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Investigation of Peak Ground Acceleration on the Kuala Penyu Fault and Its Influence on the Malaysia National Annex

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Abstract

This study investigates the peak ground acceleration (PGA) using probabilistic seismic hazard assessment (PSHA) in Kuala Penyu, Sabah. The data from four earthquake events and mud volcano activity in four highly active areas in the region provided the basis for this in-depth study. The PSHA considered parameters such as earthquake data, source modeling, ground motion model (GMM), maximum magnitudes, and logic trees. The evaluations performed in this study were based on three objectives. The first objective is to update the available earthquake catalog around the Sabah region. The second objective is to characterize the seismic source model by determining seismic hazard parameters, including selecting a suitable GMM and identifying the maximum magnitudes. Finally, the third objective is to conduct a PSHA to calculate hazard estimates in terms of PGA. The PGA for Kuala Penyu, Sabah, was measured at 0.106 g, an increase of 430% when considering the Kuala Penyu fault source in the analysis. Based on this significant change, more in-depth studies are needed, particularly in low-seismicity regions with active fault movements, to enhance seismic analysis. This effort could provide better insights into source modeling for seismic hazard assessments in the region.

1. Introduction

Malaysia is located on the Eurasian Plate, where it interacts with the prehistoric subduction zone of the Philippine Plate, as detailed by Karlo et al. [1]. As a result, there is considerable strike-slip movement between the two plates when they move laterally in relation to one another. According to Eldert et al. [2] and Metcalfe [3], this motion is accompanied by the subduction of the Indo-Australian Plate's oceanic crust, which moves north and beneath the south-moving Sunda Plate. Moreover, due to Sabah's position within three areas of the Pacific Ring of Fire, namely the Philippines, Sulawesi, and Kalimantan, Indonesia, earthquakes, particularly large ones, can trigger others in distant locations through a process known as dynamic stress transfer [4]. This means that the energy from the seismic wave passing through can cause a new earthquake, especially in vulnerable locations such as Sabah. As of now, there is a lack of in-depth studies that examine earthquakes in Sabah. Statistically, the largest earthquake recorded in the region took place in 1923, with a magnitude of 6.6 [5]. Meanwhile, the first-ever recorded earthquake in Sabah occurred in 1902. Since then, 4 earthquakes of magnitude 6 have been recorded, with the most recent one happening in 2015 [6]. In addition, the type of fault that causes earthquakes is still not fully understood due to its low to mild seismic activity and unpredictability [7]. Furthermore, Sabah faults are also quite divided, and their positions are different from each other [8-10]. Because multiple earthquake centers exist across Sabah, buildings should be designed to account for earthquake loads. On top of that, since the epicenters are scattered, seismic hazard analysis must use probabilistic methods to model these faults as line sources, area sources, and point sources [11]. This approach helps identify high-risk areas where earthquake activity is more frequent and assigns them higher seismic design parameters. In contrast, areas with fewer recorded earthquakes are given lower seismic design values.

Peak ground acceleration (PGA) measures the maximum horizontal acceleration the ground experiences during an earthquake. It is typically expressed in units of gravity (g). PGA is one of the seismic design parameters required for building analysis (as adopted by Qinghui et al. [12] and Xinyu et al. [13]), major structures such as bridges (studied by Charu et al. [14], Zhenlei et al. [15], and Hao et al. [16]), dams (analyzed by Ashesh et al. [17] and Thulfiqar et al. [18]), and offshore structures (examined by Piguang et al. [19] and Carlos & Luis [20]). The value can be influenced by several seismic factors such as magnitude, type of fault, source-to-site distance, and soil type [21]. Magnitude refers to the size of an earthquake that can be measured in terms of moment magnitude, MW. Compared to similar metrics, the MW scale gives the most reliable estimate of earthquake size. Meanwhile, a fault is a fracture in rocks that make up Earth's crust. These faults can be classified as one of three types: normal faults, reverse faults, and strike-slip. Next, the source-to-site distance is the distance between the earthquake source and the site affected by the shaking. The source of earthquakes can be influenced by the distance and depth of the fault rupture. Lastly, soil type is determined based on the shear wave velocity. Generally, the softer the soil, the greater the shaking or amplification of waves produced by an earthquake.

The compilation of the earthquake catalog can be obtained from several sources, such as the Malaysian Meteorological Department (METMalaysia) [22], the United States Geological Survey (USGS) [5], and the International Seismological Centre (ISC) [23]. In this study, earthquake records from the selected area were gathered, with four documented epicenters identified and presented in Table 1. The earthquake assessment study began with the collection of fault characteristics based on the study by Tongkul [6], the geological map of Sabah (as in Mohd Zainudin et al. [24]), and literature by Abdullah et al. [25]. In the geological map of Sabah, four faults were identified along the area, differing from Tongkul [6], where the fault extends from Northeast to Southwest. The indication of mud volcanoes has been marked on maps based on several news articles by Abdullah [26] and Corlleus [27]. Their locations in Sabah are referenced in an old report published in 1986 and plotted in Fig. 1. Studying the relationship between earthquakes and mud volcanoes is significant since mud volcanoes are commonly triggered by seismic activity, as identified by Manga et al. [28], Bonini [29], Siling et al. [30], Bonini and Maestrelli [31], and Seropian et al. [32]. These volcanoes typically erupt within days after nearby earthquakes and are highly sensitive to ground motion [28]. The magnitude of such stress changes may exceed the tensile strength of many rock anisotropies and increase crustal permeability by dilating fault-controlled conduits channeling fluids upwards. Also, seepage features may be associated with seismogenic faults in fold-and-thrust belts. There have been a few cases showing that mud volcanoes were triggered by earthquakes, such as those in Japan, Azerbaijan, Pakistan, and Italy, with magnitudes ranging from 4.5 to 9.1. These findings were reported by Bonini et al. [33], Maestrelli et al. [34], Wu et al. [35], and Komatsu and Feyzullayev [36]. In the current research, areas with low seismic activity that are nonetheless considered potentially active were examined due to the presence of mud volcanoes. The analysis was conducted from the perspective of seismic evaluation, specifically based on the PGA value. To achieve this, the study was guided by three main objectives: collecting earthquake data, identifying source modeling, and conducting a probabilistic seismic hazard analysis.

Table 1 *List of earthquake epicentres in the region of Kuala Penyu*

Year	Latitude (Degree)	Longitude (Degree)	Depth (km)	Magnitude (M_W)
2017	5.30	115.60	0.0	3.4
1939	5.30	115.33	10.0	3.5
1995	5.40	115.50	18.3	4.5
1920	5.30	115.33	10.0	4.7

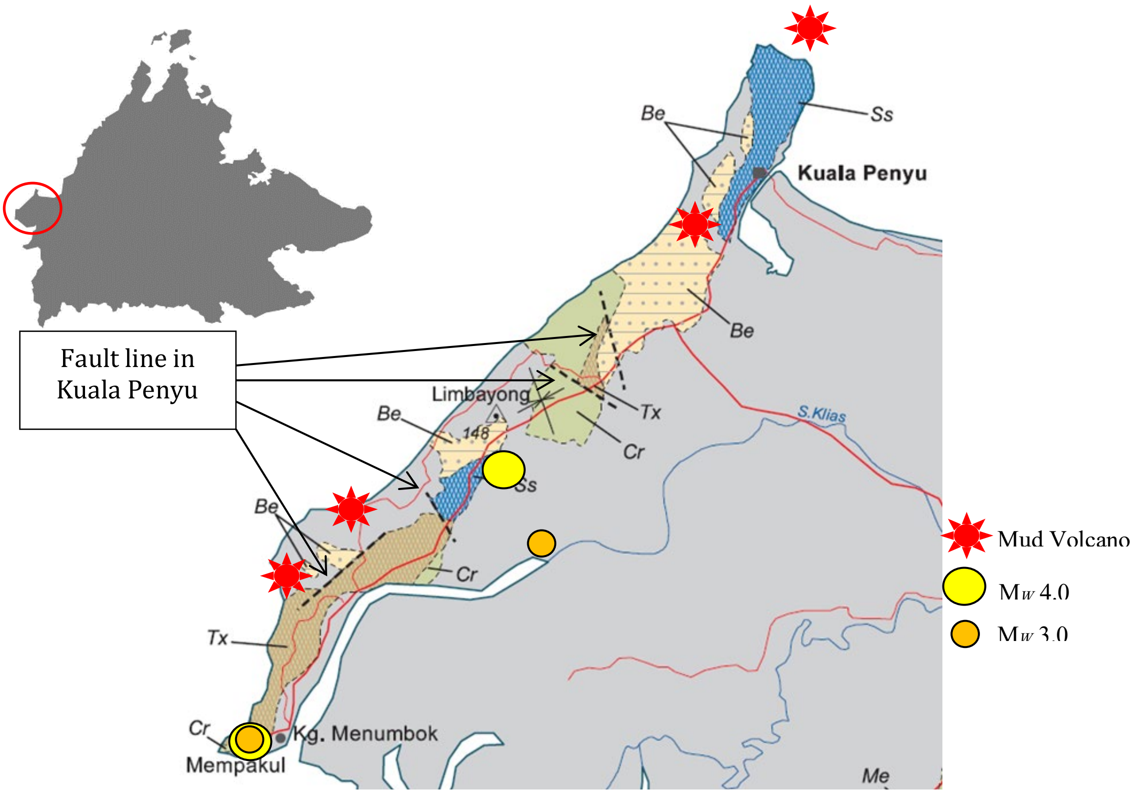

Fig. 1 *Geological structure in the Kuala Penyu area (Ss: Setap Shale, Be: Belait, Tx: Temburong, Cr: Crocker) to identified fault lines in the area (modified from Mohd Zainudin et al. [26]) and earthquake epicenters*

Symbols and Abbreviation	
PSHA	probabilistic seismic hazard assessment
PGA	peak ground acceleration
GMM	ground motion model
M_W	moment magnitude
g	unit of gravity

2. Methodology

Fig. 2 shows the research workflow for analyzing seismic activities in Kuala Penyu, where the earthquake's influence on the seismic design parameter can be observed. This study underwent three phases. In the first phase, the earthquake data catalog was processed through three key analyses: (1) earthquake size analysis, (2) declustering of earthquake events to remove foreshocks and aftershocks from the main events, and (3) completeness analysis. The processed historical earthquake data, combined with seismotectonic conditions, were used to develop a seismic source model. The second phase focused on characterizing the seismic source model by determining seismic hazard parameters. This includes selecting a suitable ground motion model (GMM) and identifying the maximum magnitudes for each fault source. Finally, a Probabilistic Seismic Hazard Assessment (PSHA) was performed to calculate hazard estimates in terms of PGA.

One of the fundamental inputs for seismic hazard assessment of a region of interest is a reliable, complete earthquake catalog for that location. Earthquake catalogs contain the date and time of occurrence, latitude and longitude, magnitude, and focal depth of historical earthquakes. This study verified earthquake data in terms of magnitude values and epicenter information using records from the local earthquake data collection center, the Malaysian Meteorological Department (Met Malaysia) [22], as well as international data, such as that from the United States Geological Survey (USGS) [5] and the International Seismological Centre (ISC) [23], to ensure a reliable data catalog in case there are missing or ambiguous data. Several critical procedures, such as magnitude conversion, declustering (removing before and aftershocks), and completeness analysis, were performed to make sure that the final earthquake catalog is reliable and suitable for the study. The compilation of distinct earthquake sources from the worldwide catalog is important to avoid earthquake location errors and short-term incompletion [37-38]. From these data, the location of mud volcano occurrences was determined using local geological maps and reliable sources of information. The seismic hazard analysis was then performed using site response motion based on bedrock. Next, by referring to the study by Harith et al. [11], the selection of suitable characterization of ground motion was made.

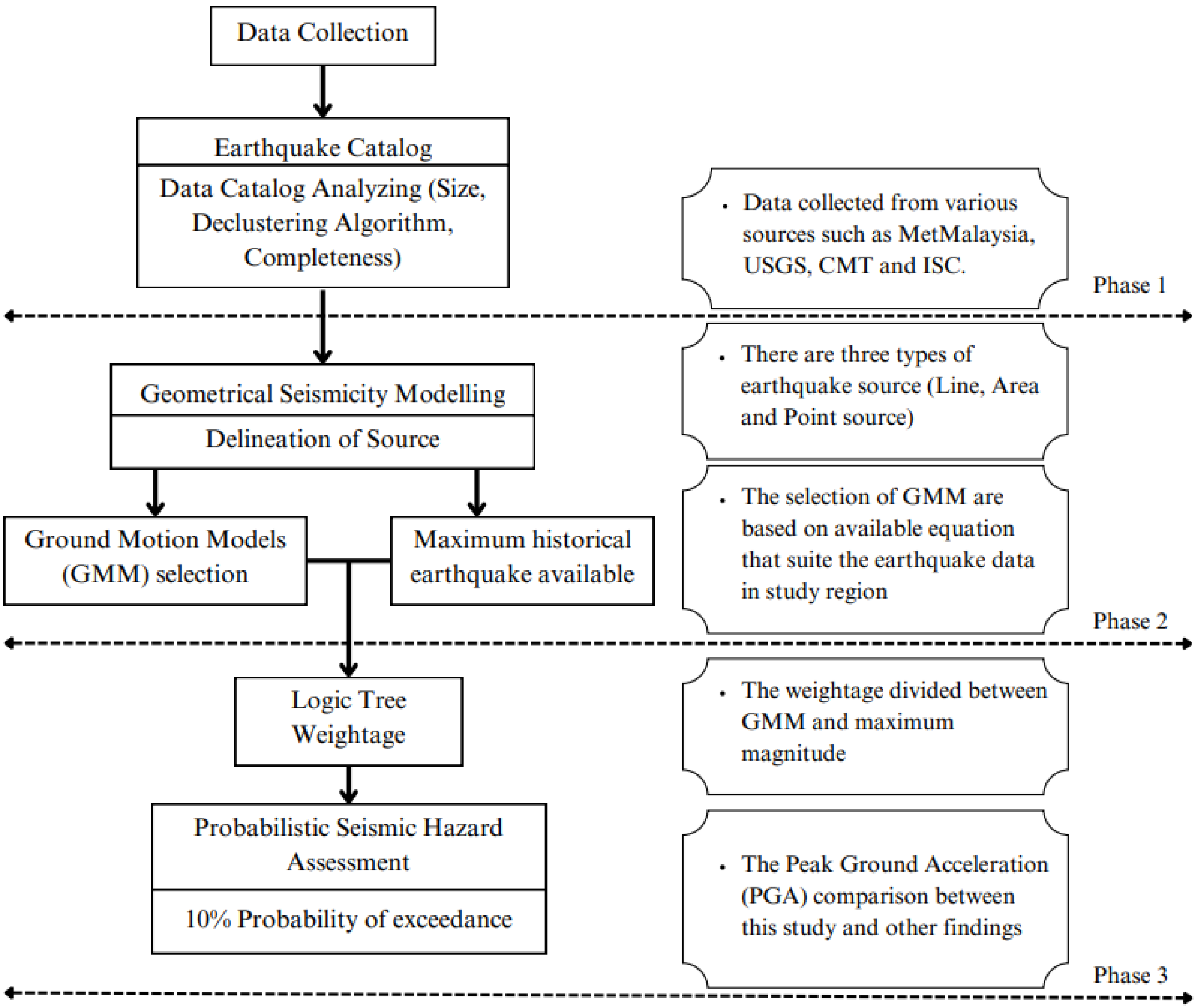

Fig. 2 *Research workflow*

2.1 Data Collection

An earthquake catalog data spanning from 1900 to 2024 was obtained from various earthquake data centers. Based on this compiled catalog, which documents the historical seismic activity in the region extending from 40°S to 80°N and from 105°E to 120°E, seismicity analysis was conducted. In the process of preparing the catalog, only seismic events with a magnitude greater than 2.0 were considered. In low-to-moderate seismic regions, seismicity can be categorized by the dispersed spatial distribution of earthquakes, which indicates that the possibility of moderate-strong earthquake occurrence is rare and inhomogeneous [41]. The non-homogeneous distribution between different magnitude scales requires empirical relationships for converting various reported magnitude scales to M_W. The distribution of earthquake events was then decluttered by removing dependent events, such as foreshocks and aftershocks, from the main event. Information from different databases was used in this analysis to overcome inconsistency and improve the quantity and quality of earthquake data.

All the existing earthquake epicenters were carefully checked to remove any duplicate events. In the raw catalog, many events were classified as dependent events that occurred in a cluster associated with a main shock. These aftershocks and foreshocks must be removed from the catalog using a declustering algorithm to assure a Poissonian distribution of earthquake events. This process is widely used in seismology, particularly in defining seismicity or processing seismic hazard assessment. After declustering, a total of 1308 events remained in the catalog, out of which 14% were events of $M_W \geq 6.0$, 85% were events of $M_W \geq 5.0$, and 1% were events of MW ≥ 3.0. In short, the process of declustering eliminated about 68% of the total recorded events. The final decluttered

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catalog contained the main shocks within the threshold magnitudes M_W 3.0 – 8.6 in the region from 1900 to 2024. The declustering procedure was carried out based on Gardner and Knopoff algorithm methodology because of its efficacy in removing the non-main shock sequences [42]. In addition, the process was also made by considering Teng and Baker [43], Bi et al. [44], and Malakar et al. [45] to improve accuracy. During the incompleteness analysis, the results indicate that strike-slip earthquake events with magnitudes below 6.0 have been fully documented only in the most recent 41-year period, starting from 1964. In comparison, events with magnitudes greater than or equal to 6.0 are fully reported throughout the entire 124-year sample. Nevertheless, this contrasts with the findings in local earthquake historical records, where earthquake events with magnitudes below 4.0 are fully reported only from the year 1982 onward.

2.2 Geometrical Seismicity Modelling

The compilation of earthquake records involves collecting and analyzing historical and instrumental data on seismic activity in the region of interest. This is one of the key activities in earthquake data compilation, particularly when analyzing the PGA level of a region, as demonstrated by Mueller [46]. Then, data on fault characteristics and earthquake records were combined to understand the potential hazards associated with a fault [47-48]. By examining the relationship between the location, orientation, and activity of a fault and the seismic activity in the region, it is possible to identify areas of high seismic risk and potential hazards, such as the likelihood of ground shaking or surface faulting. One way to combine these data sets is to use a Geographic Information System (GIS) to create maps and models of the area. By inputting the data on fault characteristics and earthquake records into a GIS, it is possible to analyze and visualize the spatial relationships between the two datasets. This can help identify patterns in seismic activity that are linked to fault characteristics and inform efforts to mitigate seismic risk. In the case of the Kuala Penyu Fault, earthquake data records and fault characteristics were merged to assess the fault's potential seismic hazard. This fault is believed to be a steeply dipping reverse fault with a strike-slip component and runs roughly north-south through the region. Although there is limited information about the area's stratigraphy, it is believed to be composed of Tertiary-aged sedimentary rocks, including mudstone, siltstone, sandstone, and conglomerate. Additionally, the fault is thought to cut through these rocks, which mainly formed in a shallow marine environment within a foreland basin.

Identification and delineation of seismic source zones is one of the necessary steps in seismic hazard analysis. These zones represent areas with uniform seismicity characteristics, such as focal depth, seismicity rate, and maximum magnitude. The characterization relied on geological and seismological investigations. First, the earthquake data was selected from a defined area where seismic activity is expected to occur within a source zone with similar seismic characteristics. Second, the earthquake catalog, which is spatially heterogeneous, was grouped into zones with similar seismic characteristics within defined spatial boundaries. The source modeling for the Sabah region is illustrated in Fig. 3. Since most earthquakes in the area are classified as moderate, the region exhibits an earthquake pattern that highlights the non-uniformity of seismic activity. The first source model was considered based on characteristic earthquakes generated by line faults. There are five line faults that possibly act as the source of active earthquakes, which are assigned as Lines 1, 2, 3, 4, and 5. In addition, several possible seismic sources were identified, each of which can be characterized by earthquake concentration in areas 6, 7, and 8. A background point source was designated for an unknown location to take into consideration the spatial variation in seismicity. The method to identify source modeling was based on smooth seismicity, where the analysis used a spatial grid (0.10 cells in latitude and longitude) to determine seismic event rates. A similar technique can be found in various studies such as Abdalzaher et al. [49], Pandolfi et al. [50], and Abdalzaher et al. [51]. In other words, this study performs the seismic hazard analysis by including all the sources modeling available in Sabah with additional faults in Kuala Penyu.

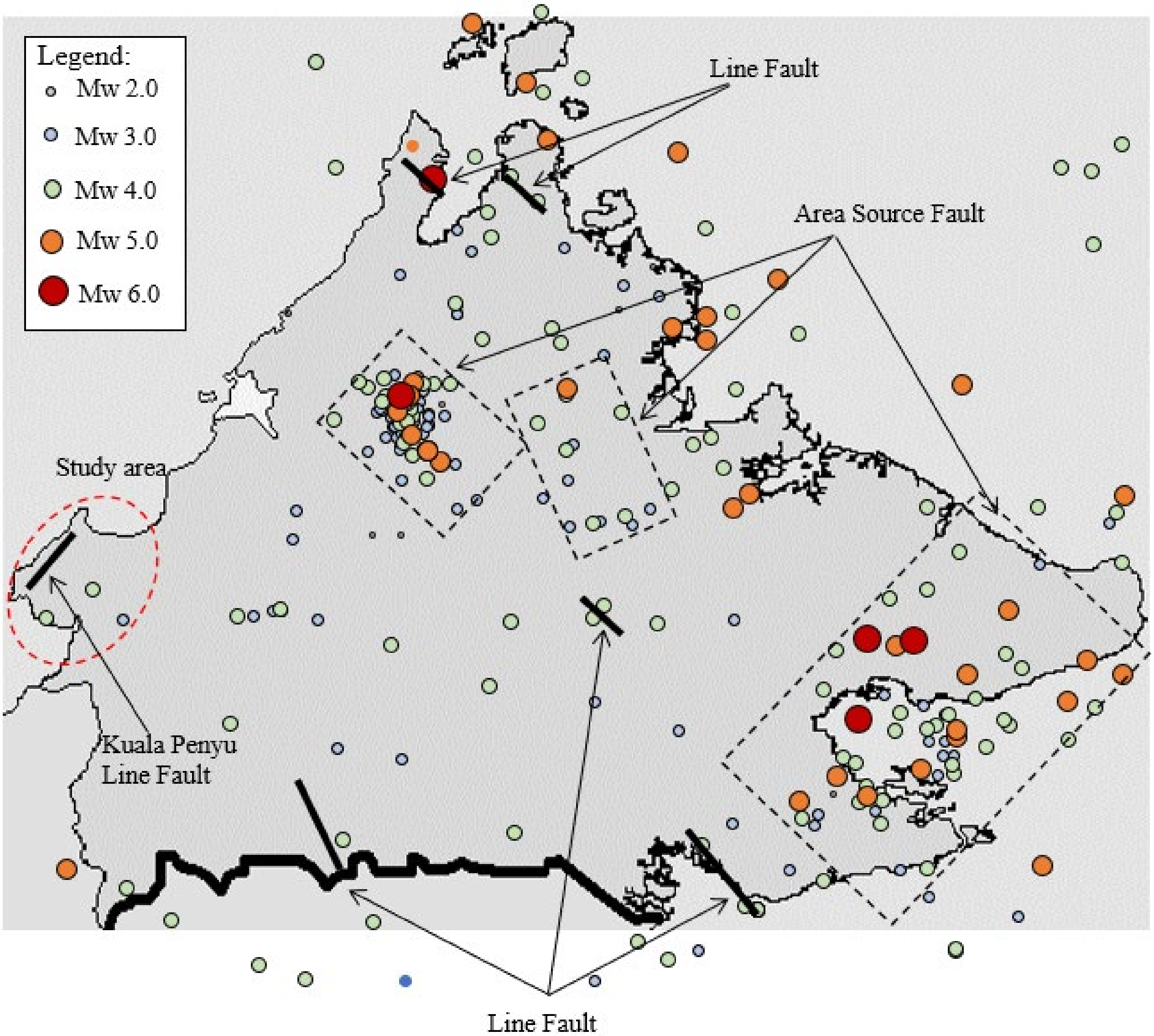

Fig. 3 *Seismic sources available in the Sabah region, along with the fault source of the site investigated (Kuala Penyu). (This map is based on the latest geological studies provided by the Malaysian Meteorological Department (METMalaysia [22]) and as modified by Harith et al. [11])*

2.3 Ground Motion Models–GMM s

Since Sabah has a small number of ground motions, this study needs to incorporate equations used by Zhao et al. [52], Atkinson and Boore [53], Pezeshk et al. [54], Boore et al. [55] and Chiou and Youngs [56] into the analysis. The Zhao et al. [52] GMM was developed for shallow crustal earthquakes in the Japan region, whereas the one by Atkinson and Boore [53] was used for shallow crustal earthquakes due to both global and local faults. As mentioned previously, these selected spectral GMMs are the ones recommended by Stewart et al. [57] for use in seismic hazard assessments in the global earthquake model project. As such, owing to their suitability, Zhao et al. [52] and Atkinson and Boore [53] GMMs have been identified as appropriate for active crustal regions (ACRs) and stable continental regions (SCRs), respectively. To the best of the author's understanding, both models are considered valid for short and long distances analysis. In order to enrich the seismic hazard analysis and to have more accurate probabilistic results, the next-generation attenuation (NGA) ground-motion relations that were developed for the shallow crustal earthquakes were also selected to predict the ground motion parameters being generated by the local faults. In this regard, the NGA models proposed by Boore et al. [55], Chiou and Youngs [56], and Pezeshk et al. [54] were used in this study.

The GMM model was chosen based on two conditions: magnitude and distance. For the equations of Zhao et al. [52] and Pezeshk et al. [54], the range of magnitude was set to be between 5.0 and 8.0. Meanwhile, for the equations of Atkinson and Boore [53], Boore et al. [55], and Chiou and Youngs [56], the range of magnitude was set to be between 3.5 and 8.0. The distance required for the equation of Zhao et al. [52], Boore et al. [55], and Chiou and Youngs [56] was less than 400 km, while less than 1000 km was needed for the Atkinson and Boore [53] and Pezeshk et al. [54]. From the two GMM characters used, the logic tree weight was estimated to be 0.10 for Zhao et al. [52], 0.30 for Atkinson and Boore [53] and Pezeshk et al. [54], and 0.15 for Boore et al. [55] and Chiou and Youngs [56]. The summary for all GMM models used is as described in Table 2.

Table 2 *List of suitable ground motion models based magnitude, distance range, and its respective logic tree weight*

Ground-motion Model	Magnitude range (M_W)	Distance range (km)	Logic Tree Weight
Zhao et al. [52]	5.1 – 7.3	0 - 300	0.10
Atkinson and Boore [53]	3.5 – 8.0	0 - 1000	0.30
Pezeshk et al. [54]	5.0 – 8.0	0 - 1000	0.30
Boore et al. [55]	3.5 – 8.5	0 - 400	0.15
Chiou and Youngs [56]	3.5 – 8.0	0 - 400	0.15

2.4 Earthquake Assessment on Site

The classification of hazard levels based on PGA and mud volcano evidence provides a way to assess the potential seismic hazard posed by a fault. A mud volcano is a geological phenomenon that occurs when pressurized water and gas cause mud and other sediment to erupt onto the surface. This phenomenon can be triggered by tectonic activity and may be a sign of potential seismic activity in the area. By examining both the level of PGA and the presence of mud volcano evidence, it is possible to classify the potential seismic hazard in the region. For example, a low level of PGA and no evidence of mud volcanoes might suggest a low seismic hazard, while a high level of PGA and strong evidence of mud volcanoes could indicate a high level of seismic hazard. Furthermore, there is a relationship between mud volcano activity with the earthquake magnitude, as mentioned by Wang and Manga [58]. According to Morley et al. [59], mud volcano activity beneath Kuala Penyu shows evidence of fault movement. Hence, the PSHA method was calculated using a total probability theorem, which assumed that earthquake magnitude M and hypocentre distance R were continuous independent random variables. The total probability theorem is expressed in its most basic form, as illustrated in equation (1):

$$P[\mathrm{I} \geq i] = \int_r \int_m P[\mathrm{I} \geq \mathrm{i} \,|\mathrm{m\ and\ r}] \,.\, \mathrm{f}_M(m) \,.\, \mathrm{f}_R(r)\, \mathrm{dm\ dr} \qquad (1)$$

Where,

fM(m) = density function of magnitude

fR(r) = density function of hypocentre distance

P [I > i |M and R] is a conditional probability of (random) intensity I exceeding value i at a site, given an earthquake magnitude M and hypocentre distance R. Using this theorem and all of the information described above, the value of PGAs for a specific return period of the earthquake was calculated. In addition, different equations utilized two types of mathematical logarithmic transformations: the natural and normal logarithm. The normal logarithm of a product is the sum of the logarithms of the numbers being multiplied. In contrast, the natural logarithm of a number is its logarithm to the base e. The relationship between both logarithms can be translated through the equation (2);

$$LOG10(PGA) = LN(PGA)/LN(10) \qquad (2)$$

3. Results and Discussion

This study examined and analyzed the PSHA of Kuala Penyu. Its primary purpose is to present the new PGA results using a combination of the Sabah earthquake faults and the fault source of Kuala Penyu. Line and area background source models were used to simulate the seismic sources with variable characteristics. A logic tree framework was used to incorporate basic quantities such as GMMs and maximum magnitudes to consider epistemic uncertainty. The probabilistic hazard results are presented in Table 3 for a 10% probability of exceedance in 50 years, corresponding to a return period of 475 years. The results from previous literature by MSEN1998-1:2015 [39], Johnson et al. [40], Giardini et al. [60], Petersen et al. [61], Adnan et al. [62], and Leyu et al. [63] are also elucidated for comparison. On average, research findings from various studies such as MSEN1998-1:2015 [39], Johnson et al. [40], Giardini et al. [60], Petersen et al. [61], Adnan et al. [62] and Leyu et al. [63], gave PGA values of 0.020, 0.030 g, 0.080 g, 0.060 g, 0.080 g and 0.092 g, respectively. Among these studies, MSEN1998-1:2015 [39] has the lowest PGA, whereas Leyu et al. [62] exhibited the highest. One factor that affects the PGA values is the modeling of the fault source. Studies by Giardini et al. [60], Petersen et al. [61], and Leyu et al. [63] used the area source model in their analysis, while Adnan et al. [62] used the line source model. This study adopted three types of source modeling (line, area, and background) similar to the study by MSEN1998-1:2015 [39] and Johnson et al. [40], as this method provides the most accurate representation of the source models of Sabah. The current study's findings indicate an increase in PGA value compared to other studies with 0.106 g when the Kuala Penyu source modeling was treated as background and line source.

Table 3 *Value of expected maximum PGA (PGAmax) for 10% probability of exceedance in Kuala Penyu area*

Reference	Peak Ground Acceleration (PGA) (g)	Source Model for Sabah
MSEN1998-1:2015 [39]	0.020	Line, area, and background (Kuala Penyu identify as background)
Johnson et al. [40]	0.030	Line, area, and background (no further information on Kuala Penyu)
Giardini et al. [60]	0.080	Area (no further information on Kuala Penyu)
Petersen et al. [61]	0.060	Area (including Kuala Penyu)
Adnan et al. [62]	0.080	Line (no information on Kuala Penyu)
Leyu et al. [63]	0.092	Area (not include Kuala Penyu)
This study (with Kuala Penyu fault)	0.106	Line, Area, and Background (Kuala Penyu identify as line and background)

The seismic hazard analysis heavily relies on earthquake data and source modeling. This study focuses specifically on the Kuala Penyu area because the region has been found to exhibit seismic activity with the presence of mud volcanoes, indicating an active seismic region. The PGA values for Kuala Penyu and its neighboring regions showed an increase. Without considering the Kuala Penyu fault, the average PGA values were determined to be generally consistent with those reported in MSEN1998:2015 [39] and Johnson et al. [40]. Specifically, the PGA values for Kuala Penyu, Beaufort, Sipitang, and Keningau were 0.020g, 0.021g, 0.015g, and 0.030g, respectively. However, these values are lower than those measured by Giardini et al. [60], Petersen et al. [61], Adnan et al. [62], and Leyu et al. [63].

When the Kuala Penyu fault was included in the analysis, the PGA value for the area increased significantly to 0.106g, surpassing the values from the analysis without the fault and those from other studies, such as MSEN1998:2015 [39], Johnson et al. [40], Giardini et al. [60], Petersen et al. [61], Adnan et al. [62], and Leyu et al. [63]. A similar increment was previously observed in Keningau, while Beaufort has a higher PGA value than the analysis without the fault but remains comparable to Petersen et al. [61]. Meanwhile, the PGA value for Sipitang was slightly higher than that from the analysis without the Kuala Penyu fault, MSEN1998:2015 [39], and Johnson et al. [40], but lower than those reported by Giardini et al. [60], Petersen et al. [61], Adnan et al. [62], and Leyu et al. [63].

Table 3 *Result of PGA for Kuala Penyu and surrounding areas due to Kuala Penyu fault*

Site	This Study (with Kuala Penyu Fault)	This Study (without the Kuala Penyu Fault)	MSEN1998: 2015 [39]	Johnson et al. [40]	Giardini [60]	Petersen [61]	Adnan et al. [62]	Leyu [63]
Kuala Penyu	0.106	0.020	0.020	0.020	0.080	0.060	0.080	0.080
Beaufort	0.065	0.021	0.020	0.020	0.080	0.060	0.080	0.080
Sipitang	0.027	0.015	0.015	0.010	0.080	0.060	0.080	0.080
Keningau	0.164	0.030	0.025	0.030	0.080	0.060	0.080	0.080

In summary, this study showed that the occurrence of earthquakes can significantly influence the PGA values in the area and its surroundings. As such, there is a need for more in-depth studies, particularly in low-seismicity regions with active fault movements, to be incorporated into seismic analysis. Furthermore, this effort could contribute to future seismic hazard assessments in the region. Overall, the study highlights the importance of ongoing research and monitoring of seismic activity in Sabah to better understand earthquake risks. Additionally, the results may serve as a valuable reference for other regions prone to earthquakes that face similar challenges in assessing and mitigating seismic hazards.

4. Conclusion

The data from four earthquake events and mud volcano activity in four highly active areas in Kuala Penyu provides a basis for an in-depth study of seismic impacts through a seismic hazard assessment. The PSHA considered parameters such as earthquake data, source modeling, GMM, maximum magnitudes, and logic trees for the analysis in the study area. In conclusion, the PGA for Kuala Penyu increased by 430% when considering the Kuala Penyu Fault, compared to analyses that did not include the fault. Moreover, the resulting value of 0.106g was similar to the 0.08g observed in studies by Giardini et al. [60], Adnan et al. [62], and Leyu et al. [63], with a difference of 32.5%. The seismic hazard assessment offers critical insights into the potential earthquake risks in the region. The study revealed that the fault can generate low-magnitude earthquakes, which could significantly increase PGA values in surrounding areas. Additionally, the study uncovered considerable variations in PGA values across different regions of Sabah. Beaufort and Sipitang areas exhibited lower PGA values compared to Kuala Penyu and Keningau. Based on these findings, it is crucial to implement suitable measures to reduce the risks associated with seismic activity (such as mud volcanoes) and low earthquakes. The effective implementation of the initiative is expected to aid in the creation of more precise seismic hazard maps, as well as the comprehensive review and updating of seismic design codes.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design****: Noor Sheena Herayani Harith, Felix Tongkul, Azlan Adnan;* ***data collection****: Noor Sheena Herayani Harith;* ***analysis and interpretation of results****: Noor Sheena Herayani, Felix Tongkul;* ***draft manuscript preparation****: Noor Sheena Herayani Harith, Azlan Adnan. All authors reviewed the results and approved the final version of the manuscript..*

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