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A Preliminary Ground Motion To Intensity Conversion Equation (GMICE) For Northern Semarang City Based On Dominant Frequency And Theoretical PGA Estimates

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Abstract: This study develops preliminary Ground Motion to Intensity Conversion Equations (GMICE) for the northern part of Semarang City, Indonesia, by integrating dominant frequency data from microtremor surveys with theoretical peak ground acceleration (PGA) estimates derived from the Kanai equation. A total of 436 data pairs, generated from four earthquake events between 2019 and 2024, were analyzed using both simple and complex regression models. The simple GMICE, defined as a function of log-transformed PGA, and the complex model, which incorporates magnitude (Mw) and epicentral distance (R), yielded R^2 values of 0.679 and 0.788, respectively. The optimization of the near-source parameter (R_0) enhanced the model's stability, while uncertainty analysis using standard deviation (±σ, ±2σ) confirmed consistent predictive performance. These results indicate that the derived GMICE models can reasonably represent the seismic intensity distribution across the alluvial-dominated northern Semarang region. Despite the limited number of earthquake events, this study provides an important initial framework for region-specific GMICE development in Indonesia. The proposed models can support seismic hazard assessment, post-earthquake impact estimation, and future refinement as additional earthquake data and instrumental recordings become available.

Keywords: Ground Motion to Intensity Conversion Equation (GMICE), Peak Ground Acceleration (PGA), Dominant Frequency, Seismic Intensity.

1. INTRODUCTION

Semarang City, the capital of Central Java Province, is located between 110º16'20'' – 110º30'29'' East Longitude and 6°55'34" – 7°07'04" South Latitude, covering an area of approximately 373,78 km² (Badan Pusat Statistik Kota Semarang, 2024). According to the Central Bureau of Statistics (2024), based on the Population Projection Results for 2020–2050, the population of Semarang City in 2023 was recorded at 1.694,74 thousand. The city's complex geographical and demographic characteristics demand greater attention in terms of disaster risk monitoring and mitigation. Due to the city's high population density and infrastructure vulnerability, an effective early warning system and a detailed understanding of seismic behavior are critically required.

The measurement of earthquake intensity is crucial to minimize the impacts of seismic disasters through effective disaster management strategies (Wijaya, 2023). Earthquake intensity provides information on how strongly the shaking is felt by people and the extent of damage caused to structures. The Ground Motion to Intensity Conversion Equation (GMICE) offers an empirical approach to understanding and quantifying seismic effects, serving as a practical tool for regions such as Semarang, which

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frequently experience earthquake activity. GMICE can be defined as an empirical formulation that establishes a relationship between ground motion parameters and the felt intensity of an earthquake.

There are generally two model of GMICEs, simple equation and complex equation. The simple equation has been widely studied across various countries, typically involving only the parameters Modified Mercalli Intensity (MMI) and Peak Ground Acceleration (PGA). Meanwhile, Ahmadzadeh et al. (2020) introduced an extended, more complex equation by incorporating additional parameters such as epicentral distance (*R*) and moment magnitude (*Mw*). This complex equation has not been extensively explored for different study areas. Studies applying the complex equations of GMICE remain limited across different regions. The inclusion of epicentral distance and magnitude parameters provides the potential to develop localized GMICE models, which can better represent regional seismic responses. Therefore, this study not only determines the GMICE in its simple form but also develops a complex GMICE specifically calibrated for the conditions of Northern Semarang City.

Several previous studies have been conducted in various regions, both in Indonesia and globally, on the relationship between PGA and seismic intensity (MMI). Santoso et al. (2011) conducted a seismic hazard study on Sumatra Island using Probabilistic Seismic Hazard Analysis (PSHA), incorporating earthquake catalog data, fault data, subduction data, and Indonesian Meteorological, Climatological, and Geophysical Agency (BMKG) accelerograph records. The results revealed a positive linear correlation between PGA and MMI, with the equation MMI = 0,008 × PGA + 3,159. A major advantage of this study is the use of long-term data from an earthquake-prone region like Sumatra, which provided a representative model for the area. However, the model developed is more specific to Sumatra and may not be directly applicable in regions with different geological conditions. Kadnan (2019) explored the empirical relationship between seismic intensity, PGA, and PGV in West Java using Indonesian Meteorological, Climatological, and Geophysical Agency (BMKG) earthquake data from 2009–2011, producing the equations IMM = 3,56 *log*(PGV) + 2,88 and IMM = 3,69 *log*(PGA) – 1,12 for MMI intensities V–VIII.

On the other hand, Mega et al. (2024) conducted a study in West Nusa Tenggara focusing on interface subduction earthquakes using Indonesian Meteorological, Climatological, and Geophysical Agency (BMKG) accelerograph data from 2017–2023. The results produced a GMICE equation IMM = 1,005 *log*(PGA) + 2,443 for MMI intensities < V, with the advantage of using a larger dataset of 324 earthquakes. However, the dominance of small to medium earthquakes (MMI I–V) limited the range of the equation, making it less representative for large earthquakes. The most recent study by Gunawan et al. (2025) on background earthquakes for GMICE studies in West Nusa Tenggara using Indonesian Meteorological, Climatological, and Geophysical Agency (BMKG) macroseismic intensity data and strong motion ground measurements. The study showed a relatively strong linear relationship between PGA and MMI, although some deviations occurred due to local geological variations. Despite the study's focus on an earthquake-prone area, the limitation of the dataset means the resulting equation is not yet robust across the full range of seismic intensities.

However, there are some limitations in this study. The earthquake data used for the analysis is limited to only four earthquake events that occurred between 2019 and 2024 within a radius of less than 100 km from the city, and only earthquakes with magnitudes greater than 3.5 *Mw*. Additionally, the dominant frequency data were obtained from 109 microtremor measurement points within a specified region. This limited dataset may affect the robustness of the GMICE model, and future studies will need to incorporate a larger dataset for better model generalization.

Furthermore, due to the absence of available accelerograph data for Semarang, PGA values were estimated using the Kanai et al. (1966) empirical relation, which is based on dominant frequency data from microtremor surveys. While this approach provides an alternative when accelerograph data is not available, it introduces potential uncertainty in the estimation of ground motion. Therefore, the GMICE models developed in this study are preliminary and should be validated with actual accelerometric data in future research.

The objective of this research is to establish a preliminary of Ground Motion to Intensity Conversion Equation (GMICE) for Northern Semarang City, Central Java, which is expected to contribute to the development of a localized seismic intensity model and to fill the existing research gap in this field.

2. THEORETICAL FOUNDATION

Earthquake

An earthquake is a natural disaster that occurs suddenly and within a short duration, yet it can cause extensive destruction to the Earth's surface, including damage to property and loss of human life (Hidayat & Santoso, 1997). According to Lutgens & Tarbuck (1982), an earthquake is defined as a vibration of the Earth produced by the rapid release of accumulated energy that propagates outward in all directions from its source. In Indonesia, earthquakes are frequent due to the country's tectonic setting, which lies at the convergence of three major lithospheric plates, forming both seismic and volcanic belts (Hidayat & Santoso, 1997).

An earthquake event is generally characterized by several seismological parameters, which are represented numerically and include the date, origin time, epicenter coordinates (latitude and longitude), magnitude, focal depth, and maximum intensity. The term intensity refers to the degree of shaking and the resulting damage on the Earth's surface, commonly measured using the Modified Mercalli Intensity (MMI) scale, which ranges from I to XII. Other important parameters include fault dimensions, seismic moment orientation, and recorded ground motion (Hidayat & Santoso, 1997).

Seismic Intensity

Seismic intensity has been widely used around the world to describe the effects of earthquakes. It also serves as a valuable parameter for interpreting structural responses in disaster management planning and for estimating potential earthquake-induced losses in the future (Du et al., 2019). Earthquake intensity can be expressed using either the Modified Mercalli Intensity (MMI) scale or the Richter magnitude (*M*) scale. The MMI scale is subjective, as it is based on the observed effects of an earthquake on humans and structures. In contrast, the Richter scale is objective, as it quantifies the earthquake's magnitude derived from instrumental recordings at the time of the seismic event (Irawan et al., 2020). Table 1 presents the classification of earthquake scales based on both the Richter and MMI scales, as well as the relationship between magnitude and intensity.

Table 1. Relationship Between Earthquake Magnitude and Intensity (Irawan et al., 2020)

Magnitude (Richter)	Intensity (MMI)	Typical Effects
<2	I – II	Generally, not felt by humans.
4	IV – V	Felt by many people; objects may move; no structural damage.
5	VI – VII	Minor structural damage may occur, such as cracks in walls.
6	VII – VIII	Moderate damage, including partial wall collapse.
7	IX – X	Major damage; buildings may collapse.
>8	XI – XII	Complete or near-total destruction.

Dominant Frequency

The dominant frequency is a fundamental parameter in the analysis of the dynamic characteristics of surface soil layers, representing both the natural period of the soil and its primary response to seismic excitation. Nakamura (1989) emphasized that conventional methods, such as borehole investigations, although providing accurate estimations, are often limited by high costs, lengthy implementation time, and restricted data availability at certain sites. As a more efficient alternative, Nakamura (1989) proposed a method based on microtremor observations at the ground surface. This approach employs the horizontal-to-vertical (H/V) spectral ratio of microtremor signals, wherein both horizontal and vertical components are recorded and their respective power spectra computed. The peak of the H/V ratio curve is interpreted as the dominant frequency, reflecting the principal response of the surface layers to horizontal motion.

Peak Ground Acceleration (PGA)

The damage caused by an earthquake can be assessed using seismic parameters, particularly through the Peak Ground Acceleration (PGA) approach. The PGA value represents the maximum ground acceleration generated during an earthquake and can be estimated based on magnitude and hypocentral distance (Netrisa et al., 2018). The determination of PGA values can be

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performed either empirically or through instrumental measurements using an accelerograph. Accelerograph measurements are conducted by placing instruments at specific locations to record the variation in ground shaking during an earthquake, which reflects the influence of the surrounding geological structures. Meanwhile, the estimation of PGA values at specific sites can also be performed using empirical approaches, especially in regions where accelerograph networks are sparse (Kusumawardani et al., 2020).

One of the well-established empirical models for estimating Peak Ground Acceleration (PGA) is the Kanai et al. (1966) equation, which is derived based on parameters such as dominant period (T_G), magnitude (Mw), and hypocentral distance (R). The mathematical form of the Kanai equation is presented as follows (Kanai et al., 1966):

$$\alpha = \frac{5}{\sqrt{T_G}} 10^{\left(0,61M - \left(1,66 + \frac{3,6}{R}\right)\log(R) + \left(0,167 \ \ \frac{1,83}{R}\right)\right)} \tag{1}$$

Relationship between Peak Ground Acceleration and Seismic Intensity

The degree of ground shaking caused by an earthquake can be identified either qualitatively through seismic intensity or quantitatively using recorded ground motion parameters, such as Peak Ground Acceleration (PGA). Establishing a correlation between seismic intensity and ground motion parameters is essential for various purposes, including the transformation of observed intensity data into ground motion parameters. This correlation can further be applied to multiple aspects of seismic studies, such as reconciling different intensity scales (Du et al., 2019).

Table 2. Relationship between MMI and PGA (Wald et al., 1999)

Intensity (MMI)	Peak Ground Acceleration (%g)
I	< 0,17
II – III	0,17 – 1,4
IV	1,4 – 3,9
V	3,9 – 9,2
VI	9,2 – 18
VII	18 – 34
VIII	34 – 65
IX	65 – 124
+X	> 124

Seismic intensity also demonstrates a significant relationship with PGA, which is crucial for seismic-resistant design, since both PGA and mass are directly related to the inertial forces acting on a structure during an earthquake (Du et al., 2019). Tabel 2 presents the relationship between seismic intensity on the Modified Mercalli Intensity (MMI) scale and corresponding PGA values.

Ground Motion to Intensity Conversion Equation

The Ground Motion Intensity Conversion Equation (GMICE) can be defined as an empirical formulation that establishes a relationship between ground motion parameters and perceived seismic intensity. This empirical relationship enables the rapid estimation of expected earthquake intensity for future seismic events (Ahmadzadeh et al., 2020). Most previous studies have employed a simple GMICE models, which generally relate earthquake intensity to the logarithm of a single ground motion parameter. On the other hand, several complex GMICE models have been developed by incorporating additional parameters such as magnitude, epicentral distance, and site classification. Ahmadzadeh et al. (2020) in his research, introduced both magnitude and epicentral distance as additional parameters, resulting a complex equation of GMICE. The simply equation of GMICE can be expressed as follows (Ahmadzadeh et al., 2020):

$$MMI = a_0 + b_0 \log Y \tag{2}$$

Meanwhile, the complex equation of GMICE, which includes additional parameters such as magnitude and epicentral distance, can be expressed as (Ahmadzadeh et al., 2020):

$$MMI = c_0 + c_1 \log Y + c_2 Mw + c_3 \log(R + R_0) + c_4 R \tag{3}$$

where MMI represents the earthquake intensity scale, *Y* is the ground motion parameter, *Mw* is the moment magnitude, *R* is the epicentral distance, R_0 represents the saturation distance for near-source areas, and a_0, b_0, c_1, c_2, c_3, and c_4 are the regression coefficients.

3. RESEARCH METHODOLOGY

The research workflow in this study comprises several phases, including the preparation phase, the estimation of Peak Ground Acceleration (PGA), the formulation of the Ground Motion Intensity Conversion Equation (GMICE), and the analysis and conclusion phases. Each phase of the study is described in detail as follows. Data processing and analysis were conducted using Microsoft Excel for initial data organization, Python for statistical analysis and iterative procedures, and ArcGIS for spatial analysis. These tools enabled efficient handling and analysis of large datasets, allowing for the precise calculation and visualization required in the GMICE formulation. This study is based on a limited dataset comprising four earthquake events recorded between 2019 and 2024, complemented by 109 microtremor observation points. While the total number of 436 data records provides sufficient statistical variability for preliminary regression analysis, the limited number of independent seismic events constrains the generalization of the developed GMICE. Therefore, the results presented in this paper should be interpreted as preliminary findings that require further refinement as additional earthquake data become available.

Preparation Phase

This phase involved a literature review of previous studies, research proposal development, and acquisition of research permits. Supporting datasets, including administrative and geological maps, were collected. The input data consisted of secondary data such as dominant frequency values derived from microtremor measurements and an earthquake database of events with focal depths less than 20 km within a 300 km radius of Semarang City, and only earthquakes with magnitudes greater than 3.5 *Mw* were used. All datasets were preprocessed to remove incomplete, duplicated, and non-physical values. Only events with complete PGA, magnitude, and distance information were included in the regression analysis.

PGA Estimation Phase Based on Dominant Frequency Parameters

In this phase, the data including dominant frequency, microtremor coordinates, and earthquake parameters (longitude, latitude, and magnitude) were used to estimate Peak Ground Acceleration (PGA) using the Kanai equation. The hypocentral distance was computed from the spatial difference between microtremor sites and earthquake sources, while the period value was derived from the dominant frequency. These parameters were then used to calculate the PGA values.

The use of the Kanai equation in this study is due to the unavailability of accelerograph data for Semarang City, which limits the ability to directly measure ground motion. The Kanai equation provides an alternative method by estimating PGA based on dominant frequency data obtained from microtremor surveys, which are more readily available in areas lacking accelerograph networks. However, this approach introduces potential uncertainty in the PGA estimation, as it relies on indirect data rather than actual ground motion recordings. Therefore, the Kanai-based PGA estimation is considered a limitation of this study, and future research will aim to validate these results with actual accelerometric data for improved accuracy.

The conversion from Peak Ground Acceleration (PGA) to Modified Mercalli Intensity (MMI) was based on the predefined PGA–MMI ranges presented in Table 2. For intermediate intensity levels, the boundary between MMI II and MMI III conducted using a midpoint-based range classification approach. This method was adopted to ensure objectivity in defining class boundaries while maintaining reproducibility and avoiding any subjective adjustment of intensity values.

GMICE Formulation Phase

Data processing was performed using Python to derive empirical Ground Motion Intensity Conversion Equations (GMICE) in both simple and complex forms. The simple GMICE model was developed using PGA values and corresponding MMI levels based on the classification by Wald et al. (1999). Meanwhile, the complex GMICE model incorporated additional parameters, namely magnitude and epicentral distance, along with PGA and MMI. Python scripts were executed to determine regression coefficients for both models.

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The development of the complex equation of the Ground Motion Intensity Conversion Equation (GMICE) differs from the simple equation due to the inclusion of a coefficient term $c_3\ log(R + R_0)$, where R_0 represents the near-field saturation effect, occurring at very short distances from the earthquake source. This effect is observed when an increase in ground motion amplitude no longer produces a proportional increase in macroseismic intensity (MMI). The inclusion of R_0 prevents the logarithmic component from becoming undefined or unrealistic as the epicentral distance (R) approaches zero, ensuring that the equation remains numerically stable and physically consistent, reflecting the condition that seismic intensity does not increase indefinitely near the source. To determine the optimal value of R_0, data processing was carried out using an iterative procedure in Python, testing R_0 values ranging from 1 to 30 to identify the value that yields the best statistical performance. The optimal R_0 was found in the first iteration, which resulted in the highest R^2 and the lowest Mean Squared Error (MSE) values.

Prior to regression analysis, a data quality control procedure was conducted to ensure consistency and reliability. Numerical validation was applied to remove missing, duplicated, and non-numeric entries, followed by normalization of units and range checks for physical plausibility. Outlier analysis was also performed through residual inspection, and data points exceeding ±2σ from the regression trend were examined to minimize bias. This process ensured that only statistically consistent and physically meaningful data were included in the GMICE modeling.

4. RESULTS AND DISCUSSION

Peak Ground Acceleration (PGA) Data and Earthquake Events in the Study Area

Based on the data obtained for Northern Semarang City, a total of 109 observation points representing dominant frequency (f_0) parameters were identified, predominantly distributed across the northern part of the Semarang city. From a geological perspective, most of these data points are located within the alluvial unit. The illustration in Figure 1 and Figure 2 presents the spatial distribution of dominant frequency (f_0) values across Semarang City and Map of Earthquake Event Distribution Around Semarang City Within a 100 km Radius and Magnitudes Greater Than 3.5 *Mw*.

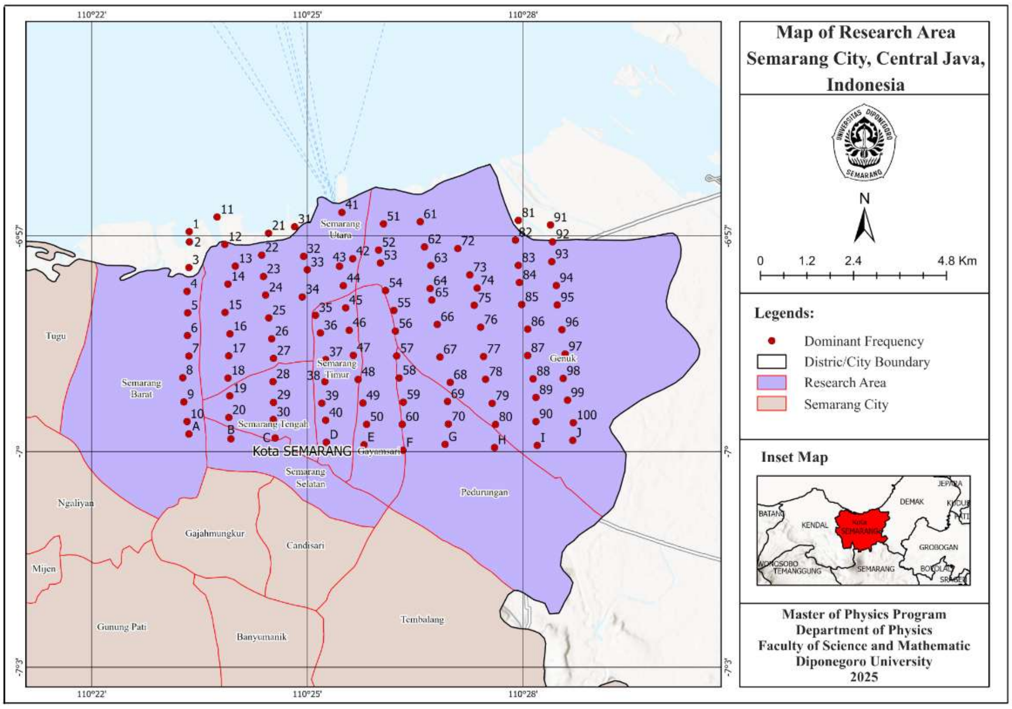

Figure 1. Map of Dominant Frequency (f_0) Distribution in the Study Area

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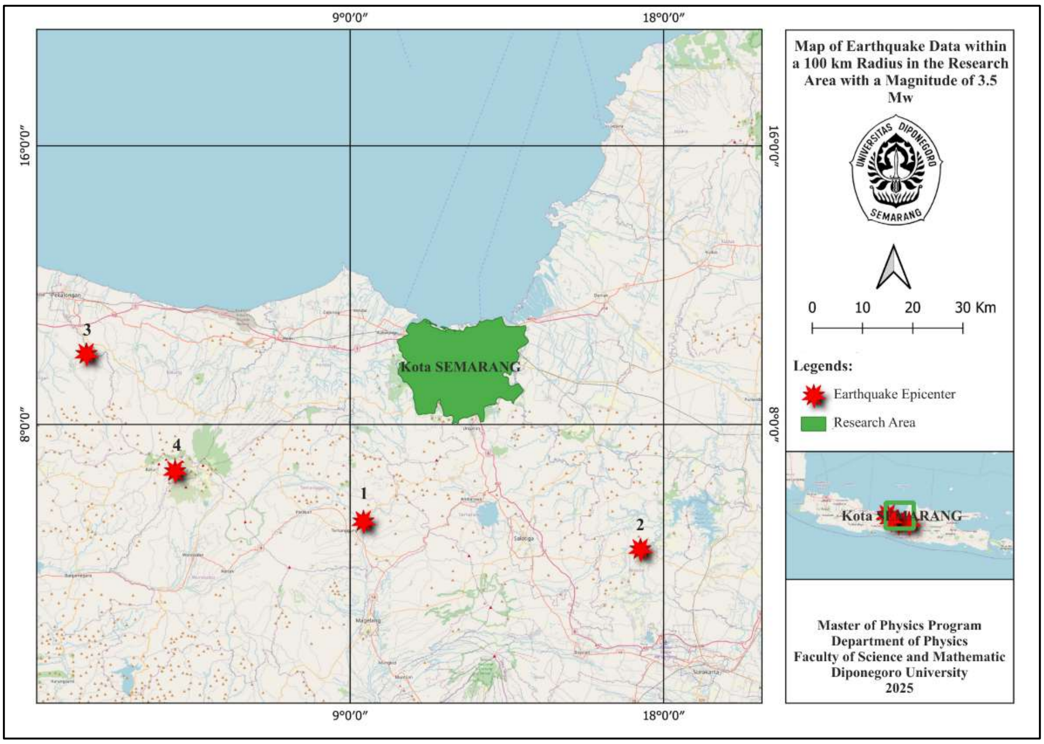

Figure 2. Map of Earthquake Event Distribution Around Semarang City Within a 100 Km Radius and Magnitudes Greater Than 3.5 Mw

The subsequent data processing involved estimating Peak Ground Acceleration (PGA) values based on dominant frequency parameters and earthquake events, particularly earthquake coordinates. From these parameters, the hypocentral distance (R) was calculated and subsequently used to derive the PGA values. The obtained PGA values were then classified to determine the corresponding Modified Mercalli Intensity (MMI) levels based on Table 2. The final dataset consisted of 436 records, including PGA, MMI, magnitude, and epicentral distance parameters. These parameters were then used to develop the Ground Motion Intensity Conversion Equation (GMICE) in both its simple and complex equations.

The study area in northern Semarang is dominated by young alluvial deposits with low dominant frequencies, which tend to amplify seismic waves and result in higher perceived intensities for the same ground acceleration. Therefore, the developed GMICE primarily represents alluvial site conditions and may not fully reflect the seismic response of stiffer geological formations in southern Semarang. Future research should extend this approach to other geological units to improve model generalization.

Simple Equation of GMICE for Semarang City

The simple equation of the Ground Motion Intensity Conversion Equation (GMICE) for Northern Semarang City was derived based on Equation (2), employing Peak Ground Acceleration (PGA) and Modified Mercalli Intensity (MMI) as the principal parameters. A linear regression analysis was performed to quantify the empirical relationship between these variables, yielding a best-fit regression model that represents the simple model of GMICE for the study area. The scatter plot illustrating the relationship between MMI and PGA is presented in Figure 3.

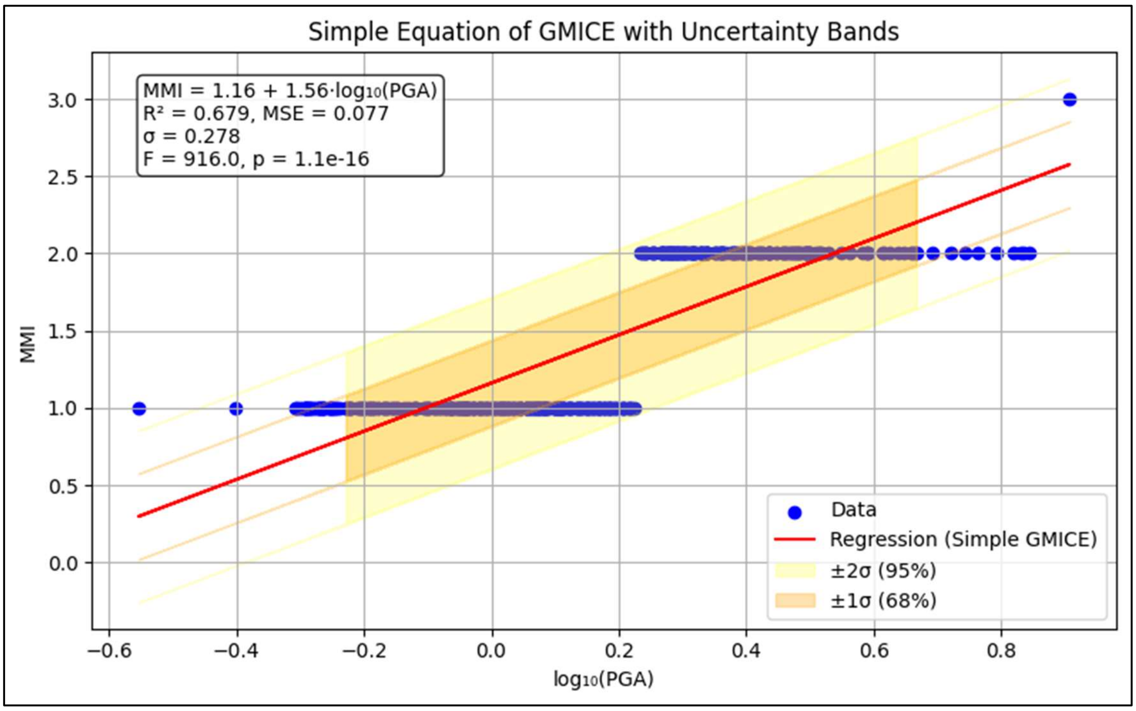

Figure 3. Simple Equation of the Ground Motion Intensity Conversion Equation (GMICE) Derived from Linear Regression Analysis

As shown in Figure 3, the simple equation of the Ground Motion Intensity Conversion Equation (GMICE) is obtained as follows:

$$MMI = 1{,}16 + 1{,}56\log(PGA) \quad (4)$$

In this simple equation of GMICE, the regression coefficients were obtained as $a_0 = 1{,}16$ and $b_0 = 1{,}56$. Furthermore, the statistical evaluation of the simple equation of GMICE produced an $R^2 = 0{,}679$, MSE = 0,0077, $F = 916$, and $p = 1{,}1 \times 10^{-16}$, demonstrating a strong correlation and statistically significant relationship between PGA and MMI.

The results of the linear regression analysis demonstrate that the proposed model exhibits statistical significance. This finding is supported by an $F = 916$ and $p = 1{,}1 \times 10^{-16}$, which is considerably lower than the conventional significance threshold of 0,05. Accordingly, it can be inferred that the independent variable (X) exerts a statistically significant effect on the dependent variable (Y), thereby validating the suitability of the proposed regression model.

Furthermore, the coefficient of determination ($R^2 = 0{,}679$) indicates that approximately 67,9% of the variability in the dependent variable is accounted for by the model, while the remaining 32,1% is attributed to other unmodeled factors. This level of explanatory power suggests that the relationship between the predictor and response variables can be considered moderately strong within the context of the dataset.

In addition, the Mean Squared Error (MSE) value of 0,0077 implies that the model yields a relatively small average squared deviation between predicted and observed values. This low prediction error indicates a high degree of numerical accuracy, reinforcing the model's reliability in representing the observed seismic intensity behavior.

Overall, the regression model can be regarded as statistically robust and demonstrates satisfactory predictive capability. Nevertheless, further diagnostic evaluations—such as testing regression assumptions, examining residual distributions, and assessing the magnitude of regression coefficients—are recommended to ensure the practical and physical interpretability of the proposed GMICE model.

Complex Equation of GMICE for Semarang City

The complex equation of the Ground Motion Intensity Conversion Equation (GMICE) for Northern Semarang City was derived based on Equation (3), employing multiple linear regression analysis with Peak Ground Acceleration (PGA), Modified Mercalli Intensity (MMI), moment magnitude (*Mw*), and epicentral distance (*R*) as the primary parameters. This regression analysis was conducted to establish the empirical relationship among these variables, resulting in a best-fit multivariate regression model that represents the complex equation of GMICE for the study area. The scatter plot illustrating the relationship between MMI and PGA is presented in Figure 4.

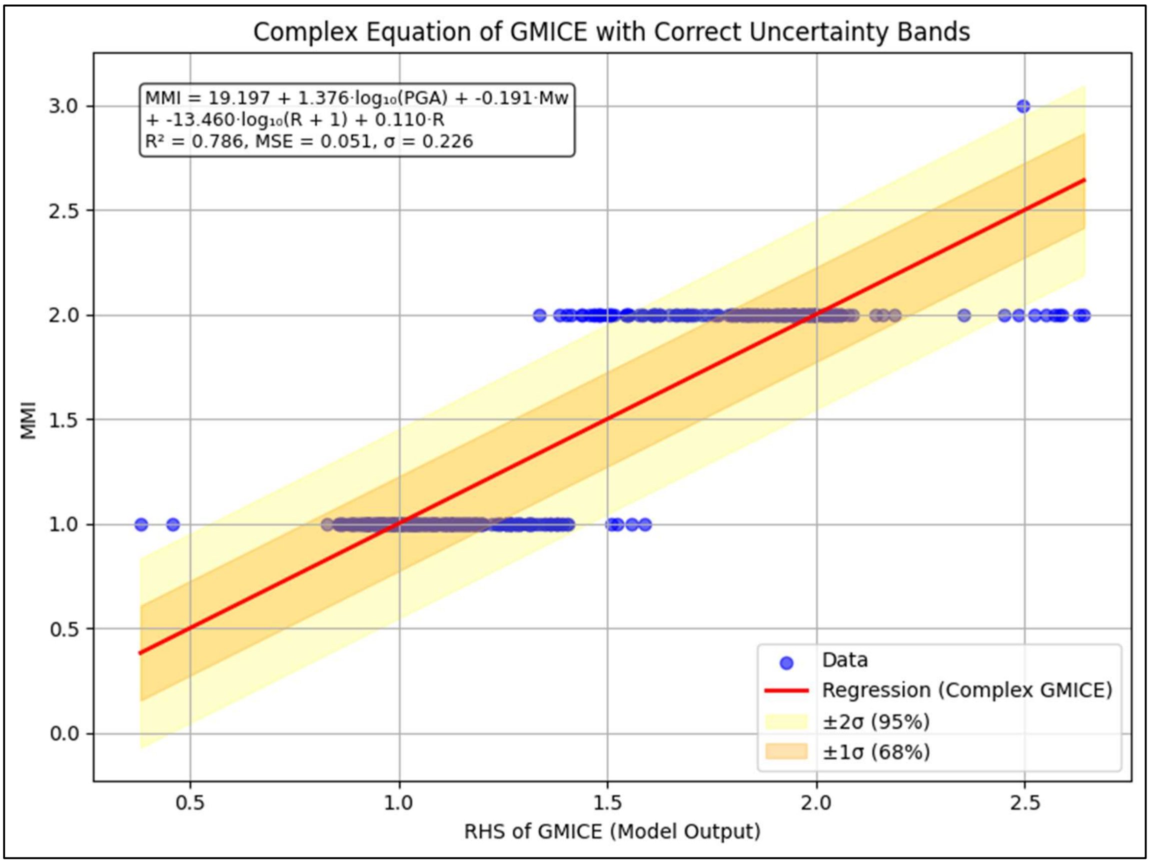

Figure 4. Complex Equation of the Ground Motion Intensity Conversion Equation (GMICE) Derived from Multiple Linear Regression Analysis

The development of the complex equation of the Ground Motion Intensity Conversion Equation (GMICE) differs slightly from the simple equation discussed in the previous section. This difference arises because Equation (3) includes a coefficient term $c_3 \log(R + R_0)$, where R_0 represents the near-field saturation effect that occurs at very short distances from the earthquake source.

The near-field saturation effect occurs when an increase in ground motion amplitude no longer produces a proportional increase in macroseismic intensity (MMI). The inclusion of the R_0 parameter serves to prevent the logarithmic component from becoming undefined or physically unrealistic as the epicentral distance (R) approaches zero. This ensures that, for small values of R, the equation remains numerically stable and physically consistent—reflecting the realistic condition that seismic intensity does not increase indefinitely near the source.

To determine the optimal value of R_0, the data processing was performed in Python using an iterative looping procedure. This process systematically tested R_0 values ranging from 1 to 30 to identify the parameter that yields the best statistical performance

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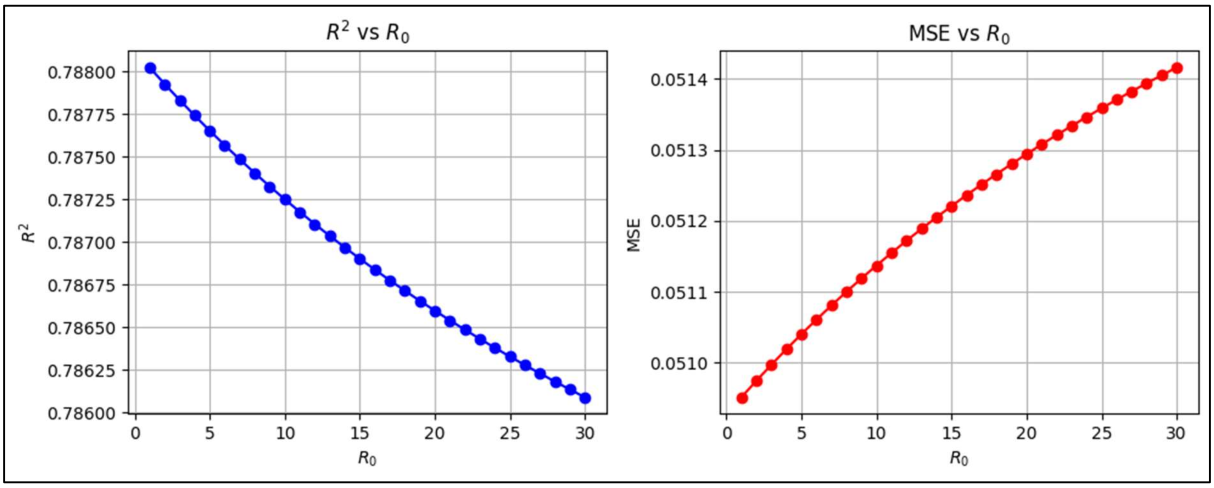
based on the coefficient of determination (R^2) and the Mean Squared Error (MSE). The results indicate that the optimal R_0 was obtained in the first iteration, which produced the highest R^2 and the lowest MSE values.

This outcome aligns with fundamental statistical principles, where a higher R^2 value indicates that a larger proportion of the variance in the dependent variable (Y) is explained by the independent variables (X), implying a better model fit, while a lower MSE value reflects smaller average squared prediction errors, indicating higher predictive accuracy. Therefore, the regression coefficients c_0 through c_4 obtained from the first R_0 iteration were adopted as the final parameters for the complex GMICE model.

Figures 5(a) and 5(b) illustrate the relationship between R^2 and R_0, and between MSE and R_0, respectively. These plots further confirm the statistical justification for selecting the first R_0 iteration as the optimal model configuration.



(a) (b)

Figure 5. (a) Relationship between R_0 and the Coefficient of Determination (R^2)

(b) Relationship between MSE and the Coefficient of Determination (R^2)

As shown in Figure 4, the complex equation of the Ground Motion Intensity Conversion Equation (GMICE) is obtained as follows:

$$MMI = 19{,}197 + 1{,}376 \log(PGA) - 0{,}191\ Mw - 13{,}460 \log(R + 1) + \ 0.11R \qquad (5)$$

In this complex equation of GMICE, the regression coefficients were determined as $c_0 = 19{,}197$, $c_1 = 1{,}376$, $c_2 = –0{,}191$, $c_3 = –13{,}460$, and $c_4 = 0{,}11$. Furthermore, the statistical evaluation of the complex equation of GMICE yielded $R^2 = 0{,}788$, MSE = 0,051, $F = 1.613{,}4$, and $p = 1 \times 10^{-16}$, indicating a strong model fit and a statistically significant relationship among PGA, MMI, magnitude, and epicentral distance.

The results of the multiple linear regression analysis demonstrate that the proposed complex GMICE model is statistically significant. This conclusion is supported by an F-statistic of 1,613.4 and a p-value of 1×10^{-16}, which is substantially lower than the conventional significance threshold of 0,05. Accordingly, it can be inferred that the independent variables collectively exert a statistically significant influence on the dependent variable (MMI), validating the suitability and robustness of the proposed regression model.

Furthermore, the coefficient of determination (R^2 = 0,788) indicates that approximately 78,8% of the variability in the dependent variable is explained by the model, while the remaining 21,2% is attributed to other factors not captured within the regression framework. This high explanatory power suggests a strong relationship between the predictor variables (PGA, magnitude, and epicentral distance) and seismic intensity within the study area.

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In addition, the Mean Squared Error (MSE) value of 0,051 demonstrates that the model exhibits a relatively small average squared deviation between predicted and observed values, indicating a high level of numerical accuracy. This low prediction error reinforces the model's reliability and precision in characterizing the observed seismic response.

Overall, the complex GMICE regression model can be considered statistically sound and exhibits strong predictive capability. Nonetheless, further diagnostic evaluations—such as verification of regression assumptions, assessment of residual distributions, and examination of the physical relevance of regression coefficients—are recommended to ensure the practical applicability and scientific validity of the proposed model.

Physical Relevance of Regression Coefficients

The statistical analysis results obtained from the data processing using Python are presented in Table 3.

Table 3. Statistical Analysis Results of the Coefficients in the Complex Equation

Coefficient	Value	*Standard Eror*	*t*	*P* > [*t*]	Confidence Interval	
					0,025	0,975
C_0	19,1974	2,707	7,091	0,000	13,9876	24,519
C_1	1,3759	0,073	18,876	0,000	1,233	1,519
C_2	–0,1913	0,068	–2,810	0,005	–0,325	–0,058
C_3	–13,4596	1,933	–6,962	0,000	–17,259	–9,660
C_4	0,1098	0,015	7,563	0,000	0,081	0,138

The multiple linear regression analysis indicates that the intercept coefficient (c_0) has a value of 19,1974 with a standard error of 2,707 and a *t*-statistic of 7,091. The corresponding *p*-value is 0,000, which is smaller than the significance level of 0,05. The 95% confidence interval ranges from 13,9876 to 24,519, not including zero, confirming that the intercept is statistically significant.

The variable *log*(PGA) exhibits a coefficient of 1,3759 with a standard error of 0,073 and a *t*-value of 18,876. The *p*-value (0,000) indicates a statistically significant positive effect. The 95% confidence interval, ranging from 1,233 to 1,519, is entirely positive and does not cross zero, signifying that an increase in *log*(PGA) leads to a statistically significant increase in the dependent variable.

The variable *Mw* has a negative regression coefficient of –0,1913, a standard error of 0,068, and a *t*-value of –2,810. With a *p*-value of 0,005 (less than 0,05), *Mw* is statistically significant. The 95% confidence interval (–0,325 to –0,058) is fully negative, confirming that an increase in *Mw* tends to decrease the dependent variable.

The variable $log(R + R_0)$ has a coefficient of –13,4596, with a standard error of 1,933 and a *t*-statistic of –6,962. The *p*-value (0,000) indicates a highly significant relationship. The 95% confidence interval (–17,259 to –9,660) excludes zero, suggesting that $log(R + R_0)$ exerts a significant negative influence on the dependent variable.

The variable *R* presents a positive coefficient of 0,1098, a standard error of 0,015, and a *t*-value of 7,563. The *p*-value (0,000) confirms that *R* has a statistically significant positive impact. The 95% confidence interval (0,081 to 0,138) is entirely positive, supporting the interpretation that increasing *R* contributes positively to the dependent variable.

The interpretation of the *p*-value (*P* > [*t*]) and confidence interval [0,025; 0,975] columns are consistent. The *p*-values confirm that all independent variables are statistically significant ($p < 0,05$), while the confidence intervals provide the plausible ranges for each coefficient. Since none of the intervals include zero, all variables have a demonstrable effect on the dependent variable. Thus, the regression model is not only statistically valid but also interpretable in terms of the magnitude and direction of each predictor's effect.

Physically, the derived GMICE model is consistent with seismological principles. The positive coefficient of *log*(PGA) indicates that Peak Ground Acceleration is the dominant factor governing seismic intensity, as stronger ground acceleration directly corresponds to higher perceived shaking at the surface.

Conversely, the negative coefficient of *Mw* may appear counterintuitive from a theoretical standpoint, since larger magnitudes typically produce stronger shaking. However, in empirical GMICE modeling, *Mw* often serves as a corrective variable rather than a primary predictor, given that the influence of seismic energy is already represented by PGA. In practice, larger earthquakes release greater energy but distribute it over a wider area, which can result in lower local intensity (MMI) compared to smaller, shallow events producing stronger localized shaking. Hence, the negative *Mw* coefficient reflects empirical calibration consistent with observed seismic behavior.

The negative coefficient of magnitude (*Mw*) observed in the complex GMICE model is not necessarily indicative of a physical inconsistency but rather reflects a compensatory adjustment between correlated variables, particularly between *Mw* and PGA. Similar trends have been reported in previous empirical GMICE studies where the magnitude term functions as a corrective factor to balance the influence of distance and local amplification effects.

The negative coefficient of $log(R + R_0)$ accurately captures the physical attenuation of seismic energy with distance: as the distance from the epicenter increases, wave energy dissipates, leading to weaker ground motion. The inclusion of R_0 ensures numerical stability near zero distance, preventing undefined logarithmic values.

The positive coefficient of *R*, though small, implies a linear corrective effect associated with distance. This term accounts for local geological variations and the non-logarithmic component of energy propagation that can slightly enhance or reduce shaking intensity.

Overall, the results demonstrate that seismic intensity (MMI) is predominantly governed by PGA, while Mw, $log(R + R_0)$, and *R* act as secondary corrective factors that adjust for distance and magnitude effects. The model successfully integrates both physical and empirical aspects of earthquake behavior, providing a statistically sound and physically interpretable representation of ground motion intensity in the study area.

In conclusion, the developed GMICE model for Northern Semarang City demonstrates a robust statistical foundation and strong predictive capability. The combination of empirical calibration and physical interpretability makes it a reliable tool for estimating seismic intensity from ground motion parameters. This model can therefore be effectively applied in regional seismic hazard assessments, urban resilience planning, and earthquake risk mitigation strategies.

Model Validation and Uncertainty Analysis

The comparison between the simple GMICE model and the complex GMICE model revealed that the latter significantly improves prediction accuracy. The Adjusted R^2 values of 0,679 for the simple model and 0,788 for the complex model confirm that the complex model explains a larger portion of the variability in seismic intensity data. This increase in explanatory power can be attributed to the inclusion of additional parameters such as epicentral distance (*R*) and moment magnitude (*Mw*), which are crucial for capturing regional seismic characteristics, particularly for areas with complex geological features like Semarang.

Table 4. Performance Evaluation of Simple and Complex GMICE Models: R^2, Adj. R^2, AIC, BIC, and Standard Deviation of Residuals

Model	R^2	Adj. R^2	AIC	BIC	Std. Dev. of Residuals
Simple	0,678521	–	–	–	0,278297
Complex	0,788025	0,786057	-50,610073	-30,221862	0,225983

The Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) values further supported the superior performance of the complex model. A lower AIC and BIC for the complex model suggest that, while it includes additional parameters, it achieves a better balance between fit and model complexity, avoiding overfitting while still providing more accurate predictions. The complex model's ability to improve prediction accuracy without adding unnecessary complexity underscores its relevance in regional seismic modeling.

The Standard Deviation of Residuals, which was smaller for the complex model compared to the simple model, indicates that the complex GMICE produces more precise predictions with less variability. This is an important factor for the applicability of the model, as it suggests that the model will provide consistent results when used in practice.

The results of the *K*-fold cross-validation also emphasized the robustness of the complex GMICE model. The consistent performance across all folds, with an average R^2 of 0,7701 ± 0,0867 and MSE of 0,0537 ± 0,0203, indicates that the complex model generalizes well to new data. This is a critical finding, as the model's ability to predict seismic intensity reliably across different folds demonstrates its utility for real-world applications, such as disaster mitigation and infrastructure planning in regions susceptible to seismic events.

Table 5. *K*-fold Cross-variation for Both Models

Model	*k*	`R^2	Adj. R^2	MSE
Simple	10	0,6640 ± 0,0456	0,6632	0,0783 ± 0,0105
Complex		0,7701 ± 0,0867	0,7680	0,0537 ± 0,0203

Despite the promising results, it is important to recognize the limitations and uncertainties associated with the PGA estimations used in this study. As accelerograph data was not available for Semarang City, the Kanai (1966) empirical relation was employed to estimate PGA from dominant frequency data obtained from microtremor surveys. While this approach is common in regions lacking accelerographic data, it introduces potential uncertainty, as PGA estimates derived from dominant frequency might not fully capture the complexity of ground motion during seismic events.

The uncertainty in the model predictions is also influenced by the limited dataset of only four earthquake events and the use of data from 109 microtremor measurement points. Although this is an acceptable method for preliminary studies, the limited data coverage may impact the model's ability to generalize to other regions or larger seismic events. Future research should focus on expanding the dataset to include more earthquake events and gathering accelerograph data for more accurate PGA estimations. Incorporating actual accelerometer data will improve the precision of the GMICE model and reduce the uncertainty associated with the PGA estimates. Furthermore, expanding the scope of the dataset, especially in terms of earthquake magnitude, epicentral distance, and geological variations across Semarang, will be crucial in improving the model's predictive power.

Comparison from Previous Studies

To evaluate the consistency and applicability of the developed GMICE, a comparison with previous Indonesian studies was conducted. Existing regional models have demonstrated that the relationship between ground motion parameters and seismic intensity varies according to local geological and tectonic conditions.

Previous GMICE studies in Indonesia have shown notable regional variability depending on geological conditions and data sources. Kadnan (2019) developed a relationship between PGA and MMI for West Java using empirical earthquake data, expressed as IMM = 3,69 *log*(PGA) – 1,12. This model effectively captures intensity levels ranging from V to VIII and reflects the attenuation characteristics of ground motion in volcanic and sedimentary environments typical of western Java. Meanwhile, Santoso et al. (2011) derived a regional GMICE for West Nusa Tenggara based on recent shallow earthquakes, indicating relatively lower intensity responses (MMI I–III) due to differences in local site amplification and tectonic settings.

Compared to these previous models, the proposed GMICE for Northern Semarang (MMI = 1,56 *log*(PGA) + 116) exhibits a moderate slope value that lies within the general empirical range of Indonesian studies. The smaller coefficient compared to Kadnan (2019) suggests reduced amplification, consistent with the predominance of young alluvial deposits in Semarang's northern plain. Furthermore, this study differs methodologically by incorporating microtremor-derived dominant frequency data to estimate theoretical PGA, providing a novel framework applicable to urban areas with limited accelerograph networks. These findings confirm that the Semarang GMICE aligns statistically and physically with existing Indonesian models while offering improved adaptability for data-sparse regions.

The developed GMICE models provide valuable practical implications for both seismic hazard assessment and post-earthquake response planning in Semarang City, particularly for the northern part of Semarang City. The simple model offers a rapid estimation framework suitable for preliminary mapping or real-time earthquake impact assessment, particularly in regions with limited instrumental coverage. In contrast, the complex model incorporates additional seismological parameters, making it more appropriate for detailed risk analyses and engineering applications that require higher accuracy. These models contribute to the advancement of localized seismic intensity prediction in Indonesia by integrating dominant frequency characteristics as a site-response indicator. Future research should aim to refine the models through the inclusion of a larger and more diverse earthquake dataset, integration of additional site classification parameters such as Vs30, and comparative validation across different geological settings. Such efforts would enhance the reliability, regional applicability, and practical relevance of GMICE development for seismic hazard mitigation and urban resilience planning.

5. CONCLUSION

This study developed preliminary Ground Motion to Intensity Conversion Equations (GMICE) for the northern part of Semarang City by integrating dominant frequency data derived from microtremor surveys with theoretical peak ground acceleration (PGA) estimates. Two models were established: a simple GMICE based on log-transformed PGA and a complex GMICE incorporating magnitude and distance parameters. Both models exhibited strong statistical performance, with the complex model demonstrating improved predictive capability. The integration of dominant frequency as a site-specific parameter enhances the physical relevance of the model, particularly for the alluvial deposits that characterize northern Semarang. Despite the limited number of recorded earthquake events, the results provide an important first step toward establishing localized GMICE relationships for this seismically vulnerable region.

The developed models have practical applications for rapid intensity estimation, seismic hazard assessment, and urban resilience planning. The simple model offers an efficient tool for quick evaluations where only basic ground motion parameters are available, whereas the complex model is more suitable for detailed analyses involving source and path effects. Future studies should focus on expanding the earthquake dataset, validating the model against recorded instrumental data, and incorporating additional site classification parameters to further improve reliability. Overall, this research contributes to the advancement of region-specific GMICE development in Indonesia and provides a foundation for future refinement as more seismic data become available.

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