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Article

Mitigation strategies and policies recommendation for the economic impact of the Sunda Strait Megathrust: Seismic risk probability assessment and cost loss estimates

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Abstract: This study investigates seismic risk and potential impacts of future earthquakes in the Sunda Strait region, known for its susceptibility to significant seismic events due to the subduction of the Indo-Australian Plate beneath the Eurasian Plate. The aim is to assess the likelihood of major earthquakes, estimate their impact, and propose strategies to mitigate associated risks. The research uses historical seismic data and probabilistic models to forecast earthquakes with magnitudes ranging from 6.0 to 8.2 Mw. The Gutenberg-Richter model helps project potential earthquake occurrences and their impacts. The findings suggest that the probability of a major earthquake could occur as early as 2026–2027, with a more significant event estimated to likely occur around 2031. Economic estimates for a 7.8–8.2 Mw earthquake suggest potential damage of up to USD 1.255 billion with significant loss of life. The study identifies key vulnerabilities, such as inadequate building foundations and ineffective disaster management infrastructure, which could worsen the impact of future seismic events. In conclusion, the research highlights the urgent need for comprehensive seismic risk mitigation strategies. Recommendations include reinforcing infrastructure to comply with seismic standards, implementing advanced early warning systems, and enhancing public education on earthquake preparedness. Additionally, government policies must address these issues by increasing funding for disaster management, enforcing building regulations, and incorporating traditional knowledge into construction practices. These measures are essential to reducing future earthquake impacts and improving community resilience.

Keywords: government policy; infrastructure reinforcement; seismic risk; Sunda-strait earthquake; Gutenberg-Richter model

1. Introduction

The Earth formed billions of years ago through the slow process of tectonic plate subduction, which continuously generated new geological conditions and movements supporting earthquakes (Pilchin and Eppelbaum, 2020). Indonesia is situated along the Pacific Ring of Fire, making it one of the most earthquake- and volcanic-activity-prone countries. The Pacific Ring of Fire intersects with three major tectonic plates: the Indo-Australian Plate, the Eurasian Plate, and the Pacific Plate (Mukesh et al., 2024). This condition results in frequent natural disasters in Indonesia, such as earthquakes, volcanic eruptions, and tsunamis (Prakoso et al., 2022). Mexico ranks second with 1,833 earthquakes in the past year, with the strongest quake measuring 6.4 on the Richter scale (Ramírez-Herrera et al., 2020).

According to data from the Earthquake News (2024), Indonesia is among the countries with the highest frequency of significant earthquakes globally. In 2023, Indonesia experienced 2234 earthquakes, marking an increase of 27 events compared to the previous year (BMKG, 2021). Data also indicate that within a 300-kilometer radius of Indonesia, there will be 2205 major earthquakes with magnitudes of 4 or higher throughout 2023 (Annur, 2024). The strongest earthquakes ever recorded in Indonesia were a magnitude 9.1 earthquake in Aceh, Sunda Strait, in 2004 and a magnitude 9.2 earthquake in 1833, caused by the rupture of a 1000 km segment of the Sunda Trench in the southeast. These earthquakes occurred at nearly the same coordinates (Megawati et al., 2024). The Sunda Trench segment is connected to the Sunda Strait segment, located at the southern tip of the Sunda Strait, bordering the island of Java.

Recently, Japan experienced a magnitude 7.1 earthquake on 8 August 2024, northeast of Nichinan, Japan. This earthquake was triggered by seismic activity and crustal deformation, with a shallow fault rupture occurring at the interface of the subduction zone between the Philippine Sea and the Eurasian Plate (Journal of Midwifery Science, 2024 (USGS, 2024b). On Friday, 15 August 2024, Taiwan experienced a magnitude 6.1 earthquake with its epicenter at a depth of 15 kilometers in the Hualien region (USGS, 2024a). A few days after the earthquakes in Japan and Taiwan, the Indonesian government issued widespread warnings to the public, urging them to remain vigilant (Yeung et al., 2024). The Meteorology, Climatology, and Geophysics Agency (BMKG) indicated via its Instagram account the potential for earthquakes in two megathrust zones in Indonesia: the Sunda Strait Megathrust, estimated to have a magnitude of M8.9, and the Sunda Seismic Gap, predicted to have a magnitude of M8.7. BMKG advised the public not to panic regarding this information. Discussions about the earthquake potential in the Sunda Strait and Sunda Seismic Gap megathrust zones have been ongoing since before the 2004 Aceh earthquake and tsunami. The term "seismic gap" refers to a zone where large earthquakes have not occurred long (Foulger et al., 2017; Oluwafemi et al., 2018).

Based on two critical factors, BMKG has announced information regarding the potential for megathrust earthquakes. First, the region has experienced some of the strongest earthquakes globally. According to Live Science, Indonesia has witnessed two of the ten largest earthquakes in history. One of these events was the Banda Aceh earthquake on 26 December 2004, with a magnitude of 9.1 on the Richter scale, making it the third-largest earthquake ever recorded. Live Science reported that this earthquake resulted in nearly 300,000 deaths and displaced around 1.2 million people, with the subsequent tsunami being the most-deadly aspect. On 11 April 2012, an 8.6Mw earthquake occurred off the northern coast, with tremors felt as far away as Mumbai, India, and Broome, Australia, making it one of the largest recorded earthquakes in history (Syifa and Umar, 2024).

Second, BMKG emphasizes that discussions regarding the potential for megathrust earthquakes are not early warnings of imminent large earthquakes but are based on observations of seismic gaps and zones that have been earthquake-free for extensive periods spanning hundreds of years. BMKG explains that current scientific knowledge and technology cannot accurately predict when, where, or how strong an earthquake will be; rather, they can only estimate the likelihood of its occurrence. For instance, the most recent major earthquake in the Nankai Trough occurred in 1946, with a seismic gap of 78 years (Jarah et al., 2023). BMKG estimates that the last significant earthquake in the Sunda Strait occurred in 1797 with a seismic gap of 227 years, and another in the Sunda Strait occurred in 1757 with a seismic gap of 267 years. These gaps are significantly longer than the seismic gap in Nankai, indicating the need for more comprehensive mitigation preparation (Fauziyah, 2024; Supendi et al., 2020).

This study aims to project the likelihood of major earthquakes based on historical data from the Sunda Strait. Between 1883 and 2019, there were 20 earthquakes with magnitudes ranging from 5.1 to 8.2, according to BMKG data. From 1907 to 2022, there were 1762 earthquakes with magnitudes of 4.7 to 8Mw, according to USGS data, and from 1907 to 2010, there were 16 earthquakes with magnitudes above 7Mw, based on data from BMKG and USGS. The study also seeks to estimate potential losses, including casualties, injuries, structural damage, and overall costs if a megathrust earthquake occurs. It underscores the importance of central and provincial government policies to prepare and promote mitigation measures, particularly concerning earthquake-resistant building conditions and readiness to address the impacts of megathrust zones.

2. Method

This study employs the Probabilistic Seismic Hazard Assessment approach (Kumar et al., 2022), which is useful for evaluating and estimating the probability of earthquakes in the Sunda Strait region. The first step involves collecting historical earthquake data, including location information, estimated and actual magnitudes, depth, seismic intensity (MMI), fatalities and injuries, building damage, displacement, and potential tsunami impacts. The data collected since 1883 can be analyzed to identify patterns and frequencies of earthquakes in the region (Ansari et al., 2021; Rehman et al., 2016). The Gutenberg-Richter model estimates the annual frequency of earthquakes with specific magnitudes. This model relies on seismicity parameters calculated from historical data, with magnitude distributions typically ranging from 7 to 10. The model will likely provide predictions for future megathrust events, which is crucial for long-term risk assessment (Kijko and Smit, 2016). Subsequently, Ground Motion Prediction Equations (GMPEs) are utilized to estimate ground shaking intensity based on the earthquake magnitude and distance from the epicenter. GMPEs assist in predicting potential damage to infrastructure and buildings in affected areas and provide information on expected shaking levels at various distances from future earthquake sources. Using historical earthquake data and GMPE predictions, the analysis concludes by estimating the social and economic impacts of earthquakes in the Sunda Strait region, including fatalities, injuries, building damage, and total economic losses. This process ends with calculating the potential total losses (in USD), fatalities, injuries, and building damage caused by hypothetical megathrust earthquakes with magnitudes ranging from 9.0 to 9.3Mw. These approaches are intended to facilitate more accurate and comprehensive earthquake risk analysis, providing better guidance for future disaster mitigation and planning (Kumar et al., 2022).

2.1. Data catalog

This study utilizes earthquake catalogs from BMKG, USGS, and other historical sources related to earthquakes and tsunamis in the Sunda Strait. The catalogs include major earthquakes with magnitudes above 7.0 from 1613 to 2023. In the Sunda Strait region, between 1883 and 2019, there were 20 earthquakes with magnitudes ranging from 5.1 to 8.2, according to BMKG data. From 1907 to 2022, there were 1762 earthquakes with magnitudes ranging from 4.7 to 8Mw according to USGS data; and from 1907 to 2010, there were 16 earthquakes with magnitudes above 7 Mw, based on data from both BMKG and USGS. Local catalogs record thousands of earthquakes with magnitudes ≥ 4. Four of the ten strongest earthquakes in Indonesia occurred in this region (BMKG, 2021; Earthquake Bulletin, 2024). **Figure 1** and **Table 1** illustrate major earthquakes in the Sunda Strait from 1613 to 2023 with magnitudes above 7.

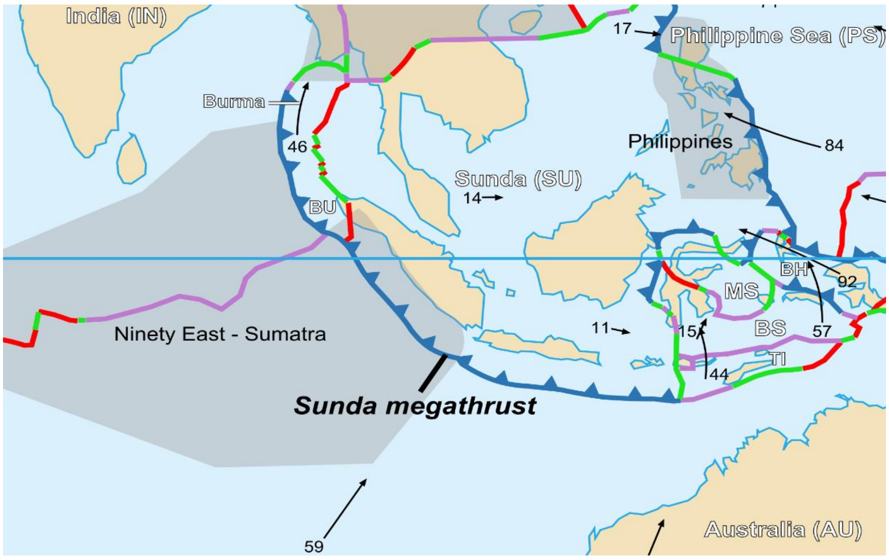

Figure 1. Seismic map of megathrust earthquakes in the Sunda strait region, Indonesia.

Source: Adopted from USGS and redesigned with ArcGIS software (2024).

Table 1. Major earthquakes in the Sunda Strait (1903–2023) with Magnitudes above 7 Mw.

No	Date	Latitude	Longitude	Depth (km)	Magnitude	MMI Scale	Land Movement (mm/year)	Duration of Earthquake/Tsunami (Minutes)	Deaths	Injuries	Destroyed Houses/Buildings	Evacuated	Data Source	Impact	Aftershocks	Tsunami (Meter)
a	**b**	**c**	**d**	**e**	**f**	**g**	**h**	**i**	**j**	**k**	**l**	**m**	**n**	**o**	**p**	**q**
1	1883-11-24	−3.50	102.20	10	8.2	VIII	49–60	60			5000		BMKG	Significant damage	3	
2	1851-05-04	−5.45	105.27	25	7.0	VII	49–60	60	216		20,000	30,000	BMKG	Significant damage	1.5	
3	1852-12-20	6.84	105.39	30	7.1	VII	49–60	60	319		812	6000	BMKG	Significant damage	1.5	
4	1903-27-02	6.81	105.34	15	7.9	VII	49–60	60	500		3000		BMKG	Significant damage	4	
5	1921-11-09	−10.1	110.65	15	7.6	VII	49–60	60			1500		USGS	Significant damage	0.5	
6	1926-10-09	−9.17	110.63	35	7.1	VII	49–60	1.5	300		1500		USGS	Significant damage	5	
7	1928-03-09	6.73	105.45	30	7.0	VII	49–60	60	200		2000		BMKG	Significant damage	7	3
8	1931-02-10	−5.36	102.59	35	7.1	VII	49–60	60	300		2500		USGS	Significant damage	3	
9	1933-06-24	6.79	105.41	20	7.5	VII	49–60	55	788	1000	686	8000	BMKG	Significant damage	5	
10	1943-04-01	6.71	105.34	35	7.1	VII	49–60	30	200		2000		BMKG	Significant damage	5	
11	1952-01-09	−5.45	105.27	25	7.0	VII	49–60	80	200		2000		BMKG	Significant damage	1	
12	1958-04-21	6.83	105.32	30	7.7	VII	49–60	80	200		2000		BMKG	Significant damage	4	8
13	1994-06-02	−10.5	112.84	18	7.8	VII	49–60	70	273		3000		USGS	Significant damage	18	14
14	2006-07-17	−9.28	107.42	20	7.7	VII	49–60	60	733	9299	1000	8026	USGS	Significant damage	19	21
15	2018-12-12	6.90	104.42	54	7.5	VII	49–60	120	583	1485	16,082	426	BMKG	Significant damage	0	5
16	2019-02-08	6.90	104.42	53	7.0	VII	49–60	20	8	8	505	33	BMKG	Significant damage	0	5

Notes: Numbers 1–4 and rows ‘l’ and ‘*n*’ are derived from historical literature; some are estimated figures.
Columns ‘d’ and ‘e’ are sourced from the USGS website.

2.2. Data analysis

Megathrust earthquakes occur at subduction boundaries—large fault lines within subduction zones—where denser tectonic plates move beneath lighter plates. This movement generates pressure that can lead to high-magnitude earthquakes if the pressure is suddenly released. Megathrust earthquakes typically occur in long and deep subduction zones. Information was collected from various sources to present location data with varying levels of completeness and accuracy. The discrepancy between predicted and actual magnitudes ranges from 0.1 to 1.4. Data for each location was manually reviewed to ensure accuracy and validity, referencing sources such as BMKG, USGS, historical catalogs, and other online sources. Subsequently, Peak Ground Acceleration (PGA) results were mapped using ArcGIS software, 2024, incorporating longitude, latitude, and PGA data for each island in the Sunda Strait region (Zera and Nafian, 2018). Based on PGA values, earthquake hazard levels can be assessed. According to BNPB (No.2 Year 2012), earthquake hazard classification includes Low Risk (PGA < 0.2501 gal), Moderate Risk (PGA 0.2501–0.70 gal), and High Risk (PGA > 0.70 gal). Data analysis was then performed by examining PGA values and mapping earthquake hazard zones. Higher PGA values indicate a greater risk of earthquakes at specific locations (Djazilus et al., 2018). Earthquake hazard is also based on seismic parameters a and b, with higher values indicating greater seismicity in the Sunda Strait region.

3. Literature review

Seismic Risk (SR) measures the likelihood of an earthquake causing social and economic impacts that exceed certain thresholds within a specific region and time frame. Two primary factors influencing SR are Seismic Hazard (SH) and Seismic Vulnerability (SV). Seismic Hazard refers to the potential damage an earthquake can cause in a given area. It assesses earthquake characteristics such as magnitude, frequency, and impact on structures. Seismic Vulnerability evaluates the likelihood of structural damage based on the intensity of the earthquake and the structural integrity of buildings. It considers the resilience of buildings and construction quality in the affected area (Zobin and Plascencia, 2022). SR integrates SH and SV to project potential financial losses and damage. Regions with high seismic activity and poor housing quality face greater seismic risk, reflecting global patterns. Housing quality can vary significantly within areas of similar seismic Hazard, affecting overall risk levels (Zobin, 2017).

Advanced disaster mitigation technologies, while costly, require continuous monitoring to be effective. Seismic hazard analysis can be deterministic for critical structures such as nuclear power plants or probabilistic for designing engineering structures. Evaluating SR involves determining seismic hazards (SH) by the maximum earthquake magnitude (Mmax), recurrence intervals, and intensity attenuation with distance. Mmax is estimated from historical records or geological faults, with recurrence intervals predicted using catalogs and Poisson distributions. Intensity attenuation is measured using the Modified Mercalli Intensity scale. Seismic Vulnerability (SV) uses Damage Probability Matrices to estimate the likelihood of damage to various types of buildings and calculates potential cost losses from different levels of damage (Salgado-Gálvez et al., 2015).

3.1. Earthquake probability theory

This study employs Probabilistic Seismic Hazard Assessment (PSHA) due to its relevance in evaluating future earthquake risks and its ability to integrate factors such as earthquake frequency and magnitude. PSHA combines historical data with mathematical models to predict future earthquake risks. The Gutenberg-Richter Law connects earthquake frequency and magnitude to estimate future occurrences. Historical data is used to estimate hazard parameters by comparing historical data with magnitude frequency curves and attenuation models (Pedercini and Barney, 2010). Plate Tectonics Theory, developed by Alfred Wegener, Arthur Holmes, and Harry Hess, explains that earthquakes occur along tectonic plate boundaries. Fault Theory, proposed by Charles Richter and Beno Gutenberg, details how seismic energy is released through crustal fractures and studies earthquake frequency and magnitude using historical data (Ince and Yılmazoğlu, 2021).

3.2. Earthquake risk management policy

To effectively manage seismic risk in the southern tip of Sunda Strait, particularly near Mount Krakatau, an integrated policy approach is essential. This region exhibits residential characteristics that heighten earthquake vulnerability, with many buildings being low-rise structures constructed using traditional techniques and local materials, which may be less resistant to large earthquakes (Saputra et al., 2017). This situation is similar to Colima, Mexico, where earthquake risk is higher in areas with poorer housing quality (Zobin and Plascencia, 2022). A comprehensive seismic risk assessment should integrate both seismic hazard and vulnerability analyses to identify and prioritize areas with the highest risk (Bintialiumar et al., 2020). Utilizing the Probabilistic Seismic Hazard Assessment (PSHA) model enables risk prediction based on historical data and future projections, with continuous monitoring to adapt to changing conditions. Building policies should enforce strict construction standards to enhance earthquake resilience, including retrofitting older structures. Educating the community through training and information campaigns is crucial for raising awareness and preparedness. Monitoring and evaluating seismic risk and supporting research into mitigation technologies are also vital. Risk classification based on local data ensures that mitigation efforts are tailored to regional characteristics. This holistic approach aims to reduce the impact of earthquakes in the Sunda Strait region, which faces high risk due to its location in an active subduction zone.

4. Results and analysis

4.1. Results

4.1.1. Presentation of megathrust locations in Indonesia

Information was gathered from various sources to present location data with differing levels of completeness and accuracy. According to expert records, megathrust earthquakes occur at subduction zones, where one tectonic plate descends beneath another. These events can produce extremely large and devastating earthquakes, often accompanied by destructive tsunamis (Amini et al., 2022). Megathrusts typically occur in long and deep subduction zones. Indonesia has a long history of significant seismic activity, particularly in the megathrust zone of the Sunda Strait. Two notable historical seismic events include the 8.2 Mw earthquake with a tsunami on 24 November 1883, the 7.9 Mw earthquake on 27 February 1903, and the 7.8 Mw earthquake on 2 June 1994.

4.1.2. Application of the Gutenberg-Richter law

The data in **Table 1** were analyzed based on recent reports from BMKG and USGS, which estimate the potential for megathrust earthquakes using several sources. Various indicators were calculated using the PSHA formula based on the ten strongest earthquakes in the Sunda Strait.

1) Earthquake estimation based on the Gutenberg-Richter formula

The Gutenberg-Richter relationship is a common approach for seismic analysis. The law describes the relationship between the magnitude and number of earthquakes and is usually expressed as:

$$\log 10(N) = a - b \times M \tag{1}$$

where:

N is the number of earthquakes with a magnitude M or greater.

M is the magnitude of the earthquake.

a and b are constants that need to be determined from earthquake data.

2) Analysis procedure

a. Cumulative Earthquake Count: In order to analyze the cumulative number of earthquakes in the Sunda Strait, the following steps were taken:

- Magnitude ≥ 8.0: 1 earthquake
- Magnitude ≥ 7.0: 13 earthquakes
- Magnitude ≥ 6.0: 16 earthquakes.

b. Linear Regression to Determine Constants a and b: Applying linear regression to the log-linear results yielded:

- Constant a: 1.859
- Constant b: −0.629
- R^2 value: 0.952 (indicating a strong correlation between magnitude and cumulative number of earthquakes).

c. Interpretation:

- Constant a: 1.859, representing the log 10(N) when magnitude M is 0.
- Constant b: −0.629, showing how much log 10(N) decreases for each unit increase in magnitude. The negative value indicates a decrease in earthquakes with higher magnitudes.
- R^2: 0.952, indicating that the linear regression model effectively explains the variability in cumulative earthquake data based on magnitude.

These results confirm that the relationship between magnitude and the cumulative number of earthquakes adheres to the Gutenberg-Richter law, and the linear regression model is very good at describing the data.

d. Conclusions from the Gutenberg-Richter Analysis:

1) Seismic activity level (value a**)**: 1.859

The Gutenberg-Richter law's value of functions is the regression model's intercept. This value represents log 10(N) when magnitude M is 0. Practically, it reflects the average seismic activity level. A higher value indicates relatively high seismic activity, suggesting frequent earthquakes across a range of magnitudes.

2) Ratio of small to large earthquake frequencies (value b: −0.629)

The value b is the slope of the regression line and indicates how the cumulative frequency of earthquakes with a certain magnitude decreases with increasing magnitude. The negative value suggests that higher-magnitude earthquakes are less frequent. Smaller magnitude earthquakes occur much more frequently than larger ones. A value of b less than 1 but positive (−0.629) indicates that while smaller earthquakes are more common, larger earthquakes are rarer. It does not imply that the region is more susceptible to large earthquakes but shows that large earthquakes are less frequent than smaller ones.

3) Correlation between magnitude and cumulative earthquake count (R^2: 0.952).

The R^2 value represents the proportion of variability in the cumulative number of earthquakes that changes in earthquake magnitude can explain. An R^2 value of 0.952 indicates that the linear regression model effectively explains the data. The high R^2 value (close to 1) suggests a strong correlation between magnitude and the cumulative number of earthquakes, meaning the model used aligns well with the data, and the relationship between magnitude and frequency is clear and well-predicted.

The analysis shows that the Sunda Megathrust region experiences a high level of seismic activity characterized by frequent earthquakes. The frequency of smaller magnitude earthquakes far exceeds that of larger ones, aligning with the Gutenberg-Richter law, which suggests a logarithmic distribution of earthquake magnitudes. It implies that while smaller quakes are common, larger, potentially more damaging events are relatively rare. Applying a linear regression model to the earthquake data proves highly effective. The model demonstrates a clear and predictable relationship between earthquake magnitude and the cumulative count of seismic events, affirming that the seismic activity in this region follows a consistent pattern. This predictive capability is crucial for understanding seismic risks and planning mitigation strategies. The findings underscore the importance of ongoing monitoring and modeling seismic activity in the Sunda Megathrust region. The data confirms that while high-magnitude earthquakes are less frequent, their potential impact underscores the need for preparedness and resilience measures. The predictable nature of the data, as indicated by the linear regression model, provides a solid foundation for forecasting future seismic activity and developing effective strategies to mitigate potential risks. This analysis provides insights into the seismic patterns in the Sunda Strait region and demonstrates that the Gutenberg-Richter model is a useful tool for understanding and predicting earthquake occurrences.

4.1.3. Earthquake estimation based on the Gutenberg-Richter formula

In order to forecast future earthquake occurrences using the Gutenberg-Richter model, the log-linear relationship described by the Gutenberg-Richter law is utilized log $10N = a - b.M.$

a) Determine constants a and b

These constants are obtained from regional historical earthquake data using linear regression. In this case, the following constants were identified: $a = 4.96$ and $b = 0.50$.

b) Predict earthquake frequency for specific magnitudes

- The number of earthquakes (N) with magnitude M or greater over a specified period can be predicted using the Gutenberg-Richter formula.
- For predicting the number of earthquakes with magnitudes of $M = 6$ and $M \geq 7$:

$$\log 10N = 4.96 - 0.50 \times 7$$

$$\log 10N = 4.96 - 3.50 = 1.46$$

Transforming the logarithmic result to a cumulative number:

$$N = 101.46 \approx 28.98$$

It indicates the cumulative number of earthquakes of 7 or greater magnitude over the considered period. It suggests that an earthquake of magnitude 7 or greater in the near term is unrealistic for a short period. Hence, according to the Gutenberg-Richter formula, it is unlikely that an earthquake with a magnitude of 7 or greater will occur in the Sunda Strait over the next 10 years.

c) Annual frequency prediction

A more realistic estimate can be obtained by using more detailed historical data, including the number of earthquakes with magnitude 6 or greater over a shorter period. For example, if there were approximately 1 to 2 earthquakes with magnitude 6 or greater in the past 10 years, the average annual frequency can be calculated as follows:

$$N_{\text{annual}} = \text{number of events in 10 years}/10$$

10 is the number of events in 10 years

If there are 2 events in 10 years: $N_{\text{annual}} = 2/10 = 0.2$

In conclusion, the average annual frequency in more realistic historical data is about 0.2 earthquakes of magnitude 6 or greater per year. Thus, to obtain a more accurate annual frequency prediction, the Gutenberg-Richter model's results must be validated with more specific historical data.

4.1.4. Ground motion based on GMPE analysis

GMPE can estimate the intensity of ground shaking at a specific distance from the earthquake's epicenter. The general form of GMPE is:

$$\ln(Y) = c1 + c2M - c3\log 10(R) \tag{2}$$

where:

- $M = 7$ (magnitude)
- $R = 25.5$ miles (distance from the epicenter)
- $c1$, $c2$ and $c3$ are GMPE coefficients specific to the region and soil conditions.

Assuming typical values for $c1$, $c2$, and $c3$, the GMPE formula can predict high ground shaking levels, resulting in an MMI intensity of VII (damage). It indicates potential significant infrastructure damage and substantial impact on the affected area. To calculate ground shaking using GMPE:

- Substitute values into the GMPE formula: $\ln(Y) = 0.1 + 0.2 \times 7 - 0.3\log 10(25.2)$
- Calculate: $\log 10(25.2) = 1.402$
- Value substitute log10 (25.2) into the equation: $\ln(Y) = 0.1 + 0.2 \times 7 - 0.3 \times 1.402 = 1.0779$

- Exponentiate to find $Y = e1.0779 \approx 2.93$
- The Interpretation of the Result $Y \approx 2.93$

The Interpretation of the calculation results is $Y \approx 2.93$, which is ground-shaking. This value is related to the intensity scale of the MMI, which provides a quantitative description of the impact of ground shaking on buildings and humans, which can be significantly damaging but not extreme.

4.2. Analysis

4.2.1. Characteristics of tectonic and seismic activity in the Sunda Strait region

The Sunda Strait subduction zone is part of the Pacific Ring of Fire and is seismically active due to the subduction of the Indo-Australian Plate beneath the Eurasian Plate along the megathrust in this region (Haridhi et al., 2018; Ogunkeye, 2018). The tectonic activity in this area has resulted in several significant earthquakes, including those on 26–27 August 1883 (8.2 Mw and 7.9 Mw), 24 November 1883 (7.7 Mw), and April 30, 1885 (7.8Mw) (**Figure 2**). This region is also linked to the 2004 Aceh earthquake, which had a magnitude of 9.1, causing numerous casualties and a devastating tsunami (Daly et al., 2019).

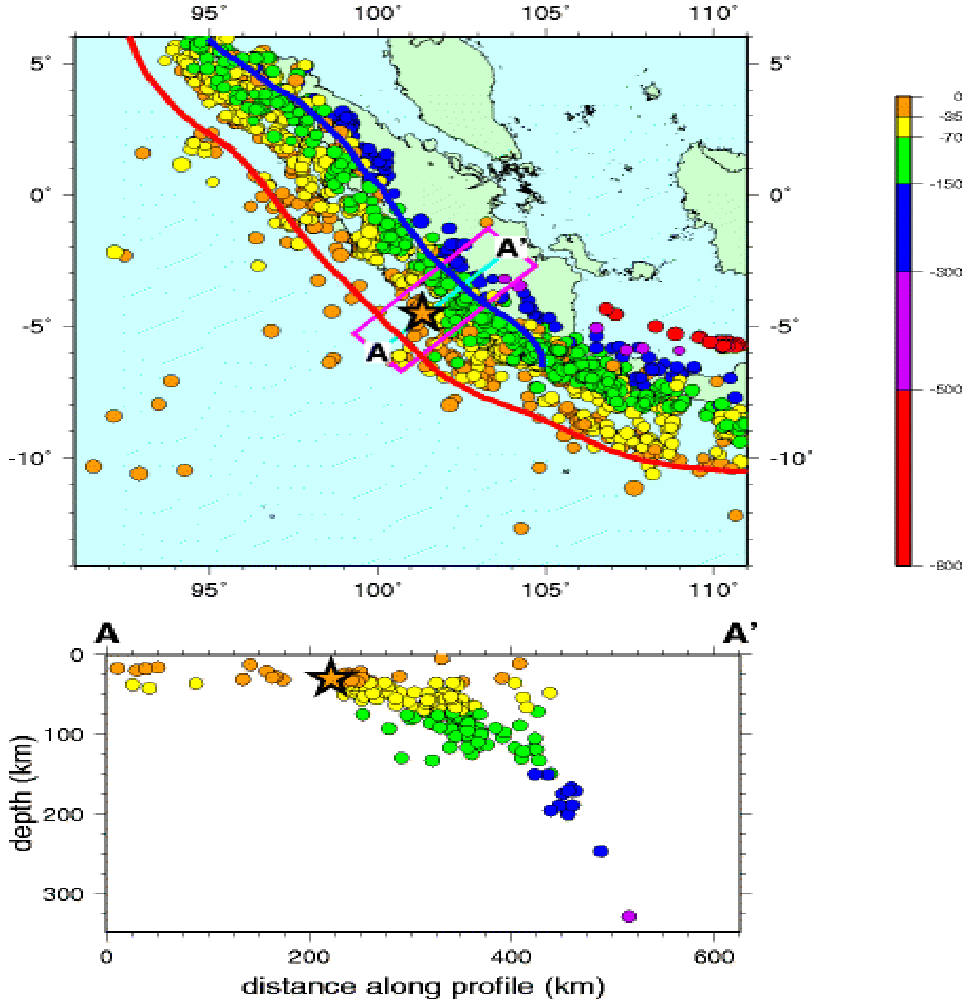

Figure 2. The megathrust segment of the Sunda Strait (pink line) was partially damaged in 1757, 1883, 1903, and 1994.

Source: USGS (2016).

The Sunda Strait region, a located along this fault line, faces a high risk of earthquakes due to the intense movement of the Earth's crust. Historical seismic events in this region highlight the importance of ongoing monitoring and preparedness to manage future earthquakes' impact effectively (Hurukawa et al., 2014; Syifa and Umar, 2024). Recent seismic activity, including earthquakes on 12 December 2018 (6.82 Mw) and 2 August 2019 (6.8 Mw), has heightened the risk along the Sunda Strait plate boundary (Pranata et al., 2023, Sugianto et al., 2023).

4.2.2. Calculating the hazard curve

In order to estimate the probability of exceeding a certain earthquake intensity threshold within a certain period (50 and 100 years), the hazard curve formula is used:

$$\text{Equation } (Y) = 1 - \exp(-\lambda \times T) \tag{3}$$

Long-term probabilities for various magnitudes can be obtained using the λ values calculated from annual frequency data. For a large earthquake in the Sunda Strait with a magnitude of $M \geq 7$Mw, the 50- and 100-year probabilities in the Long-term period are explained as follows.

a) Extrapolation for Longer Periods (10 and 20 years)

If the probability of an earthquake with a certain magnitude occurring in a 10-year and 20-year period is calculated, using the equation:

Table 2. Probability of earthquake occurrence based on magnitude and Period 10, 20 years.

Magnitude (Mw)	**λ (per year)**	**Probability in 10 Years (Y10)**	**Probability in 20 Years (Y20)**
6	0.05	$1 - \exp(-0.05 \times 10) = 1 - \exp(-0.5) \approx 0.3935$	$1 - \exp(-0.05 \times 20) = 1 - \exp(-1) \approx 0.6321$
6.5	0.03	$1 - \exp(-0.03 \times 10) = 1 - \exp(-0.3) \approx 0.2592$	$1 - \exp(-0.03 \times 20) = 1 - \exp(-0.6) \approx 0.4518$
7	0.01	$1 - \exp(-0.01 \times 10) = 1 - \exp(-0.1) \approx 0.0952$	$1 - \exp(-0.01 \times 20) = 1 - \exp(-0.2) \approx 0.1813$
8	0.001	$1 - \exp(-0.001 \times 10) = 1 - \exp(-0.01) \approx 0.00995$	$1 - \exp(-0.001 \times 20) = 1 - \exp(-0.02) \approx 0.0198$

Table 2 shows the probability of at least one earthquake of a given magnitude occurring in a 10-year and 20-year period. The larger the magnitude of an earthquake, the lower the probability of that earthquake occurring in a shorter period. The probability increases with longer periods but remains lower for larger magnitudes.

b) Extrapolation for longer periods (50, and 100 years)

Based on the parameters of the Gutenberg-Richter Law, where $a = 1.859$, and $b = 0.629$, so to estimate the number of earthquakes in a longer period (50 and 100 years in the Sunda Strait), namely N50 years and N100, the following results are obtained:

- Y50 = 0.6321. This means there is a 63.21% chance that an earthquake of magnitude 6 or greater will occur at least once in the next 50 years.
- Y100 = 0.8647. It means there is about an 86.47% chance that an earthquake of magnitude 6 or greater will occur at least once in the next 100 years.

4.2.3 Probability based on time interval

Based on the historical data in **Table 1,** we analyze the interval between earthquakes of different magnitudes from 1903 to 2023. The steps are the same as calculating the average interval between earthquakes of the same magnitude and using this data to predict future events. Then, the data will be analyzed, and the time interval will be calculated. For each magnitude, determine the interval between successive earthquakes by subtracting the year of one earthquake from the year of the next earthquake, calculating the Average Interval, and creating a Prediction Table. Based on the average interval, predict the year when the next earthquake is likely to occur.

a) Possibility of a strong earthquake in the time interval of 2026–2007

To predict the probability of an earthquake in the Sunda Strait in the next 10 or 20 years based on available data, we must understand the pattern of time intervals between earthquakes of a certain magnitude. Using data that includes earthquakes of magnitude 6.0 and higher from previous years, we make projections about when similar earthquakes might occur. This approach involves several important steps. First, this study identifies relevant earthquake data, including the event date, magnitude, and the time interval between two earthquakes of the same magnitude or greater. The data used covers events from early 1903 to 2023. By grouping the data by magnitude, we calculate the time interval between earthquakes of similar strength. For example, for earthquakes with magnitudes 6.0 to 6.9, the analysis shows that the interval between the last earthquake in 2022 and the previous earthquake in 2018 is about 4 years. If this pattern continues, we can estimate the probability of the next earthquake in this magnitude range between 2026 and 2027. On the other hand, if we look at a longer interval, such as between the 2018 earthquake and the previous earthquake in 2006, which took 12 years, the predictions can extend from 2030 to 2031. For earthquakes with magnitudes 7.0 and higher, the last detected time interval was between the 2022 earthquake and the previous earthquake in 2018, which also showed a 4-year interval. Assuming this pattern remains consistent, the probability of the next earthquake in this magnitude range is estimated to be between 2026 and 2027.

b) Possibility of 7.8–8.2 Mw earthquake at long time interval in 2031

However, considering a longer interval, such as the 36-year interval between the 1994 and 1958 earthquakes, the prediction can be extended to around 2031. This approach provides an idea of when an earthquake of a certain magnitude might occur based on historical time intervals. The closest prediction for an earthquake of a certain magnitude in the Sunda Strait is around 2026–2027, with longer projections of 2040 and 2058, if considering longer time intervals. This prediction is based on existing time interval data and observed earthquake frequency patterns, providing a guide to the likelihood of future earthquakes.

4.2.4. Future earthquake prediction: 100-year interval

The idea that a major earthquake occurs approximately every 100 years is a commonly cited estimate in seismology, but this is not a universal rule and can vary by region. This 100-year estimate is often derived from historical seismic records and long-term observations of earthquake frequency. For example, historical data on past major earthquakes can provide a rough average interval in a region of known seismic activity. Seismologists use probabilistic models to assess the likelihood of an earthquake (Hariyono, 2018; Neely et al., 2019). These models consider historical earthquake data, geological studies, and seismic activity patterns to estimate earthquake frequency. The 100-year estimate is sometimes used as a general guideline based on such modeling, especially in areas with limited data (Moustafa et al., 2024). The frequency of large earthquakes can vary significantly depending on tectonic conditions. In some areas, large earthquakes may occur more frequently than every

100 years, while the interval may be longer in other areas. For example, in California, the San Andreas Fault experiences a large earthquake approximately every 100 to 200 years, although this can vary (Williams et al., 2019). In Japan, areas along the Pacific Ring of Fire may experience large earthquakes more frequently due to its tectonic activity (Takahashi, 2017). The interval between major earthquakes can be much longer in areas with lower seismic activity.

Seismic hazard assessments conducted by organizations such as the United States Geological Survey (USGS) and national geological surveys can provide estimates for specific areas (Jena et al., 2020). Research articles and seismology textbooks often discuss earthquake recurrence intervals based on data from different regions. For example, studies in regions such as the Pacific Northwest or the Himalayas provide insight into regional seismic activity (Bungum et al., 2017). Reference Examples: a). USGS Earthquake Hazards Program: Provides resources on earthquake probability and hazard assessments for various regions (USSG, 2024b). Scientific Journals: Research articles discussing earthquake recurrence intervals and probabilistic seismic hazard assessments can be found in journals such as the Journal of Geophysical Research or Seismological Research Letters (AAAS, 2024) and Books on Seismology: Textbooks such as “Introduction to Seismology” by Shaver (2019) or “Earthquake Seismology” by Okal offers a basic understanding of how earthquake frequency is studied. The estimate that a major earthquake occurs every 100 years is a useful guideline but should be interpreted cautiously. This estimate is derived from historical data and probabilistic models that vary based on regional and geological conditions. Accurate predictions require detailed seismic hazard assessments tailored to local conditions.

4.2.5. Estimated time of magnitude 7.8–8.2 earthquakes that will occur in the future

To predict the possible time of a major earthquake in the Sunda Strait based on historical data, we refer to four significant earthquake events: 1883, 1903, 1921, and 1994. These data record high-magnitude earthquakes that have occurred in the Sunda Strait region. To estimate the time interval between earthquakes and project the next earthquake event, we calculate the average interval between these earthquakes. The time intervals between major earthquakes are as follows: between the earthquakes in 1883 and 1903 was 20 years, between 1903 and 1921 was 18 years, and between 1921 and 1994 was 73 years. By combining these time intervals, the average interval between major earthquakes becomes 37 years. Then, the average interval is used to estimate the time of the next major earthquake. Starting from the latest data in 1994, then by adding an average interval of 37 years, it can be estimated that the next major earthquake will occur around 2031. Continuing this projection into the future, by adding 100 years from the first projection, we get the year 2094 as the likely time for the next major earthquake. Projecting further by adding 200 years from the original projection gives the year 2157. Using historical data and this average interval, we estimate the likelihood of a major earthquake occurring in the next 100 years or even the next 200 years. This projection provides an idea of the frequency and likely timing of major earthquakes in the Sunda Strait based on past patterns. The steps are to create a table of estimated times for aftershocks with magnitudes 8 and 9 based on historical data: a). Calculating the Time Interval Between Earthquakes: For each magnitude, calculate the time interval between recorded earthquakes; Calculating the Average Time Interval: Determine the average time interval for each magnitude based on historical data; and c). Predicting the next year using the average interval to project the next earthquake year after the last recorded year. The results are presented in **Table 3**.

Table 3. Earthquake projections based on historical time intervals.

Last Date Data	Time Interval (years old)	Projection of the Next Earthquake	Projections for the Next 100 Years	Projections for the Next 200 Years	Estimated Magnitude	Estimated Depth (km)	Probability
1994-06-02	37	2031	2094	2157	7.8–8.2	15–35	Tall
1883-11-24	37	1920	2020	2120	7.5–8.2	15–60	Tall
1903-02-27	37	1940	2040	2140	7.5–8.2	15–60	Tall
1921-09-11	37	1958	2058	2158	7.5–7.8	15–60	Currently

4.2.6. Prediction of casualties and damage

This table summarizes estimates of fatalities, injuries, building damage, and financial losses from a potential future major earthquake based on historical data from the Sunda Strait. In order to calculate these estimates, regression coefficients for fatalities, injuries, building damage, and total damage costs were determined using the following data:

Count β_1 and $\beta 0$:

$$\beta 1 = \frac{N(\sum XY) - (\sum X)(\sum Y)}{N(\sum X2) - (\sum X)2} \tag{4}$$

$$\beta 0 = \frac{(\sum Y) - \beta 1(\sum X)}{N} \tag{5}$$

Estimated total losses due to earthquakes in 2026 and 2031.

We use historical data to make estimates and calculate the loss costs based on the predetermined compensation value to predict earthquake losses based on the magnitude and data provided. We create a loss estimation table for a 6.0–7.0 Mw earthquake in 2026–2027 and a 7.8–8.2 Mw earthquake in 2031. The steps are a). Use historical data to estimate the number of fatalities, injuries, building damage, and evacuation costs; b). Compensation fee: using the compensation value provided to calculate the total cost commonly used by life insurance in Indonesia; and c). Estimating the total cost of an earthquake by calculating: Calculate the total cost of losses by adding up the costs of compensation for death, injury, building damage, and evacuation costs (**Table 4**).

Table 4. Estimated total losses due to earthquake.

Year	Magnitude (Mw)	Estimated Death	Estimated Injury	Estimated Building Damage	Estimated Evacuation (Person)	Total Cost (Million USD)	Total Cost (Trillion IDR)
2026–2027	6.0-7.0	500	2000	2000	2000	534.56	8.263 trillion
2031	7.8-8.2	1000	5000	5000	5000	1,255	19.403 trillion

a) For a magnitude of 6–7 Mw in 2026–2027

- Estimated Death: 500 people.
- Injury Estimate: 2000 people.
- Building Damage Estimate: 2000 buildings.
- Evacuation Estimate: 2000 people.

Compensation Fee:

- Death Compensation: 500 people × USD 325,000 = USD 162,500,000
- Injury Compensation: 2000 people × USD 160,000 = USD 320,000,000
- Building Damage: 2000 buildings × USD 26,000 = USD 52,000,000
- Evacuation Costs: 2000 people × USD 30/day × 1 day = USD 60,000

Total cost = USD 534,560,000

b) For a magnitude of 7.8–8.2 Mw in 2031

- Estimated Death: 1000 people
- Injury Estimate: 5000 people
- Building Damage Estimate: 5000 buildings
- Evacuation Estimate: 5000 people

Compensation Fee:

- Death Compensation: 1000 people × USD 325,000 = USD 325,000,000
- Injury Compensation: 5000 people × USD 160,000 = USD 800,000,000
- Building Damage: 5000 buildings × USD 26,000 = USD 130,000,000
- Evacuation Costs: 5000 people × USD 30/day × 1 day = USD 150,000

Total cost (USD) = 1,255,150,000

The estimated losses associated with this high-magnitude earthquake highlight the urgent need to implement robust risk mitigation strategies. The scale of these potential losses underscores the need for substantial investment in strengthening infrastructure, developing early warning systems, and improving public education and training. Strengthening infrastructure aims to increase the resilience of buildings to seismic forces, while sophisticated early warning systems can provide timely warnings to reduce the risk of casualties. In addition, improving education and training will strengthen community preparedness for disaster scenarios. In disaster management training and education, it is essential to integrate technological solutions with traditional knowledge. Understanding cultural practices and local wisdom, such as those of the Baduy, Minangkabau, Sundanese, Javanese, Balinese, and Sasak peoples in Lombok and Halmahera, has proven effective (Samudra, 2024). For example, no Baduy houses collapsed during the recent major earthquake measuring 8 on the Richter scale. The Baduy attribute this resilience to the bamboo plants surrounding their homes, which they believe help absorb seismic vibrations through their strong root systems. This suggests governments and communities should consider incorporating traditional practices into building construction and design. Research on the relationship between bamboo and earthquakes was conducted by Fajrin et al. (2021) in Indonesia, and Rampal et al. (2023) in India.

However, field observations show that the area faces several additional challenges that could worsen the situation in the future if a major earthquake occurs. The results of these observations need to be included in formulating future policies, namely the many buildings and houses in this area that have weak foundations and often need to comply with the established operational procedures (SOP) for infrastructure development, and it concerns the issue of socialization. The lack of socialization is evident from the large number of houses that were rebuilt in disaster-prone areas after the previous earthquake, increasing the risk of further damage and loss of life. Another example is that several 'Deep-ocean tsunami detection buoys (Buoys) and tsunami early warning systems (EWS) were lost or stolen by the community, indicating a need for more public information about the importance of these tsunami detection devices. BMKG explained that these infrastructures are currently no longer functioning due to limited maintenance budgets, even when buying Buoys and EWS batteries. Therefore, socialization and education on disaster management must be carried out more frequently, reducing the effectiveness of preparedness efforts. The disaster management budget is also limited; the National Disaster Management Agency has only allocated USD 103 million. (VOI, 2024),

Moreover, disaster management funding at the regional level is, on average, only 2%–4% of the total Regional Revenue and Expenditure Budget. Implementing comprehensive and coordinated strategic actions is essential to reducing the potential impact of future earthquakes. This includes proper planning and investment to ensure that infrastructure can withstand earthquake events and that communities are prepared for their potential impacts.

5. Conclusion

This study assesses seismic risk and impact prediction in the Sunda Strait region by analyzing historical earthquake data and forecasting models. The area is highly vulnerable to major seismic events due to the subduction of the Indo-Australian Plate beneath the Eurasian Plate, with a historical earthquake magnitude of 8.2 indicating significant risk. The Gutenberg-Richter model estimates that earthquakes of magnitude 6.0–7.0 Mw or higher could occur every 4 years in the short term and every 37 years in the long term. A magnitude 7.8–8.2 Mw earthquake is projected around 2031.

Potential damages from these earthquakes could reach USD 8.263 billion for 7 Mw and USD 19.403 billion for 7.8–8.2 Mw, including fatalities, injuries, and property damage. The study emphasizes the need for robust risk mitigation strategies, such as strengthening infrastructure and implementing advanced early warning systems. Integrating traditional knowledge, like that of the Baduy community, can enhance resilience. Addressing issues like weak building foundations and inadequate disaster management outreach is essential.

Coordinated efforts to improve infrastructure resilience and secure additional funding for disaster management are crucial. Future research should focus on detailed geophysical models and continuous monitoring to enhance earthquake prediction and preparedness.

6. Recommendation

Several actions are essential to manage seismic risks in the Sunda Strait region. Strengthening and upgrading infrastructure to comply with seismic building codes, especially for critical buildings such as hospitals and schools, is essential. Implementing an early warning system will provide timely warnings to minimize casualties and damage. Public education on earthquake preparedness through campaigns and drills will enhance community preparedness. Integrating traditional knowledge, such as local building techniques, can enhance resilience. Disaster management plans should be regularly updated and include clear evacuation routes and procedures. Enforcing building codes, inspecting buildings, securing disaster preparedness funding, and prioritizing ongoing seismic research are essential. Supporting community initiatives and encouraging collaboration will further strengthen preparedness and resilience.

7. Implications

A study of megathrust earthquakes in the Sunda Strait region highlights significant seismic risk, predicting a magnitude 6.0–7.0 earthquake around 2026–2027 and a magnitude 7.8–8.2 Mw earthquake around 2031. The study emphasizes the need for proactive risk mitigation, including strengthening infrastructure, improving early warning systems, and integrating traditional construction knowledge. Policymakers should enforce building codes, increase disaster preparedness funding, and engage communities in risk reduction. With projected economic impacts, including major losses, careful financial planning and insurance are essential. Ongoing research and community engagement, combining local knowledge with modern techniques, are essential to improve seismic prediction accuracy and structural resilience.

8. Limitation

The study uses historical earthquake data to predict future events, but its accuracy is limited by the scope of available records and the inherent variability in seismic events. Reliance on historical data and the Gutenberg-Richter model may simplify the complex seismic behavior of the region, ignoring current geophysical insights and real-time monitoring technologies. Furthermore, economic impact estimates based on historical data and regressions may not reflect current infrastructure, population, and socioeconomic conditions. While the study’s recommendations are sound, their implementation poses challenges, such as integrating traditional knowledge into construction and strengthening infrastructure, which require substantial investment and coordination. Further research is needed to improve earthquake preparedness and mitigation.

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