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Probabilistic seismic hazard analysis for East Likupang Special Economic Zones, North Sulawesi

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Abstract

East Likupang, designated by the central government as a Special Economic Zone, is located on the North Arm of Sulawesi. Tectonically, this region situated in close proximity to several earthquake sources, such as the North Sulawesi Subduction, Molluca Sea Double Collision, Cotabato trench and several other active faults. This research aims to assess the risk of earthquake disasters using the Probabilistic method approach. The Probabilistic Seismic Hazard Analysis (PSHA) method was employed in seismic risk hazard analysis to quantify earthquake risk. This approach was selected due to the creation of a probability distribution function that accounts for and integrates uncertainties in the magnitude, location, and frequency of earthquake events to produce a comprehensive picture of the overall risk for the target site. The seismic source models employed in this study encompassed background, fault and subduction (megathrust). The modeling results indicate that an earthquake's peak ground acceleration (PGA) at a 10 percent probability of being exceeded in 50 years at a return period of 475 years is 0.27 g. This conclusion has been drawn following the several theories of earthquake sources, including shallow earthquake sources with magnitude of 0.24 g, deep earthquake sources with magnitude of 0.13 g, fault earthquake sources with magnitude of 0.22 g, and megathrust earthquake sources with magnitude of 0.08 g. The results of the hazard curve analysis suggest that the most frequent earthquakes are deep earthquakes with a depth of 50-300 km, while those that provide the greatest hazard are shallow background and faults.

Keywords: peak ground acceleration; probabilistic seismic hazard; special economic zones

1. Introduction

East Likupang, situated within the North Minahasa Regency of North Sulawesi Province, is one of 18 areas designated by the central government as a Special Economic Zone (SEZ) throughout Indonesia. Its designation as a Special Economic Zone was regulated through Government Regulation Number 84 of 2019. This development aims to accelerate to expedite economic growth in North Minahasa Regency, North Sulawesi Province, as well as support the acceleration and expansion of national economic development, as stated in the Government Regulation (Government of The Republic of Indonesia, 2019). Besides, East Likupang has also been designated as a new economic growth centre, projected to experience rapid development in industrial sectors, tourism, and civil infrastructure. Consequently, it is imperative to address the risk of disasters, particularly earthquake hazards, in order to develop the special economic zone.

East Likupang is located in the northern part of Sulawesi Island and forms part of the north arm of Sulawesi, where the world's major plates converge, including the Pacific, Indo-Australian, Philippine, and Eurasian Plates (Cipta et al., 2017). As a result of the movement of these plates, this region experiences high seismic activity (Pasari et al., 2021; Rachman et al., 2022). The interaction between these plates has created new earthquake sources, including the North Sulawesi subduction, the Molluca Sea double collision, the Cotabato Trench, and several other faults. Consequently, the East Likupang area is susceptible to earthquakes and tsunamis (G Pasau et al., 2023). Historical records indicate that the region has experienced multiple earthquakes and tsunamis (Pasau et al., 2019).

An earthquake is a series of motions caused by a sudden release of strain, characterized by the rupture of the outermost layer of the earth's crust (Lacidogna et al., 2023; Teguh & Erlangga, 2019). These seismic tremors cause the ground to vibrate, potentially affecting the surrounding area of the earthquake region, resulting in the collapse of buildings. Building collapse contributes significantly to earthquake-related mortality and morbidity (Zhang et al., 2022). Therefore, to minimize the effects of earthquake shaking, buildings and non-structural elements must withstand seismic loads to reduce the number of casualties due to earthquake shaking (Harith et al., 2023).

Seismic hazard analysis methods provide the ability to predict the likelihood of future earthquakes of varying magnitudes to prevent collapse or damage to building structures caused by earthquakes. The methods used in seismic hazard analysis include deterministic and probabilistic methods. Deterministic Seismic Hazard Analysis (DSHA) requires determining earthquake source and magnitude while ignoring uncertainties in data and calculations that can lead to an overestimation of risk (Guo et al., 2023). The probabilistic method (Probabilistic Seismic Hazard Analysis, PSHA) employs a statistical approach to assess the probability of earthquakes occurring at a specific return period. This involves integrating uncertainties associated with the number, size, and location of earthquakes and the potential for varying levels of ground motion in a given area (Cornell, 1968). The Probabilistic Seismic Hazard Analysis (PSHA) method is widely used in seismic risk analysis due to its rationality and popularity in recent decades for quantifying seismic hazards (Mulargia et al., 2017; Ramalho et al., 2022).

The aim of this study is to analyze earthquake risk in the East Likupang area of North Minahasa Regency using the probabilistic PSHA method. Further, this study also seeks to determine the peak ground acceleration (PGA) and hazard curve at a probability exceedance (PE) of 10% in 50 years. The study's findings serves as valuable insights into earthquake risk for the development of the East Likupang area as a special economic zone. This will ensure that he potential for seismic activity is considered when constructing civil infrastructure and beach tourism.

In addition, earthquake risk refers to the probability of exceedance of an earthquake of a certain intensity during a building's lifetime. The probability of exceedance of an event with a certain intensity is expressed as a function P(N) (Osetinsky-Tzidaki & Fredj, 2022), as written in equations (1)-(2).

$$p = 1(1 - P[N](y)^{1/N} \tag{1}$$

$$T = 1/(1 - P[N](y)^{1/N}) \tag{2}$$

Where:
N = length of the period (years)
P = annual exceedance probability of the event
T = return period of the event in years
$P[N]$y = exceedance probability

The study employs the probabilistic method to analyze seismicity risk, specifically, the total probability method developed by McGuire (1976) following the Cornell's (1968) concept of probability. The theory of Probabilistic Seismic Hazard Analysis (PSHA) involves five steps, including: (1) identification of earthquake sources capable of producing destructive ground motions, (2) characterization of earthquake magnitudes distribution, (3) characterization of the distribution of sources to locations associated with earthquake potential, (4) prediction on the distribution of ground motion intensity based on earthquake magnitude, distance, and other relevant factors, and (5) uncertainties in earthquake size, location, and ground motion intensity to be combined using a calculation known as the total probability theorem (Baker et al., 2021). The theorem of total probability assumes that earthquake events with magnitude M and hypocentral distance R, are continuous independent random variables. The formula for the total probability theory is expressed in equation (3).

$$P[I \geq i] = \iint_{r\,m} P[I \geq i|m \; and \; r].fM(m).fR(r)dm\,dr \tag{3}$$

Where:

fM = magnitude distribution function

fR = hypocentral distance distribution function

$P\ [I > i\ |m$ dan $r]$ = conditional probability of intensity I exceeding a value of i at the location under review for an earthquake event with magnitude m and hypocentre distance r

In earthquake risk analysis using the PSHA method, the Gutenberg-Richter recurrence model is frequently utilized to reflect the frequency-magnitude distribution (FMD) (Taroni et al., 2021). The Gutenberg-Richter recurrence model represents a linear relationship between the logarithm of frequency and magnitude (Motaghed et al., 2023). The parameters resulting from this frequency-magnitude relationship are known as seismic parameters. Seismic parameters comprise of mathematical models that characterise earthquake activity in a region over a period of time. These parameters are based on the Guttenberg-Richter model, also known as the Least Square technique. This model characterizes that the frequency of earthquakes with magnitude $M \geq m$ per unit time decreases exponentially as the earthquake magnitude increases (El-Isa, 2013; Noora, 2019). This relationship is expressed in the equation 4.

$$Log\ N(m) = a - bM \tag{4}$$

In seismicity studies, the variables $N(m)$ and M are of significant importance. They represent the number of earthquakes with a magnitude other than M that occur within a specified time frame, where M denotes the earthquake's magnitude, with constants a and b also playing crucial roles. The constant a is the characteristic constant of the earthquake area, which depends on the seismicity level of the source location and the observation period. Conversely, parameter *b* serves as a constant that expresses the relative magnitude distribution at any point source within the earthquake region. Parameters *a* and *b* are both crucial in seismic studies, including seismic hazard estimation and calculating recurrence intervals for earthquakes of varying magnitudes. Moreover, these parameters have extensive applications in volcanic seismology, especially in mapping subsurface magmatic spaces (El-Isa, 2013; Wiemer & Wyss, 2000).

Seismicity parameters, such as *b*-value and *a*-value, are constants that exhibit variability in both time and space. The b-value, often close to 1, is a reliable tectonic parameter that can be influenced by the stress level and tectonic characteristics of a given site (Mizrahi et al., 2021). In contrast, the a-value parameter reflects the level of seismic activity within a region over a given period, with higher seismic activity generally corresponding to higher a-value parameter values (Lacidogna et al., 2023).

2. Method

2.1. Research Location

The study was conducted in the East Likupang Special Economic Zone, located in the North Minahasa Regency of the North Sulawesi Province with geographical coordinates of 125°01'29"E-125°10'35"E and 1°33'18"E-1°41'40"E, as shown in Figure 1.

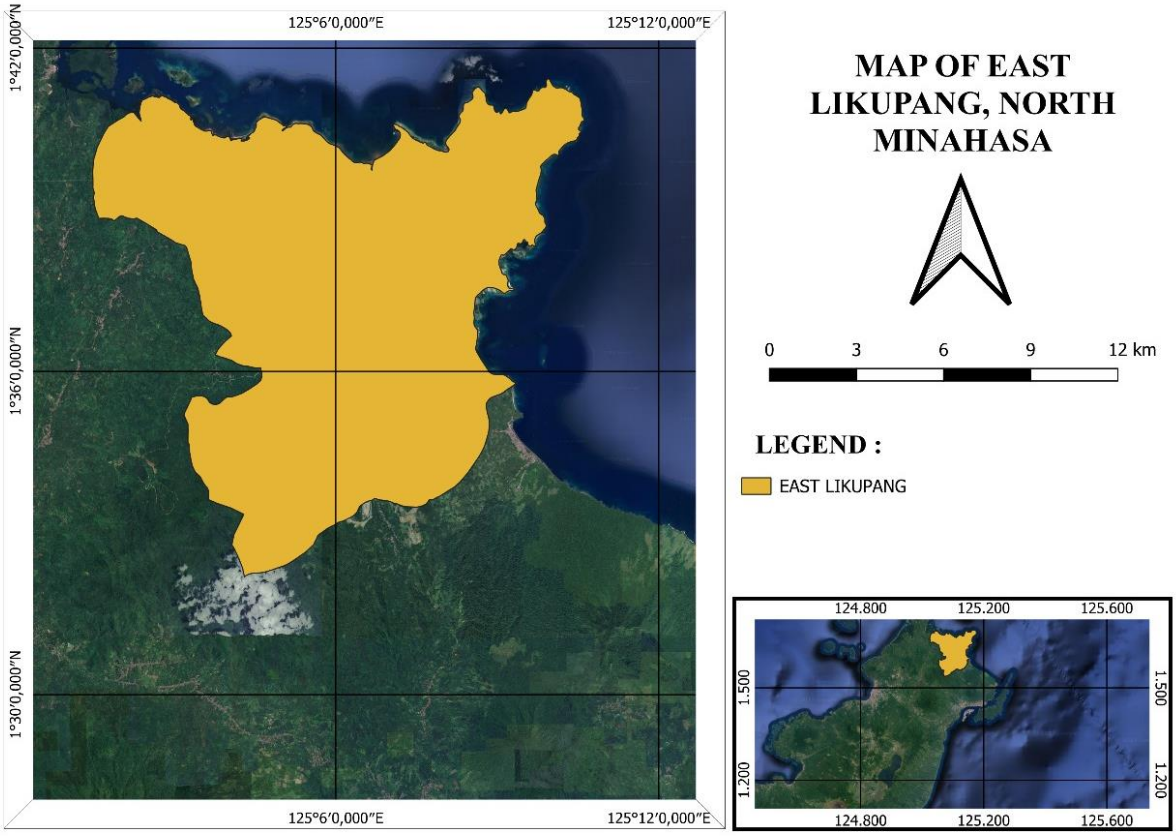

Figure 1. Research Location

2.2. Seismic Source

Seismic sources are defined as those capable of causeing earthquakes or vibrations that may affect the target location. The PSHA earthquake risk analysis method involves earthquake catalogues, tectonic boundaries, and active crustal fault data as seismic source models. In this study, three seismic source models were employed, including: 1) background (gridded seismicity), 2) megathrust, and 3) fault. The earthquake sources in the background comprise both shallow (0-50 km) and deep background earthquakes, including deep 1 (50-100 km), deep 2 (100-150 km), deep 3 (150-200 km), and deep 4 (200-300 km). Subduction (megathrust) earthquake sources are used up to a depth of 50 km, while deep background earthquake sources accommodate depths above 50 km. Meanwhile, the subduction earthquake source observed was originated from the North Sulawesi subduction zone. The seismic source designated as the megathrust is subducted to a depth of 300 km and is capable of causing earthquakes considerable magnitude (Greenfield et al., 2021). In contrast, fault seismic sources are used up to a depth of 30 km. The seismic fault source in this study is the Molluca Sea double collision, which is divided into two parts, the west and the east. The seismic fault source in this study is the Molluca Sea double collision, which is divided into two parts, the west and the east. These parts were modelled as faults as they were only collisions, not dives like the subduction model. These seismic source models have been used in previous studies, including those of Irsyam et al. (2020) and Pusgen (2017).

2.3. Earthquake Data

The earthquake data utillized in the Probabilistic Seismic Hazard Analysis (PSHA) encompassed of hypocenter data, including the earthquake location (latitude and longitude), origin time (year, month, day, hour, minute, second), depth, magnitude, and magnitude type. These data used were constraine to a 300 km radius of the research centre (East Likupang, 125.1˚E, 1.6˚N) where significant tremors within this distance were perceptible. Data was collected from two earthquake catalogues, the International Seismological Center (ISC-EHB) and the United States Geological Survey (USGS) during the observation interval of 1963-2023. The analysis was performed using a minimum magnitude scale of Mc ≥ 4.6 Mw and a maximum depth of 300 km because earthquakes with depths greater than 300 km were assumed to have no damaging effects at the surface (Pusgen, 2017).

2.4. Magnitude Conversion

The use of disparate magnitude scales across various catalogs necessitates the standardization of the magnitude scale to moment magnitude (Mw). Moment magnitude (Mw) is the preferred standard magnitude scale for measuring earthquakes, as it allows for the representation of the amount of energy released from a fault plane or ground motion model (Grünthal et al., 2009; Prasetyo et al., 2024). This study employed the Scordilis method to convert magnitude to moment magnitude (Pusgen, 2017; Scordilis, 2006). The conversion equation is described in the equation (5)-(7).

$$M_w = 1{,}0107m_b + 0{,}0801 \quad (5)$$

For range 3,7 ≤m_b≤ 8,2

$$M_w = 0{,}0616M_s + 2{,}476 \quad (6)$$

For range 2,8 ≤m_s≤ 6,1

$$M_w = 0{,}0923M_s + 0{,}5671 \quad (7)$$

For range 6,2 ≤M_s≤ 8,7

2.5. Decluster Catalog

Declustering catalog represents the process of separating the mainshock from foreshocks and aftershocks (Mizrahi et al., 2021). The declustering catalog employs time span and distance span criteria. The process of separating the main earthquake from foreshocks and aftershocks employs the empirical method proposed by Gardner and Knopoff (1974), which is implemented with the assistance of ZMAP software (Wiemer, 2001).

2.6. Research Flowchart

The research workflow is illustrated in Figure 2.

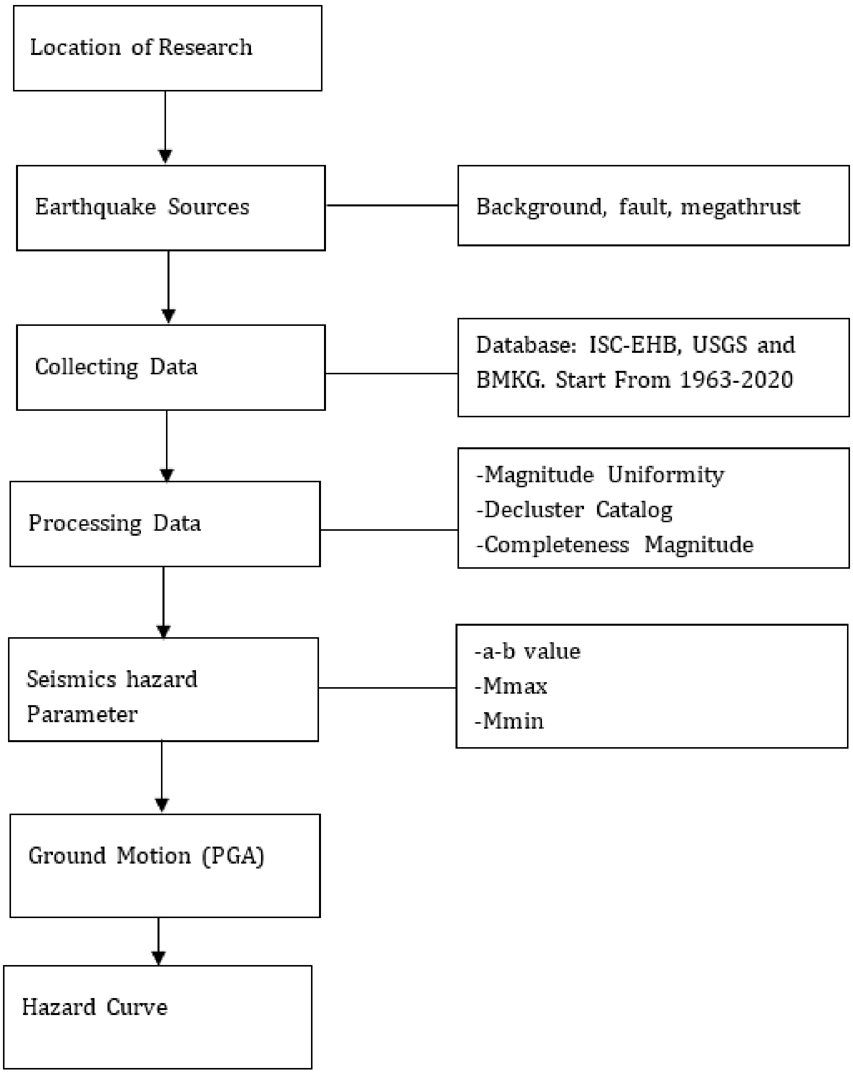

Figure 2. Flow Chart of Methodology Research

In the context of earthquake risk analysis, the most crucial aspect is determining ground motion or peak ground acceleration and hazard curves. For that purpose, this study employed the PSHA-USGS software (Harmsen, 2007). Measurements of peak ground acceleration (PGA) are typically expressed in units of gravitational acceleration (g) or centimetres per second squared (cm/sec^2), with the standard value of gravitational acceleration being 9.81 cm/sec^2. In addition, PGA can be expressed in units of gals, with one gals is equivalent to 0.01 cm/sec^2 (1 G = 981 gals). This approach provides a commonly used reference framework for assessing and understanding seismic impacts on structures and the environment (Prasetyo et al., 2024).

3. Results and Discussion

3.1. Tectonic Setting

The tectonics of East Likupang, located in the northern arm of Sulawesi, represent a highly complex geological setting. This area is a convergence zone where several active plates meet. These include the Philippine Plate, the Pacific Plate and the Eurasian Plate. In addition, the East Likupang region is geologically distinct, having been formed about 50 million years ago during the Early Eocene Epoch (Hall, 2012). This region is also prone to earthquakes due to the convergence of several tectonic plates, including the Philippine Sea Plate, which moves at an average rate of 9 cm/year from the east, the Indo-Australia Plate, which moves at an average rate of 7.5 cm/year from the south, and the Eurasia Plate, which moves at an average rate of 2 cm/year from the west (Brehme et al., 2014). The interactions between these plates have resulted in the formation of the North Sulawesi Subduction and the Molluca Sea double collision (Pasari et al., 2021; Song et al., 2022). The high level of seismicity in the East Likupang area and its surrounding areas is mainly attributed to the activity of the Molucca Sea Collision Zone, one of the most active seismic zone in the world due to seismic activity from the collision zone (Rachman et al., 2022). Besides, the earth's crust in this region is fragmented and highly susceptible to earthquakes and tsunamis due to pressure from various sources.

The East Likupang Region is characterized as a volcanic hill country, with landforms typically consisting of conical hills at varying slopes and a surface dominated by extrusive igneous rock (lava flows) (Hall, 2012). The lava produced by the volcanic activity in this region is generally effusive, thereby, it flows out of the volcano without explosive force (Cassidy et al., 2018). The combination of these geological features and tectonic activity positions East Likupang as a fascinating area for geological and seismic research.

The tectonic and magmatic evolution of the northern arm of Sulawesi, including East Likupang, has been the focus of several studies (Hall, 2012). Most of these studies have investigated the role of tectonic plates in the formation of the region's volcanic hill country, as well as the volcanic and tectonic evolution of the Sangihe Arc, which includes East Likupang. A study has also described the seismic activity in the northern arm of Sulawesi (Massinai et al., 2019).

3.2. Mainshock

The data on historical earthquake occurrences within a 300 km radius of the epicenter of Likupanng Timur from 1963 to July 2023 was garnered from two catalogues, the International Seismological Center (ISC) and the United States Geological Survey (USGS). These gathered data were comibined, resulting in a total of 15,663 earthquake events being recorded, with magnitudes ranging from 3.0 *Mb* to 7.8 *Mb* and a maximum depth of 573 km, as shown in Figure 3 using the ZMAP program (Wiemer, 2001). Further, the plot of the epicenters, as illustrated in the figure, indicates that the most frequent shallow earthquakes occur in the vicinity of the Molucca Sea, a consequence of the double collision activity in the Molucca Sea. .

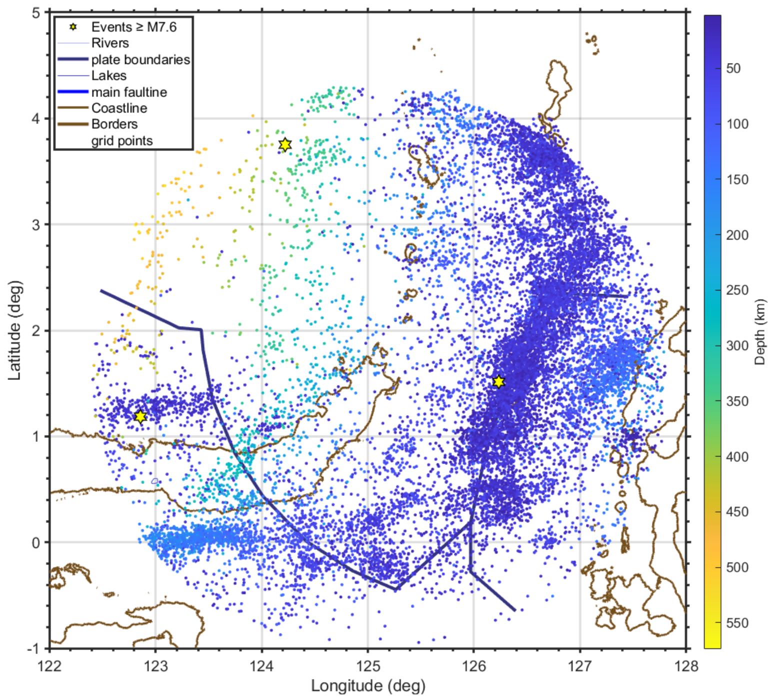

Figure 3. Distribution of Earthquake Events Within a 300 Km Radius of East Likupang During the Period 1963-2023, Based on Their Depth
Source: ISC and USGS Catalog

Figure 3 displays a combination of foreshocks, mainshocks, and aftershocks related to the earthquake events. During the PSHA, only the mainshock hypocenter data, free of foreshocks and aftershocks were utilized (Irsyam et al., 2020). In the following stage, the data were filtered using time and distance window criteria with the algorithm developed by Gardner and Knopoff. This algorithm is commonly used in PSHA seismic hazard analysis to generate Poisson decluster catalogs (Taroni & Akinci, 2021). The declustering process identified 4,837 earthquake cluster events out of a total of 15,663 earthquake events. From this process, 10,826 events were identified as foreshocks or aftershocks, leaving a total of 1,049 main earthquakes, as shown in Figure 4.

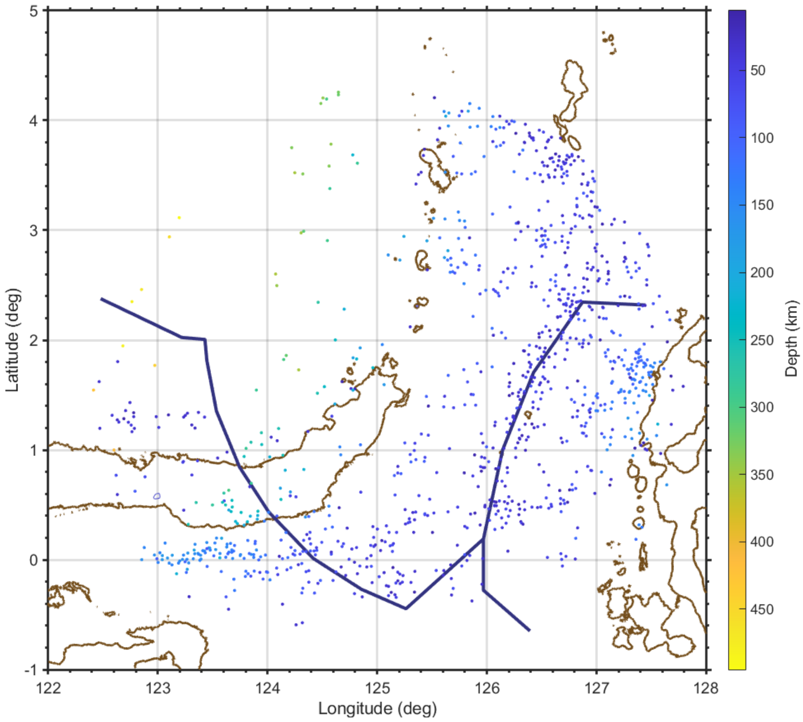

Figure 4. Distribution of Mainshock within a 300 Km Radius of East Likupang for the Period 1963-2023 based on Depth
Source: ISC and USGS Catalog

The PSHA data input only considered earthquakes with a maximum depth of 300 km. Earthquakes with a depth greater than 300 km were excluded as they were not expected to cause significant damage to the earth's surface.

3.3. Magnitude of Completeness

Earthquake catalog quality tests are required to estimate seismicity parameters, such as the magnitude of completeness (*Mc*-value), *a*-value, and *b*-value. The magnitude of completeness evaluates the completeness of the catalog by assessing the stability of the average activity level of earthquakes above a completeness magnitude with respect to the time interval. In this study, the *Mc* was estimated using the procedure introduced by Stepp (Irsyam et al., 2020). The accuracy of *b*-value estimation significantly impacts earthquake risk assessment. This evaluation depends on the accuracy of the magnitude of completeness (*Mc*) estimation. The highly small *Mc* suggests that the *b*-value may be underestimated as it should be more prominent, ideally. Conversely, a large *Mc* value may indicate significant deviations due to a considerable reduction in the magnitude interval (Chasanah & Handoyo, 2021). This method is based on the observation that the Gutenberg-Richter distribution is exponential only for magnitudes larger than *Mc* (Godano & Petrillo, 2023).

One common method for determining seismicity parameters in a region is analysis on the Gutenberg-Richter distribution relation. Figure 5 illustrates the frequency distribution of earthquake occurrences versus magnitude (FMD), as well as the relationship between magnitude and the number of occurring earthquakes.

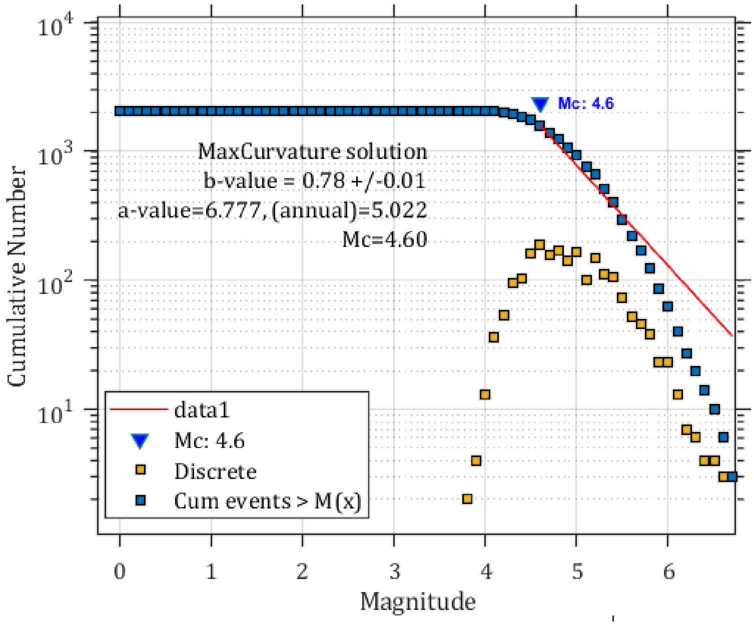

Figure 5. Completeness Magnitude (*Mc*) and *b*-Value Characteristics

In addition, Figure 5 presents the obtained Magnitude Completeness (Mc) of 4.6. Therefore, only earthquakes with magnitudes of at least 4.6 was used in further data processing, while those below this threshold were eliminated.

3.4. *a*-Value and *b*-Value of the Seismic Source Model

The PSHA-USGS software parameter input requires a value and b value for each seismic source model. The calculation results of a and b values for background seismic sources are shown in Table 1, while megathrust in Table 2 with fault seismic sources of 1 (Irsyam et al., 2020; Pusgen, 2017).

Table 1. *a-b* Value for Background Source

Earthquake Source	Depth (km)	b-value	a-value
Shallow background	0-50	0.812	5.32
Deep background 1	50-100	1.21	7.40
Deep background 2	100-150	1.20	7.38
Deep background 3	150-200	1.21	7.40
Deep background 4	200-300	1.20	7.39

By using the available historical data, a statistical analysis using the maximum likelihood model was conducted to determine the a-b value for the source of the North Sulawesi Subduction (*megathrust*) earthquake.

Table 2. Source of the Megathrust, *a-b Value*

Earthquake Source	Depth (km)	b-value	a-value
Megathrust	0-50	0.971	5.28

3.5. Peak Ground Acceleration (PGA)

Probabilistic seismic hazard analysis was conducted using PSHA-USGS software (Harmsen, 2007) with a site spacing of 0.10 x 0.10 (latitude, longitude). The analysis considered a 10% exceedance probability in 50 years at a return period of 475 years from various seismic sources. Table 3 presents the results of the peak ground acceleration (PGA) analysis in East Likupang.

Table 3. Seismic Hazard Probability Exceedance 10% in 50 Year

Shallow (g)	Deep (g)	Fault (g)	Megathrust (g)	Combine (g)
0.24	0.13	0.22	0.08	0.27

In East Likupang, the peak ground acceleration (PGA) amounted to 0.27 g. The largest contribution was from shallow background (0-50 km) at 0.24 g and faults at 0.22 g. Deep background and megathrust seismic sources were identified as having non-significant contributions. Meanwhile, the significant value of the shallow background seismic source is likely attributed to two seismic sources. Firstly, the double collision activity of the Moluccan Sea at a depth of 0-50 km, and secondly, the presence of local faults that have not been detected geologically around East Likupang. The peak ground acceleration (PGA) results from this study are comparable to those of other researchers, such as Silva et al. (2023), who reported values ranging from 0.2-0.5 g, and Pusgen (2017), who identified values between 0.25-0.3 g.

3.6. Hazard Curve

Hazard curves are plots that can be transformed into response spectra using various time procedures to probabilistically assess seismic vulnerability. These plots provide a relationship between ground motion parameters and earthquake return period at a given location (Mulargia et al., 2017).

Seismic hazard curves have been established for specific vibration periods at different stages of motion. The design values of acceleration for those periods were obtained through interpolation of the hazard curves at a 10% probability of exceedance. Figure 6 illustrates these hazard curves, which demonstrate the relationship between mean annual exceedance rate and peak ground acceleration (PGA) for East Likupang. The figure presents the hazard curve graph positioning deep earthquakes (50-300 km) as the most frequent earthquakes in the East Likupang area. These earthquakes are caused by the double collision activity of the Moluccan Sea, which dips to a depth of 553 km, as indicated by the seismicity map. Faults and shallow background sources pose the greatest hazard in terms of peak ground acceleration, followed by deep background and megathrust sources. The significant impact of shallow background and fault seismic sources in the East Likupang area is attributed to its proximity to the western Molluca Sea double collision seismic source.

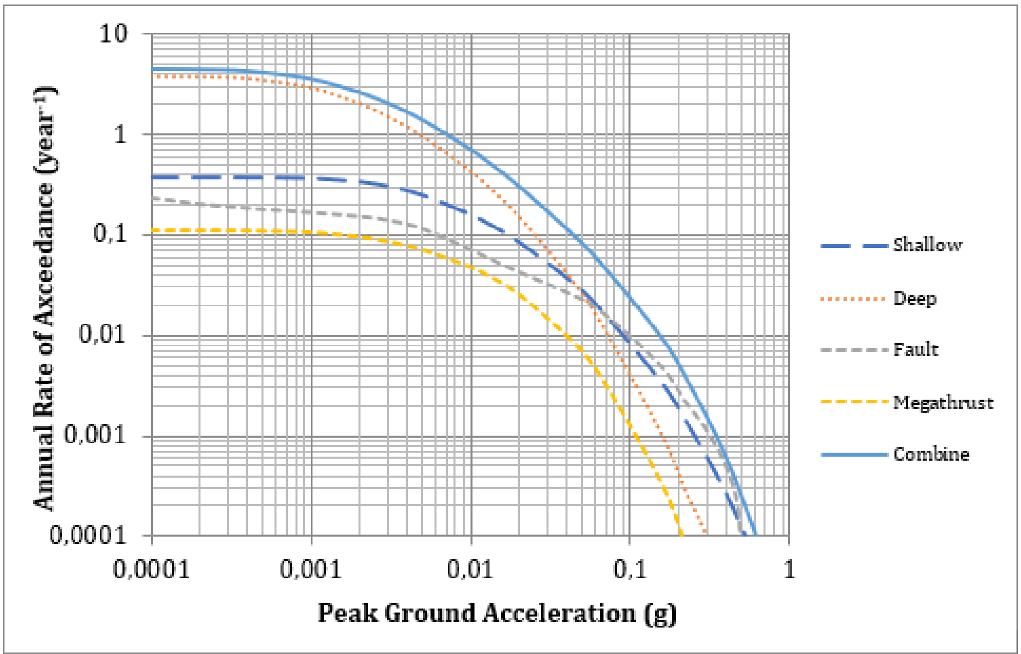

Figure 6. PE 10% in 50 Years and Return Period 475 years

The results of our research on earthquake risk analysis in the East Likupang area with a 10% exceedance probability in 50 years, indicate a moderate peak ground acceleration (PGA) of 0.27g. The results obtained possess no significant differences from previous research. For instance, Silva et al. (2023) reported PGA values within the range of 0.2-0.5 g and Pusgen (2017) obtained PGA values of 0.25-0.3 g. A higher result was found by Cipta et al. (2017), which was 0.4 g. However, they conducted their research in all areas of North Sulawesi, rather than focusing on East Likupang specifically.

In seismic risk analysis employing the probabilistic method, the maximum ground acceleration value obtained relies substantially on the Ground Motion Prediction Equations (GMPE) model. This research revealed that some of the GMPE models currently in use are outdated and utilize models derived from other countries. It is crucial to acknowledge that this GMPE model has been utilized by numerous previous researchers, including in the creation of the Indonesian earthquake hazard map in 2010 and 2017 (Pusgen, 2017). To conduct comprehensive seismic risk analysis research, it is essential to employ a locally-specific Ground Motion Prediction Equations (GMPE) model that incorporates the unique geological and geotectonic characteristics of the region. Local GMPEs are also useful in developing earthquake early warning systems for the purpose of accurate prediction.

4. Conclusion

Probabilistic methods has been employed in an earthquake risk analysis in the East Likupang Special Economic Zone. The results of peak ground acceleration and hazard curve analyses indicate that the area is vulnerable to earthquake shaking. The maximum ground acceleration (PGA) value at bedrock at a 10% exceedance probability in 50 years is 0.27 g. The hazard curve analysis indicates that the most frequent earthquake sources come from seismic sources of deep earthquakes, with depths of 50-300 km. Meanwhile, the most hazardous seismic source is the shallow earthquake source. The high acceleration value associated with shallow earthquake sources suggests the presence of undiscovered fault earthquake sources in the area.

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Author Contributions

All authors have accepted responsibility for the entire content of this manuscript and approved its submission.

Conflict of Interest

Authors state no conflict of interest.

Data Availability Statement

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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