

Article

Mitigating Shallow Earthquake Risk: A Reliable Seismicity Rate Model for Southern Sumatra and West Java

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Abstract

This study offers a new approach to probabilistic earthquake hazard assessment (PEHA) in the densely populated regions of Southern Sumatra and West Java, Indonesia. While much attention is given to powerful, offshore megathrust earthquakes, this research focuses on a different yet equally dangerous threat: shallow, moderate-magnitude earthquakes ($4.5 \leq M_w \leq 6.5$) that occur on land. These events, often caused by unmapped faults, pose a significant risk due to their proximity to major cities and infrastructure. To develop a more reliable model, a best-fit earthquake rate model was estimated using declustered shallow earthquake events as a reference. This model enhances existing methods by offering a more precise depiction of where these shallow, damaging earthquakes are likely to occur. We accomplished this by analyzing a comprehensive probability of exceedance (PoE) of earthquakes with magnitudes up to 6.5 and depths up to 50 km that occurred between 1963 and 2022, mapping and modeling both the known active faults and the historical seismic activity in the region, and using advanced statistical methods to create a highly reliable, integrated seismicity rate model. The final product, the Integrated Most Reliable Spatial Seismicity Rate Model (Model_{IMRSSR}), is proposed as a useful tool for government authorities and urban planners. It can be used to create detailed seismic hazard maps that highlight areas of highest risk, especially those with unmapped faults. By guiding development away from these high-risk zones and identifying specific locations for physical reinforcement, this research provides a framework for sustainable investment. The proactive use of these findings can lead to more resilient communities and a significant reduction in potential damage and loss of life from future earthquakes.

Keywords: PEHA; moderate-shallow earthquake; Model_{IMRSSR}; sustainable; reinforcement



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1. Introduction

The Sunda Arc is a seismically active region defined by the subduction of the Indo-Australian Plate beneath the Eurasian Plate—a mechanism primarily responsible for the region's frequent high-magnitude earthquakes. This activity is particularly intense along southern Sumatra and western Java. Geologically, this subduction process has formed the Sumatra–Java trench, an accretionary wedge of accumulated sediments, and an outer ridge [1,2]. Additionally, the Bengkulu–Mentawai and Java forearc basins are positioned between the trench and the volcanic arc.

While subduction near Java is characterized by near-orthogonal convergence, the tectonic regime transitions to oblique movement west of the Sunda Strait. This shift induces right-lateral shear within the Eurasian Plate [3,4], primarily accommodated by the Sumatran

Fault Zone (SFZ) with an estimated slip rate of 1.1 to 2.8 cm/year [5–7]. Complementary lateral slip occurs along the offshore Mentawai Fault Zone (MFZ), which is linked to the SFZ via the Batee Fault. Furthermore, the southward deflection of the SFZ southeast of Sumatra creates a transtensional environment, leading to the formation of pull-apart basins and increasing the region's structural complexity [8–10].

The Liwa region is situated within the Sumatran Fault Zone (SFZ), specifically along the Liwa fault segment. This prominent right-lateral strike-slip structure bisects the island of Sumatra [11]. This segment comprises the Kumering and Semangko faults [12], which are capable of generating significant seismic events with estimated magnitudes of approximately M_w 7.6 and 7.2, respectively [13]. Recent assessments by Natawidjaja et al. [14] indicate elevated stress levels and slip rates that exceed previous estimates, thereby increasing the probability of major strike-slip ruptures. Historically, the area's vulnerability is evidenced by damaging earthquakes in 1908, 1933, and 1994, all with magnitudes near 6.8 [15].

Java's tectonic framework is dominated by the subduction of the Australian Plate beneath the Sunda Plate, a process capable of generating megathrust events, tsunamis, and deep intraslab earthquakes. Convergence along this boundary is primarily orthogonal, with a minor oblique component accommodated by structures like the Cimandiri Fault [16,17]. This fault is characterized as a broad zone of deformation and folding, subdivided into six distinct segments [18,19]. While older segments exhibit strike-slip motion, younger sections demonstrate a transpressional mix of shortening and lateral sliding. Despite Java's high population density, its terrestrial faults are less well characterized than those on neighboring islands [20]—likely due to a 200-year seismic hiatus in the north and to subtle surface expressions. Convergence rates along the island decrease from east to west, ranging from approximately 65 to 58 mm/year [21]. In addition to the Cimandiri, Lembang, and Opak systems, the Baribis-Kendeng Fault System (BKFS) represents a major longitudinal compression zone, leading Aribowo et al. [20] to propose its redesignation as the Java Back-Arc Thrust (JBT).

Cianjur, West Java, has a long history of destructive seismicity, with notable events recorded in 1844, 1910, 1912, 1958, 1982, 2000, and most recently in 2022 [22]. While shallow inland earthquakes are statistically less frequent in Java, their potential for devastation is disproportionately high. This vulnerability is starkly illustrated by the 1924 Wonosobo event, which resulted in approximately 800 fatalities, and the 2006 Yogyakarta earthquake, which claimed 5749 lives [22].

Utilizing k-means analysis on shallow strike-slip earthquake data along the Sumatran Fault Zone (SFZ), Burton and Hall [13] identified around 16 seismicity clusters grouped into eight significant segments. This clustering provides a basis for refining probabilistic seismic hazard assessments, advancing on earlier work [23,24]. Subsequently, Triyoso et al. [25], in their study of Sumatra, referenced the findings of Burton and Hall [13] and identified a link between regions with high Correlation Dimension (D_C) values and past earthquake occurrences (1925–2014). This correlation suggests heightened stress accumulation in these areas, indicating an elevated likelihood of future large earthquakes. Moreover, Triyoso et al. [25] introduced an improved methodology for estimating the yearly earthquake rate along the SFZ, incorporating shallow earthquake data, mapped fault lines, and GPS measurements.

Recognizing that simply knowing where faults are is not enough to estimate earthquake rates, Triyoso [26,27] developed a model to better assess where future large earthquakes might occur. This model improves basic earthquake rate estimates by incorporating earthquake data with aftershocks removed and stress buildup indicators from surface deformation. The goal was to improve forecasting accuracy by studying small-to-moderate

earthquake rates (less than magnitude 6.5 and shallower than 50 km), while focusing on magnitude 6.5 and larger earthquakes, which are likely caused by known faults. The model combines earthquake data and stress rate information, using a method to smooth the earthquake data. Its effectiveness in identifying earthquake-prone areas in Sumatra was tested. This research identified the best approach for forecasting earthquakes in space and time, highlighting the need for long-term earthquake records. Combining earthquake probability with the relative frequency of small to large earthquakes over time can improve hazard assessment. Changes in earthquake probability might also precede large earthquakes.

Triyoso et al. [28] proposed a robust, widely applicable framework for refining the spatial precision of earthquake forecasts, specifically tailored for subduction zones like the Sunda Arc. Their methodology leverages spatiotemporal analysis of seismic hazard probabilities to enhance the reliability and resolution of future earthquake location forecasts. This probability is derived from earthquake data (magnitudes below 6.5) and stress-rate models using a ground deformation simulation method. The authors highlighted that earthquake catalogs or detailed seismicity records provide the most robust basis for these models, particularly when geologically determined recurrence rates for active faults are unavailable. However, when active faults are directly observed, incorporating geological data is crucial, as relying solely on instrumental and historical seismicity might overlook potential earthquake-prone areas. Following previous work of Triyoso et al. [28] and Triyoso [27], moderate-sized earthquakes serve as benchmarks for assessing the best model fit. This model combines techniques from various studies to identify active earthquake sources better and improve predictions of where earthquake faults are likely to rupture. This study provides a useful method for assessing earthquake hazards in the Sunda Arc and other regions. Combining data from smaller earthquakes, stress buildup, and other sources creates a strong foundation for future research and can be further strengthened with improved fault models. The results emphasize the importance of using comprehensive data to identify future earthquake-prone areas along subduction zones. The study also suggests that accounting for how the frequency of small to large earthquakes varies across locations could significantly improve predictions of future large earthquakes.

Between 1933 and 2022, southern Sumatra and western Java had about 42 shallow earthquakes on land, mostly between magnitude 3.0 and 6.0, with larger ones (magnitude 6.0 or greater) concentrated around the Sunda Strait and southern Sumatra (<https://vsi.esdm.go.id/portalmbg/>, accessed on 8 October 2024). Even moderate shallow earthquakes (4.5 or higher) can cause significant damage in this densely populated area. Earthquakes around magnitude 6.5 often occur without breaking the surface [24], making the faults that cause them (“hidden active faults”) difficult to identify and particularly dangerous [29]. Consequently, the development of models to identify the locations of hidden or ‘blind’ faults is fundamental to conducting rigorous Seismic Hazard Analysis (SHA) and quantifying earthquake risk. The stochastic nature of seismic events—characterized by their random distribution across time, space, and magnitude—along with other inherent uncertainties, mandates a probabilistic framework for effective hazard assessment [30].

This research endeavors to improve earthquake hazard evaluation in Southern Sumatra and West Java by applying a PSHA approach informed by spatiotemporal variations [28]. Specifically, the study targets shallow onshore earthquakes (depth ≤ 50 km) with moderate magnitudes in which the surface break is usually difficult to identify. By combining the approaches of Triyoso and Shimazaki [31] and Triyoso et al. [25], we evaluate hazard models using small-event catalogs, ground deformation, and stress rate data. This study introduces a novel reliability methodology to determine the best-fit seismicity rate model for moderate onshore earthquakes in South Sumatra and West Java. It validates it against shallow declustered earthquake catalogs as the reference. In line with previous studies [32,33], the

best-fit seismicity rate model serves as a critical input for vulnerability analysis, particularly regarding shallow onshore earthquakes in the study area.

2. Data and Method

2.1. Data

The seismic and active fault datasets utilized in this study are derived from the 2017 National Center for Earthquake Studies [34]. The earthquake catalog focuses on events with depths not exceeding 50 km within the southern offshore region of Sumatra and West Java. This primary dataset spans from 1963 to 2016, supplemented by an additional catalog covering 2017 to 2022. Data compilation followed a strict hierarchical prioritization of global and local sources by Rosalia et al. [35]: the ISC-EHB Bulletin, the original EHB Bulletin, the ISC-GEM catalog, relocated BMKG data, the Global Centroid-Moment Tensor (GCMT) catalog, and the NEIC-USGS Bulletin. To ensure data integrity, the compilation process involved removing redundant entries across various agency reports and homogenizing all seismic events to the moment magnitude (M_w) scale. For events missing a direct M_w value, we applied the empirical conversion frameworks established by Rosalia et al. [35]. These frameworks utilize linear and polynomial regression equations (Table 1) to derive M_w from other scales, including m_b , M_s , and M_{Iv} . The resulting catalog serves as a unified, high-fidelity dataset with standardized magnitudes suitable for probabilistic analysis. This study primarily draws on the NEIC-USGS (2658 events) and ISC-EHB (1861 events) catalogs. These are supplemented by 1227 relocated BMKG events and 100 events from the original EHB bulletin. Minority contributions include the ISC-GEM (78 events) and GCMT (8 events) catalogs. Integrating relocated BMKG data provides essential local precision, while including global catalogs ensures overall dataset completeness. Figure 1A presents the merged shallow earthquake catalog (1963–2022, maximum depth: 50 km) overlaid with active fault data.

Table 1. The empirical conversion equations were derived from linear and polynomial regression between different magnitude types (e.g., m_b vs. M_w , M_s vs. M_w , M_{Iv} vs. M_w) for events lacking M_w in the catalog [35].

Conversion Equation	Application Range	R^2
$M_w = 0.933m_b + 0.502$	$m_b \leq 6.2$	0.661
$M_w = 1.273m_b - 1.212$	$m_b > 6.2$	0.200
$M_w = 0.1M_s^2 - 0.431M_s + 5.086$	$M_s \geq 2.75$	0.899
$M_w = 0.756M_{Iv} + 1.060$	$M_{Iv} \geq 3.0$	0.872

2.2. The b -Value

The b -value, a crucial statistical parameter from the Gutenberg–Richter Equation [36], is linked to the scaling characteristics of seismicity, specifically the distribution of earthquake sizes. While this value is typically stable and around one globally, it exhibits greater variability at a regional scale [37,38]. Two alternative algorithms for estimating the b -value are the Least Squares Regression (LSR) and Maximum Likelihood (MLH) approaches [39,40]. The LSR method minimizes the sum of squared differences between observed and estimated values, whereas the MLH method maximizes the likelihood that the estimated function fits the observed data. We aim to contextualize our results by comparing them with findings from previous probabilistic seismic hazard studies of Triyoso [26,27,41], Triyoso et al. [28], and the 2017 PusGEN [34]. These prior studies, along with Aki's [42] recommendation, suggest that the Maximum Likelihood method is the most robust approach for calculating

the b-value. Therefore, this study uses the MLH method to estimate b-values. Following the formulation by Utsu [43], the formula used for this estimation is

$$b = \frac{1}{\ln(10)(\bar{M} - M_c - 0.05)} \quad (1)$$

in which $\bar{M}$ is the average moment magnitude larger than or equal to the magnitude of completeness (M_c). Figure 1B shows the frequency-magnitude distribution (FMD) graph, and the maximum likelihood of the b-value is approximately 0.9, reflecting a magnitude completeness (M_c) of around 4.2. The magnitude completeness (M_c) is determined based on the maximum curvature method of the Gutenberg–Richter law of earthquake magnitude distribution [44].

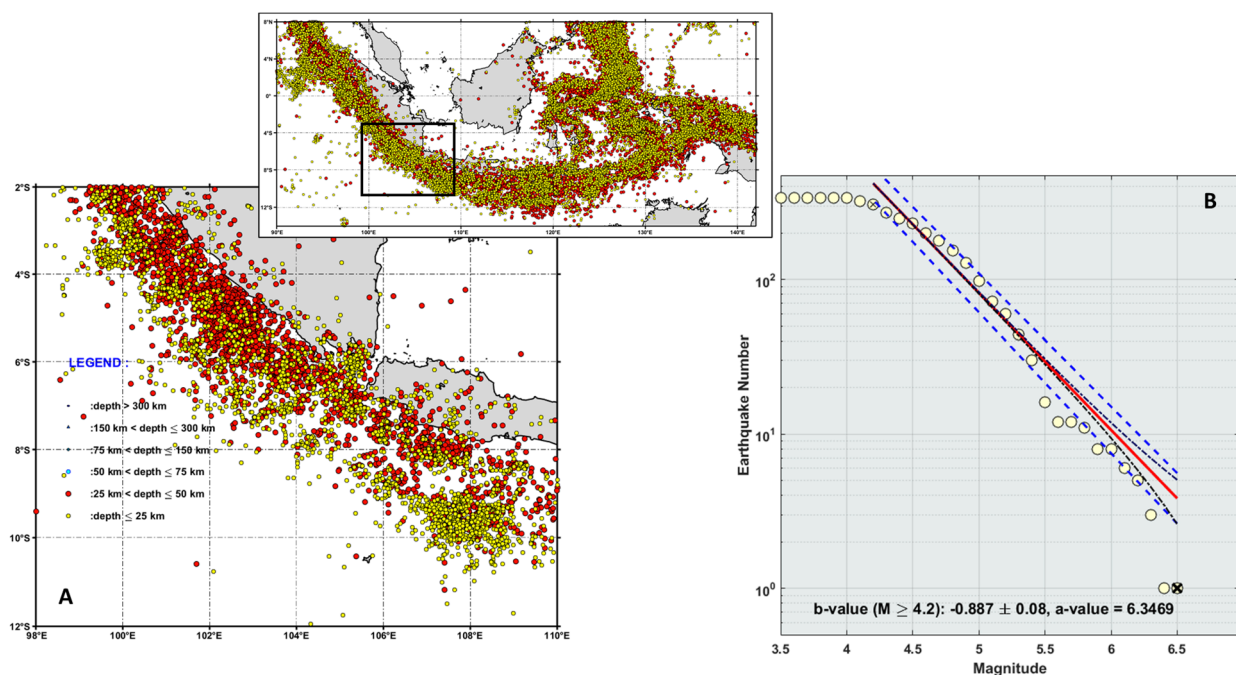


Figure 1. The distribution of shallow earthquake data sources for events with depths ≤ 50 km (A). The merged shallow earthquake catalog (1963–2022, maximum depth: 50 km). Data compilation followed a strict hierarchical prioritization of global and local sources by Rosalia et al. [35]. Subfigure (B) shows the frequency-magnitude distribution (FMD) graph, and the b-value analysis was estimated using the maximum likelihood method [43]. The b-value is approximately 0.9, reflecting a magnitude completeness (M_c) of around 4.2. M_c is determined based on the maximum curvature method of the Gutenberg–Richter law of earthquake magnitude distribution [44].

2.3. Declustering Shallow Earthquake Catalog

We have to remove aftershocks from earthquake catalogs to understand the true rate of independent earthquakes. This process is called declustering, and there are three main types of methods:

- **Link-based methods:** These methods link earthquakes that are close in time and space. By identifying these related events, we can remove the aftershocks. Savage [45], Reasen-berg [46], and Zaliapin and Ben-Zion [47] describe some examples of this approach.
- **Window-based methods:** This approach, as developed by Gardner and Knopoff [48], involves setting up specific time and area “windows” around larger earthquakes. Any smaller earthquakes within these windows are considered potential aftershocks and are removed.

- ETAS-based methods: These methods use a statistical model called the Epidemic-Type Aftershock Sequence (ETAS) model (developed by Ogata in 1998 [49] and later used by others such as Zhuang et al. [50], Marsan & Lengline [51], Chu et al. [52], and Llenos and Michael [53]). This model helps statistically differentiate between aftershocks and independent earthquakes.

For this study, we needed to develop a reliable model of earthquake frequency. We used Gardner and Knopoff's [48] window-based declustering method, implemented in ZMAP [44], to analyze earthquake data with magnitudes $M_w \geq 4.2$ after removing aftershocks to determine the reliable seismicity rate. In this study, we follow the work of Triyoso and Suwondo [15]. For a shallow earthquake with a depth of less than or equal to 50 km, we follow the window-based formulation declustering method [48] as follows,

$$d = 10^{0.1238M+0.983} \text{ (km)} \quad (2)$$

$$t = \begin{cases} 10^{0.032M+2.7389}, & \text{if } M \geq 6.5 \\ 10^{0.5409M-0.5470}, & \text{if } M < 6.5 \end{cases} \text{ (days)} \quad (3)$$

In which d radius in km is and t is time in days.

2.4. Spatial Distribution Seismicity Model

Seismic density was determined by applying an isotropic adaptive $K_d(r)$ smoothing kernel to the earthquake locations. The smoothing function followed a power-law distribution as described by Frankel [54] and Helmsteter et al. [55] as follows,

$$K_{di}(r) = \frac{C(d_i)}{(|r|^2 + d_i^2)^{1.5}} \quad (4)$$

where d_i are the smoothing distances and $C(d_i)$ are normalizing factors, the integral of $K_{di}(r)$ over an infinite area equals 1. In this study, $C(d_i)$ is estimated by following the suggestion of Taroni and Akinci [56]. Thus, the study utilizes an enriched seismic catalog that includes foreshocks and aftershocks, employing a methodology developed by Marzocchi and Taroni [57]. Following the suggestion of Triyoso et al. [25] and Frankel [54], the 25 km and 75 km smoothing distances were used in this study. They are normalized and combined with equal weights.

2.5. Seismicity Active Fault Modeling

To develop seismicity based on active faults, we followed the algorithms of Triyoso and Shimazaki [31] and Triyoso et al. [25,58] to derive the spatial distribution of seismicity from active-fault data. We first create the synthetic epicenter of an earthquake using fault distribution data as the reference, following Triyoso and Shimazaki [31] and Triyoso et al. [25]. First, the fault earthquake epicenter positions were distributed uniformly along the active fault, with each interval ranging from about 5 to 10 km. Subsequent synthetic epicenter distributions were smoothed with a 25 km distance correlation [25] and then normalized to develop the spatial active-fault seismicity pattern model.

2.6. Geodetic Modeling: Seismic Moment Rate Estimation

Following the framework established by Triyoso [27], a seismic moment rate model was constructed. This model uses pre-seismic GPS data together with the spatial distribution of shallow earthquakes ($M_w \geq M_c$), as depicted in Figure 2A. The basic assumptions and methodology can be described as follows: The model assumes that the seismogenic thickness is homogeneous and isotropic at each observation point. Additionally, following the proposal by El-Fiky et al. [59], the horizontal displacement components in the East–West

(u) and North–South (v) directions are treated as uncorrelated. To facilitate precise strain-rate estimation, the study area was divided into a 10 km × 10 km grid. The development process followed these three primary stages as follows:

- ✓ Horizontal Strain Calculation: The crustal strain rate for each individual grid cell was computed using established procedures [25,26,58,60].
- ✓ Least-Squares Collocation (LSC): By applying LSC with local covariance functions derived from surface displacement data, the researchers estimated both the horizontal surface displacement for each cell and the overall crustal strain.
- ✓ Principal Strain Estimation: Finally, the principal strain was calculated to serve as the foundational input for determining the seismic moment rate across the entire study area.

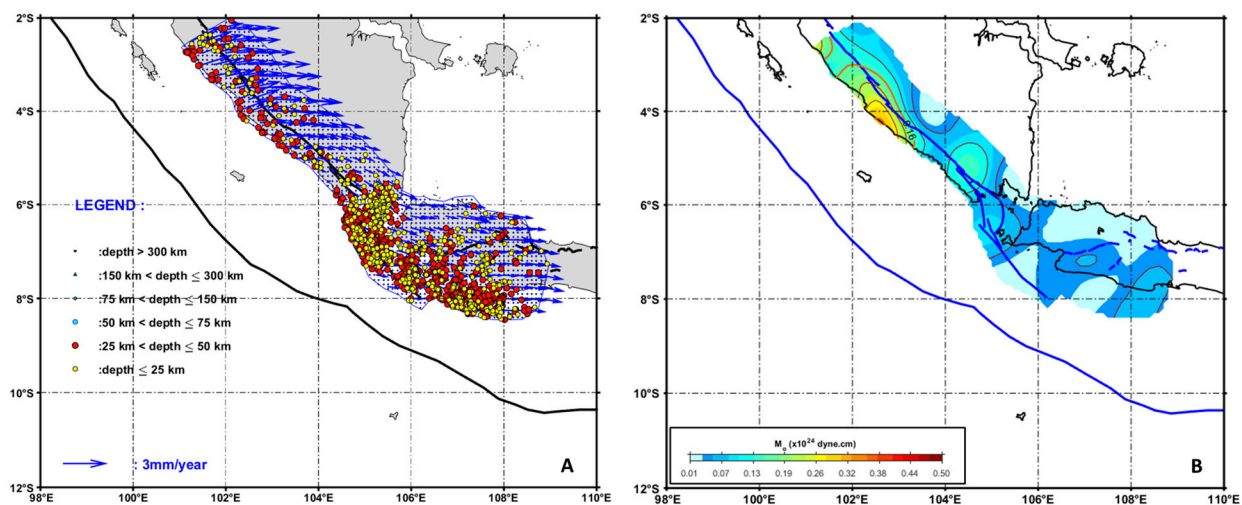


Figure 2. The pre-seismic surface displacement model based on Triyoso [27] overlaid with the selected shallow earthquake (maximum depth ~50 km) in the study area (A), along with the study's visualizations of the estimated seismic moment rate (B).

In this sense, by building upon the approximation introduced by Ward [61] and further developed by [62,63], and others (Triyoso and Suwondo [15], Triyoso [27], Triyoso et al. [25,58], and Triyoso and Sahara [60]), the LSC-derived surface strain rate model was used to calculate the scalar moment rate. The following Equation represents this calculation:

$$\dot{M}_0 = 2\mu H A \max(|e_1|, |e_2|) \quad (5)$$

where $\dot{M}_0$ represents the seismic moment rate. μ denotes the rigidity, assigned a value of 3.4×10^{11} dyn·cm^{−2} based on [59,60]. H represents the seismogenic thickness, set at 20 km, consistent with Ito and Nakamura [64] and others (Triyoso and Shimazaki [31], The 2017 PusGEN [34], Triyoso et al. [59], Triyoso and Sahara [60], and Viveros et al. [65]). A is the unit area in km², and e_1 and e_2 represent the principal strain rates. Figure 2B presents the visualizations of the seismic moment rate from this study.

3. The Best-Fit Spatial Seismicity Rate Model for Seismic Hazard Analysis

To develop the best-fit model for seismic hazard analysis, we expected to characterize spatiotemporal seismicity, especially for moderate-sized land earthquakes; the following steps of the algorithm have been completed.

- ✓ Earthquake Spatial Distribution Seismicity Model: This step uses an enriched seismic catalog that includes foreshocks and aftershocks of shallow earthquakes with magni-

tude above or equal to completeness (M_c), where $M_c \sim 4.2$ and depth ≤ 50 km, from 1963 to 2022, employing a methodology developed by Marzocchi and Taroni [57]. Due to high population density and shallow seismic activity, even moderate events ($M_w \geq 4.5$) can result in significant damage in which historical data from 1933 to 2022 record approximately 42 shallow onshore earthquakes, primarily within the M_w 3.0–6.0 range, with larger events ($M_w \geq 6.0$) concentrated near the Sunda Strait and Southern Sumatra [22], thus in this study is addressed to evaluate possible hazard of small to moderate earthquake magnitude. Following the suggestion of Triyoso et al. [25] and Frankel [54], the 25 km and 75 km smoothing distances were used in this study. The chosen radius primarily characterizes the potential source area for small-to moderate-magnitude earthquakes in the study area [54]. They are normalized and combined with the same weight ($\text{Model}_{\text{moderate-eq}}$).

- ✓ Seismicity Active Fault Modeling: Following the methods of Triyoso and Suwondo [15], Triyoso and Shimazaki [31], and Triyoso et al. [25,59], we derived a spatial seismicity distribution model based on active fault data. Based on [34], the geologist provides the data as a result of active fault strike characterisation. Furthermore, synthetic earthquake epicenters are generated along these faults, spaced roughly 5–10 km apart. To refine the distribution, we smoothed the epicenters using a 25 km distance correlation [15,25]. We normalized the results to create the active-fault seismicity pattern ($\text{Model}_{\text{active-fault}}$).
- ✓ Seismic Moment Rate Estimation: The seismic moment rate is estimated from surface displacement rate data, assuming that the horizontal displacement field at each observation point over the entire seismogenic depth is homogeneous and isotropic. The principal strain rate is estimated from the LSC result of horizontal surface displacement across the study area, which is then normalized to produce the spatial distribution surface crustal seismicity model ($\text{Model}_{\text{Mo-rate}}$).
- ✓ Integrated Spatial Seismicity Rate Model: In this step, we normalized the product of $\text{Model}_{\text{moderate-eq}}$, $\text{Model}_{\text{active-fault}}$, and $\text{Model}_{\text{Mo-rate}}$. The result is an integrated spatial seismicity model. To derive an integrated seismicity rate model, we produce the integrated spatial seismicity model using the uniform background seismicity model derived from the declustered earthquake catalog of shallow earthquakes with depths less than 50 km and selected for $M_w \geq 4.5$ and ≤ 6.5 , to produce the Integrated Spatial Seismicity Rate model ($\text{Model}_{\text{ISSR}}$), as shown in Figure 3A.
- ✓ The Most Reliable Spatial Seismicity Rate Model: The quantitative methods by Triyoso [26,27], Triyoso et al. [28], and Triyoso and Shimazaki [31], are used to assess which model better characterizes the probable active areas and earthquake activity rates over the entire study area. Because these models are not time-dependent, they focus on calculating the best-fit spatial seismicity rate for shallow moderate earthquake magnitudes. It allows for the calculation of the log-likelihood for each rate of the model that can be expressed as follows.

$$\log L = \sum_{i=1}^n (c_i \log(p_i) + (1 - c_i) \log(1 - p_i)) = \sum_{i=1}^n (c_i \log \frac{p_i}{1 - p_i} + \log(1 - p_i)) \quad (6)$$

Following Kagan and Jackson [66,67] and Jackson and Kagan [68], n represents the total number of grid cells, p_i is the occurrence frequency in the i th grid, and c_i is one if an earthquake event occurs in the i th grid and zero otherwise. Triyoso and Shimazaki [31], Triyoso [26,27], and Triyoso et al. [28] use a seismogenic earthquake catalog to evaluate the most suitable earthquake potential models. This study utilizes a reference dataset of shallow declustered earthquakes (depth ≤ 50 km) with magnitudes $M_w \geq 4.5$ (Figure 3B). To address potential gaps in the seismic record—particularly regarding earthquakes associated with unmapped active faults—an adjustment factor (k) is introduced. We employ a declustered

earthquake catalog to ensure the model fits mainshock data, treating foreshocks and aftershocks as dependent events or noise. Following the methodology of Triyoso [27] and Triyoso et al. [28] for subduction zones, the reference time window should ideally remain distinct from the period used to construct the best-fit seismicity rate model. However, given the time span of lower seismicity rates and the limited time window data availability for onshore events compared to subduction events, a spatial smoothing methodology is applied. This approach generates a spatially continuous model, where the k factor ensures a distribution that best fits the seismicity rate, using the declustered earthquake as the reference. Referring to the previous study (Triyoso and Shimazaki [31], Triyoso [26,27], and Triyoso et al. [28]), this study focuses on the spatial distribution patterns of earthquake occurrences and the note of Kagan and Jackson [67] that an ‘N-test’ cannot be performed due to potential gaps in the data record, leading to underestimation of the earthquake rate production above or equal to the reference magnitude (M_{ref}). The M_{ref} in this study is 4.5. Instead of using p_i directly, it is scaled by the factor k to obtain a relative value kp_i . The equation is then modified to incorporate this scaling factor as follows:

$$\log L = \sum_{i=1}^n (c_i \log(kp_i) + (1 - c_i) \log(1 - kp_i)) \quad (7)$$

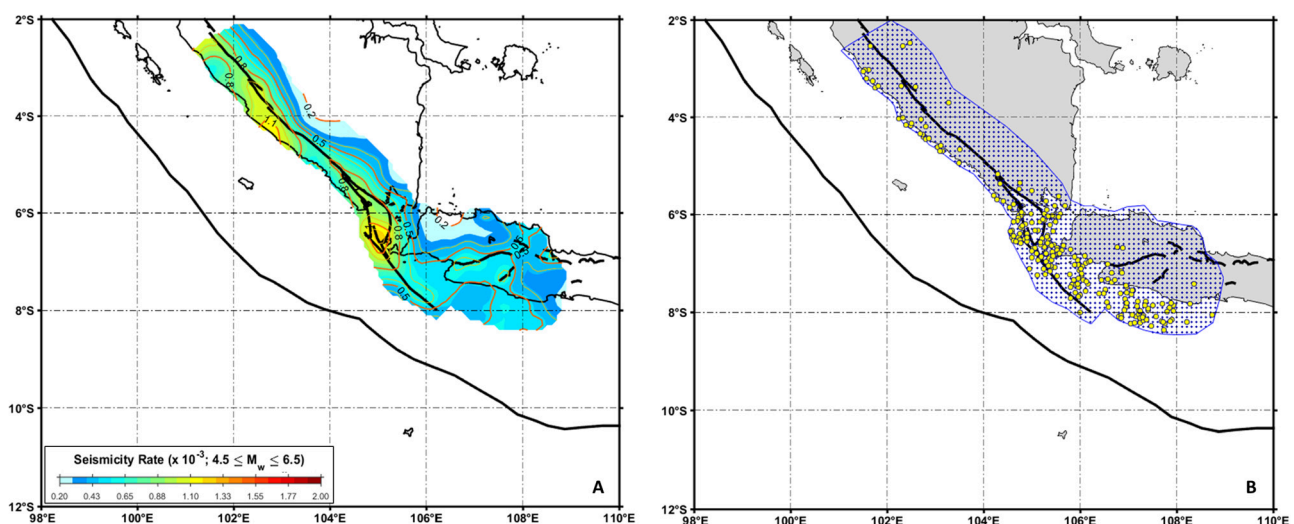


Figure 3. The integrated seismicity rate model (Model_{ISSR}) is developed based on rigorously integrating three key components: data from moderate earthquakes, contributions from active faults, and estimated seismic moment rates. These elements were combined to create a single, normalized, integrated model, which was then combined with a background shallow seismicity model of the declustered catalog selected for $M_w \geq 4.5$ and ≤ 6.5 to estimate the seismicity rate of the moderate shallow earthquake model (A). The spatial distribution patterns of the declustered shallow earthquake occurrences with $M_w \geq 4.5$ were used as a reference to determine the best-fit seismicity rate model (B). The declustered earthquake catalog is used to ensure the model fits mainshock data, treating foreshocks and aftershocks as dependent events or noise.

Maximizing Equation (7) with respect to parameter k yields the best-fit seismicity rate model referred to as the Integrated Most Reliable Spatial Seismicity Rate Model (Model_{IMRSSR}).

4. Probabilistic Seismic Hazard Function (PSHF): Ground Motion Model (GMM) and Probability of Exceedance (PoE)

The PSHF maps the probability that a given Peak Ground Acceleration (PGA) value will exceed the annual frequency of earthquakes with magnitudes equal to or greater than

the complete magnitude. It is often called the probability of exceedance (PoE). This value is the estimated maximum ground acceleration a , calculated using the Ground Motion Model (GMM) at a specific observation point relative to the earthquake source located on the l th grid, which the following formula can express:

$$P(a \geq a_o) = P_l(m \geq m(a_o, R_l)) = 1 - e^{(-v_l(\geq m(a_o, R_l)))} \quad (8)$$

$P_l(m \geq m(a_o, R_l))$ is the annual probability of exceeding earthquakes in the l th grid or cell, $m(a_o, R_l)$ is the magnitude of the source in the l th grid that would produce an estimated PGA of a_o or larger at the site, and R_l is the distance between the site and the source grid; v_l is the seismicity rate with a magnitude greater than or equal to a given earthquake magnitude in the l th grid or cell. The depth of the locked seismogenic zone at the start of an earthquake is crucial for earthquake hazard prediction models.

Following the recommendations of Triyoso and Suwondo [15], Natawidjaja and Triyoso [24], and Triyoso et al. [25], we have selected the GMM of Fukushima and Tanaka [69] for strike-slip faults in the case of Sumatra. The purpose is to directly compare our seismic hazard estimates with their prior work (Triyoso and Suwondo [15], Natawidjaja and Triyoso [24], and Triyoso et al. [25]), to gain insights to improve earthquake mitigation efforts, especially for moderate land earthquake hazard analysis. In alignment with the 2017 PusGEN [34] study, this research adopts the GMM of Boore et al. [70] of NGA-West-2. Specifically for the West Java region, we implemented a weighted approach (0.33 each) utilizing the GMMs of Fukushima and Tanaka [69], Boore et al. [70], and Kanno [71] following the recommendations of Patimah [72].

The seismogenic zone in our study area, where earthquakes originate, extends from a locking depth of about 3 to 5 km down to a total thickness of roughly 20 km (as indicated by Triyoso and Shimazaki [31], The 2017 PusGEN [34], Triyoso et al. [59], Triyoso and Sahara [60], Viveros et al. [63], and Ito and Nakamura [71]). Consequently, our Seismic Hazard Function (SHF) calculations use a starting locking depth of 3 km and a seismogenic thickness of 20 km. The $m(a_o, R_l)$ is estimated using the GMM relation. The estimated total PoE distribution of PGA at the site is based on the following Equation,

$$P(a \geq a_o) = 1 - \prod P_k(m < m(a_o, R_k)) \quad (9)$$

By substituting the GMM into Equation (9), we can calculate the annual PoE for a specific PGA as follows [59,60]:

$$P(a \geq a_o) = 1 - \prod e^{(-v_i(\geq m(a_o, R_k)))} = 1 - e^{-\sum v_i(\geq m(a_o, R_k))} \quad (10)$$

For a given observation period of T , the PoE can be calculated as follows [59,60]:

$$P(a \geq a_o) = 1 - \prod e^{(-Tv_i(\geq m(a_o, R_k)))} = 1 - e^{-\sum Tv_i(\geq m(a_o, R_k))} \quad (11)$$

Equation (10) estimates each grid or cell's annual PoE for the specified peak ground motion. Equation (11) calculates the annual PoE for a given time duration T of peak ground motions.

Furthermore, the earthquake intensity on the Modified Mercalli Intensity Scale (MMI) was estimated using the following Equation by Wald et al. [73].

$$I_{mm} = 3.66 \log(\text{PGA}) - 1.66 \quad (12)$$

where

I_{mm} —Intensity in Modified Mercalli Intensity Scale.

PGA—Peak Ground Acceleration (gal).

5. Results and Discussion

Assessing earthquake hazards accurately in southern Sumatra and western Java is challenging due to shallow seismic activity and high population density, where even moderate events (magnitude ≥ 4.5 and ≤ 6.5) can cause significant damage. Historical data from 1933 to 2022 show approximately 42 shallow onshore earthquakes, mainly magnitude 3.0–6.0, with larger ones (magnitude ≥ 6.0) concentrated near the Sunda Strait and southern Sumatra [22]. A particularly difficult aspect is identifying “hidden active faults” that cause earthquakes, often of magnitude 6.5 or greater, without visible surface rupture [24,29]. These faults are difficult to locate, posing a considerable danger. To ensure long-term sustainable development, seismic risk strategies must evolve. It requires building models to locate hidden faults and shifting focus to include the impact of moderate seismic activity, not just worst-case scenarios. Moreover, the inherent randomness of earthquake occurrence in time, space, and magnitude, combined with other uncertainties, mandates a probabilistic approach to seismic hazard assessment [30]. Given these challenges, this research aims to enhance the accuracy of earthquake hazard assessment for shallow (depth < 50 km) small-to-moderate onshore earthquakes in Southern Sumatra and West Java by applying Probabilistic Seismic Hazard Analysis (PSHA). Inspired by the innovative work of Triyoso et al. [28], who demonstrated enhanced earthquake location expectation by incorporating data like smaller earthquakes (magnitude < 6.5), stress rates, and ground deformation, and drawing insights from the research of Triyoso et al. [25], this study contributes to improving earthquake hazard assessment in Southern Sumatra and West Java. We focus on shallow (≤ 50 km) small-to-moderate onshore earthquakes. The core objective is to develop a Probabilistic Seismic Hazard Analysis (PSHA) model specifically for moderate-sized onshore earthquakes in this region. To achieve this objective, the research will employ and test a combined methodology, first proposed by Triyoso and Shimazaki [31] and subsequently refined by Triyoso et al. [25]. This methodology identifies the most appropriate model for the PoE of shallow onshore earthquakes within the critical moderate-magnitude range. By employing an integrated approach, this study develops an optimal seismicity rate model to estimate PoE for hazard calculations in Southern Sumatra and West Java. Ultimately, the framework establishes a robust basis for reliably evaluating seismic hazards associated with moderate-magnitude events in these high-risk regions. Building on the methodology of Triyoso and Shimazaki [31] and further refined by Triyoso [27] and Triyoso et al. [28], this study rigorously integrates three primary components: moderate earthquake data, active fault contributions, and estimated seismic moment rates. These elements are synthesized into a single normalized integrated model, which is then merged with a background seismicity rate model to construct the Integrated Spatial Seismicity Rate Model (Model_{ISSR}), as illustrated in Figure 3A. To ensure the reliability of this framework for seismic hazard assessment, we employ a quantitative evaluation based on the likelihood of success and failure [27,31,67]. This approach identifies the optimal model for characterizing earthquake-prone areas and their corresponding activity rates against a reference catalog. Because the destructive earthquake was shallow, with a magnitude of 4.5 or greater, our methods focus on the spatial distribution patterns of earthquake occurrences (seismicity rates) for shallow earthquakes above or equal to the magnitude completeness, as a reference, as shown in Figure 3B, to determine the best-fit seismicity rate model. The declustered earthquake catalog is used to ensure the model fits mainshock data, treating foreshocks and aftershocks as dependent events or noise. We calculated the log-likelihood for each model using Equation (7). By optimizing parameter k in Equation (7), we can obtain the Model_{MIRSSR}. The results of optimizing the log-likelihood for each model rate are shown

in Figure 4A, and Figure 4B shows the integrated and most reliable spatial seismicity rate model (Model_{IMRSSR}). The integrated and best-fitting seismicity rate model has a maximum log-likelihood of -548.245 , and k is about 0.9 . Thus, Model_{IMRSSR} is constructed by multiplying Model_{ISSR} by 0.9 , which we expect will be the most reliable seismicity rate model in this study. Based on the developed seismicity rate model (Model_{IMRSSR}), we estimate seismic hazard and produce a Seismic Hazard Function (SHF). This function quantifies the likelihood of exceeding specific PGA levels at the bedrock level. Ground Motion Models (GMMs) are essential for this calculation, as they relate earthquake characteristics (magnitude, distance) to the expected peak of ground motion (PGA). Our analysis focuses on the hazard posed by moderate earthquakes ($4.5 \leq M_w \leq 6.5$) occurring within the study area, including sources associated with the Sumatra Fault Zone (SFZ) in southern Sumatra and the strike-slip-dominated land portion of West Java [74,75]. To estimate the necessary PGA values in our PSHA, we use the GMMs of Fukushima and Tanaka [69], Boore et al. [70], and Kano [71].

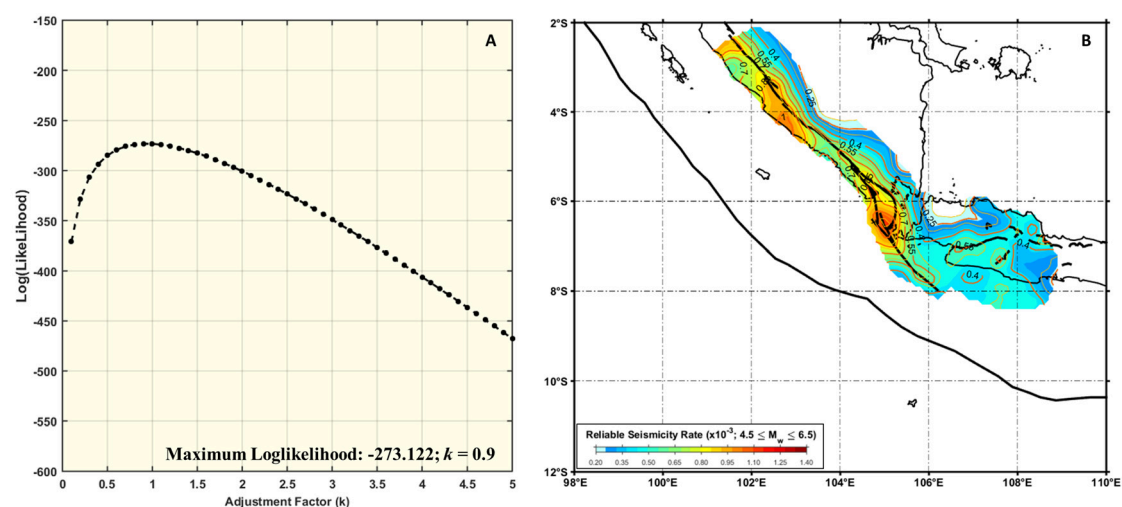


Figure 4. The result of optimizing the log-likelihood of the integrated seismicity rate model with respect to the adjustment factor k (A). The log-likelihood is calculated using Equation (7). The result of the integrated and most reliable spatial seismicity rate model (Model_{IMRSSR}) (B). It is a constructed by-product of Model_{ISSR} with parameter k , which maximizes the log-likelihood in Equation (7).

Figure 5A presents a visual synthesis of seismic risk, overlaying an Intensity map (MMI) with a 10% Probability of Exceedance (PoE). The intensities were derived by applying Equation (12) to convert Peak Ground Acceleration (PGA) values obtained from Seismic Hazard Functions (SHFs). These SHFs were calculated for 11 key sites: Bengkulu, Liwa, Ujung Kulon, Sukabumi, Bogor, Cianjur, Muara Gembong, Lembang, Garut, Kandanghaur, and Cirebon. Each function estimates the likelihood of exceeding specific bedrock PGA levels, assuming a 50 km source radius, a 50-year exposure period, and a focal depth of approximately 10 km. We utilize an intensity map to estimate base rock Peak Ground Acceleration (PGA) as a baseline for potential damage, as local site effect data (such as V_{s30}) remain limited across the study area. By applying Equation (12) to these PGA values, results indicate that ground shaking across all sites could reach or exceed a Modified Mercalli Intensity (MMI) of 5.0. It should be noted, however, that local soil conditions will significantly modulate the actual observed intensity. These estimates align with previous findings by Triyoso and Suwondo [15] for Liwa City, though they are lower than the 2017 PusGEN [34] results. This discrepancy arises from our specific focus on the probability of exceedance (PoE) for moderate-magnitude, shallow earthquakes (depth ≤ 50 km).

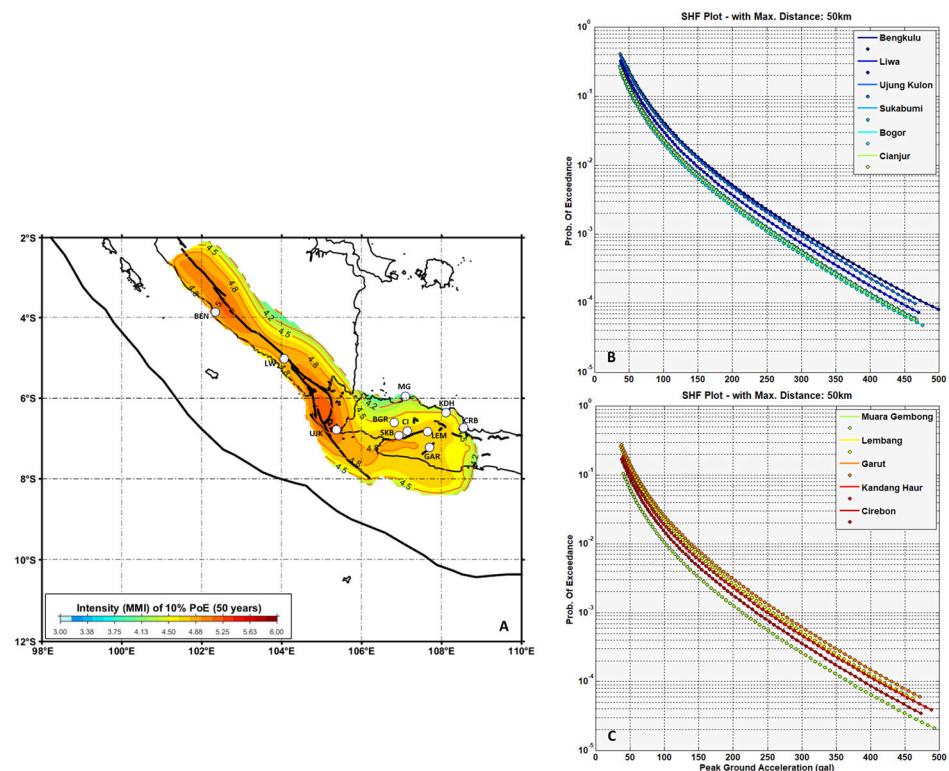


Figure 5. Intensity map in MMI of 10% PoE and the distribution site-specific seismic hazard function (SHF) analysis in this study (A). The Intensity is estimated using Equation (12) to convert these PGA values to the MMI with the calculated median seismic hazard functions (SHFs) in 50 years for 11 key sites (B,C) investigated in this study: BEN (Bengkulu), LW (Liwa), UJK (Ujung Kulon), SKB (Sukabumi), BGR (Bogor), CI (Cianjur), MG (Muara Gembong), LEM (Lembang), GAR (Garut), KDH (Kandanghaur), and CRB (Cirebon).

These results underscore the effectiveness of the integrated, reliable spatial seismicity rate model for estimating earthquake hazards and predicting ground shaking. Figure 5B,C present the detailed SHF estimates; Figure 5B covers Bengkulu, Liwa, Ujung Kulon, Sukabumi, Bogor, and Cianjur, while Figure 5C presents results for Muara Gembong, Lembang, Garut, Kandanghaur, and Cirebon. An assessment of the site-specific SHFs reveals variations in the estimated hazard. At a 10% PoE over 50 years, the estimated PGA values range from approximately 70 gals in Lembang to about 80 gals in Bengkulu. The remaining nine sites exhibit estimated PGA values ranging from 72 to 75 gals at the same probability level. To evaluate the PoE with respect to possible PGA or intensity level, the PoE map for PGA ~50 gals is produced in this study, as shown in Figure 6A. Also, SHFs for several sites are constructed to assess the possibility of seismic-related impacts across time horizons by estimating PoE vs. PGA at 25 and 75 years (Figure 6B,C). The spatial distributions in Figure 6A indicate that Bengkulu, Liwa, Ujung Kulon, Sukabumi, Cianjur, and Garut are characterized by intense ground shaking and elevated exceedance probabilities. Notably, the 2022 Cianjur earthquake provides clear empirical validation of the hazard levels identified in this study. The localized insights derived from the Model_{ISSR} reveal significant risks—driven by suspected unmapped faults and proximity to the Sumatran Fault Zone—that are frequently obscured in coarser regional models. By integrating high-resolution seismicity rates with empirical vulnerability data, this study demonstrates that socioeconomic impacts in Southern Sumatra and West Java are driven by shallow hypocentral depths and infrastructural fragility as much as earthquake magnitude. The resulting analysis offers a robust, reproducible framework for delineating high-risk zones, providing a technical foundation for targeted mitigation and damage-prevention strategies.

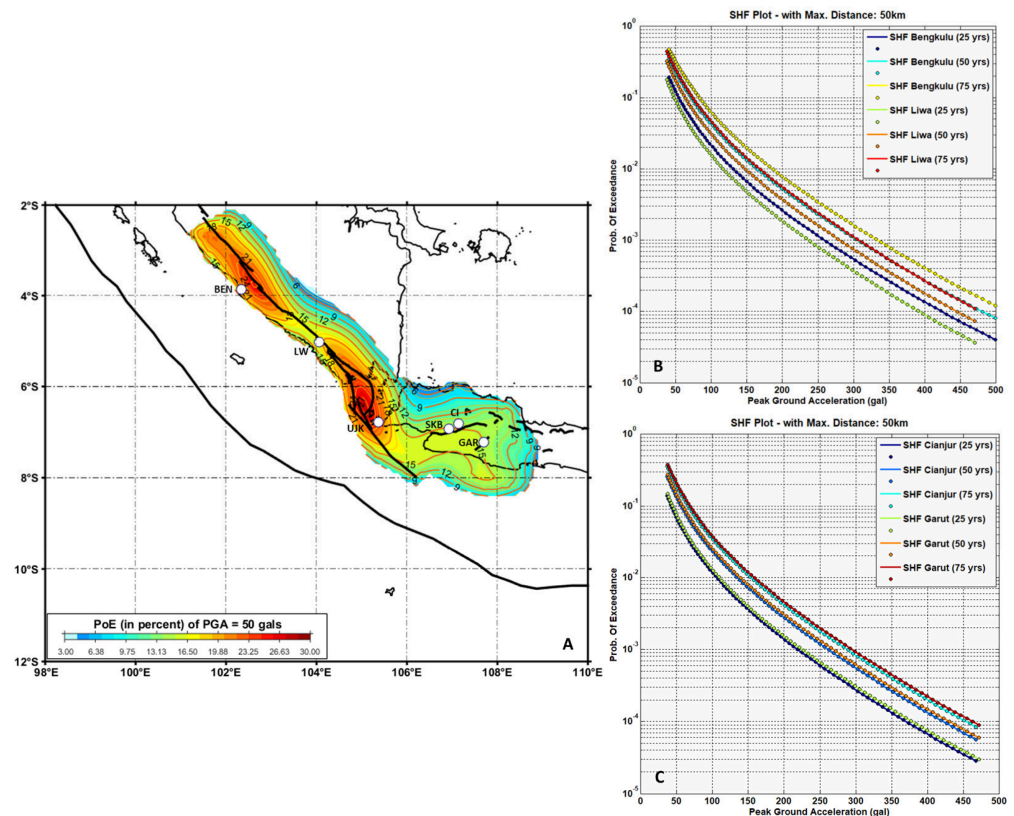


Figure 6. The PoE map with respect to a possible PGA level of 50 gals, overlaid with sites of BEN (Bengkulu), LW (Liwa), UJK (Ujung Kulon), SKB (Sukabumi), CI (Cianjur), and GAR (Garut) (A). The median SHFs for several sites are constructed to assess the possibility of seismic-related impacts across time horizons by estimating PoE vs. PGA at 25, 50, and 75 years (B,C).

6. Conclusions

This study successfully developed and applied an integrated Probabilistic Seismic Hazard Analysis (PSHA) framework to enhance earthquake hazard assessment for shallow PoE moderate onshore earthquakes (M_w 4.5–6.5) in Southern Sumatra and West Java. Addressing the challenges posed by the region's shallow seismicity, high population density, and difficult-to-identify hidden active faults, our approach used a probabilistic methodology grounded in established regional research. A central component of this framework is the integrated spatial seismicity rate model (Model_{MIRSSR}) that has been developed and validated. This model reliably characterizes the spatial distribution and rate of shallow, moderate events by rigorously combining observed earthquake data, contributions from active faults, and estimated seismic moment rates. Model_{MIRSSR} was optimized using a quantitative log-likelihood approach validated against recorded shallow $M_w \geq 4.5$ declustered earthquakes. Using Model_{MIRSSR} and appropriate Ground Motion Models (GMMs), we calculated site-specific seismic hazard functions (SHFs) for 11 key locations. The results demonstrate significant earthquake hazard across the region for moderate events, with estimated PGA values for a 10% PoE in 50 years ranging from approximately 70 to 80 gals at key sites. Across the study sites, results indicate potential ground shaking at a Modified Mercalli Intensity (MMI) of 5.0 or greater, although local surface conditions will significantly modulate the actual felt intensity. To evaluate seismic impacts across varying time horizons, we incorporated Seismic Hazard Functions (SHFs) for several sites, estimating the Probability of Exceedance (PoE) versus Peak Ground Acceleration (PGA) for 25- and 75-year periods. Crucially, the analysis delineates high-risk zones characterized by elevated background seismicity, suspected unmapped active faults,

and proximity to major systems like the Sumatran Fault Zone. These findings demonstrate the efficacy of an integrated modeling approach in complex tectonic environments. By informing sustainable seismic design through optimized structural strength and controlled drift, this study supports the long-term life-cycle performance of critical infrastructure. Ultimately, these localized hazard assessments provide a vital foundation for risk reduction and mitigation, strengthening the resilience of densely populated regions in Southern Sumatra and West Java against moderate seismic events.

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References

- Pubellier, M.; Rangin, C.; Cadet, J.P.; Tjashuri, I.; Butterlin, J.; Muller, C. L'île de Nias, un e' difice polyphase'sur la bordure interne de la fosse de la Sonde (Archipel de Mentawai, Indonésie). *Comptes Rendus Acad. Sci. Paris Ser. II* **1992**, *315*, 1019–1026.
- Samuel, M.A.; Harbury, N.A. The Mentawai fault zone and deformation of the Sumatran forearc in the Nias area. *Geol. Soc. Lond. Spec. Publ.* **1996**, *106*, 337–351. [[CrossRef](#)]
- DeMets, C.; Gordon, R.G.; Argus, D.F.; Stein, S. Current plate motions. *J. Geophys. Res.* **1990**, *101*, 425–478. [[CrossRef](#)]
- McCaffrey, R.; Zwick, P.C.; Bock, Y.; Prawirodirdjo, L.; Genrich, J.F.; Stevens, C.W.; Subarya, C. Strain partitioning during oblique plate convergence in northern Sumatra: Geodetic and seismologic constraints and numerical modeling. *J. Geophys. Res. Solid Earth* **2000**, *105*, 28363–28376. [[CrossRef](#)]
- Katili, J.A.; Hehuwat, F. On the occurrence of large transcurrent faults in Sumatra, Indonesia. *J. Geosci. Osaka City Univ.* **1967**, *10*, 5–17.
- Natawidjaja, D.H.; Sieh, K. Slip-rate along the Sumatra transcurrent fault and its tectonic significance. In *Paper Presented at Conference on Tectonic Evolution of Southeast Asia*; The Geological Society of London: London, UK, 1994.
- Baroux, E.; Avouac, J.P.; Bellier, O.; Sebrier, M. Slip-partitioning and fore-arc deformation at the Sunda Trench Indonesia. *Terra Nova* **1998**, *10*, 139–144.
- Diamant, M.; Harjono, H.; Karta, K.; Deplus, C.; Dahrin, D.; Zen, J.M.T.; Gérard, M.; Lassal, O.; Martin, A.; Malod, J. Mentawai fault zone off Sumatra: A new key to the geodynamics of western Indonesia. *Geology* **1992**, *20*, 259–262. [[CrossRef](#)]
- Malod, J.-A.; Karta, K.; Beslier, M.O.; Zen, M.T., Jr. From normal to oblique subduction: Tectonic relationships between Java and Sumatra. *J. Asian Earth Sci.* **1995**, *12*, 85–93. [[CrossRef](#)]
- Malod, J.-A.; Kemal, B.M. The Sumatra margin: Oblique subduction and lateral displacement of the accretionary prism. *Geol. Soc. Spec. Publ.* **1996**, *106*, 19–28. [[CrossRef](#)]
- Yudhicara Muslim, D.; Sudradjat, A.; Natawidjaja, D.H.; Siahaan, R. Identifying an active Sumatra Fault Segment in Liwa Region using a Morphotectonic Approach. In *Proceedings of the 5th International INQUA Meeting on Paleoseismology, Active Tectonics and Archeoseismology (PATA)*, Busan, Republic of Korea, 21–27 September 2014.
- Sieh, K.; Natawidjaja, D. Neotectonics of the Sumatran Fault, Indonesia. *J. Geophys. Res. Solid Earth* **2000**, *105*, 28295–28326. [[CrossRef](#)]
- Burton, P.W.; Hall, T.R. Segmentation of the Sumatran fault. *Geophys. Res. Lett.* **2014**, *41*, 4149–4158. [[CrossRef](#)]
- Natawidjaja, D.H.; Bradley, K.; Daryono, M.R.; Aribowo, S.; Herrin, J. Late Quaternary eruption of the Ranau Caldera and new geological slip rates of the Sumatran Fault Zone in Southern Sumatra, Indonesia. *Geosci. Lett.* **2017**, *4*, 21. [[CrossRef](#)]

15. Triyoso, W.; Suwondo, A. From the geodynamic aspect to earthquake potential hazard analysis of Liwa City and its surroundings. *Nat. Hazards* **2023**, *116*, 1329–1344. [\[CrossRef\]](#)
16. Clements, B.; Hall, R.; Smyth, H.R.; Cottam, M.A. Thrusting of a volcanic arc: A new structural model for Java. *Pet. Geosci.* **2009**, *15*, 159–174. [\[CrossRef\]](#)
17. Smyth, H.; Hall, R.; Hamilton, J.; Kinny, P. East Java: Cenozoic basins, volcanoes and ancient basement. In *Proceedings of the Indonesian Petroleum Association, 30th Annual Convention 2005*; Indonesian Petroleum Association: Jakarta, Indonesia, 2005; pp. 251–266. [\[CrossRef\]](#)
18. Arisbaya, I.; Handayani, L.; Mukti, M.M.; Sudrajat, Y.; Grandis, H.; Sumintadireja, P. Imaging the geometry of Cimandiri Fault zone based on 2D Audio-Magnetotelluric (AMT) model in Nyalindung, Sukabumi–Indonesia. *Pure Appl. Geophys.* **2019**, *176*, 4833–4845. [\[CrossRef\]](#)
19. Marliyani, G.I.; Arrowsmith, J.R.; Whipple, K.X. Characterization of slow slip rate faults in humid areas: Cimandiri fault zone, Indonesia. *J. Geophys. Res. Earth Surf.* **2016**, *121*, 2287–2308. [\[CrossRef\]](#)
20. Aribowo, S.; Husson, L.; Natawidjaja, D.H.; Authemayou, C.; Daryono, M.R.; Puji, A.R.; Valla, P.G.; Pamumpuni, A.; Wardhana, D.D.; de Gelder, G.; et al. Active back-arc thrust in North West Java, Indonesia. *Tectonics* **2022**, *41*, e2021TC007120. [\[CrossRef\]](#)
21. Koulali, A.; McClusky, S.; Susilo, S.; Leonard, Y.; Cummins, P.; Tregoning, P.; Meilano, I.; Efendi, J.; Wijanarto, A.B. The kinematics of crustal deformation in Java from GPS observations: Implications for fault slip partitioning. *Earth Planet. Sci. Lett.* **2017**, *458*, 69–79. [\[CrossRef\]](#)
22. Badan Meteorologi, Klimatologi, dan Geofisika (BMKG). *Katalog Gempa Bumi Signifikan dan Merusak Tahun 1821–2023*; Badan Meteorologi, Klimatologi, dan Geofisika (BMKG): Jakarta, Indonesia, 2024.
23. Petersen, M.D.; Dewey, J.; Hartzell, S.; Mueller, C.; Harmsen, S.; Frankel, A.; Rukstales, K. Probabilistic seismic hazard analysis for Sumatra, Indonesia and across the Southern Malaysian Peninsula. *Tectonophysics* **2004**, *390*, 141–158. [\[CrossRef\]](#)
24. Natawidjaja, D.H.; Triyoso, W. The Sumatran Fault Zone—From Source To Hazard. *J. Earthq. Tsunami.* **2007**, *1*, 21–47.
25. Triyoso, W.; Sahara, D.P.; Sarsito, D.A.; Natawidjaja, D.H.; Sukmono, S. Correlation dimension in Sumatra island based on active fault, earthquake data, and estimated horizontal crustal strain to evaluate seismic hazard functions (SHF). *GeoHazards* **2022**, *3*, 227–241. [\[CrossRef\]](#)
26. Triyoso, W. Probabilistic seismic hazard function based on spatiotemporal earthquake likelihood simulation and Akaike information criterion: The PSHF study around off the west coast of Sumatra island before large earthquake events. *Front. Earth Sci.* **2023**, *11*, 1104717. [\[CrossRef\]](#)
27. Triyoso, W. Applying the Akaike Information Criterion (AIC) in earthquake spatial forecasting: A case study on probabilistic seismic hazard function (PSHF) estimation in the Sumatra subduction zone. *Geomat. Nat. Hazards Risk* **2024**, *15*, 2319187. [\[CrossRef\]](#)
28. Triyoso, W.; Rosalia, S.; Grandis, H. Building a General Algorithm for Seismic Hazard Analysis in the Sunda Arc through Geodynamic Simulations. *Seismol. Res. Lett.* **2024**, *95*, 3360–3375. [\[CrossRef\]](#)
29. Jara-Muñoz, J.; Melnick, D.; Li, S.; Socquet, A.; Cortés-Aranda, J.; Brill, D.; Strecker, M.R. The cryptic seismic potential of the Pichilemu blind fault in Chile revealed by off-fault geomorphology. *Nat. Commun.* **2022**, *13*, 3371. [\[CrossRef\]](#) [\[PubMed\]](#)
30. Yılmaz Öztürk, N. Probabilistic Seismic Hazard Analysis: A Sensitivity Study with Respect to Different Models. Ph.D. Thesis, The Graduate School of Natural and Applied Sciences of Middle East Technical University, Ankara, Turkey, 2008.
31. Triyoso, W.; Shimazaki, K. Testing various seismic potential models for hazard estimation against a historical earthquake catalog in Japan. *Earth Planets Space* **2012**, *64*, 673–681. [\[CrossRef\]](#)
32. Chieffo, N.; Onescu, I.; Formisano, A.; Mosoarca, M.; Palade, M. Integrated Empirical-mechanical Seismic Vulnerability Analysis Method for Masonry Buildings in Timișoara: Validation based on the 2009 Italian Earthquake. *Open Civ. Eng. J.* **2020**, *14*, 314–333. [\[CrossRef\]](#)
33. Monaco, A.L.; Grillanda, N.; Onescu, I.; Fofiu, M.; Clementi, F.; D’Amato, M.; Formisano, A.; Milani, G.; Mosoarca, M. Seismic assessment of Romanian Orthodox masonry churches in the Banat area through a multi-level analysis framework. *Eng. Fail. Anal.* **2023**, *153*, 107539. [\[CrossRef\]](#)
34. Tim Pusat Studi Gempa Nasional-2017 (The 2017 PuSGen). *Peta Sumber dan Bahaya Gempa Indonesia Tahun 2017*; Kementerian Pekerjaan Umum dan Perumahan Rakyat: Jakarta, Indonesia, 2017. (In Indonesian)
35. Rosalia, S.; Putra, A.S.; Triyoso, W. 2023 Indonesia Unified Earthquake Catalogue from 1905 to 2022 as an Effort for Seismic Hazard Assessment. *Natural Hazards* **2025**. *Submitted*.
36. Gutenberg, B.; Richter, C.F. Frequency of earthquake in California. *Bull. Seismol. Soc. Am.* **1944**, *34*, 185–188. [\[CrossRef\]](#)
37. DeSalvio, N.D.; Rudolph, M.L. A Retrospective analysis of b-value changes Preceding strong earthquakes. *Seismol. Res. Lett.* **2021**, *93*, 364–375. [\[CrossRef\]](#)
38. Frohlich, C.; Davis, S. Teleseismic b-values: Or, much ado about 1.0. *J. Geophys. Res.* **1993**, *98*, 631–644. [\[CrossRef\]](#)
39. Özyazıcıoğlu, M.; Kartal, R.F.; Kılıç, T.; Yeşilyaprak, C. Probabilistic seismic hazard evaluation of eastern Anatolia observatory. *Arab. J. Geosci.* **2024**, *17*, 38. [\[CrossRef\]](#)

40. Gögen, B.; Karimzadeh, S.; Lourenço, P.B. Probabilistic seismic hazard analysis for Bagan (Myanmar). *Acta Geophys.* **2024**, *72*, 2193–2221. [[CrossRef](#)]
41. Triyoso, W. Regional earthquake likelihood models (RELMs) for probabilistic seismic hazard analysis (PSHA) around the southern off-coast of Sumatra-West Java. *Nat. Hazards* **2025**, *121*, 8785–8803. [[CrossRef](#)]
42. Aki, K. Maximum likelihood estimate of b in the formula $\log N = a + bM$ and its confidence limits. *Bull. Earthq. Res. Inst. Tokyo Univ.* **1965**, *43*, 237–239.
43. Utsu, T. Estimation of parameters in formulas for frequency-magnitude relation of earthquake occurrence. *Zisin* **1978**, *31*, 367–382. [[CrossRef](#)] [[PubMed](#)]
44. Wiemer, S. A software package to analyze seismicity: ZMAP. *Seismol. Res. Lett.* **2001**, *72*, 373–382. [[CrossRef](#)]
45. Savage, W.U. Microearthquake clustering near Fairview Peak, Nevada, and in the Nevada Seismic Zone. *J. Geophys. Res.* **1972**, *77*, 7049–7056. [[CrossRef](#)]
46. Reasenber, P. Second-order moment of central California seismicity, 1969–1982. *J. Geophys. Res.* **1985**, *90*, 5479–5495.
47. Zaliapin, I.; Ben-Zion, Y. Earthquake declustering using the nearest-neighbor approach in space-time-magnitude domain. *J. Geophys. Res.* **2020**, *125*, e2018JB017120. [[CrossRef](#)]
48. Gardner, J.K.; Knopoff, L. Is the sequence of earthquakes in southern California, with aftershocks removed, Poissonian? *Bull. Seismol. Soc. Am.* **1974**, *64*, 1363–1367. [[CrossRef](#)]
49. Ogata, Y. Space-time point-process models for earthquake occurrences. *Ann. Inst. Stat. Math.* **1998**, *50*, 379–402. [[CrossRef](#)]
50. Zhuang, J.; Ogata, Y.; Vere-Jones, D. Stochastic declustering of space-time earthquake occurrences. *J. Am. Stat. Assoc.* **2002**, *97*, 369–380. [[CrossRef](#)]
51. Marsan, D.; Lengliné, O. Extending earthquakes’ reach through cascading. *Science* **2008**, *319*, 1076. [[CrossRef](#)] [[PubMed](#)]
52. Chu, A.; Schoenberg, F.P.; Bird, P.; Jackson, D.D.; Kagan, Y.Y. Comparison of ETAS parameter estimates across different global tectonic zones. *Bull. Seismol. Soc. Am.* **2011**, *101*, 2323–2339. [[CrossRef](#)]
53. Llenos, A.L.; Michael, A.J. Regionally optimized background earthquake rates from ETAS (ROBERE) for probabilistic seismic hazard assessment. *Bull. Seismol. Soc. Am.* **2020**, *110*, 1172–1190. [[CrossRef](#)]
54. Frankel, A. Mapping seismic hazard in the Central and Eastern United States. *Seismol. Res. Lett.* **1995**, *66*, 8–21. [[CrossRef](#)]
55. Helmstetter, A.; Kagan, Y.Y.; Jackson, D.D. High-resolution time-independent grid-based forecast for $M \geq 5$ earthquakes in California. *Seismol. Res. Lett.* **2007**, *78*, 78–86.
56. Taroni, M.; Akinci, A. A New Smoothed Seismicity Approach to Include Aftershocks and Foreshocks in Spatial Earthquake Forecasting: Application to the Global $M_w \geq 5.5$ Seismicity. *Appl. Sci.* **2021**, *11*, 10899. [[CrossRef](#)]
57. Marzocchi, W.; Taroni, M. Some thoughts on declustering in probabilistic seismic-hazard analysis. *Bull. Seismol. Soc. Am.* **2014**, *104*, 1838–1845. [[CrossRef](#)]
58. Triyoso, W.; Suwondo, A.; Yudistira, T.; Sahara, D.P. Seismic Hazard Function (SHF) study of coastal sources of Sumatra Island: SHF evaluation of Padang and Bengkulu cities. *Geosci. Lett.* **2020**, *7*, 2. [[CrossRef](#)]
59. El-fiky, G.S.A.; Kato, T.; Oware, E.N. Crustal deformation and Interplate coupling in the Shikoku district, Japan, as seen from continuous GPS observation. *Tectonophysics* **1999**, *314*, 387–399. [[CrossRef](#)]
60. Triyoso, W.; Sahara, D.P. Seismic hazard function mapping using estimated horizontal crustal strain off West Coast Northern Sumatra. *Front. Earth Sci.* **2021**, *9*, 558923. [[CrossRef](#)]
61. Ward, S.N. A multidisciplinary approach to seismic hazard in Southern California. *Bull. Seismol. Soc. Am.* **1994**, *84*, 1293–1309. [[CrossRef](#)]
62. Savage, J.C.; Simpson, R.W. Surface strain accumulation and the seismic moment tensor. *Bull. Seismol. Soc. Am.* **1997**, *87*, 1345–1353. [[CrossRef](#)]
63. Field, E.H.; Jackson, D.D.; Dolan, J.F. A mutually consistent seismic-hazard source model for Southern California. *Bull. Seismol. Soc. Am.* **1999**, *89*, 559–578. [[CrossRef](#)]
64. Ito, K.; Nakamura, S. Variation in thickness of the seismogenic layer in Southwestern Japan and their relation to large inland earthquake. *Ann. Disaster Prev. Res. Inst.* **1998**, *41*, 27–35.
65. Viveros, J.A.B.; von Specht, S.; Strader, A.; Hainzl, S.; Cotton, F.; Schorlemmer, D. A regionalized seismicity model for subduction zones based on geodetic strain rates, geomechanical parameters, and earthquake-catalog data. *Bull. Seismol. Soc. Am.* **2019**, *109*, 2036–2049.
66. Kagan, Y.Y.; Jackson, D.D. Seismic gap hypothesis: Ten years after. *J. Geophys. Res.* **1991**, *96*, 21419–21431. [[CrossRef](#)]
67. Kagan, Y.Y.; Jackson, D.D. New seismic gap hypothesis: Five years after. *J. Geophys. Res.* **1995**, *100*, 3943–3959. [[CrossRef](#)]
68. Jackson, D.D.; Kagan, Y.Y. Testable Earthquake Forecast for 1999. *Seismol. Res. Lett.* **1999**, *70*, 393–403. [[CrossRef](#)]
69. Fukushima, Y.; Tanaka, H. The revision of A new attenuation relation for peak horizontal acceleration of strong earthquake ground motion in Japan, Abstracts The Seismological Society of Japan, 1992, Fall Meeting, B18. *Bull. Seismol. Soc. Am.* **1992**, *80*, 757–783. (In Japanese)

70. Boore, D.M.; Stewart, J.P.; Seyhan, E.; Atkinson, G.M. NGA-West2 Equations for Predicting PGA, PGV, and 5% Damped PSA for Shallow Crustal Earthquakes. *Earthq. Spectra* **2014**, *30*, 1057–1085.
71. Kanno, T.; Narita, A.; Morikawa, N.; Fujiwara, H.; Fukushima, Y. A New Attenuation Relation for Strong Ground Motion in Japan Based on Recorded Data. *Bull. Seismol. Soc. Am.* **2006**, *96*, 879–897. [[CrossRef](#)]
72. Patimah, S.H. Investigasi Seismic Hazard Function (SHF) dari Sesar Sumber Gempa Situbondo pada 10 Oktober Tahun 2018 Untuk Kota Situbondo dan Sekitarnya. Master's Thesis, Institut Teknologi Bandung, Bandung, Indonesia, 2022.
73. Wald, D.J.; Quitoriano, V.; Heaton, T.H.; Kanamori, H. Relationships between Peak Ground Acceleration, Peak Ground Velocity, and Modified Mercalli Intensity in California. *Earthq. Spectra* **1999**, *15*, 557–564. [[CrossRef](#)]
74. Dziewonski, A.M.; Chou, T.-A.; Woodhouse, J.H. Determination of earthquake source parameters from waveform data for studies of global and regional seismicity. *J. Geophys. Res. Earth Surf.* **1981**, *86*, 2825–2852. [[CrossRef](#)]
75. Ekström, G.; Nettles, M.; Dziewonski, A. The global CMT project 2004–2010: Centroid-moment tensors for 13,017 earthquakes. *Phys. Earth Planet. Inter.* **2012**, *200–201*, 1–9. [[CrossRef](#)]

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