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INTEGRATED SEISMIC HAZARD EVALUATION OF JAVA ISLAND BASED ON PEAK GROUND ACCELERATION AND HISTORICAL SEISMICITY

Tati Zera[1*], Talitha Adinda[1], Rindi Antika Sari[1]
[1]Department of Physics, Faculty of Science and Technology, Syarif Hidayatullah State Islamic University Jakarta, Indonesia

[*] tati_zera@uinjkt.ac.id

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Abstract. Java Island is recognized as one of the most seismically active regions in Southeast Asia due to its tectonic position at the convergence of the Indo-Australian, Eurasian, and Pacific plates. The interaction of these major tectonic systems, combined with numerous active faults, significantly increases the likelihood of destructive earthquakes throughout the region. This study evaluates seismic hazards across the observation period runs from 1974 to 2024, analyzing earthquakes with surface wave magnitudes greater than 5.0 and shallower focus depths of less than 60 km.. Peak Ground Acceleration (PGA) was employed as the principal parameter due to its direct relationship with structural damage potential and its use in seismic engineering applications. Three empirical attenuation approaches, namely the Donovan, Esteva, and McGuire models, were utilized to estimate PGA values. The resulting PGA ranges obtained from each model were 0.0046–0.1573 g, 0.00019–0.0292 g, and 0.00682–0.2206 g, respectively. These values were subsequently transformed into the Modified Mercalli Intensity (MMI) scale to facilitate practical interpretation of seismic hazard levels. The largest PGA value corresponded to the magnitude 6.6 earthquake that occurred on January 14, 2022. The findings indicate that empirically based seismic hazard assessments are essential for strengthening disaster mitigation strategies, improving community resilience, and supporting sustainable regional development planning across Java Island.

Keywords: earthquake, Esteva, Donovan, McGuire method, Peak Ground Acceleration
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INTRODUCTION

Java Island occupies a highly complex tectonic environment formed by the convergence of the Indo-Australian, Eurasian, and Pacific plates. This interaction has generated intense seismic activity across the island for a prolonged geological period. The subduction of the Indo-Australian Plate beneath the Eurasian Plate along the Sunda Trench constitutes the dominant tectonic mechanism controlling seismicity in the region, while the influence of the Pacific Plate further complicates the tectonic configuration. Continuous plate convergence has produced substantial crustal deformation expressed through volcanic arcs, thrust faults, and strike-slip fault systems distributed across Java. According to Verstappen[1], the geomorphological evolution of Indonesia is fundamentally associated with plate tectonic processes, with Java representing one of the most tectonically unstable regions because of persistent endogenous activity and active Quaternary deformation. In addition, the existence of active structures such as the Cimandiri, Opak, and Lembang Faults further intensifies the seismic threat because these faults are capable of generating shallow and destructive earthquakes in densely inhabited areas. Seismic imaging investigations have also demonstrated that the lithospheric framework beneath Central and East Java forms part of the Sunda Arc system, where subduction-related tectonic processes are strongly associated with earthquake occurrence and volcanic activity[2]. These conditions illustrate that Java's tectonic setting is not only scientifically significant but also critically important for disaster mitigation and risk management, considering the island's large population and strategic economic role.

The seismic vulnerability of Java is further enhanced by the interaction between subduction processes and local fault systems. Recent studies conducted by Xia et al.[3] revealed that the subduction of seamounts and ridges along the Java margin contributes to deformation within the upper plate, thereby decreasing crustal rigidity and increasing the probability of tsunami-generating earthquakes. Consequently, Java is exposed to dual hazards consisting of strong seismic ground shaking and secondary hazards such as tsunamis. Historical earthquake records indicate that numerous events exceeding magnitude 6 have repeatedly affected Java, including the 2006 Yogyakarta earthquake, which caused extensive casualties and infrastructure damage. Previous investigations also indicate that western Java, particularly the Banten and West Java regions, exhibits relatively high Peak Ground Acceleration values due to its proximity to the Sunda Megathrust and active crustal faults.[4] These findings emphasize the necessity of integrating empirical seismic hazard models with spatial analyses to identify high-risk areas more accurately. Variations in PGA estimates among empirical approaches such as Donovan, Esteva, and McGuire additionally demonstrate the complexity of seismic hazard evaluation in Java, where local geological and tectonic conditions strongly influence ground motion behavior. Therefore, Java represents an important natural laboratory for seismic hazard studies while simultaneously requiring comprehensive mitigation strategies. As emphasized by Marlisa et al., [5] empirical PGA assessments provide valuable information for the design of earthquake-resistant infrastructure, which is crucial for protecting communities in one of Indonesia's most earthquake-prone regions.

METHODS

Peak Ground Acceleration (PGA) was selected as the primary analytical parameter because of its close relationship with structural damage and its widespread application in earthquake engineering design standards. PGA represents the maximum acceleration experienced at the ground surface during seismic events and is commonly used as an indicator of the destructive potential of earthquakes on buildings and infrastructure.[6] This parameter is particularly relevant for Java Island because major urban centers and essential infrastructure facilities are situated within tectonically active environments. To improve methodological reliability, three empirical attenuation relationships were employed in this study, namely the Donovan, Esteva, and McGuire models.

This investigation analyzed earthquake events occurring during the period 1974–2024 by focusing on shallow destructive earthquakes considered significant for evaluating crustal seismic hazards. Earthquake data were obtained from the official catalog provided by the United States Geological Survey (USGS). The dataset included seismic events recorded within the geographical extent of Java Island, specifically between 5.5°–9.5° S latitude and 105°–115° E longitude. Only earthquakes with magnitudes equal to or greater than 5.0 and focal depths not exceeding 60 km were selected for analysis. These criteria were adopted because shallow and moderate-to-large earthquakes are more likely to generate significant surface ground shaking and substantial structural damage. Consequently, the selected dataset provides a robust basis for evaluating seismic hazard and ground motion characteristics across Java.

Each earthquake record consisted of occurrence time, epicentral coordinates, magnitude, and focal depth. Because seismic events in the catalog were reported using different magnitude scales, such as Mw and mb, all values were converted into surface-wave magnitude (Ms) to ensure consistency in the analysis. Peak Ground Acceleration values were then estimated using the Donovan, Esteva, and McGuire empirical equations,[7] which utilize surface-wave magnitude and epicentral distance as the principal input variables.

$$PGA(Donovan) = \frac{1800.e^{0,5.M_s}}{(R+25)^{1.32}} \tag{1}$$

$$PGA(Esteva) = \frac{5600.e^{M_s}}{(R+40)^{2}} \tag{2}$$

$$PGA(McGuirre) = \frac{472,3.e^{0,278.M_s}}{(R+25)^{1.301}} \tag{3}$$

In all models[7], PGA values were expressed in either Gal or g units, where 1 Gal equals 0.01 m/s² and 1 g equals 1 cm/s². These units represent the maximum intensity of ground shaking experienced at the Earth's surface. The parameter Ms denotes the converted surface-wave magnitude, whereas R represents the epicentral distance measured in kilometers between the earthquake source and the observation location.

Spatial visualization of PGA distribution across Java Island was conducted using ArcGIS. Geographic coordinates and calculated PGA values derived from each empirical model were incorporated into spatial layers to generate contour maps. This mapping procedure was intended to identify areas with elevated ground acceleration potential and to provide essential information for disaster mitigation planning and spatial development strategies. Through this approach, the spatial variability of seismic hazards across Java could be comprehensively illustrated, thereby supporting long-term seismic risk reduction efforts.

RESULT AND DISCUSSION

Earthquake events recorded in the USGS catalog between 1974 and 2024 demonstrate that Java Island has experienced substantial seismic activity over the last five decades. A total of 375 earthquakes with magnitudes greater than or equal to 5.0 and focal depths shallower than 60 km were identified within the study area. The seismicity distribution indicates that the majority of earthquakes are concentrated at shallow depths ranging from 0 to 20 km. These events are primarily associated with the subduction of the Indo-Australian Plate beneath the Eurasian Plate along the southern margin of Java. As a result, you can see in **Figure 1** below, the southern coastal region of Java represents the most seismically active zone on the island.

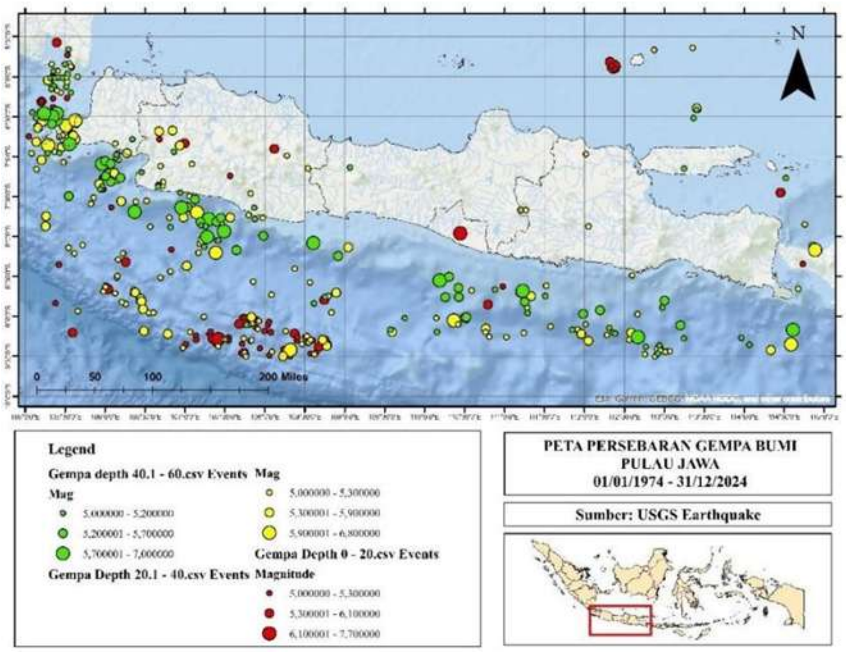

Figure 1. Seismicity map of Java from 1974 to 2024

Based on the magnitude distribution, earthquakes within the range of magnitude 5.0–6.0 dominate the recorded events during the observation period. Nevertheless, larger earthquakes exceeding magnitude 6.0 were also frequently documented, particularly in southern West Java, Yogyakarta, southern Central Java, and southern East Java. This distribution pattern confirms that the southern segment of Java possesses significant potential for destructive earthquakes and tsunami generation, especially when seismic sources are located offshore.

The calculation of values and the plotting of PGA contours of the three models described earlier are detailed as follows,

1. Donovan model

   The Donovan model provides an empirical representation of the Peak Ground Acceleration distribution across Java Island. The contour map generated from this model reveals substantial spatial variation in seismic hazard intensity as you can see in **Figure 2**. The highest PGA values, ranging from 0.1318 to 0.1573 g, are concentrated in western Java, particularly within Banten and the western parts of West Java. These elevated values indicate the strongest potential ground shaking across the island. They are closely associated with the tectonic influence of the Sunda subduction zone as well as active crustal structures such as the Cimandiri and Lembang Faults.

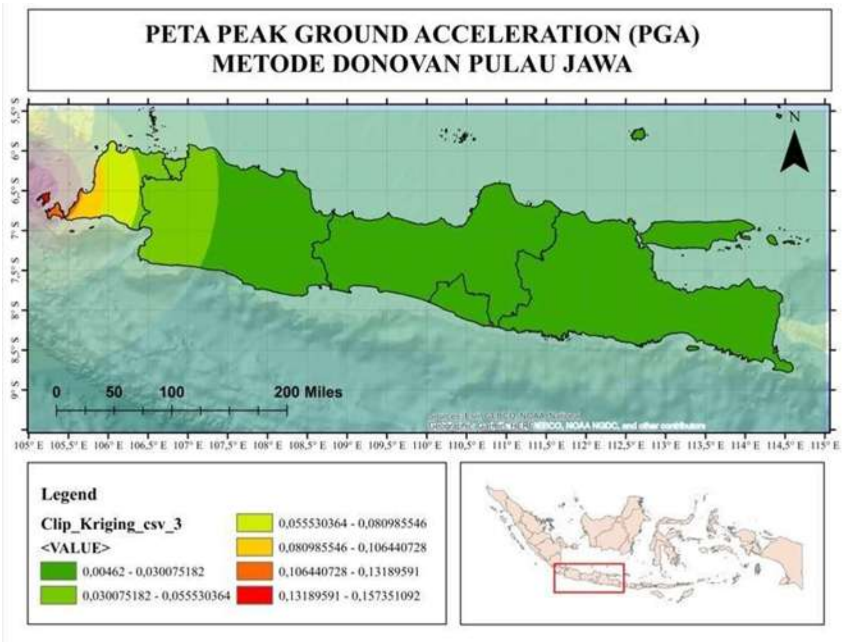

Figure 2. Peak Ground Acceleration (PGA) Map of Java using Donovan's model

A progressive reduction in PGA values is observed toward the eastern part of Java. Areas covering central and eastern West Java, together with extensive portions of Central Java and the Special Region of Yogyakarta, generally exhibit moderate to relatively low PGA values ranging from approximately 0.055 to 0.106 g. Further east, most of East Java is characterized by the lowest PGA values, ranging from 0.0046 to 0.0300 g, depicted in dark green tones on the contour map. Although these values indicate a comparatively lower level of seismic hazard than that of western Java, they should not be interpreted as evidence of negligible earthquake risk, since seismic events associated with subduction processes can still occur in these regions.

The spatial variation of PGA across Java highlights the importance of combining empirical ground-motion models with regional tectonic analyses to achieve a more comprehensive understanding of seismic hazard patterns. From a risk-management perspective, the results suggest that mitigation measures should be tailored according to regional hazard levels. Western Java, where the highest PGA values are concentrated, requires more stringent and precautionary mitigation approaches, whereas central and eastern Java would benefit from strategies adapted to their relatively lower, yet still consequential, levels of seismic risk. These findings emphasize the value of spatially explicit disaster risk reduction policies and support the integration of empirical PGA assessments into long-term infrastructure planning and resilience-building initiatives.

2. Esteva Model

   The Esteva model offers a significant empirical basis for evaluating Peak Ground Acceleration (PGA) and mapping its spatial variability across Java Island, as demonstrated in **Figure 3**. below

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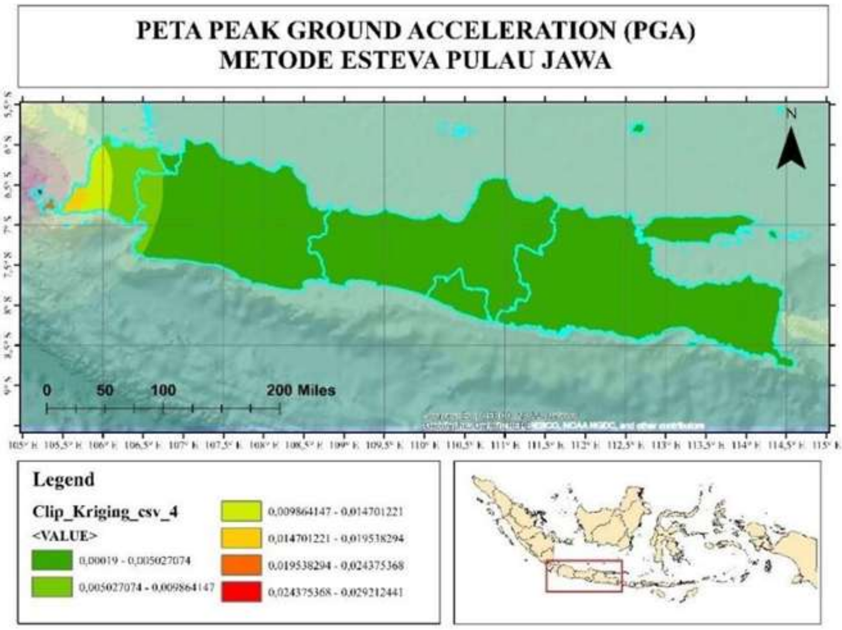

Figure 3. Peak Ground Acceleration (PGA) Map of Java using Esteva's model

Figure 3 presents the spatial pattern of Peak Ground Acceleration (PGA) across Java Island derived from the Esteva attenuation model. The resulting map demonstrates considerable variation in PGA values, ranging from 0.00019 g to 0.0292 g. The highest levels are concentrated in the northwestern sector of the island, particularly within Banten Province, where values exceeding 0.0195 g are represented by red and orange color gradients. These elevated PGA values indicate a greater potential for intense ground shaking. Meanwhile, moderate PGA values are distributed across parts of West Java, whereas much of Central Java and East Java is characterized by lower values between 0.00019 g and 0.0098 g. This distribution pattern indicates that western Java experiences a relatively greater seismic threat than the central and eastern portions of the island, highlighting the necessity of region-specific seismic hazard assessments to support effective disaster risk management.

The spatial distribution generated by the Esteva model is consistent with the historical record of seismic activity in Java. Earthquakes with magnitudes of 5.0 or greater and focal depths ranging from 0 to 60 km are predominantly clustered along the southern offshore margin of the island, particularly in southwestern Banten and southern West Java. These locations are situated within the active Indo-Australian subduction system and are influenced by nearby tectonic faults, both of which contribute to increased seismic hazard. In contrast, although seismic events continue to occur in Central and East Java, their occurrence tends to be less frequent and generally associated with lower levels of seismic intensity, which corresponds well with the lower PGA values estimated by the Esteva approach. The strong agreement between the empirical

PGA results and the observed seismicity pattern demonstrates the capability of the Esteva model to represent regional seismic hazard characteristics and further supports the implementation of mitigation measures that are tailored to the varying tectonic conditions across Java Island

3. McGuirre Model
   The McGuire model constitutes a key empirical method for evaluating Peak Ground Acceleration (PGA) and mapping its regional variation across Java Island, as evidenced in **Figure 4** below.

Figure 4. Peak Ground Acceleration (PGA) Map of Java using McGuirre's model

Figure 4 illustrates the spatial pattern of Peak Ground Acceleration (PGA) across Java Island derived from the McGuire attenuation model. The resulting distribution demonstrates considerable variability in PGA values, ranging from 0.00682 g to 0.2206 g throughout the study area. The highest PGA values are concentrated in western Java, particularly within the Banten region, where estimated accelerations range between 0.1493 g and 0.2206 g. These areas are represented by orange to red color gradients on the contour map, indicating the strongest levels of expected ground shaking. The elevated PGA values observed in this region are consistent with its tectonic setting, which is strongly influenced by the Sunda subduction zone and the activity of major fault systems such as the Cimandiri Fault. Consequently, western Java exhibits the highest level of seismic hazard among the regions analyzed. In contrast, the majority of Central Java, the Special Region of Yogyakarta, and East Java are characterized by lower PGA values, generally below 0.0781 g, as indicated by the predominance of green shades on the map. These lower values suggest a reduced potential for intense ground motion relative to western Java. Nevertheless, this should not be interpreted as an absence of seismic hazard, since the entire island remains affected by complex tectonic interactions associated with subduction processes and active faulting. Therefore, although the expected level of ground shaking is comparatively lower in central and eastern Java, earthquake risk continues to be a relevant consideration in regional disaster mitigation and infrastructure planning.

The PGA pattern obtained from the McGuire model closely corresponds with the historical distribution of earthquakes shown in **Figure 1**, where seismic activity is concentrated predominantly in the southwestern sector of Java. The frequent occurrence of earthquakes in southern Banten and along the western coast of West Java is reflected in the relatively high PGA values estimated by this model. In contrast, despite the occurrence of earthquakes in eastern Java, the associated PGA values remain lower because many events are characterized by smaller magnitudes or are located at greater depths and distances from populated areas. Relative to the Esteva model, the McGuire approach consistently produces larger PGA estimates, highlighting its more conservative representation of seismic hazard. This tendency makes the model particularly suitable for disaster mitigation planning and the development of earthquake-resistant infrastructure, as it provides precautionary estimates for areas exposed to elevated seismic risk. Consequently, the results emphasize the importance of incorporating conservative ground-motion models into hazard assessments to enhance resilience in highly vulnerable regions such as western Java.

A comparative evaluation of the Donovan, Esteva, and McGuire models indicates a consistent spatial pattern of seismic hazard across Java Island, with the highest PGA concentrations occurring in western Java, especially in Banten, Jakarta, and neighboring areas. This pattern is closely associated with the tectonic influence of the Sunda subduction zone and the activity of major fault systems, including the Cimandiri and Lembang Faults, which significantly contribute to regional seismicity. Although the three models identify similar high-hazard zones, substantial differences are observed in the estimated PGA magnitudes. The Donovan model produces maximum values of approximately 0.1573 g, whereas the McGuire model yields the highest estimate at about 0.2206 g. In contrast, the Esteva model provides considerably lower values, with a maximum PGA of only 0.0292 g. These discrepancies reflect differences in the mathematical formulations and assumptions used by each model, particularly regarding earthquake magnitude, source-to-site distance, and attenuation characteristics.

The differences observed among these models are consistent with findings reported in the broader seismic hazard literature, where the application

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of multiple ground-motion prediction approaches is widely recommended to address uncertainties associated with earthquake hazard characterization and ground-motion forecasting [6][8]. The integration of several empirical models enables a more balanced and comprehensive assessment of seismic risk by incorporating both conservative and moderate estimates. Such an approach not only strengthens the scientific robustness of hazard evaluations but also provides a more reliable basis for disaster risk reduction, infrastructure

From a broader perspective, the combined application of the Donovan, Esteva, and McGuire models provides a comprehensive framework for evaluating seismic hazards across Java Island. The consistent identification of western Java as the region of greatest hazard reinforces the need for targeted risk reduction measures in densely populated and economically strategic areas. At the same time, differences among the model outputs demonstrate the importance of incorporating conservative estimates into infrastructure planning, particularly where structural resilience is a primary concern. Comparable methodologies have been implemented in other seismically active regions, including California and Japan, where empirical PGA models are integrated with probabilistic seismic hazard assessments to support evidence-based decision-making[9][10]. Consequently, the findings obtained for Java contribute not only to regional seismic hazard characterization but also align with internationally recognized practices in earthquake engineering and disaster risk management. The utilization of multiple empirical models ultimately strengthens the robustness and reliability of seismic hazard evaluations, providing a sound scientific basis for sustainable development in earthquake-prone environments.

The relationship between Peak Ground Acceleration (PGA) and Modified Mercalli Intensity (MMI) is commonly established through Ground Motion to Intensity Conversion Equations (GMICEs). One of the most widely adopted formulations was developed by Worden et al. [8], who proposed empirical relationships linking instrumental measurements of PGA to observed intensity levels. These equations have subsequently been incorporated into hazard assessment procedures used by the USGS. In addition, the estimated intensity ranges can be validated through comparison with the internationally recognized PGA–MMI conversion Table.[11], thereby facilitating the translation of quantitative ground-motion parameters into more practical indicators of earthquake impacts.

Table 1. Conversion of PGA to MMI Scale

Model	PGA Range (g)	Aproximate MMI	Interpretation
Donovan	0.0046 – 0.1573	III – VII	Weak shaking in eastern Java (MMI III–IV), strong shaking in western Java (MMI VI–VII).
Esteva	0.00019 – 0.0292	II – V	Very weak shaking in most of Java (MMI II–III), moderate shaking in Banten (MMI IV–V).
MicGuirre	0.00682 – 0.2206	IV – VIII	Moderate shaking in central/eastern Java (MMI IV–V), very strong shaking in western Java (MMI VII–VIII).

The conversion of PGA values into the Modified Mercalli Intensity (MMI) scale provides a clearer interpretation of seismic hazard levels across Java Island. Based on this conversion, the Donovan model generates moderate PGA estimates that correspond to MMI VI–VII in western Java, a range that is consistent with the intensity of several historically destructive earthquakes affecting Banten and Jakarta. In contrast, the Esteva model produces lower PGA values equivalent to MMI II–V. Although these estimates may lead to a less conservative representation of seismic hazard, they remain valuable for comparative assessments and regional hazard mapping. The McGuire model, meanwhile, yields the highest PGA estimates, reaching MMI VIII in western Java, thereby reflecting a more precautionary approach that is particularly suitable for the planning and design of critical infrastructure.

These findings are consistent with previous international studies indicating that the application of multiple ground-motion models is essential for addressing uncertainties inherent in seismic hazard evaluations [6][8]. Furthermore, expressing PGA values in terms of MMI enhances the practical relevance of the results by translating technical ground-motion measurements into intensity levels that are more readily understood by decision-makers, stakeholders, and local communities. As a result, the conversion facilitates more effective risk communication and supports the integration of scientific hazard assessments into disaster preparedness and mitigation planning.

CONCLUSION

The comparative assessment of Peak Ground Acceleration (PGA) values generated using the Donovan, Esteva, and McGuire models offers a detailed perspective on the spatial variability of seismic hazards across Java Island. Despite differences in the numerical results, all three models consistently identify West Java particularly the Banten and Jakarta regions, as well as the surrounding as the region most at risk of a major earthquake. However, it is important to note as a limitation of this study that these hazard maps are macro-deterministic and do not yet account for the highly significant local ground amplification in alluvial plain areas. This pattern is closely associated with the tectonic influence of the Sunda subduction system and the presence of active fault structures, including the Cimandiri and Lembang Faults, which play a major role in controlling regional seismic activity. The variation in PGA estimates among the three approaches highlights the importance of employing multiple methodologies when evaluating seismic hazards.

The Donovan model produces moderate PGA values ranging from 0.0046 to 0.1573 g, corresponding to Modified Mercalli Intensity (MMI) levels III–VII. These estimates are generally consistent with the intensity of historically damaging earthquakes that have affected Banten and Jakarta, indicating the model's suitability for regional-scale hazard assessments and comparative studies. In contrast, the Esteva model generates lower PGA values, ranging from 0.00019 to 0.0292 g, which correspond to MMI II–V. Although such estimates may not fully represent extreme seismic scenarios, they remain useful for broad regional evaluations and for identifying areas characterized by relatively low seismic intensity. Among the three approaches, the McGuire model yields the highest PGA values, varying between 0.00682 and 0.2206 g and corresponding to MMI IV–VIII. Its tendency to produce more conservative estimates reflects stronger ground-motion scenarios, making the model particularly valuable for disaster risk reduction initiatives, infrastructure resilience assessments, and the planning of critical facilities in earthquake-prone regions.

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