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Effect of Magnitude and Distance on Peak Ground Acceleration Using a Modified Akkar & Boomer (2007) GMPE for North Sumatra

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ABSTRACT

The Ground Motion Prediction Equation (GMPE) is very important in estimating the intensity of earthquake shocks as a basis for risk mitigation. This study aims to modify and validate the Akkar & Boomer (2007) GMPE using shallow earthquake data in the North Sumatra region for the period 2017–2023. The earthquake data were obtained from BMKG and included parameters such as magnitude, depth, and distance from the source. The analysis method involved nonlinear regression, data cleaning, and validation using residual analysis. The results showed that the maximum ground acceleration (PGA) tended to decrease nonlinearly with increasing distance from the earthquake source. The modified GMPE equation was: $\text{Log}_{10}\ PGA = -0.5916 + 0.5875M + 0.0576M^2 + (-0.8699 + -0.1985M)\ \text{Log}_{10}(\sqrt{R^2 + 8.2032^2}) + 0.105$, with an R^2 value of 0.56 and prediction error values such as 0.21; MAE 0.36; RMSE 0.46; STD 0.46). Thus, the modification of GMPE based on local data can provide a more representative estimate of earthquake hazards to support mitigation efforts in North Sumatra.

Keywords: Distance, Magnitude, Modified GMPE, PGA

ABSTRAK

Ground Motion Prediction Equation (GMPE) sangat penting dalam memperkirakan intensitas guncangan gempa bumi sebagai dasar mitigasi risiko. Penelitian ini bertujuan untuk memodifikasi dan memvalidasi persamaan GMPE Akkar & Boomer (2007) dengan menggunakan data gempa bumi dangkal di wilayah Sumatera Utara periode 2017–2023. Data gempa diperoleh dari BMKG dan mencakup parameter magnitudo, kedalaman, dan jarak sumber. Metode analisis dilakukan dengan regresi nonlinier, data cleaning, serta validasi menggunakan analisis residual. Hasil penelitian menunjukkan bahwa nilai percepatan tanah maksimum (PGA) cenderung menurun secara nonlinear seiring bertambahnya jarak dari sumber gempa. Persamaan GMPE modifikasi yang dihasilkan yaitu: $\text{Log}_{10}\ PGA = -0{,}5916 + 0{,}5875M + 0{,}0576M^2 + (-0{,}8699 + -0{,}1985M)\ \text{Log}_{10}(\sqrt{R^2 + 8{,}2032^2}) + 0{,}105$, dengan nilai R^2 sebesar 0,56 dan nilai kesalahan prediksi seperti 0,21;MAE 0,36; RMSE 0,46; STD 0,46). Dengan demikian, modifikasi GMPE berbasis data lokal dapat memberikan estimasi bahaya gempa yang lebih representatif untuk mendukung upaya mitigasi di Sumatera Utara.

Kata kunci: Jarak, Magnitudo, Modifikasi GMPE, PGA

1. Introduction

The island of Sumatra is located in an active tectonic zone due to the convergence of the Eurasian and Indo-Australian plates. Tectonic interactions cause major earthquakes with magnitudes ranging from 6 to 9 Mw, particularly in North Sumatra [1]. Major earthquakes that have occurred include the 2004 Aceh earthquake (Mw 9.2), the 2005 Nias earthquake (Mw 8.7), and the 2010 Mentawai earthquake (Mw 7.8).

North Sumatra is traversed by the active Sumatra fault and is located in a subduction zone, making it highly vulnerable to shallow earthquakes at depths of 3–40 km [2], [3]. Shallow earthquakes tend to produce stronger surface shaking and have the potential to cause major damage [4]. Earthquake shaking can cause damage to buildings and loss of life. One important parameter for measuring the level of damage is Peak Ground Acceleration (PGA). Structural damage generally occurs due to strong ground motion, so it is necessary to analyze the Ground Motion Prediction Equation (GMPE) to predict and reduce the impact of this risk.

The GMPE equation is used to estimate the value of ground acceleration at a location due to earthquake shaking. This value is important for determining the magnitude of the impact that may occur at that location. Accurate PGA estimates help in assessing the potential for ground shaking and reducing the risk of damage [5], [6].

Most GMPE models are developed from data from other tectonic regions, such as the Akkar & Boomer (2007). This model is not entirely suitable for the soil characteristics in North Sumatra [7], as it was developed based on earthquake data from Europe and the Middle East, which have significant differences in geological conditions, earthquake source mechanisms, and soil response. This model was developed in an active tectonic region similar to North Sumatra.

This study aims to modify and validate the Akkar & Boomer (2007) GMPE model using shallow earthquake observation data in North Sumatra from 2017 to 2023 using nonlinear regression and residual analysis to produce a more accurate and representative GMPE model in North Sumatra [8].

2. Methode

This research was conducted from January to May 2025 in North Sumatra Province, Indonesia, with geographical coordinates 1°–4°N and 98°–100°E. The hardware and software used included a Zyrex Sky Mini64 laptop, ArcGIS 10.8 for mapping, Microsoft Excel and Word for data processing, and Visual Studio Code and the Python programming language for data analysis and regression. The data in this study were obtained from the BMKG for the 2017–2023 period with shallow earthquake clusters. The parameters analyzed were magnitude and depth.

The data was loaded in CSV format and processed using Python programming language. The initial stage included cleaning the data of zero amplitudes, removing missing values (NaN), and calculating the geometric mean of the horizontal PGA values on a logarithmic scale.

Next, data exploration was carried out to understand the distribution of magnitude, depth, distance, and PGA values. Modification of the PGA prediction model equation refers to the 2007 GMPE Akkar & Boomer (Akbom) equation, taking into account modified magnitude and distance parameters to improve the model's suitability for empirical ground motion data characteristics. The equation is as follows:

$$logy=b1+b2M+b3M2+(b4+b5M)\ log\ Rjb2+b62+b7SS+b8SA+b9FN+b10FR \qquad (1)$$

where, Mw is the moment magnitude, R is the distance from the source to the location, h is the depth filtering parameter, SS and SA are dummy variables for soft soil and hard soil, and FN and FR represent the fault mechanism. Parameters b1 to b8 are regression coefficients obtained from empirical ground motion data [9].

Model parameters are estimated using the least-squares optimization method. The model is evaluated by calculating the MSE, RMSE, MAE, standard deviation, and R-square values. Residual analysis is also performed on magnitude and distance.

The model is also tested on one earthquake event with the most observations to assess prediction accuracy. Then, PGA predictions for magnitudes M3, M5, and M6 are simulated to see the sensitivity of the model. The analysis process in this study uses programming languages such as pandas, numpy, matplotlib, seaborn, and scipy.

The modified GMPE model is verified using PGA data from BMKG accelerograph stations to ensure its suitability in the context of earthquake hazards in North Sumatra.

3. Results and Discussion

3.1. Modification of Equations

Analysis of the Ground Motion Prediction Equation (GMPE) model by Akkar & Boomer (2007) based on observational data of shallow earthquakes in North Sumatra shows that PGA values decrease with increasing distance from the earthquake source. The relationship between PGA values and distance is nonlinear [10].

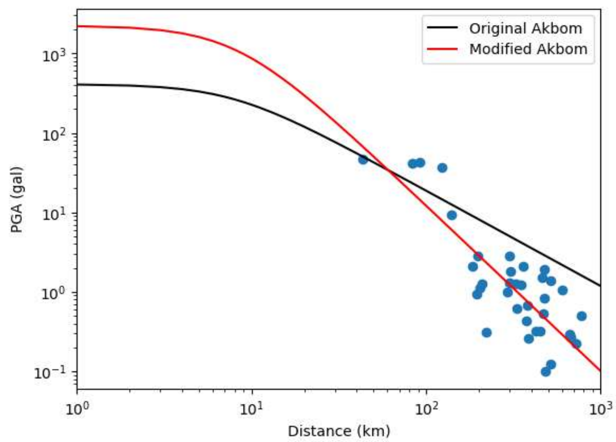

Figure 1. Graph showing the relationship between PGA values and distance (Equation by Akkar & Boomer, 2007).

Figure 1 shows that PGA values tend to decrease with increasing distance from the earthquake source. This pattern is consistent with the GMPE model developed by Boore et al. (2008), which states that the relationship between PGA values and distance is nonlinear.

The intersection between the original Akbom model curve and the modified Akbom model is shown in Figure 1. This difference is caused by variations in the input parameters used in the GMPE. The modified Akbom model includes adjustments to several parameters such as magnitude and focus depth, because changes in input parameters can significantly affect PGA prediction results [11]. Thus, the intersection between the two models reflects the sensitivity of PGA values to GMPE parameters.

The distribution of observation data points at distances of 10 to >100 km shows that the modified Akbom model curve more consistently follows the downward trend of the observation data. This indicates that the modified model is able to represent the GMPE model with better accuracy in that range. Kalkan et al. (2010) in their findings explain that modifying parameters in GMPE can improve the suitability of the model to the observation data [12].

The results of the analysis of the relationship between distance and PGA values also take into account the magnitude of the earthquake. Earthquakes with large magnitudes produce relatively high PGA values, even at great distances. Meanwhile, earthquakes with small magnitudes produce lower PGA values and tend to decrease rapidly with increasing distance from the earthquake source.

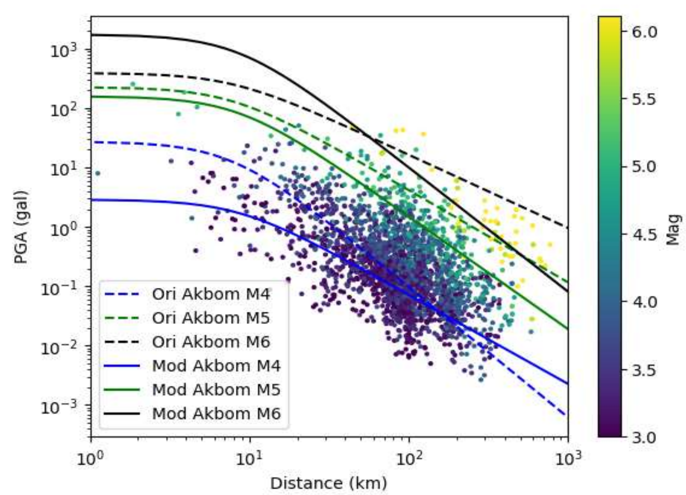

Figure 2. Graph of the relationship between distance and PGA value, taking into account magnitude (Akkar & Boomer equation, 2007).

The relationship between distance and PGA values, taking magnitude into account, can be seen in Figure 2. Each data point on the graph is colored to represent the magnitude of the earthquake, based on a specific color scale. Magnitude plays an important role in influencing PGA values, as can be seen from the distribution of data points on the graph:

a. Magnitude 3.0–4.0 (dark blue–purple): The distribution of data points is concentrated at the bottom of the graph, with low PGA values (<1 gal), and located at medium to long distances (>10 km to >200 km). This indicates that small earthquakes produce vibrations that are quickly dampened and less significant at more distant locations. Small earthquakes are unable to produce high ground acceleration, especially at long distances [13].
b. Magnitude 4.0–5.0 (green–yellow): Distributed in the middle of the graph, reflecting moderate PGA values (1–100 gal), and covering close to far distances. Within this magnitude range, PGA values increase because some earthquakes are relatively shallow, resulting in high acceleration in areas close to the source. Shallow earthquakes tend to produce greater acceleration responses at the surface [14].
c. Magnitude 5.0–6.0 (light yellow–dark yellow): Dominant at the top of the graph, with high PGA values (>100 gal to >1000 gal) indicating that large earthquakes generate strong seismic energy, which can be felt with high intensity around the source location. Dauglas (2011) explained in his research that large magnitude earthquakes can have a strong impact even at considerable distances [15].

The difference in prediction results shows that the modified Akbom model has better accuracy in presenting conditions at the research location. This finding is reinforced by the research of Rahma, et al. (2024), who conducted a similar study in North Sumatra, where there was a decrease in PGA values as the distance from the earthquake source increased, with a significant influence from the magnitude [16].

The modified GMPE equation obtained for the North Sumatra region is:

$$Log10PGA=-0.5916+0.5875M+0.0576M2+-0.8699 + -0.1985M\ Log10\ R2+8.20322+0.105 \quad (2)$$

From equation 2, the value of the constant has been obtained. b_1 = -0.5916, b_2 = 0.5875, b_3 = 0.0576, b_4 = -0.8699, b_5 = -0.1985, b_6 = 8.2032, b_7 = 0.105, b_8 = 0.1878, the explanation of the function of each constant is described in equation 1.

3.2. Validation Ground Motion Prediction (GMPE)

Validation of the performance of the modified GMPE model by Akbom was carried out by analyzing the magnitude and distance parameters of the earthquake source. The resulting modified GMPE model must be evaluated using residual analysis. This analysis is calculated by finding the logarithmic difference between the predicted PGA value and the observed result.

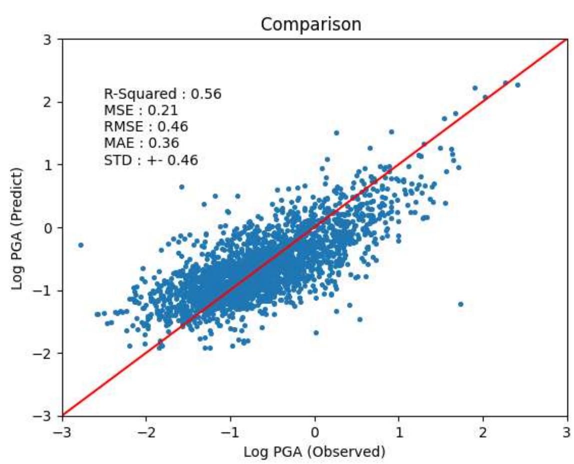

Figure 3. Graph showing the relationship between observed PGA values and predicted PGA values (Akkar & Boomer equation, 2007).

Figure 3 shows the relationship between observed PGA values and PGA values predicted by the modified GMPE equation on a logarithmic scale. This graph is used to assess the accuracy of the model in predicting ground acceleration due to earthquakes. If the points are on the red line, it means that the model's predictions are very accurate. Conversely, the further the points are from this line, the greater the prediction error [14]. The statistics generated are:

a. R-Squared = 0.56: The model is able to explain 56% of the variation in the observed data. This is considered moderate for empirical models in the field of seismology [17].
b. MSE (Mean Absolute Error) = 0.21, RMSE (Root Mean Squared Error) = 0.46, MAE (Mean Absolute Error) = 0.36: These three error values are relatively low, indicating that the model's prediction error is not too large on a log scale. An RMSE value below 0.5 on a log scale indicates that the GMPE model performs well, especially if the MAE and MSE values are also low, meaning that the model is quite stable in predicting PGA values [18].
c. STD (Standard Deviation) Residual = ± 0.46: Indicates that the error distribution is fairly consistent and does not spread extremely. An STD value ranging from 0.4 to 0.6 is considered acceptable for GMPE, because earthquake data causes residual variation [19].

4. Conclusion

This study successfully modified and validated the Ground Motion Prediction Equation (GMPE) model by Akkar & Boomer (2007) using shallow earthquake data in North Sumatra for the period 2017–2023. The analysis results show that the maximum ground acceleration (PGA) decreases with increasing distance from the earthquake source in a nonlinear pattern, and is significantly influenced by magnitude and soil conditions (site class). The modified GMPE model shows a coefficient of determination (R^2) of 0.56 and relatively low prediction errors (MSE 0.21; MAE 0.36; RMSE 0.46; STD ± 0.46). Site class proved to be an important contributor, with soft soil producing higher PGA values than hard rock at close distances. Thus, GMPE modification based on local data and considering site class can improve the reliability of earthquake hazard estimation in North Sumatra, while also serving as an important basis for earthquake risk mitigation planning and the design of earthquake-resistant structures in vulnerable areas.

5. Acknowledgment

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