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RESEARCH ARTICLE

Seismic Hazard Estimation for Sumatra and Kalimantan Region Using Event-Based Probabilistic Seismic Hazard Analysis (EB-PSHA)

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Abstract

Indonesia is located in a tectonically active region influenced by the interactions of several tectonic plates. This tectonics setting give rise to numerous active faults and subduction zones, making Indonesia highly susceptible to earthquakes. To mitigate earthquake risk, seismic hazard assessments are essential and contribute directly to the development of earthquake-resistant building codes or premium assets estimation for assets insurance. This study aims to assess seismic hazard analysis in Sumatra and Kalimantan using the Event-Based Probabilistic Seismic Hazard Analysis (EB-PSHA) method for a 250-year return period (0.4% annual exceedance probability in one year) for Peak Ground Acceleration (PGA) and Spectral Acceleration (SA) at 0.3 s and 0.6 s. Three seismic source models, Active Shallow Crusts, Subduction Interfaces, and Background Sources, are used in this analysis. A combined earthquake catalog from several agencies is used to estimate the magnitude of completeness (M_c), a-value, and b-value based on the mainshock earthquake only. This analysis utilize Ground Motion Prediction Equations (GMPEs) randomly sampled to estimate the potential intensities. These findings reveal significant regional variations in seismicity, with the southern Sumatra showing high seismicity rate and the northern part indicating potential stress accumulation. Particularly in Bengkulu Province, due to the relative high seismicity rate based on the seismicity statistical parameters of a-value and b-value. It also suggests the influence of multiple megathrusts and active faults. In contrast, Kalimantan shows lower hazard overall, though East Kalimantan records localized high intensities due to the Meratus and Mangkahilat faults. Although Kalimantan's seismicity is low, historical events demonstrate that distant earthquakes can still cause substantial impacts. The model has been validated by using six historical events and it is in good agreement more than 75% of correlation. The results offer valuable input for seismic risk analysis on the potential building loss estimation through Event Loss Table (ELT).

Keywords: Seismic Hazard Analysis, Event Based, PSHA

1. Introduction

Indonesia is surrounded by major tectonic plates, Indo-Australian Plate, Sunda Plate, Philippine Sea Plate, and Caroline Plate. These plates move relative to each other at a rate of ~52 mm/y to ~103 mm/y (Hutchings and Mooney, 2021). The implication of the plate movement is the formation of faults on land and subduction zone. The subduction zone is the intersection between two plates (oceanic plate and continental plate), where the oceanic plate goes down (subducting) to the mantle below the continental plate (Tarbuck and Lutgens, 2015) and it is also called megathrust zone. Either faults and subduction zones can generate an earthquake with vary of magnitudes. Indonesia has about more than 200 active faults and 16 megathrusts lies from western to eastern part of Indonesia (Tim Pusat Studi Gempa Nasional, 2017). Therefore, Indonesia has a high potential earthquake.

Some destructive earthquakes from megathrust zones have been recorded such as Mw 7.9 Flores earthquake on December 12, 1992 (Beckers and Lay, 1995), Mw 9.1 Aceh Earthquake on December 26, 2004 (Lay et al., 2005), Mw 8.6 Nias-Simeulue earthquake on March 28, 2005 (Borrero et al., 2011; Nuannin et al., 2012), Mw 7.7 South of Java earthquake on July 17, 2006 (Mori et al., 2007), and Mw 8.4 Bengkulu earthquake on September 12, 2007 (Ambikapathy et al., 2010). Furthermore, the disastrous earthquakes have also been identified, such as Mw 7.6 Padang earthquake on September 30, 2009 (McCloskey et al., 2010), Mw 6.2 Central Aceh earthquake on July 2, 2013 (Prasetyo et al., 2015), Mw 6.5 Pidie Jaya, Aceh earthquake on December 6, 2016 (Muzli et al., 2018), Mw 6.5 Tasikmalaya, West Java earthquake on December 15, 2017 (Sirait et al., 2020), Mw 7 Lombok earthquake on August 5, 2018 (Supendi et al., 2020), Mw 6 Situbondo, East Java earthquake on October 10, 2018 (Patimah et al., 2022), Mw 7.2 Halmahera earthquake on July 14, 2019 (Yuliatmoko and Kurniawan, 2019), Mw 6.2 Mamuju-Majene earthquake on January 14, 2021 (Supendi et al., 2021), Mw 6.1 Pasaman Barat, West Sumatra earthquake on February 25, 2022 (Dewanto et al., 2022; Supendi et al., 2023a; Wulandari et al., 2023), and Mw 5.6 Cianjur, West Java earthquake on November 21, 2022 (Supendi et al., 2023b; Zulfakriza et al., 2024).

These earthquakes took many human fatalities, collapsed buildings, and produced high economic losses. The human fatalities caused by an earthquake are mainly due to building collapse (Doocy et al., 2013). The building collapse due to an earthquake may have several factors, such as subsoil conditions, material quality, and construction practices (Ecemis, 2020; Narayan et al., 2018; Obiora et al., 2022).

Therefore, the construction of building must follow the earthquake building code standardization for constructing an earthquake resistant building. The purpose of earthquake building code is to prevent building collapse severe, thereby it could reduce number of casualties and high losses (Burby and May, 1999; Nugroho et al., 2022). Therefore, currently, Indonesia has SNI 1726:2019 as earthquake (seismic) building code that must be followed (BSN, 2019).

One of the factors to develop the seismic building code is seismic hazard analysis (Daniell, 2015). The seismic hazard can be modelled by using probabilistic approach, Probabilistic Seismic Hazard Analysis (PSHA). Indonesia has the latest National Seismic Hazard Map (NSHM) in 2017 (Irsyam et al., 2020; Tim Pusat Studi Gempa Nasional, 2017) as the reference for earthquake resistant building construction. This map was developed by using classical PSHA method which is applied integration over all possible earthquakes and ground motion values (Baker, 2013; McGuire, 2008; McGuire and Arabasz, 1985). To evaluate risk in terms of building losses besides considering seismic building code, another approach is used by using Event-Based Probabilistic Seismic Hazard Analysis (EB-PSHA). Some researchers have done using this method to estimate a certain building loss such as schools (Purwana et al., 2022) and residential (Lambang-Goro et al., 2022). Before estimating the building losses, the event-based seismic hazard must be modelled first.

Therefore, the research aims to estimate the seismic hazard by using EB-PSHA method in Sumatra and Kalimantan for return period of 250-year or equivalent to 0.4% probability of exceedance in one year. The Intensity Measure Types (IMTs) of Peak Ground Acceleration (PGA), Spectral Acceleration (SA) 0.3 s and 0.6 s as well as zonal statistics in terms of the majority on the province level are considered in this analysis for corresponding return period and each IMTs. These are the limitations of this research.

2. Data and Methods

The seismic hazard estimation utilizes the earthquake catalog, seismic source models and Ground Motion Prediction Equations (GMPEs). The earthquake catalog is used to calculate the seismicity parameters; magnitude of completeness (M_c), a-value, and b-value for each seismic source models. The a-value and b-value are calculated by using linear regression (Allen L. Edwards, 1984) and M_c is estimated based on the higher frequency earthquake in a non-cumulative earthquake distribution (Wiemer and Wyss, 2000). These parameters are then used to calculate the occurrence rate for each seismic source models through the Gutenberg-Richter relationship as shown in Eqn 1, where the M is moment magnitude (M_w) and it could be represented by the M_c and N is the number of earthquakes (Gutenberg and Richter, 1944). The catalog is compiled from three agencies; Indonesia Agency of Geophysical, Meteorogical, and Climatology (BMKG) (Jihad et al., 2021), US Geological Survey (USGS) (USGS, 1879), and International Seismological Centre (ISC) (Lentas et al., 2019) that have been evaluated. The year of catalog are range from 1906 to 2022. The heterogeneity of magnitude unit is then converted to the moment magnitude (M_w) unit by using the magnitude scaling relationship from National Earthquake Study Center of Indonesia (Tim Pusat Studi Gempa Nasional, 2017) as written in the Eqn 2. The mainshock earthquake only is consider to be used for the processing. The Reasenberg's declustering algorithm (Reasenberg, 1985) is used to separate between foreshock, mainshock, and aftershock. The declustering process is done by using ZMAP MATLAB® package software (Wiemer, 2001; Wyss et al., 2001) with the declustering parameter as shown in Table 1. The declustered catalog (mainshock) is assumed Possion distribution in time domain. This is then evaluated statistically by using Kolmogorov-Smirnov test where the p-value should be greater than 0.05 (Berger and Zhou, 2014).

$$\log_{10} N = a - bM \tag{1}$$

$$M_w = \begin{cases} 1.0107\, m_b + 0.0801, & 3.7 \le m_b \le 8.2 \\ 0.6016\, M_s + 2.476, & 2.8 \le M_s \le 6.1 \\ 0.9239 M_s + 0.5671, & 6.2 \le M_s \le 8.7 \\ M_L, & All \end{cases} \tag{2}$$

$$SES(T) = \{k\ x\ rup, k \sim P_{rup}(k|T)\ \forall\ rup\ in\ Src\ \forall\ in\ SSM\}$$
(3)

Table 1. Declustering parameter by using Reasenberg's algorithm.

Parameter	Value
$\boldsymbol{\tau_{min}(days)}$	1
$\boldsymbol{\tau_{max}(days)}$	10
$\boldsymbol{p_1}$	0.95
$\boldsymbol{x_k}$	0.5
$\boldsymbol{x_{meff}}$	1.5
$\boldsymbol{r_{fact}}$	10

The main seismic source models, Active Shallow Crust (ASC) and megathrust (Subduction Interface) are retrieved from National Earthquake Study Center of Indonesia (Tim Pusat Studi Gempa Nasional, 2017). This processing considers to include some potential local faults in Aceh; Panteraja segment (Muzli et al., 2018), Extended Batee and Langsa Backthrust Segments (Muksin et al., 2023) also Lokop Segment (Muksin et al., 2019). There are 66 ASCs and 7 megathrust zones in total for Sumatra and Kalimantan region. The background seismicity is also considered to estimate the seismic hazard other than ASC and Subduction Interface source models. This model uses 0.5° gridded seismicity. The depth distribution of earthquake 10 - 40 Km for ASC, 20 Km – 50 Km for Subduction Interface, and 10 Km – 300 Km for background source are used in the processing.

The processing uses the logic-tree GMPEs as illustrated in Fig. 1 for each seismic source model where each GMPE is defined an uncertainty weight for sampling process. The GMPEs are used to calculate a ground motion amplification intensity. The IMTs are configured to Peak Ground Acceleration (PGA) and Spectral Acceleration (SA). The SA is calculated for two periods at 0.3 s and 0.6 s. Both the GMPEs and the uncertainty weight refer to the configuration from National Earthquake Study Center of Indonesia (Tim Pusat Studi Gempa Nasional, 2017). A site classification of average shear wave velocity to a depth of 30 meters (V_{s30}) from USGS takes account to ground amplification estimation (Wald and Allen, 2007). Furthermore, the reference depth of 1.0 Km/s and 2.5 Km/s are calculated by using the relationship of (Chiou and Youngs, 2014) and (Campbell and Bozorgnia, 2014) respectively.

All these configuration parameters then used for seismic hazard analysis by using OpenQuake engine through the Event-Based Probabilistic Seismic Hazard Analysis (EB-PSHA) method (Pagani et al., 2014). The engine will simulate the ground shaking based on the given source models on a set region with ground motion model. The simulation applies

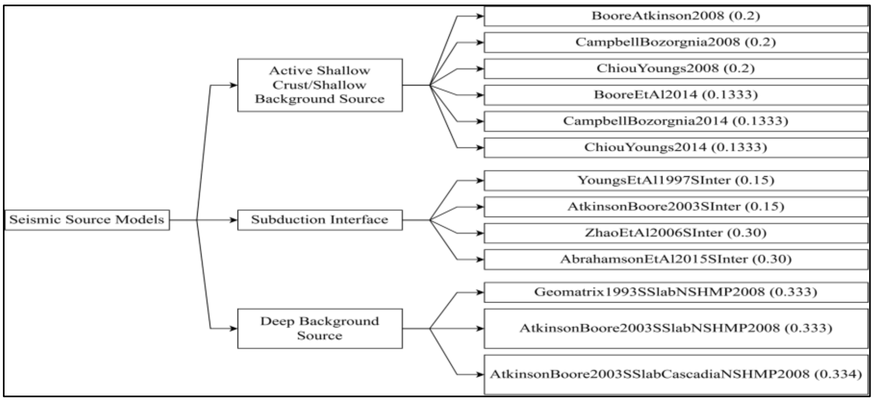


Fig 1. Logic-tree of Seismic Source Models and Ground Motion Prediction Equations (GMPEs) used for the seismic hazard analysis

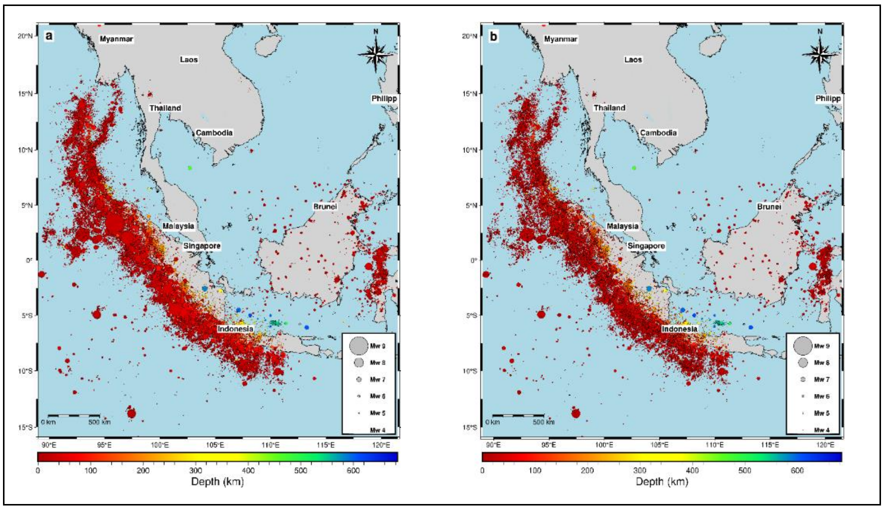


Fig 2. The seismicity in around Sumatra and Kalimantan where (a) the initial dataset before declustering and (b) the declustering dataset seismicity. This data was retrieved from BMKG, USGS and ISC from 1906-2022.

The Monte Carlo sampling algorithm (i.e. random). It generates a Stochastic Event Set (SES) or synthetic earthquake catalog of ruptures for given time span T. Furthermore, the number of occurrences in a T is simulated by sampling the probability distribution $(P_{rup}(k|T)$ for each rupture generated by seismic source models based on the logic tree configuration as shown in Fig. 1. Mathematically, the SES is written as Eqn 3 where the k is the number of occurrences and rup is the ruptures. It will be sampled based one the $P_{rup}(k|T)$ randomly. For the sake of a simple explanation, the rup is repeated by k times in the SES. The T and number of SES are adjusted to 1 year and 1.000 respectively.

Furthermore, the sampling of logic tree is adjusted to 1 realization instead of full enumeration for each seismic source model. The output of seismic hazard analysis will be seismic hazard map for return period of 250-year or equivalent to 0.4 % probability of exceedance in one year and heatmap of zonal statistics in terms of intensity level for each IMTs and province level. The seismic hazard model will be validated by using some historical data through the GMPEs validation and evaluated using statistical methods.

3. Results and Discussion

Three earthquake catalogs (BMKG, USGS, and ISC) were combined into single initial dataset. In total 77.469 earthquakes were collected in this dataset as shown in Fig. 2a. General statistics shows the dataset has magnitude range of 1.6 to 9.1 after the magnitude conversion to moment magnitude, M_w and depth range of 0 Km to 684 Km. The magnitude of completeness (M_c) is estimated of M_w 4.3 for this dataset where the seismicity statistical parameters of a-value and b-value are 9.12 and 1 respectively as shown in Fig. 3a. The Fig. 4a depicts the non-cumulative and cumulative of number of earthquakes from 1906 to 2022 for the initial dataset. The number of earthquakes has cumulatively increased. The non-cumulative earthquake shows the increment prior 2005 and decrease after 2005. Furthermore, the declustered dataset produced 54.285 recorded mainshock only or about 30 % earthquakes have been reduced of initial dataset after the declustering algorithm was applied as depicted in Fig. 2b. The declustered dataset follows the Poisson distribution in the time distribution where the p-value of 0.500032 based on the goodness-of-fit using Kolmogorov-Smirnov test. The declustered dataset has magnitude range of M_w 1.7 to M_w 9.1 and the depth distribution remains the same, this is a final dataset. The seismicity statistical parameters of the final dataset show the a-value and b-value of 8.84 and 0.99 and the M_w 4.3 is captured as the M_c (Fig. 3b). Both datasets show also that the M_w 2.6 is dominant for magnitude distribution below M_w 3. The difference of b-value from both datasets are relatively small and close to 1 as the global value parameter while the a-value decrease due to the declustered process. It indicates the dataset well captured either small and large earthquake in Sumatra and Kalimantan. The non-cumulative time distribution of the final dataset exhibits a similar pattern to that the initial dataset (Fig. 4b). It suggests that the seismicity has decreased after the large energies were released of M_w 9.1 Aceh earthquake in 2004 and M_w8.6 Nias-Simeulue in 2005 for the past 17 years based on the dataset from the geological time scale perspective.

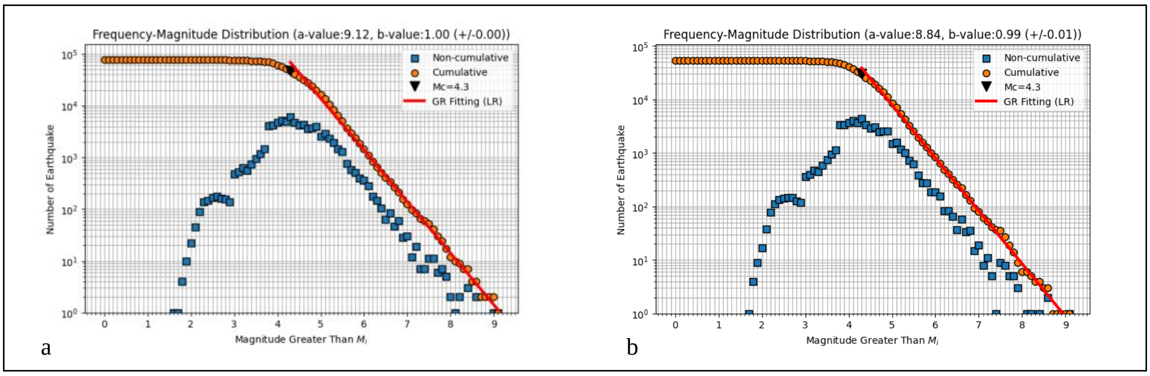


Fig 3. The frequency-magnitude distribution for (a) initial dataset and (b) final dataset (filtered) where both have much experienced of M_w 4.3 as the magnitude of completeness (M_c) besides M_w 2.6 as the other M_c below the magnitude distribution of M_w 3 in Sumatra and Kalimantan region.

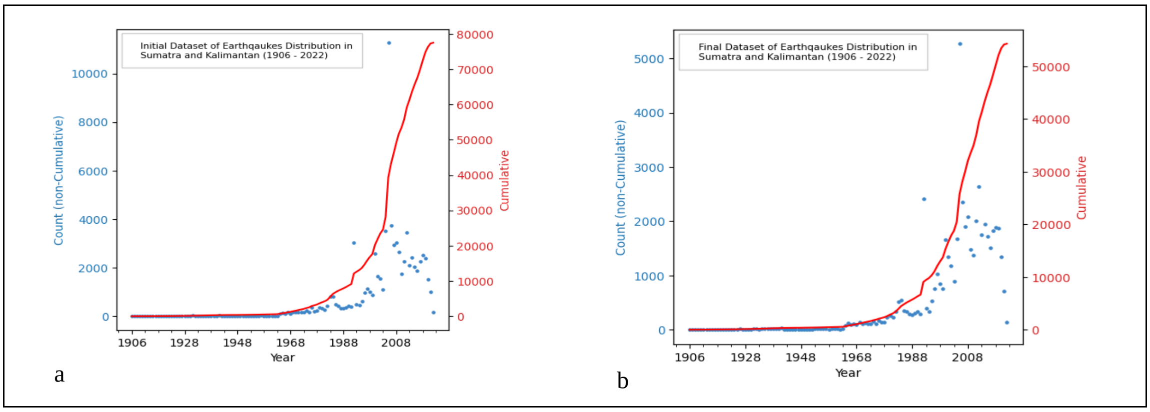


Fig 4. The non-cumulative and cumulative of number of earthquakes from 1906 – 2022 in Sumatra and Kalimantan for (a) initial dataset and (b) final dataset after the declustering process. Both datasets depict the increment number of earthquakes before 2005 and decrease after 2005.

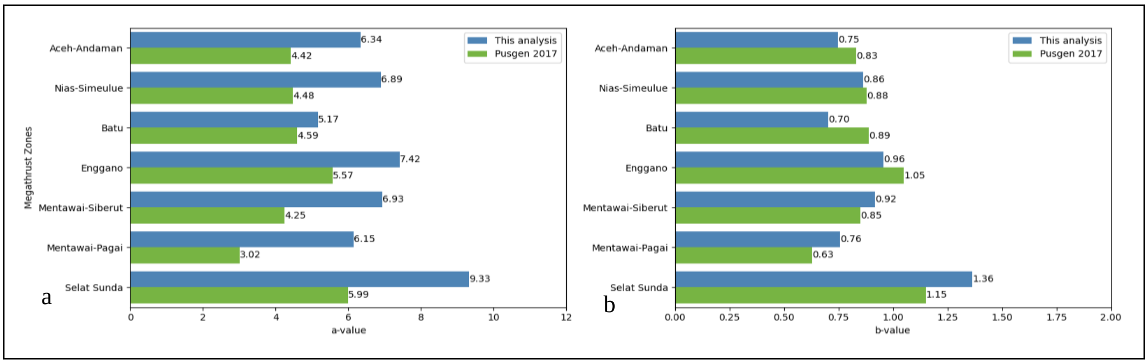
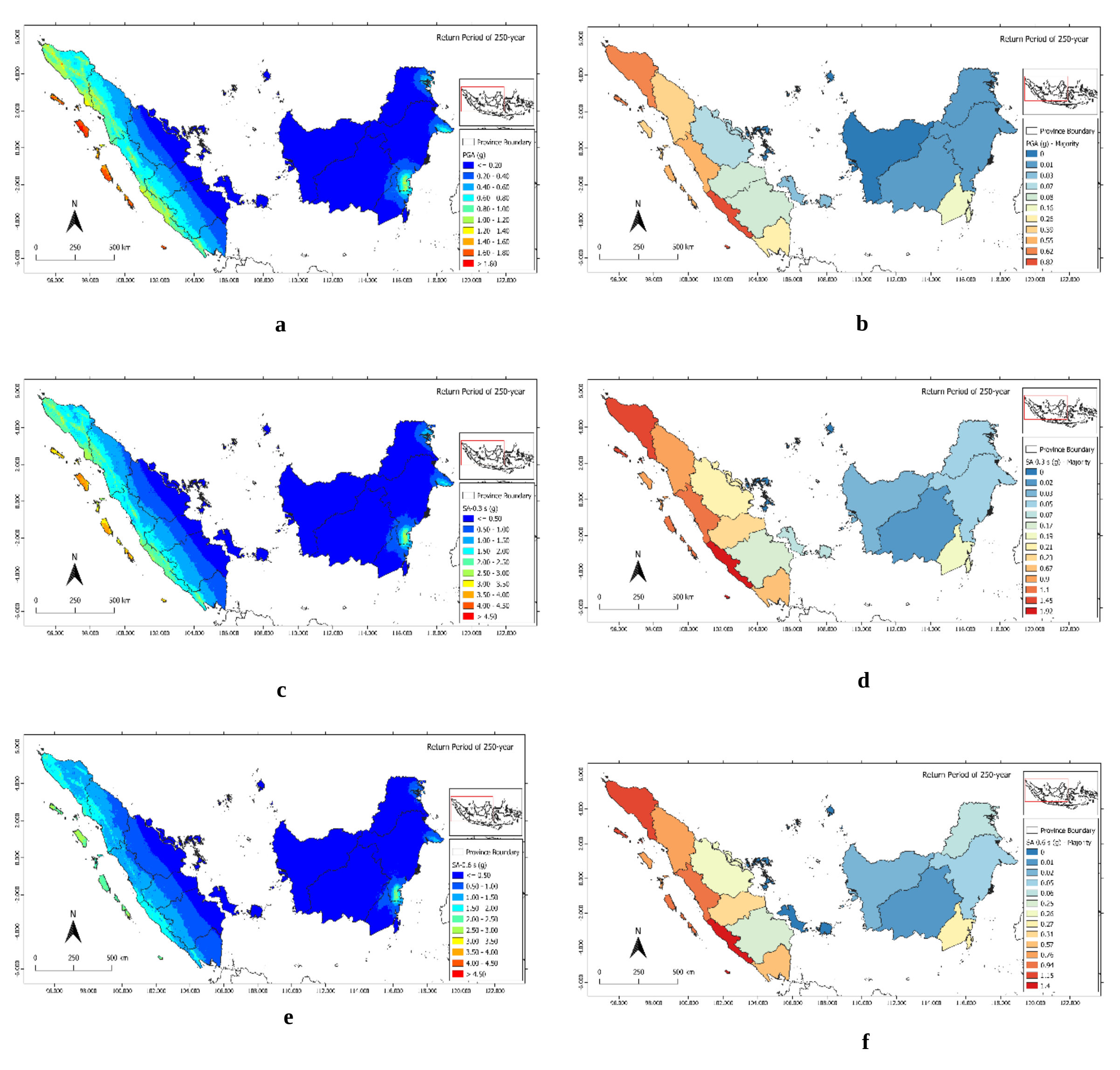


Fig 5. The comparison of statistical parameters of seven megathrust zones, (a) a-value and (b) b-value, around Sumatra between this analysis (blue bar) and NSHM of Indonesia-Pusgen 2017 (green bar).

The statistical parameters of the megathrust zones are also provided in this analysis. These are limited for seven megathrusts in around Sumatra as shown in Fig. 5. The seismicity rate (a-value in Fig. 5a) of this analysis reflects an increasing trend compared to the 2017 NSHM of Indonesia for all zones where the Selat Sunda zone has undergone significant changes. It agrees with the cumulative earthquake distribution in time domain as shown in Fig. 4b. The b-value (Fig. 5b) indicates an increase in the three zones, Mentawai-Siberut, Mentawai-Pagai, and Selat Sunda compared to the 2017 NSHM of Indonesia. This result indicates that the three zones have more experienced for small earthquakes relative to large earthquakes during this period. The remaining of zones, Aceh-Andaman, Nias-Simeulue, Batu, and Enggano, show a slight decrease compared to the 2017 NSHM of Indonesia. It suggests high-stress accumulation state and possibly to generate a large earthquake in the next time window as explained by (Khalqillah & Umar, 2023; Nurana et al., 2021; Syukri et al., 2021).

The stochastic process of the EB-PSHA method yields three GMPEs that have been sampled for each seismic source model as shown in Table 2. These GMPEs are used to generates seismic hazard maps for a 250-year return period for the Sumatra and Kalimantan regions, as shown in Fig. 6 on the left side. A one-year time window is used to estimate the probability of ground motion exceedance within that period. The results are validated by using six historical data in terms of Peak Ground Acceleration (PGA) around Sumatra and Kalimantan as visualized in Fig. 7. The models are in good agreement with the observation data where the correlation coefficient (R^2) is 75.78% and Mean Square Error (MSE) is 0.001125 g although three of six intensities are slightly out of deviation limits.



a

b

c

d

e

f

Fig 6. Seismic hazard maps for return period of 250-year or equivalent to 0.4% probability of exceedance in 1 year in Sumatra and Kalimantan regions based on Event-Based PSHA (EB-PSHA) method (left-side) and the majority intensity level on province level (right-side) where (a & b) are PGA, (c & d) are SA (0.3 s), and (e & f) are SA (0.6 s).

The seismic hazard maps indicate that the Sumatra region exhibits a higher potential seismic hazard level than the Kalimantan region. In western Sumatra, seismic hazard levels are elevated due to contributions from seven megathrust zones as well as active segments of Sumatra Fault, whereas the intensity decreases toward eastern Sumatra due to lower seismicity. In Kalimantan, relatively higher intensity levels are observed in the eastern part of the region, where three active faults have been identified. The maximum seismic hazard levels in Sumatra and Kalimantan for different intensity measures, PGA, SA (0.3 s), and SA (0.6 s), are 2.44 g, 5.17 g, and 4.4 g, respectively. Among the 15 provinces analyzed, Bengkulu Province exhibits the highest majority intensity levels, with 0.82 g for PGA, 1.92 g for SA (0.3 s), and 1.4 g for SA (0.6 s) as shown in Fig. 6b on the right side. This corresponds with increasing seismicity around three megathrust zones, Enggano, Mentawai-Siberut, and Mentawai-Pagai (Fig. 5a), as well as several active segments of the Sumatra Fault, which likely contribute to the relatively high ground motion intensity in Bengkulu Province and its surrounding areas. In contrast, the majority intensity level of Kalimantan exhibits seismic hazard levels below 0.16 g for PGA, 0.19 g for SA (0.3 s), and 0.27 g for SA (0.6 s). However, the highest intensities for all intensity measures are observed in East Kalimantan, where PGA, SA (0.3 s), and SA (0.6 s) reach 1.95 g, 4.82 g, and 4.35 g, respectively. This is attributed to the presence of two active faults in the region, the Meratus and Mangkahilat faults.

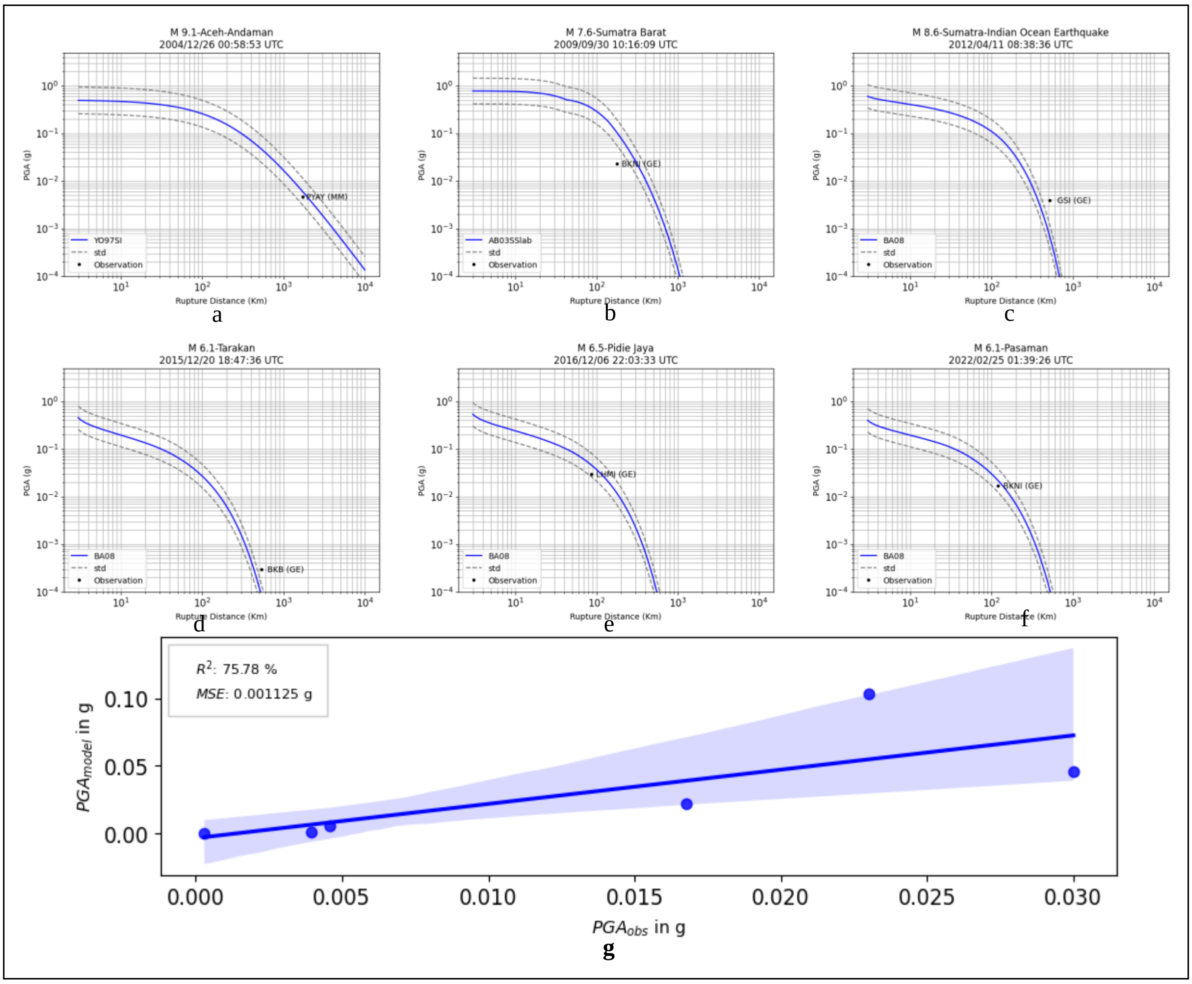


Fig 7. The validation of ground motion in terms of PGA between simulation and historical data (a) M_w9.1 Aceh-Andaman, (b) M_w7.6 Sumatra-Barat, (c) M_w 8.6 Sumatra-Indian Ocean, (d) M_w 6.1 Tarakan, (e) M_w6.5 Pidie Jaya, (f) M_w6.1 Pasaman, and (g) the correlation coefficient and quantitative statistic error between observation and model.

Table 2. The sampled GMPEs based on stochastic process which are used in the analysis.

GMPE	Abbreviation	Seismic Source Model
BooreAtkinson2008	BA08	Active Shallow Crust, Shallow Background Source
YoungsEtAl1997SInter	YO97SI	Subduction Interface
AtkinsonBoore2003SSlabCascadiaNSHMP2008	AB03SSlab	Deep Background Source

These results suggest to put the high attention on earthquake risk mitigation, especially for the Sumatra that indicates high seismicity rate (low stress accumulation) in the southern of Sumatra and low seismicity rate (high stress accumulation) in the northern of Sumatra based on the earthquake dataset used in this analysis. Although the seismicity in Kalimantan is low, does not mean to avoid the earthquake risk mitigation. Since the long period earthquake could impact high potential damage such as M_w8.3 Tokachi-oki, Japan earthquake in 2003 (Koketsu et al., 2005) and M_w7.7 Myanmar earthquake in 2025 that makes unfinished building construction collapsed in Thailand approximately 1000 Km away from the epicenter (Witze, 2025). Finally, this result can be utilized for estimating the annual average loss of a set of building portfolio through the Event Loss Table (ELT) for further analysis.

4. Conclusion

This study provides a seismic hazard assessment for Sumatra and Kalimantan using the EB-PSHA method. The declustered dataset has a magnitude of completeness (M_c) of 4.3 and b-values close to 1, ensuring robust seismicity representation.

Seismic hazard maps for a 250-year return period (0.4% probability of exceedance in one year) are in good correlation above 75% compared to the six historical events. These maps show that Sumatra, especially western areas like Bengkulu, faces higher hazard levels due to high seismicity rate in megathrusts. Regional variations in seismicity suggest high activity in southern Sumatra and possible stress accumulation in the north. Kalimantan shows lower hazard, though East Kalimantan exhibits localized risk from the Meratus and Mangkahilat faults. Despite lower seismicity, Kalimantan still requires mitigation due to potential distant earthquake impacts.

These results can be used for supporting risk analysis and estimating losses of a set of asset portfolios by providing Event Loss Table (ELT).

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