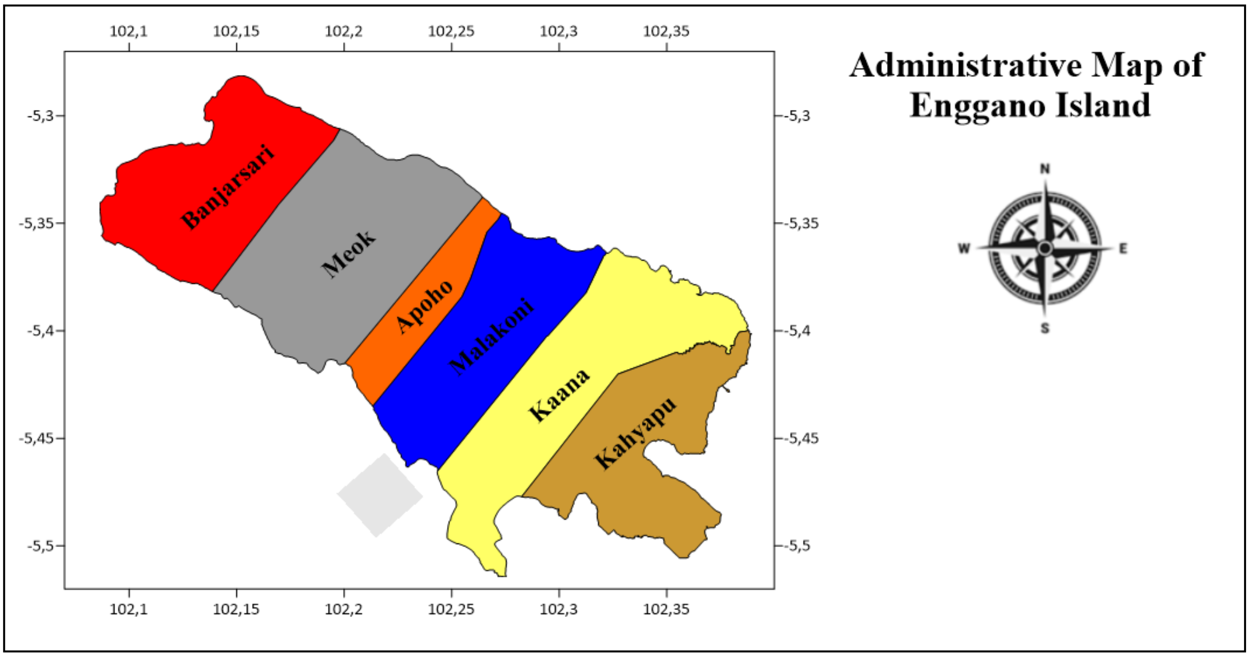

Figure 1. Administrative Map of Enggano Island

Enggano Island is one of the oceanic islands located in the outermost part of Bengkulu Province, which makes it highly vulnerable to tectonic earthquake hazards. One of the largest earthquakes that has ever occurred on Enggano Island was the earthquake in the year 2000, with a magnitude of 7.9 Mw, which caused severe impacts, including structural damage to buildings and loss of life [7]. Therefore, appropriate measures are required to effectively mitigate and respond to such natural disasters.

Disasters are unavoidable events; however, their impacts can be minimized [8]. One of the ways to minimize the impact of earthquake disasters in the Enggano Island region is by creating a hazard vulnerability map using Peak Ground Acceleration (PGA) analysis to determine the level of the island's susceptibility to earthquakes. PGA represents the maximum value of ground acceleration at a given location resulting from earthquake-induced ground shaking over a specific period of time [9]. PGA values can be derived based on earthquake magnitude, the distance from the earthquake focus to the observation location, and the depth of the earthquake source.

Therefore, a study was conducted to analyze the level of earthquake hazard vulnerability in the Enggano Island region, Bengkulu Province. This analysis was carried out by utilizing PGA values as the main indicator for measuring earthquake hazard potential. An evaluation of twelve PGA equations for subduction-zone earthquake sources was conducted using 3090 accelerograph records from the Java and Sumatra regions. The results indicate that the equations developed by Youngs et al. and Zhao et al. show the best agreement with the accelerograph data from these regions [10]. In this study, PGA values were calculated using an empirical equation developed by Youngs et al., which is widely used in seismic hazard studies due to its ability to accurately estimate peak ground acceleration based on the distance to the earthquake source and other seismic parameters.

The PGA values obtained from these calculations were then mapped in the form of contour maps using spatial modelling methods. The resulting PGA contour map is expected to serve as an important reference for identifying areas with higher levels of earthquake vulnerability on Enggano Island.

2. Materials and Methods

This study was conducted using earthquake event data that occurred in the vicinity of Enggano Island within the time span from January 1990 to April 2025. The earthquake data used in this analysis focused on events with a magnitude of 4 Mw or greater and depth less than 50 km, considering that earthquakes of such magnitude generally have the potential to cause significant impacts on the surrounding geological conditions and environment.

During this period, a total of 37 earthquake events met the criteria and were used as the basis for calculations in this study. The epicenter points of these 37 earthquakes were mapped to illustrate the distribution of seismic activity around Enggano Island. This earthquake data serves as a crucial element in determining the Peak Ground Acceleration (PGA) values at each grid point within the study area. The PGA values can be calculated using Microsoft Excel. To obtain representative PGA values for each part of the study area, the region is divided into grids with an interval of 1 km (equivalent to 0.01°). This interval is suitable for relatively small areas or small islands, such as Enggano Island. Subsequently, the highest PGA value at each calculation point is used in the interpolation process and earthquake intensity calculation [11].

In this study, Enggano Island was divided into 402 evenly distributed grid points. At each grid point, the PGA value was calculated based on all identified earthquake sources. The calculations were performed using the Youngs et al. equation, which is capable of estimating PGA values based on the distance from the earthquake source as well as the magnitude of the earthquake. The earthquake location map, which serves as the research object, is presented in Figure 2, providing a visual representation of the spatial distribution of the analyzed earthquakes.

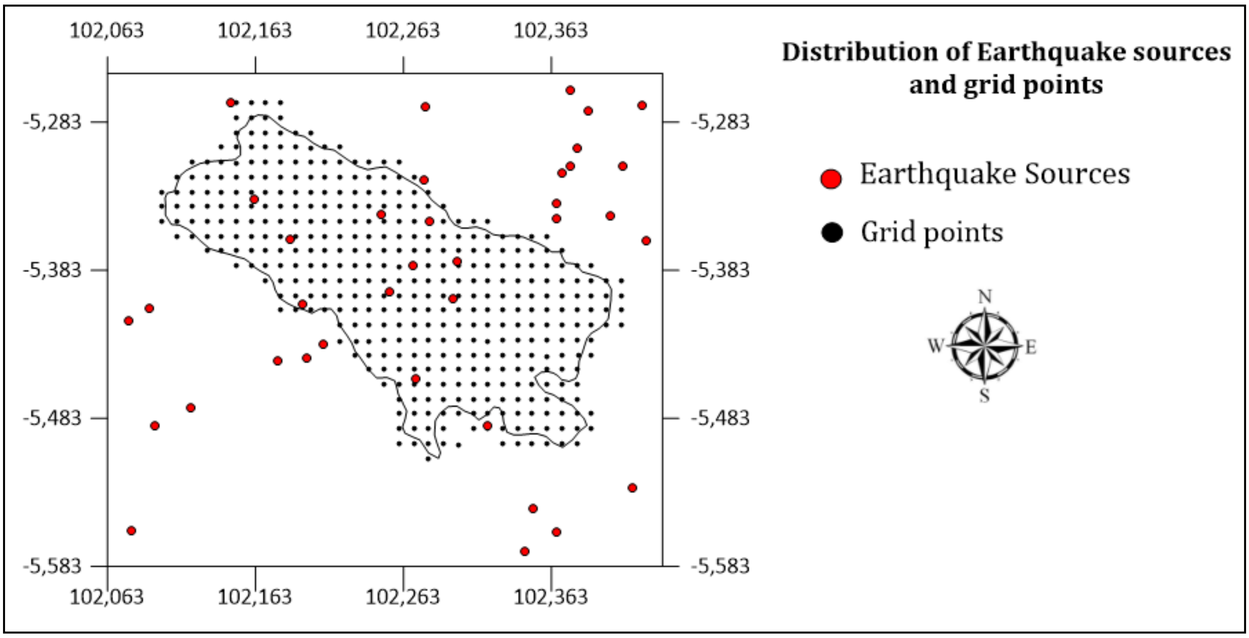

Figure 2. Distribution of Earthquake Epicenters in the Enggano Island Region (1990–2025) and grid points [12]

Each grid point will produce 37 PGA values, each representing a different earthquake source. The highest PGA value is then selected to obtain a representative PGA value for each grid point. The results of these calculations are used to create a PGA distribution map that shows the variation in ground acceleration levels across Enggano Island, ultimately serving as a reference for identifying areas with higher earthquake hazard potential.

The PGA values can be calculated using an empirical formula based on the Youngs et al. method. The formula is based on earthquake data with a subduction mechanism. The data used in developing this function come from earthquakes with focal depths ranging from 10 km to 229 km, making it suitable for the Enggano Island area and the earthquake data used. The equation is described as expressed [13]:

$$\ln(PGA) = -0.6687 + 1.438M - 2.329\, ln(R + 1.097\, e^{0.617M}) + 0.00648H + 0.3643Zt \quad (1)$$

where,
PGA = Peak Ground Acceleration (g)
M = moment magnitude (Mw)
R = hypocentral distance (km)
H = focal depth (km)
Zt = earthquake source type (0 for interface earthquake, and 1 for intraslab earthquake)

The distance from the surface point to the earthquake hypocenter is calculated using the equation:

$$R = \sqrt{\Delta S^2 + H^2} \quad (2)$$

where the epicentral (horizontal) distance between two points on the surface is calculated using the following Haversine equation:

$$\Delta S = 2R_e\left(\sqrt{sin^2\left(\frac{\theta_2-\theta_1}{2}\right) + cos\theta_1\, cos\theta_2\, sin^2\left(\frac{\gamma_2-\gamma_1}{2}\right)}\right) \quad (3)$$

where,
θ_1, γ_1 = latitude and longitude of the surface point
θ_2, γ_2 = latitude and longitude of the epicenter
H = earthquake depth
R_e = Earth's radius ≈ 6371 km

The calculation of earthquake intensity is carried out using the following equation [14]:

$$MMI = 3.66 \log PGA_{(in\ gal)} - 1.66 \quad (4)$$

MMI = Modified Mercalli Intensity.

3. Result and Discussion

In this study, the Enggano Island region was divided into 402 grids as the basis for spatial analysis to calculate Peak Ground Acceleration (PGA) values. For each grid, PGA values were calculated based on the contributions from 37 previously identified earthquake sources. These calculations employed the empirical equation developed by Youngs et al., which allows for the estimation of maximum ground acceleration at a specific location by considering the distance from the earthquake source and relevant seismic parameters.

Each grid produces 37 PGA values, each representing the ground acceleration impact from an individual earthquake event. The highest PGA value at each calculation point is used in the interpolation process and earthquake intensity calculation. These PGA values serve as the basis for analyzing the level of earthquake hazard across Enggano Island.

Subsequently, the PGA values were converted into Modified Mercalli Intensity (MMI) values to illustrate the level of earthquake shaking intensity felt at the surface. This conversion provides a more understandable representation of the earthquake's impact, particularly in the context of its effects on communities and infrastructure.

Complete data on the PGA values and the corresponding MMI values calculated for each grid are presented in Table 1, which serves as the primary reference for generating the intensity distribution map and analyzing earthquake-prone areas within the study region.

Table 1. Calculated PGA and MMI Values at Each Grid Point

Grid	Longitude	Latitude	PGA (gal)	MMI
1	102.150	-5.270	86.42	V
2	102.160	-5.270	86.76	V
3	102.170	-5.270	86.99	V
4	102.180	-5.270	87.11	V
5	102.180	-5.280	88.19	V
6	102.170	-5.280	88.15	V
7	102.160	-5.280	87.97	V
8	102.150	-5.280	87.66	V
9	102.150	-5.290	89.89	V
10	102.160	-5.290	90.22	V
11	102.170	-5.290	90.41	V
12	102.180	-5.290	90.46	VI
13	102.190	-5.290	90.35	V
14	102.150	-5.300	92.11	VI
15	102.160	-5.300	92.45	VI
16	102.170	-5.300	92.65	VI
17	102.180	-5.300	92.70	VI
18	102.190	-5.300	92.59	VI
19	102.200	-5.290	90.11	V
20	102.200	-5.301	92.55	VI

Complete data can be accessed here https://doi.org/10.5281/zenodo.17330100

Based on the calculated PGA values at each predefined grid point, a spatial modeling process was conducted to illustrate the distribution of PGA values across Enggano Island. This modeling was carried out using Surfer software, which enables the visualization of data in the form of contour maps that are more informative and easier to interpret.

The result of this modeling is a PGA distribution map that illustrates the variation of peak ground acceleration at each grid point across Enggano Island. This map is highly significant, as it can be used to identify areas with higher potential seismic hazards. By understanding the distribution of PGA values, further analysis can be conducted to assess the level of seismic risk faced by each region on Enggano Island. The PGA map visualization resulting from the spatial modeling can be seen in Figure 3, which clearly shows the distribution of PGA values across the entire area of Enggano Island.

Based on the distribution map of PGA on Enggano Island, the areas with the highest ground acceleration are located in the southwestern part of the island. The orange and red colors on the map indicate the highest PGA values, ranging from approximately 106 to 114 gal, which signify a higher level of seismic hazard compared to other areas. When compared with the administrative map of Enggano Island, these high-PGA zones cover most parts of Banjar Sari, Meok, Malakoni, and also a portion of Apoho.

The moderate PGA values, ranging from 94 to 104 gal and represented by green to yellow colors, form a transitional zone extending from the northwest to the southeast of Enggano Island. This indicates areas with a moderate level of seismic hazard. The zone includes the upper parts of Banjar Sari, Meok, Apoho, and Malakoni, as well as the southern portions of Kaana and Kahyapu.

In contrast, the lowest PGA values are found in the northeastern part of Enggano Island. This area is represented by purple and light blue colors, with PGA values ranging from 78 to 92 gal. Based on the administrative map, the low-PGA zone is located around the northern areas of Kaana and Kahyapu. These regions fall within a lower seismic hazard zone compared to other parts of the island.

From a geological perspective, Enggano Island consists of alluvial deposits, bedded and reef limestones, and sandstone units [15]. Areas with high Peak Ground Acceleration (PGA) values are geologically dominated by alluvial deposits, sandstone, quartz sandstone, siltstone, claystone, and tuffaceous sandstone units. These lithologies are poorly to moderately consolidated, resulting in low seismic impedance and greater seismic wave amplification. Consequently, the maximum ground acceleration increases as seismic waves propagate through these rock units. Areas with moderate to low Peak Ground Acceleration (PGA) values are generally composed of reef limestone and bedded limestone units. Limestone is relatively more compact and rigid, resulting in higher shear-wave velocities and reduced seismic wave amplification. Consequently, ground motion response in these areas tends to be lower.

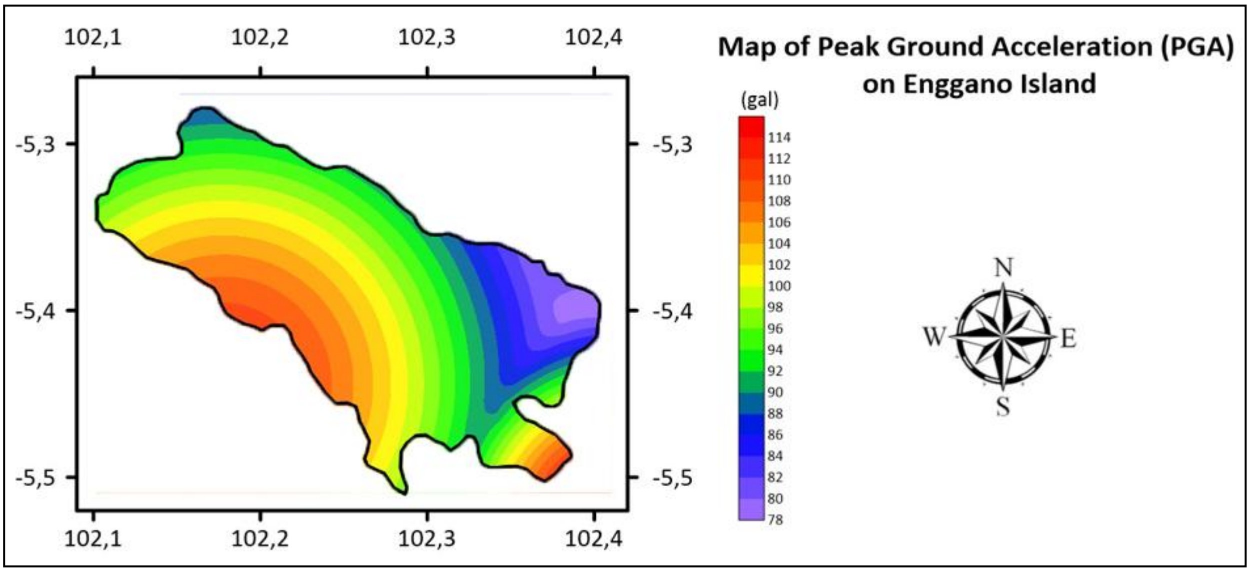

Figure 3. Map of Peak Ground Acceleration on Enggano Island

The risk from earthquake disasters can be assessed based on the Modified Mercalli Intensity (MMI) values in the affected area. Enggano Island has MMI values ranging from V to VI. The MMI map visualization resulting from the spatial modeling can be seen in Figure 4.

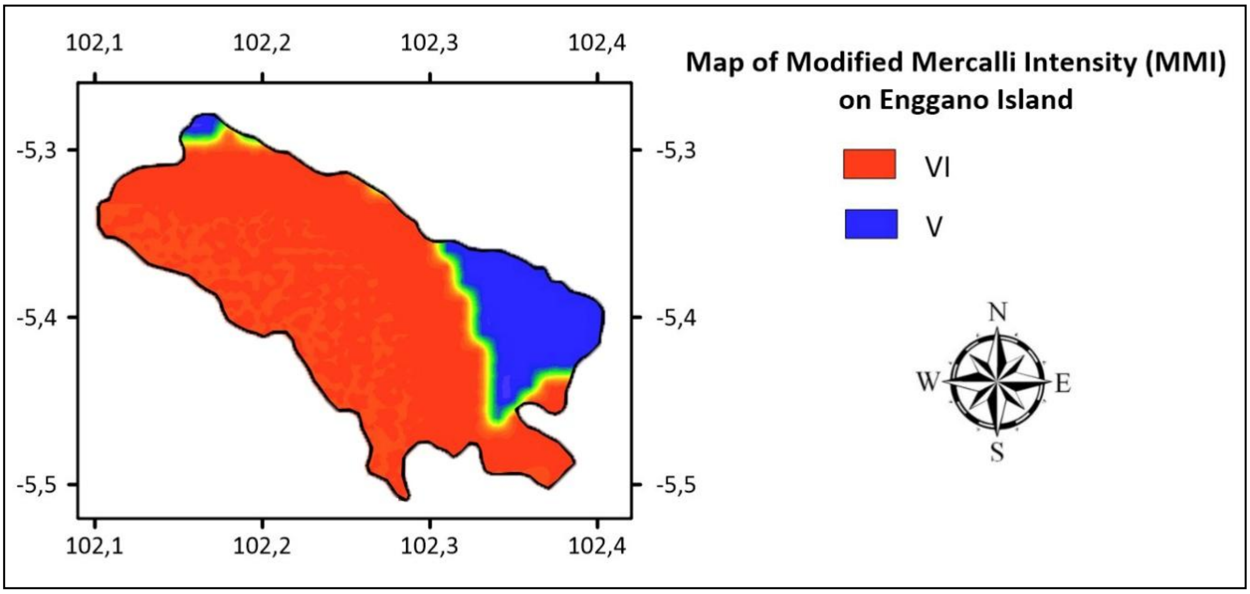

Figure 4. Map of MMI on Enggano Island

Based on the MMI (Modified Mercalli Intensity) map of Enggano Island, the island is predominantly characterized by MMI scale VI, which covers the areas of Banjar Sari, Meok, Apoho, Malakoni, as well as the southern parts of Kaana and Kahyapu. A small area with MMI scale V appears in the northeastern part of Enggano Island, encompassing the northern sections of Kaana and Kahyapu. This pattern is consistent with the island's geographical position, which faces directly toward the Sumatra subduction zone, where the strongest seismic energy is received by the southwestern region of Enggano Island.

The effects of earthquakes on infrastructure and communities can be correlated with the MMI scale in each area. The details of the MMI scale are presented in Table 2.

Table 2. Modified Mercalli Intensity (MMI) Scale

MMI	Earthquake Effects
I	The tremor is not felt except under exceptional circumstances by a few people.
II	Felt by a few people; light, hanging objects may sway.
III	Clearly felt indoors; vibrations are similar to those caused by a passing truck.
IV	Felt by many people indoors and by a few outdoors; ceramics may break, windows and doors rattle, and walls make creaking sounds.
V	Felt by nearly everyone; many people are awakened. Ceramics break, objects are displaced, poles and large items sway visibly.
VI	Felt by everyone. Most people are frightened and run outdoors. Plaster may fall from walls, factory chimneys are damaged; minor structural damage occurs.
VII	Slight damage to well-constructed buildings; poorly built structures suffer cracks or partial collapse. Factory chimneys may break. Felt by people in moving vehicles.
VIII	Slight damage to strong buildings; significant cracks in weak structures; walls may separate from frames; factory chimneys and monuments collapse; water becomes turbid.
IX	Damage to well-built structures; building frames become distorted and cracked; houses may shift from their foundations; water and gas pipes are broken.
X	Well-built wooden structures are destroyed; building frames separate from foundations; the ground cracks; railway lines bend; landslides occur along rivers and steep slopes.
XI	Very few buildings remain standing; bridges are destroyed; ground fissures form; underground pipes are completely broken; railway lines are severely bent.
XII	Total destruction. Waves are seen on the ground surface; the landscape becomes dark; objects are thrown into the air.

Table 2 illustrates the earthquake effects experienced by both the population and infrastructure. Enggano Island, which is predominantly classified under MMI scale VI, indicates that the observed effects include minor structural damage, such as fine cracks on walls of houses or buildings. In contrast, areas categorized under MMI scale V experience noticeable shaking felt by many people, causing household objects to fall, but without causing structural damage to infrastructure. This study indicates that Enggano Island is classified within a moderate earthquake hazard category.

The earthquake disaster mitigation efforts on Enggano Island are highly important. This is because Enggano Island is prone to earthquakes, as it is located in close proximity to the Indian Ocean and lies at the convergence of the Eurasian and Indo-Australian plates within the Sunda Megathrust zone [16]. The Sunda megathrust zone has five major earthquake sources, namely the Aceh-Andaman, Nias-Simeulue, Mentawai-Siberut, Mentawai-Pagai, and Enggano segments [17].

Enggano Island is located approximately 150 km from the main subduction zone of the Sunda Megathrust, off the southwest coast of Sumatra Island. However, although the horizontal distance is relatively short, Enggano Island lies outside the main subduction zone and is situated closer to the transitional zone between the Indo-Australian and Eurasian plates.

Earthquakes are natural phenomena that cannot be predicted in terms of their occurrence. Hence, conducting more extensive research on disaster mitigation is essential to reduce potential losses and earthquake impacts on Enggano Island in the future. Disaster knowledge plays a crucial role in providing a positive impact on the community during the occurrence of a disaster [18]. An important factor contributing to the success of earthquake disaster mitigation is the community’s frequent participation in disaster preparedness training and earthquake drills, as well as their valuable experience in dealing with such disasters [19]. An individual's experience in facing earthquake disasters can influence their level of preparedness in determining appropriate actions when dealing with challenges and obstacles, including preparedness before a disaster occurs, response during the disaster, and the rehabilitation process after the disaster [20]. This earthquake disaster mitigation will be effective if the region possesses accurate and comprehensive information regarding the level of earthquake hazard.

4. Conclusion

Based on the disaster vulnerability analysis in the Enggano Island area, the regions with the highest earthquake hazard levels are Banjar Sari, Meok, Malakoni, and also a portion of Apoho, which have a Peak Ground Acceleration (PGA) range of 106 gal to 114 gal and VI MMI scale. The moderate hazard levels are upper parts of Banjar Sari, Meok, Apoho, and Malakoni, as well as the southern portions of Kaana and Kahyapu, which have a PGA range of 94 gal to 104 gal and VI MMI scale. Meanwhile, the areas with lower hazard levels are around the northern areas of Kaana and Kahyapu, which have a PGA range of 78 gal to 92 gal and V MMI scale. The results of this study indicate that Enggano Island falls within a moderate seismic hazard zone. Nevertheless, the implementation of earthquake mitigation measures remains essential, considering the island's proximity to the subduction zone. The findings of this research can be used as a reference for the planning and implementation of earthquake mitigation strategies on Enggano Island.

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