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Development of the 2025 Seismic Hazard Maps of Indonesia for earthquake-resistant design

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ABSTRACT: Indonesia encompasses one of the world's most tectonically active regions, where three major plates, the Indo-Australian, Eurasian, and Pacific plates, and one minor plate, the Philippine Sea Plate, converge and interact to form a complex network of active plate boundaries. As a result of this tectonic setting, Indonesia has experienced some of the world's most significant and devastating earthquakes. One of the most effective approaches to mitigate earthquake-related disasters involves estimating seismic hazards and incorporating this information into seismic building codes. The first Indonesian seismic hazard maps were developed in 1966, followed by updates in 1970, 1983, 2002, 2010, and 2017. A new update, based on the 2024 development work, is currently in progress for the 2025 hazard maps. The 2025 hazard maps are developed using updated seismotectonic data, refined fault models, and the latest ground motion prediction equations (GMPEs), incorporating recent active fault studies, high-resolution geospatial datasets, and updated earthquake catalogs. Hazard analysis is conducted using a probabilistic approach within a logic tree framework to account for epistemic uncertainty across alternative GMPEs and recurrence models. The 2025 Updated Seismic Hazard Maps project will produce hazard levels for return periods of 50, 100, 200, 500, 1,000, 2,500, 5,000, and 10,000 years for peak ground acceleration (PGA) and spectral accelerations at 0.2 s and 1.0 s on bedrock, supporting seismic design codes/standards for buildings, bridges, dams, tunnels, ports, and airports. This paper focuses specifically on PGA maps for a 2,500-year return period, which are particularly relevant for the design of critical and essential infrastructure such as high-rise buildings.

KEYWORDS: Seismic hazard map, earthquake resistance, earthquake catalog, earthquake sources, active fault.

1 INTRODUCTION

Indonesia lies within the Pacific "Ring of Fire," where three major plates, the Indo-Australian, Eurasian, and Pacific plates, and one minor plate, the Philippine Sea Plate, create one of the world's most seismically active environments. Historically, earthquakes in Indonesia have caused significant human casualties and widespread infrastructure damages, underscoring the critical need for continuous improvements in earthquake hazard assessment to support resilient design practices.

Since the development of Indonesia's first seismic hazard maps in 1966, successive updates in 1970, 1983, 2002, 2010, and 2017 have reflected steady advancements in seismotectonic understanding and hazard analysis methodologies. Several key factors drive the latest revision of the national hazard model. A series of recent devastating earthquakes, including the Pidie Jaya-Aceh (2016), Lombok (2018), Palu (2018), Halmahera (2019), Ambon (2019), Mamuju-Majene (2021), and Cianjur (2022) events, revealed limitations in previous models and highlighted the urgent need for refined seismic source characterization (Irsyam et al, 2024).

In parallel, substantial progress has been made in active fault mapping, earthquake relocation, and geodetic strain analysis using GPS and InSAR. The acquisition of high-resolution datasets, such as SRTM-30, IFSAR, and LiDAR imagery, has further enhanced the ability to characterize Indonesia's complex tectonic setting accurately. These scientific and technological developments, coupled with the increasing demand for robust hazard assessments, are particularly critical given the country's strategic national development priorities, such as the establishment of Super Priority Tourism Destinations. In response, a systematic and collaborative reassessment was undertaken by the Indonesian National Center for Earthquake Studies (PUSGEN), engaging a multidisciplinary team of experts from government agencies, universities, research centers, and professional associations, supported by international collaborators such as the Australian National University, the Global Earthquake Model (GEM) Foundation, and the United States Geological Survey (USGS).

A new update to Indonesia's seismic hazard maps, based on the 2024 development work, is currently in progress (Irsyam et al., 2024) to produce the 2025 Indonesian Seismic Hazard Maps. These maps aim to provide the most authoritative and scientifically up-to-date basis for seismic risk mitigation and earthquake-resistant design, directly supporting the revision plan to the national seismic design code (SNI 1726). The 2025 Updated Seismic Hazard Maps project will generate hazard levels for return periods of 50, 100, 200, 500, 1,000, 2,500, 5,000, and 10,000 years for peak ground acceleration (PGA) and spectral accelerations at 0.2 s and 1.0 s on bedrock, covering the design requirements for buildings, bridges, dams, tunnels, ports, and airports. This paper focuses specifically on PGA maps for a 2,500-year return period, which are of particular importance for the seismic design of critical and essential infrastructure, such as high-rise buildings.

2 ENHANCEMENTS IN THE 2025 INDONESIAN SEISMIC HAZARD MAPS

2.1 *Earthquake catalogs*

The update process began with a major revision of the earthquake catalogs and earthquake source model. The national earthquake catalog was expanded and refined by relocating more than 30,000 earthquake hypocenters from the past five (5) years, significantly improving the spatial representation of seismicity. Table 1 presents a comparison of the earthquake catalogs used for the 2025 seismic hazard map update and those used in 2017.

Table 1. Comparison Between the 2025 and 2017 Earthquake Catalogs

Catalog Type	2017 Catalog	Updated 2025 Catalog
ISC-EHB	15463	43734
ISC-GEM	484	1029
BMKG Relocation	4468	10491
ISC Reviewed (GCMT)	Not included	224
Katalog 2010	20003	Not included
NEIC-USGS	24267	49028
Total	64685	104506

2.2 *Earthquake source models*

Significant efforts were made to update the earthquake source models using new geological field investigations, paleoseismological trenching, geophysical surveys, and geodetic measurements. Active fault mapping was expanded across key seismic regions, including Sumatra, Java, Sulawesi, Papua, Kalimantan, and Eastern Indonesia. As a result, the number of modeled active crustal faults increased significantly, enhancing the spatial resolution and completeness of the national fault database. For example, Figure 1 illustrates the process of geological field investigations conducted to study the Matano Fault zone in Bahodopi, located in Central Sulawesi.

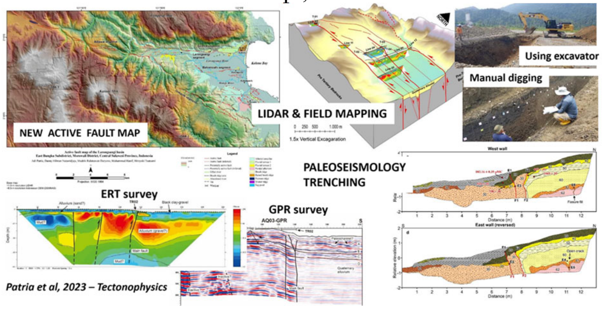

Figure 1. Overview of Geological Fieldwork Conducted for the Matano Fault (Irsyam et al, 2024)

New active fault mapping efforts were conducted in key regions, including Sumatra, Java, Sulawesi, Papua, Kalimantan, and Eastern Indonesia, leading to an increase in the number of modeled crustal fault sources from 272 in 2017 to 402 in 2025, as illustrated in Figure 2 and listed in Table 2.

In the figure, new fault structures were delineated, and existing fault traces were refined based on recent field studies and remote sensing data. Enhanced fault segmentation was applied to better represent expected rupture dimensions. At the same time, slip rates were updated using the latest Global Navigation Satellite System (GNSS) and Interferometric Synthetic Aperture Radar (InSAR) measurements. These improvements contributed to more accurate estimates of recurrence intervals and maximum magnitudes (M_{max}) for each fault.

Subduction zones were also re-segmented and updated based on improved geological and geodetic evidence, refining the hazard representation for megathrust events along the Sunda, Banda, and Philippine subduction systems (Figure 2). The characterization of subduction sources has been significantly enhanced in the 2025 seismic source model. The segmentation of the Sunda, Banda, and Philippine subduction systems has been revised based on updated seismicity data, interplate coupling studies, and tsunami modeling results. Particular attention was given to identifying asperities and locked segments, which are critical for modeling the potential occurrence of large-magnitude events. The geometry and mechanical properties of the subduction interfaces were updated to align with recent geophysical observations and a global understanding of megathrust behavior.

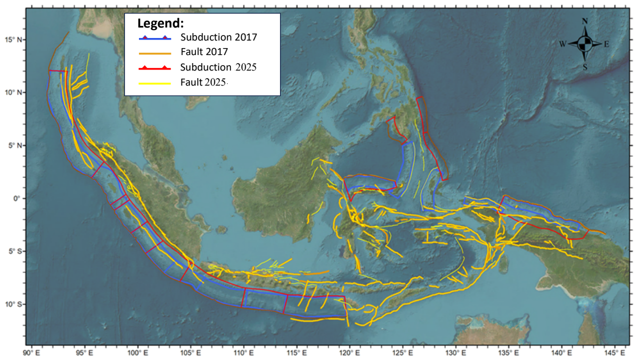

Figure 2. Comparison of Active Fault and Megathrust Segmentations from 2017 and 2025 Source Models

Table 2. Summary of the number of megathrust and crustal fault segmentations in 2010, 2017, and 2025

Segmentation	2010	2017	2025
Megathrust	10	15	15
Crustal Fault (Map)	58	272	402
▪ Sumatra	19	55	86
▪ Jawa	6	37	82
▪ Kalimantan	6	3	11
▪ Sulawesi	7	48	74
▪ Bali-NT-Banda-Maluku	4	49	52
▪ Maluku Utara-Papua	16	80	97

2.3 *Enhancements in Ground Motion Prediction Equations (GMPEs)*

In parallel with the updates to the earthquake source models, ground motion modeling was also significantly enhanced. New Ground Motion Prediction Equations (GMPEs) were selected through a structured evaluation involving both national and international experts. Weighted logic trees were applied to account for epistemic uncertainties across different earthquake types, including shallow crustal events, subduction interface earthquakes, and intraslab events.

A systematic evaluation was carried out to select GMPEs suitable for three primary earthquake types: shallow crustal events, subduction interface earthquakes, and intraslab earthquakes. The selection of GMPEs was based on the similarity of geological and tectonic conditions between the target region and the regions where the equations were originally developed. In addition, the selection was supported by comparisons between results obtained from existing GMPEs and actual ground motion or accelerograph data recorded in

Indonesia, as reported in studies by Rudiyanto (2013) and Pramono et al. (2024).

For shallow crustal sources, the GMPEs used in 2025 are similar to those in 2017, adopted from the NGA-West2 project. These include models by Boore et al. (2014), Campbell and Bozorgnia (2014), and Chiou and Youngs (2014), which provide robust predictions for moderate- to large-magnitude events in active tectonic regions.

For subduction interface and intraslab events, the GMPEs by Abrahamson and Gülerce (2020), Kuehn et al. (2020), and Zhao et al. (2006) were selected to reflect the complex ground motion behavior associated with megathrust and Benioff earthquakes. Table 3 presents the list of GMPEs used in the development of the 2025 Indonesian Seismic Hazard Maps.

Table 3. The updated GMPEs for the 2025 Indonesian Seismic Hazard Maps

Shallow crustal fault & shallow background sources
- Boore et al (2014) in the NGA-West-2
- Campbell-Bozorgnia (2014) NGA-West-2
- Chiou-Youngs (2014) NGA West 2

Subduction Interface
- Abrahamson & Gulerce (2020) Interface NGA-Sub
- Kuehn et al. (2020) Interface NGA-Sub
- Zhao et al. (2006)

Subduction Intraslab (Benioff)
- Abrahamson & Gulerce (2020) Intraslab NGA-Sub
- Kuehn et al. (2020) Intraslab NGA-Sub
- Zhao et al. (2006)

A logic tree approach was employed to select and weight the GMPEs, considering epistemic uncertainties. The weightings were assigned based on several criteria, including the quality of fit to local and regional accelerometric data, consistency with observed ground motion behavior in Indonesia, and expert judgment.

Furthermore, site effects were incorporated by applying adjustments based on V_{s30} values, which represent the average shear wave velocity in the top 30 meters of soil. This approach enables more reliable ground motion predictions for both rock and soil sites, which are crucial for site-specific hazard assessments nationwide.

3 UPDATED SEISMIC HAZARD MAPS

The hazard analysis was performed using the USGS PSHA (Petersen et al., 2014) and the OpenQuake software (Silva et al., 2014), applying probabilistic seismic hazard assessment techniques and refined uncertainty modeling. These advancements ensure that the 2025 hazard maps provide more accurate ground-shaking estimates and remain consistent with international standards.

As has been mentioned, this paper focuses solely on PGA maps for a 2,500-year return period, which are particularly relevant to the seismic design of critical and essential infrastructure such as high-rise buildings. As the validation and verification processes are still ongoing, and further refinements and adjustments may be made prior to publication of the final version, the seismic hazard map presented in this study should be regarded as a draft.

The draft version of the 2025 PGA map for a 2,500-year return period (Figure 3) shows the highest hazard values (>1.0g) concentrated along the western coast of Sumatra, Nias Island, part of northern and central Sulawesi, and parts of Papua, consistent with proximity to major subduction zones and active faults. High PGA levels are also observed in eastern Indonesia, such as Maluku and northern Halmahera. At the same time, relatively low hazard values (<0.1g) occur in central Kalimantan and parts of eastern Sumatra, reflecting more tectonically stable regions. This pattern underlines the need for engineers and planners to integrate site-specific PGA data into earthquake-resistant design, particularly in regions where seismic hazard is the highest.

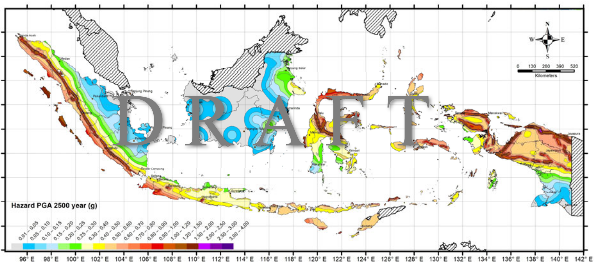

Figure 3. The 2025 Peak Ground Acceleration (PGA) Map at Bedrock (Site Class B) for a 2,500-Year Return Period *(Draft Version).*

4 COMPARISON BETWEEN 2017 AND 2025 DRAFT SEISMIC HAZARD MAPS

A detailed comparison between the 2017 and 2025 seismic source models highlights substantial improvements in the representation and characterization of earthquake sources across Indonesia. These refinements reflect advances in geophysical observations, geological mapping, and seismic hazard assessment methodologies over the past decade.

The comparison between the draft version of the 2025 PGA map for a 2,500-year return period and the 2017 PGA map (Figure 4) shows a broadly consistent spatial distribution of seismic hazard, with the highest PGA values (>1.0g) concentrated along the western coast of Sumatra and Nias Island, part of northern and central Sulawesi, and northern Papua. These regions coincide with the major subduction interfaces and active crustal fault systems. Both maps also indicate low PGA values (<0.1g) across tectonically stable regions, such as central Kalimantan and eastern Sumatra. However, the draft 2025 map demonstrates slight expansions of high-hazard zones in several areas. In Java, the 2025 exhibits a more continuous moderate-hazard belt (0.3–0.6g) along the southern coastline, particularly in West and Central Java, compared to the more segmented pattern in 2017.

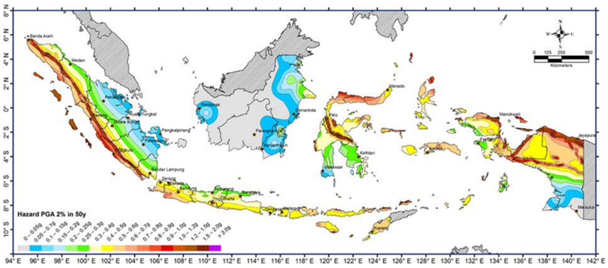

Figure 4. The 2017 PGA Map at Bedrock (Site Class B) for a 2,500-Year Return Period (Irsyam et al, 2017, 2020).

In Sulawesi, the draft 2025 map shows a notable increase in PGA intensity along the Palu-Koro Fault, with >1.0g zones covering a larger area than in the 2017 map. Eastern Indonesia, especially Maluku and northern Halmahera, displays elevated PGA values in the 2025 draft, likely due to updates in fault characterization and the application of revised GMPEs. In Papua, high-hazard zones (>1.0g) are mostly concentrated in the north, but the 2025 introduces sharper hazard gradients and localized intensification around Jayapura and adjacent areas. These changes suggest that the updated 2025 model incorporates refined seismotectonic data and revised recurrence parameters, resulting in more pronounced spatial detail compared to the 2017 map.

Changes in seismic hazard levels have direct consequences for civil and geotechnical structures because updated PGA and spectral acceleration values alter the seismic forces used in design. Higher hazard levels increase structural demand, base shear, and detailing requirements, while also affecting foundation sizing, soil–structure interaction, liquefaction potential, and slope stability under dynamic loading. Even moderate shifts in hazard can require reassessment of design assumptions, site response, and ground improvement needs. As a result, updated hazard maps play a critical role in ensuring that buildings, bridges, ports, and other essential infrastructure are designed to withstand the newly quantified earthquake loads safely.

5 CONCLUSIONS

The development of the 2025 Indonesian Seismic Hazard Maps represents a significant advancement in characterizing seismic hazards across Indonesia. Comprehensive updates to earthquake source models, combined with the adoption of advanced ground motion prediction frameworks and probabilistic hazard assessment methodologies, have resulted in a more accurate and scientifically robust national hazard model.

These advancements align with Indonesia's strategic goals for disaster risk reduction, resilient infrastructure, and sustainable growth, particularly in priority areas such as the Super Priority Tourism Destinations. The 2025 Indonesian Seismic Hazard Maps will provide essential input for the revision of the Indonesian Seismic Code of SNI 1726 to enhance earthquake-resistant design.

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