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Ground Motion Prediction Equation (GMPE) For Semarang City Based On Earthquake Data From 2019 - 2024

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Abstract: This study aims to develop a Ground Motion Prediction Equation (GMPE) that accurately represents the seismotectonic characteristics and local geological conditions of Semarang City, Indonesia, based on earthquake data recorded from 2019 to 2024. Approximately 16,000 earthquake events obtained from the Indonesian Agency for Meteorology, Climatology, and Geophysics (BMKG) were analyzed to identify source mechanisms, magnitude, depth, and hypocentral distance. The empirical GMPE proposed by Sharma (2008) was adopted as the baseline model, establishing a logarithmic relationship among peak ground acceleration (PGA), magnitude (M), and source distance (R). Residual analysis revealed that the baseline model tends to overestimate PGA at short distances and underestimate it for small-magnitude events. To improve predictive performance, the model was modified by incorporating a non-linear variation term accounting for magnitude and distance effects. The modified GMPE achieved improved performance with R2=0.8949 and RMSE = 0.3294, demonstrating a closer fit between predicted and observed PGA values. Overall, the developed GMPE provides a more accurate representation of ground motion attenuation and site effects in Semarang's complex geological setting. These findings highlight the importance of locally calibrated GMPEs for enhancing seismic hazard estimation and supporting earthquake-resistant urban planning across Indonesia.

Keywords: GMPE, Semarang, Peak Ground Acceleration (PGA), Multivariate Regression, And Residual Analysis.

1. INTRODUCTION

Semarang City is one of the Indonesian cities characterized by relatively high seismicity, primarily caused by its tectonic dynamics dominated by plate interactions[6]. The region is situated within an active tectonic zone influenced by the interaction between the Indo-Australian Plate and the Eurasian Plate, as well as by local fault activities that traverse the island of Java[8].

As the capital of Central Java Province, Semarang is considered a region with a significant level of seismic risk due to the presence of several active fault systems surrounding the city. These include the Kaigarang Fault, which extends from the southwest to the northeast cutting across the Kaligetas and Kalibeng Formations[4], as well as the Semarang, Ungaran, and Rawapening Faults, which remain active and possess the potential to generate damaging earthquakes. This geological setting highlights the importance of advancing research on Ground Motion Prediction Equations (GMPEs) in Indonesia, particularly for regions like Semarang where complex tectonic interactions and active crustal faulting contribute to elevated seismic hazards. Geologically, the study area is located within an active tectonic zone influenced by the interaction between the Indo-Australian Plate and the Eurasian Plate, as well as by local fault activities that cut across the island of Java[8]. Based on the geological map of Semarang City (Figure 1.), the region is composed of various rock units ranging in age from the Tertiary to the Quaternary periods, including the Damar, Kaligetas, Kalibeng, and Kerek Formations, along with older volcanic deposits such as the Jongkong, Kaligresik, and Gajahmungkur Formations, and alluvial deposits covering the northern part of the city.

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Vol. 53 No. 2 November 2025, pp. 429-440

This lithological diversity results in varying geotechnical and seismic properties across the area. According to Figure 1, the seismicity of Semarang City is characterized predominantly by shallow earthquakes (depth ≤ 60 km) with low-to-moderate magnitudes ($M < 5.0$). The earthquake epicenters are mostly concentrated in the southern part of the city, particularly along the Kendeng Fault Zone and several local fault systems extending from Ungaran to Purwodadi. These observations indicate that seismic sources in the Semarang region are primarily associated with shallow crustal fault activities rather than subduction processes.

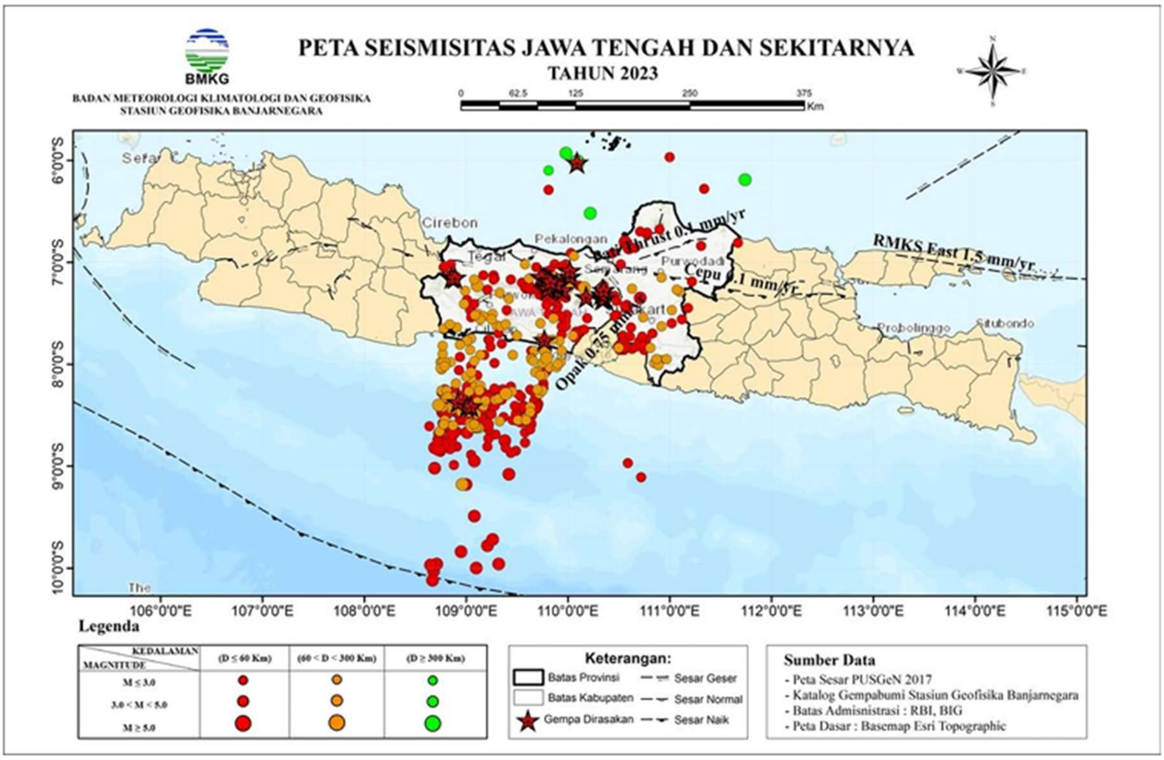

Figure 1. Seismicity map of Central Java and its surrounding areas*[1]*.

Although most earthquakes are of relatively small magnitude, shallow events have the potential to generate perceptible ground shaking, especially in coastal areas underlain by alluvial deposits that tend to amplify seismic waves. Therefore, the seismic hazard in Semarang is not primarily governed by the frequency of large-magnitude earthquakes but by the local amplification effects and the presence of active fault systems that can intensify ground motion in specific zones of the city.

In general, Ground Motion Prediction Equations (GMPEs) represent mathematical functions that relate ground-motion parameters to source characteristics, wave propagation paths, and site conditions Widodo[13],. According to Douglas[2], GMPEs are empirical relationships that link a measure of ground motion (e.g., peak ground acceleration, PGA) to a set of explanatory variables describing the earthquake source, propagation path, and local site conditions. GMPEs are typically derived through empirical analysis, taking into account parameters such as earthquake source type and site classification. Since different earthquake source mechanisms and site conditions can significantly affect ground-motion amplitudes, even for events of similar magnitude and distance, region-specific GMPE development is essential for accurately characterizing seismic hazard.

2. RESEARCH METHOD

In this study, earthquake data obtained from the Meteorology, Climatology, and Geophysics Agency (BMKG) comprised approximately 16,000 earthquake events that affected Semarang City during the 2019–2024 period. These earthquake records were subsequently filtered to classify the types of earthquake sources to be analyzed. The filtering process was conducted to categorize the seismic source types occurring in and around Semarang City, which is an essential step to facilitate the development of an

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https://ijpsat.org/
Vol. 53 No. 2 November 2025, pp. 429-440

appropriate Ground Motion Prediction Equation (GMPE) model. Moreover, the classification was based on the dominant seismic characteristics observed in the Semarang region during the study period. Therefore, the filtering process was carried out by considering parameters such as earthquake magnitude, focal depth, and epicentral distance, as well as the spatial distribution of seismic events. Following this step, additional parameters were calculated, including the epicentral distance (R_e) used to determine the Peak Ground Acceleration (PGA) based on the Kanai equation and the hypocentral distance (R_h) used to obtain the PGA values derived from the Sharma GMPE model, with the corresponding equation presented below:

$$R_{epi} = \left(\sqrt{(\varphi_E - \varphi_S)^2 + (\lambda_E - \lambda_S)^2}\right) \times 111 \tag{1}$$

$$R_{hypo} = \sqrt{{R_{epi}}^2 + D^2} \tag{2}$$

where R_{epi}: denotes the epicentral distance, φ_E and φ_S represent the latitudes of the earthquake epicenter and the observation station, respectively, while $\lambda_E$and λ_S correspond to their respective longitudes. For the hypocentral distance, R_{hypo} represents the hypocentral distance, and D denotes the focal depth of the earthquake[11].Subsequently, the peak ground acceleration (PGA) parameter was determined using the empirical equation proposed by Kanai[5]. Subsequently, the Peak Ground Acceleration (PGA) parameter was determined using the empirical equation proposed by Kanai (Kanai, 1966). This approach was employed due to the limited availability of data in the BMKG earthquake catalog, which necessitated the estimation of PGA values for each earthquake event by considering key parameters such as distance and magnitude. The use of Kanai's empirical equation allows for the calculation of PGA in cases where instrumental recordings are unavailable.Furthermore, this approach also aims to contribute to research advancements by incorporating the dominant frequency data within the study area, which serves as a representation of local site conditions. The empirical equation proposed by Kanai is expressed as follows:

$$\mathrm{PGA} = \frac{5}{\sqrt{TG}} \cdot 10^{0.61\,M - 1{,}66 + \frac{3{,}60}{R}\log 10\,R + 0{,}167 - \frac{1{,}83}{R}} \tag{3}$$

where *TG* denotes the dominant period, *M* represents the earthquake magnitude, and *R* refers to the hypocentral distance. After this stage, a filtering process was conducted to classify the dominant earthquake source types recorded in the BMKG earthquake catalog for the Semarang region during the 2019–2024 period. The data were classified based on the source mechanism type, magnitude, focal depth, and the influence of local and regional geological conditions within the study area. This classification process is essential for determining the appropriate GMPE model that best represents the local seismic characteristics of the study region. The GMPE model adopted in this research is the formulation proposed by Sharma[10], as expressed in the following equation:

$$\ln(\mathrm{Y}) = a + b\,(M) - c\,\ln(\mathrm{R}hypo) \pm \sigma \tag{4}$$

where *Y* denotes the peak ground acceleration (PGA), *M* represents the local magnitude, and *R* refers to the Joyner–Boore distance or, when the fault geometry is unknown (typically for earthquakes with $M < 5$), the epicentral or hypocentral distance. Meanwhile, *a*, *b*, and *c* are the constant coefficients in the equation, and σlog represents the standard deviation of the computed results. This model serves as the fundamental equation employed in this study and is commonly used in the development of GMPEs for regions that exhibit similar regional compatibility to the local conditions of the Himalayan area. Based on this model, a multiple linear regression analysis was performed to estimate the values of each constant required for residual analysis, which aims to evaluate how effectively the model represents the earthquake catalog data for the Semarang region during the 2019–2024 period [9]:

$$Res = \log \frac{(PGApredicted)}{(PGAobserved)} \tag{5}$$

Based on the results of the residual analysis, the model was further developed to obtain a more effective equation capable of better representing the observed data and providing a more accurate fit to local conditions within the study area. In addition, a statistical evaluation of the developed model was conducted to assess the extent to which the model could predict values that closely match the actual observations. This statistical assessment was carried out using the Root Mean Squared Error (RMSE), which serves as one of the primary indicators for quantifying the overall prediction error. The RMSE is calculated using the following equation:

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Vol. 53 No. 2 November 2025, pp. 429-440

$$RMSE = \frac{\sqrt{\Sigma\Sigma \quad _{i=1}^{n}(obs-p \quad)^2}}{n} \quad (6)$$

where *obs* denotes the observed PGA, *pre* represents the predicted PGA from the model, and *n* is the total number of data samples[3].

3. DATA

As shown in Figure 2, the map illustrates the spatial distribution of earthquake events that occurred around Semarang City during the period of this study. The map contains several key pieces of information: the red points represent the observation sites used in this research, the gray-shaded area indicates the study region corresponding to Semarang City, and the black points denote individual earthquake events that occurred between 2019 and 2024. Overall, the map depicts the earthquake source types associated with each recorded event. It can be observed that the earthquake epicenters do not entirely follow a distinct linear pattern typical of a single fault system. Instead, the epicentral distribution appears more dispersed, particularly across the Central Java region surrounding Semarang City. Most of the recorded events exhibit small-to-moderate magnitudes, indicating the dominance of background seismicity in this area. This background earthquake phenomenon has also been reported in the Indonesian Earthquake Source and Hazard Map 2017 published by the National Center for Earthquake Studies[8], which categorizes Central Java as a region characterized by diffuse seismic activity rather than concentrated fault-related events..

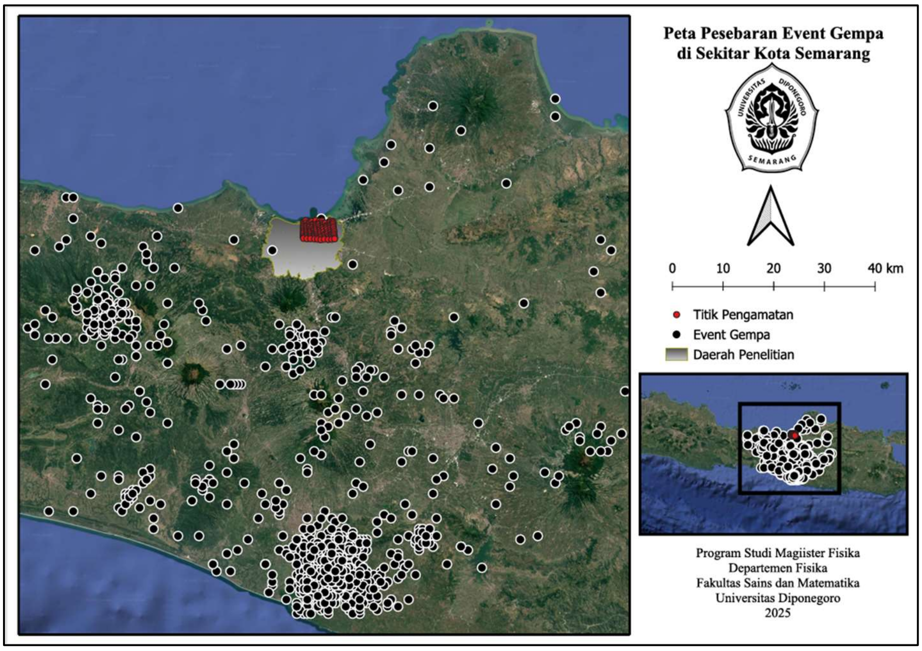

Figure 2 Map showing the spatial distribution of earthquake events in the study area

4. RESULT AND DISCUSSION

Based on the obtained data, regression analyses were performed for each GMPE model to determine the constant parameters of the respective equations. Subsequently, residual analyses were conducted for each model to evaluate their capability in representing the observed data within the study area. In addition, the residual analysis was used to examine the trends in the multivariate statistical results of the geometric mean peak ground acceleration (PGA) from strong ground motion records. The residuals are defined as the logarithmic ratio between the predicted PGA and the observed PGA values.

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https://ijpsat.org/
Vol. 53 No. 2 November 2025, pp. 429-440

4.1. Residual Analysis of the GMPE Model

Based on the previously classified data, a multivariate linear regression analysis was performed on the GMPE Model sharma. The objective of this analysis was to determine the coefficient values for each parameter in the equation and subsequently evaluate the residual distribution of the resulting model. The multivariate linear regression analysis for the Sharma GMPE model used in this study yielded the following equation:

$$ln(Y) = 0.28309 + 1.43071\,(M) - 1.32697\,ln(R) \tag{7}$$

where *a= 0.28309, b= 1.43071,dan c= 1.32697*, The coefficient of determination was found to be $R^2 = 0.8211$ and the root mean square error (RMSE) was $RMSE = 0.3506$, After determining the regression coefficients, residual analyses were conducted to assess the model's performance relative to the observed data.

Figure 3 presents the relationship between the observed peak ground acceleration (PGA) and the predicted PGA obtained from the GMPE model. The blue dots represent the observed data, while the dashed line indicates the 1:1 reference line corresponding to perfect prediction. Most of the data points are distributed around the 1:1 line within the low-to-moderate PGA range, suggesting that the Sharma GMPE provides a reasonable estimation within the moderate magnitude range. However, increasing dispersion is observed for higher PGA values, indicating an overestimation trend for large ground motions. These results highlight the need for further analysis of residuals with respect to influential parameters such as distance and magnitude to improve the model's predictive capability.

Figure 4 illustrates the residuals as a function of source-to-site distance (R). The residuals, defined as Residual=ln (Obs) – ln (Pred), describe how the difference between observed and predicted PGA varies with distance. In general, negative residuals are observed at short distances (<10 km), indicating that the model tends to overestimate PGA near the source. Beyond 10 km, the residuals approach zero and remain relatively stable, suggesting that the Sharma GMPE exhibits satisfactory distance sensitivity at intermediate to long ranges, though with slight overestimation at short distances.

Figure 5 shows the residuals as a function of earthquake magnitude. The plot indicates that most data points cluster around the zero line, demonstrating that the Sharma GMPE remains relatively stable for small-to-moderate magnitude events (M = 1–4). However, several negative residuals are evident in the magnitude range of 2–2.5, indicating that the model slightly underestimates PGA values within this range. This behavior reflects the limitations of the linear formulation in capturing variations associated with small events.

The QQ-plot of residuals presented in Figure 6 was used to assess the normality of the residual distribution, detect outliers, and evaluate the statistical adequacy of the model. The red line represents the theoretical normal distribution, while the blue dots indicate the ordered residual values. Most of the points align closely along the central straight line, though deviations appear at the lower and upper tails, indicating the presence of outliers. This pattern suggests that the residuals are not perfectly normally distributed. Therefore, although the model adequately captures the general trend of the observed data, systematic discrepancies remain for extreme PGA values particularly at very low and very high amplitudes highlighting the need for further model.

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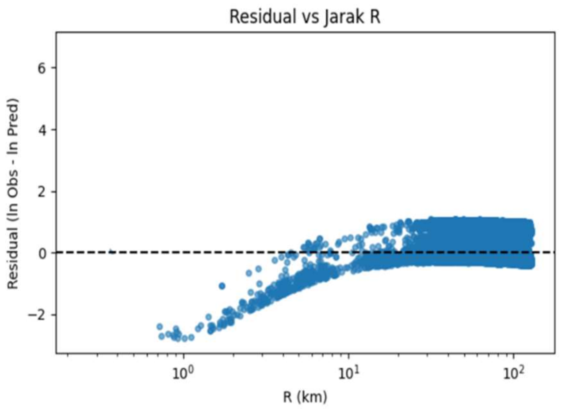

Figure 3. Plot of residual distribution

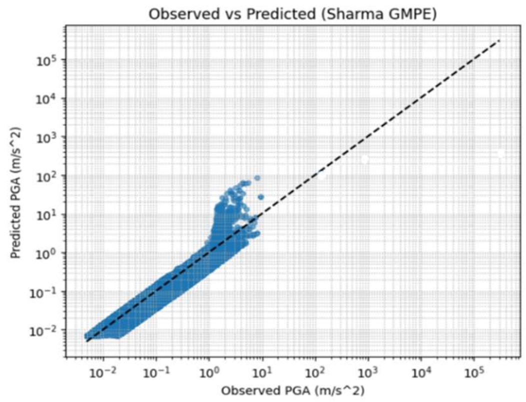

Figure 4. Plot of residuals versus distance.

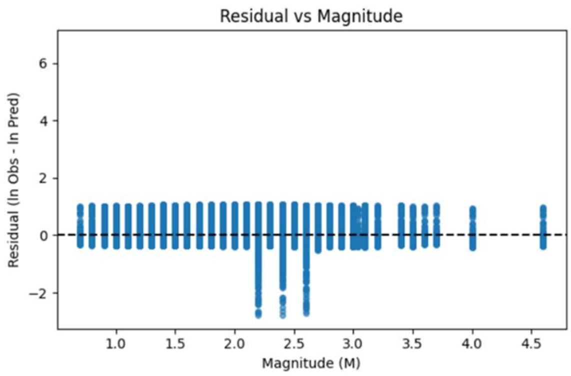

Figure 5. Plot of residuals versus magnitude

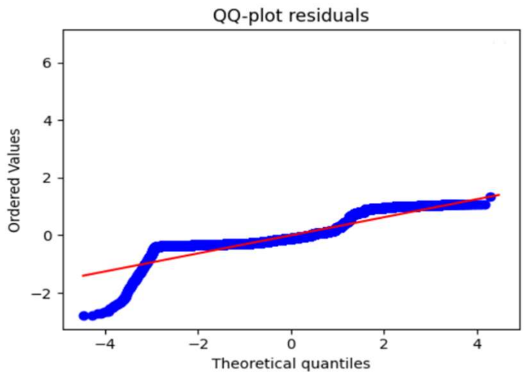

Figure 6. QQ plot of residuals

Overall, the results of the four graphs indicate that this GMPE provides a reasonably good representation of the observed PGA data, particularly within the range of moderate magnitudes and intermediate distances. However, the model tends to overestimate PGA values at short distances and large magnitudes, while showing slight underestimation at smaller magnitudes. A more detailed analysis of the residuals with respect to magnitude and distance reveals that, in the residual–distance plot, underestimation predominantly occurs at shorter distances from the observation point (i.e., the closer the distance, the greater the underestimation). This suggests that the initial GMPE model does not properly account for distance attenuation, resulting in increasingly negative residuals for smaller distance values. Therefore, the inclusion of an additional term such as (R+e) in the distance parameter is required to correct this behavior and to avoid producing negative or singular values at very small distances. Similarly, the residual–magnitude plot shows underestimation in the middle portion of the graph, approximately within the magnitude range of 2.3–2.6, indicating that the model does not adequately capture the magnitude dependency. This issue arises because the magnitude parameter is inherently nonlinear, and should not be treated as a sequential or uniformly distributed variable, since earthquake magnitudes are random and vary significantly between events. Hence, incorporating a saturation effect or a quadratic term in the magnitude parameter (M^2) is necessary to improve the model's flexibility and its ability to fit the observed data more accurately. The inclusion of such a term would allow the GMPE to better capture the nonlinear relationship between magnitude and ground motion. Consequently, further refinement and development of the model are essential to achieve a more robust representation of the observed seismic data.

4.2. Residual Analysis of the Developed GMPE Model

The residual analysis of the developed model equation was conducted to evaluate the model's performance and to identify potential bias in predicting peak ground acceleration (PGA) across different magnitudes and distances. Based on the previous

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Vol. 53 No. 2 November 2025, pp. 429-440

results, a multivariate linear regression analysis was conducted on the GMPE Model 8, which represents the modified version of the ground motion prediction equation. From the earlier analysis, it was concluded that the distributions of the parameters R (distance) and M (magnitude) were not entirely satisfactory, as several underestimations were observed within specific ranges. This indicates that the initial GMPE was unable to effectively distribute the data, thereby necessitating model modification to improve predictive performance. The subsequent regression analysis of the modified equation aimed to obtain the coefficients of each model term, which were then used to evaluate the residual distribution of the resulting model. The multivariate linear regression analysis for the modified GMPE model produced the following relationship:

$$ln(Y) = 1.18933 + 1.39412\,(M) + 0.00231\,(M)^2 - 0.75446\,ln(R + 10.86427) \tag{8}$$

where *a= 1.18933, b= 1.39412, c= 0.002d= 0.75446 ,dan e=10.86427*, Additionally, the coefficient of determination was found to be $R^2 = 0.8949$ and the RMSE value was $RMSE = 0.3294$, Using these coefficients, residual analyses were then performed to compare model predictions with observed data, as shown in the following figures.

Figure 7 compares the observed and predicted PGA values based on two models: the original GMPE by Sharma (blue plot) and the modified GMPE (orange plot). The dashed black line represents the 1:1 equilibrium line, where predicted values ideally match observations. Overall, the modified model (orange) exhibits data distributions that align more closely with the 1:1 line, particularly within the low to moderate PGA range. This indicates that the inclusion of an additional variation term improves the agreement between observed and predicted values. The original model displays greater deviations at higher PGA levels, reflecting an overestimation tendency. The enhanced stability of the modified model suggests its improved ability to capture non-linear local site effects and source characteristics that were not represented in the linear Sharma model. This improvement is particularly relevant in regions with complex geological conditions, such as Semarang City.

Figure 8 illustrates the relationship between residuals (lnObs−lnPred) and source-to-site distance R. Positive residuals indicate underestimation (predicted values too low), whereas negative residuals indicate overestimation (predicted values too high). The original model (blue) shows a negative residual trend for distances less than 10 km, suggesting overestimation of PGA at short distances, while residuals approach zero beyond 20 km. In contrast, the modified model (orange) exhibits more stable residuals around zero across the entire distance range, with reduced scatter. This demonstrates that the inclusion of a variation term successfully corrects short-distance bias, which commonly occurs in Sharma-based GMPEs. The original GMPE tends to overpredict PGA near the source and underpredict it at greater distances due to geometric spreading and local attenuation effects not fully captured in the model. Hence, these results confirm that the modified approach enhances the accuracy of distance-dependent attenuation representation.

Figure 9 presents the residual distribution with respect to earthquake magnitude. The original model (blue) shows considerable fluctuations within the magnitude range of M=2.0–2.5, with several extreme negative residuals (around -2), indicating overestimation for small-magnitude events. Conversely, the modified model (orange) produces residuals more tightly clustered around zero, indicating improved consistency across the magnitude range M<5. This behavior demonstrates that the inclusion of variation terms enhances the model's capability to represent small-to-moderate magnitude earthquakes. Similar findings were reported by Sigit Pramono[7], where GMPE applications to Central Sulawesi BMKG datasets revealed high residuals for small events due to source variability and local attenuation. Conceptually, the modified model refines the empirical magnitude–PGA relationship by introducing an additional parameter that captures local site response effects.

Finally, Figure 10 presents the QQ-plot of the residuals, which was used to assess their normality. The red line represents the theoretical normal distribution, while the blue points show the actual residual values. Most of the points follow the central linear trend, indicating that the modified model provides a significantly better fit than the original. A slight curvature in the residual distribution suggests minor positive skewness (a tendency toward overestimation), particularly for large PGA values.

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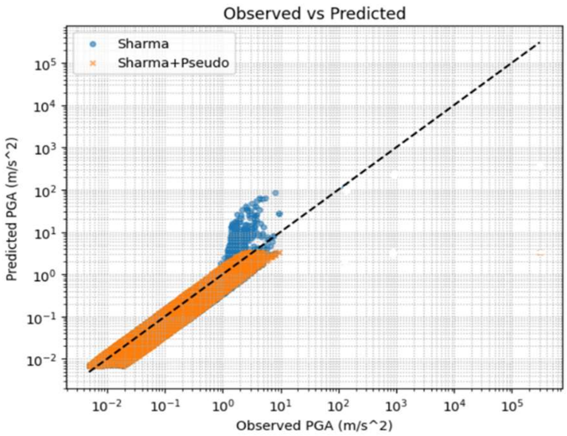

Figure 7. Plot of residual distribution for the modified model.

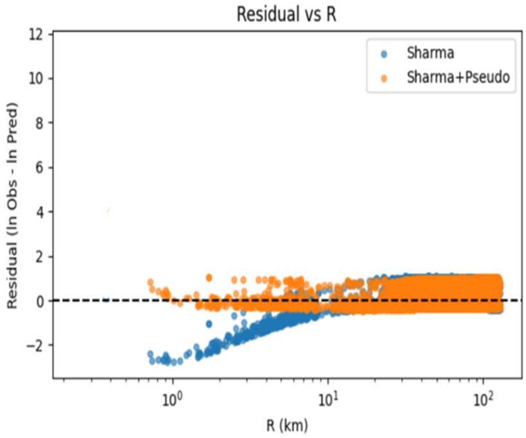

Figure 8. Residual distribution with respect to distance for the modified model.

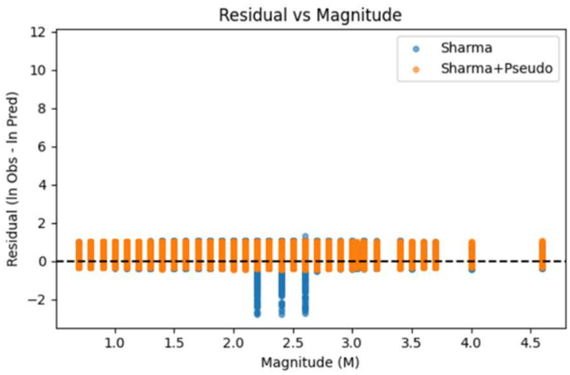

Figure 9. Residual distribution plot versus modified magnitude.

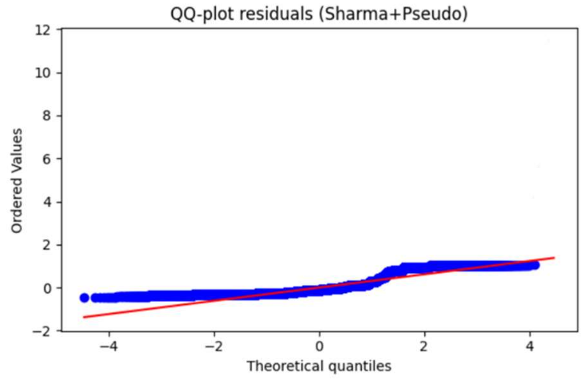

Figure 10. QQ-plot of modified residuals.

Overall, the analysis indicates that the initial model still exhibits limitations in predicting PGA values, particularly at short distances and for small magnitudes, where the model tends to produce overestimated results. In contrast, the developed model demonstrates a significant improvement, with data distributions aligning more closely with the 1:1 equilibrium line, more stable residuals with respect to distance and magnitude, and a reduced bias at short distances. These improvements suggest that the inclusion of additional variable terms effectively accommodates local effects and nonlinearities that were not captured by the original Sharma model, resulting in more realistic predictions that reflect the complex geotechnical and seismotectonic conditions in Central Indonesia. This finding is consistent with the results of Sigit Pramono[7], who emphasized the importance of developing region-specific GMPEs calibrated with local BMKG data to accurately represent the seismotectonic characteristics of Indonesia. In summary, the comparison results between the two GMPE models are presented in Table 1 below.

Table 1. Comparison of the results between the two GMPE models

Analysis Aspect	Sharma (Original Model)	Sharma + Pseudo (Modified Model)
Observed vs. Predicted	A large scatter of data points away from the 1:1 line, particularly for high PGA values, indicating prediction bias.	Data points are more concentrated around the normal distribution line, showing smaller dispersion and more stable predictions.
Residual vs. R (Distance)	Residuals tend to be negative at short distances and increase toward positive values at medium to large distances.	Residuals are more evenly distributed around zero, showing reduced dependence on distance.
Residual vs. Magnitude	Several clusters of negative residuals appear at small magnitudes ($M < 2.5$), indicating poor model performance for low-magnitude events.	Residuals are more symmetrically distributed around zero, with no strong correlation with magnitude.
QQ-Plot	Significant deviation from the straight reference line, especially in the tails of the distribution, suggesting non-normal residuals and notable outliers.	Residuals follow the normal distribution more closely, indicating improved normality.
Model Parameters	a = 0.283, b = 1.431, c = 1.327	a = 1.189, b = 1.394, c = 0.0023, d = 0.754, e = 10.864 (additional parameters increase model flexibility)
RMSE	0.3506	0.3294 (smaller → better prediction accuracy)
R^2	0.8211	0.8949 (higher → better model fit)
Standard Deviation	0.25 – 0.32	0.25 – 0.29
MAE	0.2547	0.2375

4.4. Residual Histogram Results

As shown in Figure 11, the histogram illustrates the distribution of standardized residuals from the modified Sharma model, representing the normalized difference between the observed and predicted PGA values. The mean residual value of 0.058 indicates that the model predictions are generally close to the ideal condition (mean = 0), suggesting that the model does not exhibit a systematic tendency toward either overestimation or underestimation. The standard deviation of 1.000 implies that the residual spread follows a normal deviation scale, indicating that the variation in prediction errors remains within acceptable limits and that the model demonstrates good statistical stability. However, the histogram shows a slight right-skewed pattern, meaning that there are more positive residuals, which suggests that the model slightly underestimates the PGA values (predicted values are lower than the observed ones) in several cases. This pattern indicates that, although the modified Sharma model has improved predictive accuracy compared to the original Sharma model, there may still be some local factors not fully captured by the model, such as soil heterogeneity and variations in earthquake source mechanisms. These findings are consistent with those reported by Sigit Pramono et al.[7], who stated that residual distributions in regional GMPEs are not always perfectly normal due to the complexity of source characteristics and site effects. Nevertheless, models with mean residuals close to zero and a standard deviation of approximately one are generally considered adequate in representing the regional attenuation characteristics across Indonesia.

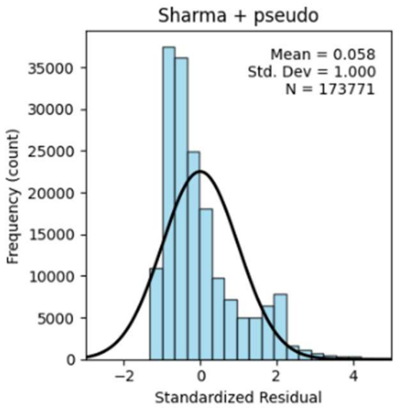

Figure 11. Histogram of Standardized Residuals

4.5. Comparison with Global GMPEs

Gunawan et al.[12] conducted a study comparing several GMPEs—namely those developed by Sadigh (1997), Fukushima (1990), and Kanno (2006)—for the same type of earthquake source mechanism as used in the present study. Therefore, a similar comparison was performed in this research between those three global models and the modified Sharma model developed herein. The results of this comparison reveal varying levels of accuracy among the four GMPEs in predicting ground motion. The Sadigh (1997) model shows a mean residual value of 0.531, which deviates considerably from zero, indicating a positive bias where the model tends to underestimate the observed PGA values. Its residual distribution is also asymmetric, suggesting a poor fit to a standard normal distribution. The Fukushima (1990) model performs better, with a mean residual of 0.093, closer to zero and with a more symmetric residual distribution, implying reduced bias. The Kanno (2006) model demonstrates even greater improvement, with a mean residual of 0.070, nearly zero, and a relatively balanced residual distribution—indicating that the predicted values are more representative of the observations. Among all models, the modified Sharma model achieves the best overall performance, with the smallest mean residual of 0.058, indicating minimal bias. Its residual distribution also closely approximates a normal distribution. Therefore, it can be concluded that among the four compared GMPEs, the modified Sharma model provides the most accurate and stable representation of the observed ground motion data.

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Vol. 53 No. 2 November 2025, pp. 429-440

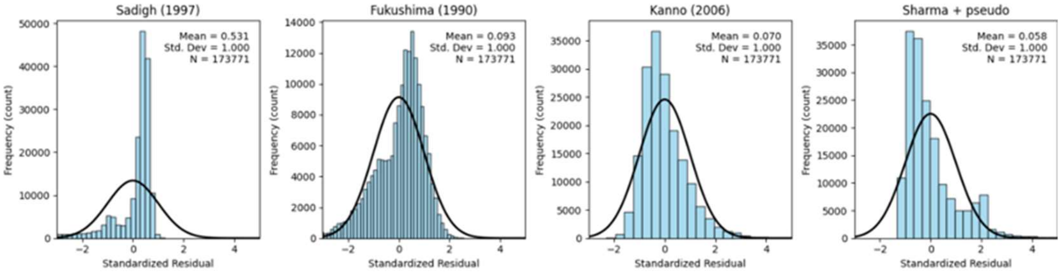

Figure 12. Comparison results between the modified Sharma model and global GMPEs.

5. CONCLUSION

The results of this study indicate that the seismic activity in Semarang City is predominantly characterized by shallow, low-magnitude earthquakes (M < 5) with spatially scattered epicenters, representing background seismicity. The baseline Sharma (2008) GMPE adequately describes the general relationship among PGA, magnitude, and distance; however, it tends to overestimate PGA at near-source distances and underestimate it for smaller magnitudes. Incorporating a non-linear variation term into the model significantly improved its predictive accuracy, yielding $R^2 = 0.8949$ and RMSE = 0.3294. The modified model exhibits more stable residual distributions across distance and magnitude ranges, providing more consistent predictions against observed data. This enhancement suggests that the model successfully captures non-linear effects of local site conditions, including alluvial deposits and complex fault mechanisms surrounding Semarang. Consequently, the modified GMPE is considered more representative of the regional seismotectonic framework and can serve as a reliable basis for regional seismic hazard modeling in Central Indonesia. The results underscore the necessity of developing locally calibrated GMPEs to improve ground motion prediction accuracy and support more resilient earthquake hazard mitigation and infrastructure planning.

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