

Advanced regional ground motion prediction equations for the Northeastern region of India

Arindam Das, Deepankar Choudhury

Department of Civil Engineering, Indian Institute of Technology Bombay, Mumbai, India, arindamdas@iitb.ac.in

ABSTRACT: One of the most critical elements of seismic hazard analysis is the development of Ground Motion Prediction Equations (GMPEs), which estimate key ground motion parameters such as Peak Ground Acceleration (PGA). These equations serve as essential tools for earthquake-resistant design and effective seismic risk mitigation. Given its intricate tectonic framework and frequent seismicity, the Northeastern region of India requires region-specific GMPEs capable of accurately representing its distinct ground motion characteristics and hazard potential. This study presents the development of advanced GMPEs for this seismically active region of India using advanced regression techniques like non-linear multiple regression analysis. Two different GMPEs are developed based on the widely used moment magnitude scale (M_w) and the recently proposed generalized moment magnitude scale (M_{wg}). This work stands as the first study to introduce GMPE in the M_{wg} scale for the North-eastern (NE) region of India. The M_{wg} scale, which was developed to improve over the shortcomings of the M_w scale, provides a number of benefits by accurately depicting the size of earthquakes, especially those with minor to intermediate magnitudes, which are quite frequent in this area. The developed GMPEs incorporate essential predictor variables, including earthquake magnitude (M), hypocentral distance (R_{hypo}), and shear wave velocity (V_{s30}), and are specific to the unique seismotectonic and geological conditions of Northeast India. Comparative analysis demonstrates that the GMPE based on the M_{wg} scale outperforms the M_w based model, offering superior predictive accuracy statistically and a better fit to observed data. This highlights the M_{wg} scale's capability to more effectively capture regional seismicity and attenuation characteristics for any region. The GMPEs were rigorously validated against observed ground motion data, confirming their reliability for seismic hazard analysis. The advanced GMPEs developed in this study provide robust and reliable tools for enhancing earthquake-resistant design and mitigating seismic risks in this tectonically active region of India.

KEYWORDS: Ground Motion Prediction Equation (GMPE), Non-linear multiple regression analysis, Northeast India, M_{wg} scale.

1 INTRODUCTION

The North-eastern (NE) region of India, forming a significant segment of the eastern Himalayan arc, is one of the most seismically active zones in the world. This region, situated at the convergence of the Indian and Eurasian plates, has experienced several devastating earthquakes in the past, including those exceeding magnitude 7.0. The high seismicity of this area is attributed to the complex tectonic processes at play, including active crustal deformation, plate subduction, and intra-plate stress accumulation. As per the seismic zonation map of India (IS:1893, 2016), the entire North-eastern region falls within seismic zone V, with a zone factor of 0.36g, reflecting a high seismic hazard potential. Despite its vulnerability, the current seismic zoning framework for Northeast India remains insufficient, as it is largely based on historical intensity data rather than comprehensive scientific hazard analysis. This shortfall emphasizes the urgent necessity to update current design codes by integrating ground motion characteristics and seismotectonic conditions specific to the region.

Ground Motion Prediction Equations (GMPEs) play a pivotal role in seismic hazard evaluation, as they estimate the expected ground shaking during an earthquake. However, there has been limited development of GMPEs tailored specifically to Northeast India. Earlier studies, such as those by Nath et al. (2005), used data from the Shillong array to analyze local events, but were constrained by a narrow magnitude range and short hypocentral distances. Simulated datasets have been used to address the scarcity of ground motion records, yet such approaches may not fully capture the complexities of the region's unique seismotectonic settings. Efforts by NDMA (2010) and Anbazhagan et al. (2013) have included Northeast India within broader Himalayan GMPE frameworks, often relying on simulated or extrapolated data. Nevertheless, the reliance on data from other tectonic regions or synthetic simulations may compromise the predictive capability for Northeast India, given its unique geological and tectonic context.

The moment magnitude scale (M_w), proposed by Hanks & Kanamori (1979), has long been regarded as the standard and most reliable measure of earthquake size because it remains consistent across varying magnitudes without exhibiting saturation. However, several recent investigations (Das et al. 2019; Das et al. 2023; Pallavi et al. 2023; Das et al. 2024; Das & Das, 2025; Das et al. 2025a) have pointed out notable limitations of this scale. Since these studies provide detailed examinations of the M_w scale's shortcomings, only a concise overview is presented here: (i) When used for small or intermediate earthquakes, the M_w scale may be imprecise, but it works well for major earthquakes (Kanamori, 1977). (ii) Its calibration was originally derived from earthquake data of South California, which restricts its general applicability to other tectonic settings. (iii) The scale was not formulated directly from observed seismic moment (M_0) data, which can introduce uncertainties in certain cases. (iv) It was originally derived from an empirical relationship between radiated energy (E) and surface-wave magnitude (M_s), and therefore may not fully reflect the underlying source physics. (v) The assumption of a constant stress drop further limits its suitability, particularly for deeper earthquakes. Overall, various researchers have emphasized that the M_w scale possesses inherent constraints and may not always provide a true estimate of earthquake size globally. To address these issues, Das et al. (2019) proposed a modified framework termed the generalized moment magnitude scale (M_{wg}). This enhanced magnitude formulation is derived directly from global seismic moment (M_0) data and demonstrates robust consistency with radiated energy and existing magnitude measures such as m_b , M_s , and M_e . Extensive validation using global seismic datasets has confirmed the M_{wg} scale's reliability.

In this context, the study aims to develop new non-linear multiple regression based GMPEs using both the M_w and M_{wg} magnitude scales, specifically calibrated for the NE Indian region. By employing real ground motion data comprising 114 records from 21 earthquake events, encompassing sources within the NE Himalayas and adjoining seismotectonic zones, the developed models are designed to reliably capture ground

motion characteristics across a broad range of hypocentral distances and magnitudes.

Researchers can apply the newly developed prediction equations to improve the accuracy of seismic hazard assessments in the Northeastern region of India. These equations offer enhanced prediction of peak ground acceleration (PGA) across a broader range of hypocentral distances and earthquake magnitudes, making them particularly suitable for the complex tectonic settings of the region. The updated attenuation relationships are expected to significantly refine seismic hazard analysis in NE India, supporting more resilient engineering design and more effective disaster mitigation strategies in this seismically active and densely populated area.

2 TECTONIC FRAMEWORK OF NORTHEAST INDIA AND ITS EARTHQUAKE DATABASE

The study area encompasses the North-Eastern (NE) region of India, which forms an integral part of the eastern Himalayan arc and extends into the complex Indo-Burma ranges. This area is widely acknowledged as one of the most seismically active regions in the world (Gupta, 2017). The high seismicity in this region is primarily attributed to the ongoing convergence of the Indian Plate with the Eurasian Plate at a rate of approximately 4.5 cm/year. This tectonic interaction has led to the formation of numerous folds, faults, and thrust systems, which continue to accumulate and release strain in the form of earthquakes. While the Himalayan Main Central Thrust (MCT), Main Boundary Thrust (MBT), and Main Frontal Thrust (MFT) are key tectonic elements in the broader Himalayan region, the NE Indian region is also significantly influenced by the Mikir Hills Fault, Oldham Fault, and the complex thrust-and-fold belt of the Indo-Burma subduction zone. The eastern extension of the Himalayan seismic belt into the Arakan Yoma further contributes to the region's dynamic seismotectonic framework (Parvez et al. 2008 and Khattri, 1987). Figure 1 illustrates the study region which is a part of north-east (NE) India along with the distribution of earthquake recording stations and the earthquake events analyzed in this regard to develop GMPE.

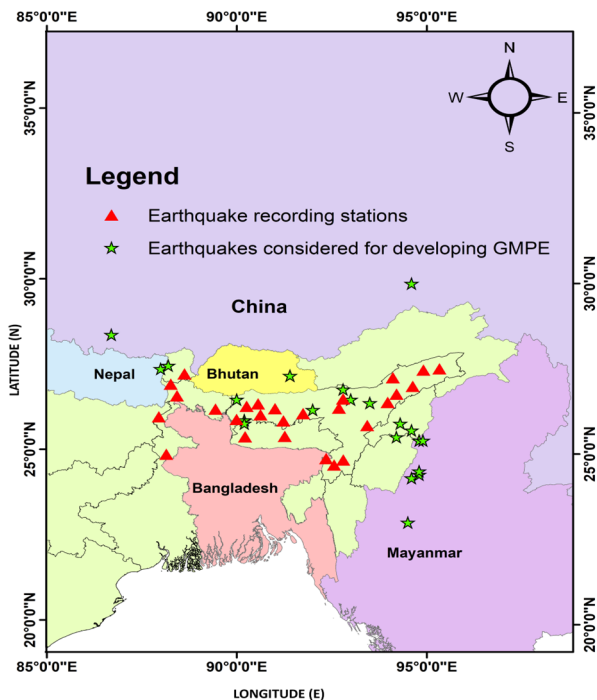


Figure 1. Study area north-east (NE) part of India showing earthquake recording stations and earthquakes considered to develop GMPE.

Figure 2 provides a graphical depiction of the compiled dataset, illustrating the relationship between earthquake magnitude and hypocentral distance.

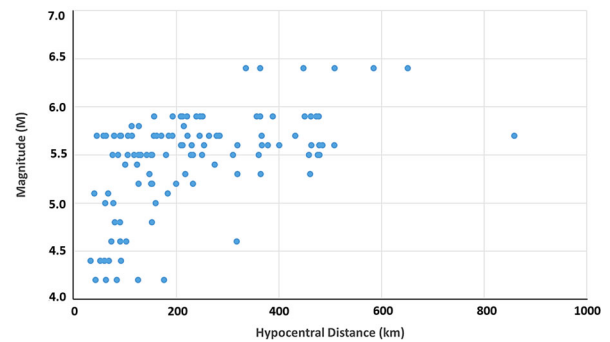


Figure 2. Plot of Magnitude vs. Hypocentral Distance of various earthquakes in the study region.

To monitor seismic activity in this region, Strong Motion Accelerograph (SMA) stations have been installed and operated by the National Center for Seismology (NCS, Delhi) and the Indian Institute of Technology Roorkee (IITR). Each SMA station houses a three-component digital accelerograph designed to capture ground motion during earthquakes. Several of these stations are strategically distributed across the NE Indian region to cover both soil and rock sites. The data is curated by the Department of Earthquake Engineering at IIT Roorkee and provided through the PESMOS (Program for Excellence in Strong Motion Studies) platform. This dataset includes metadata such as station names and coordinates, site conditions (e.g., soil or rock), average shear wave velocity ($V_{s,30}$), and ground motion parameters like Peak Ground Acceleration (PGA) and Peak Ground Velocity (PGV).

For the development of new Ground Motion Prediction Equations (GMPEs) specific to NE India, a total of 21 real recorded earthquake events were considered (Table 1). In Table 1, EQ locations refer to the earthquake locations, D indicates the depth of the earthquakes in kilometers, Date represents the date of occurrence, Lat and Long denote the latitude and longitude, respectively, M indicates the recorded magnitude, and N represents the number of stations that recorded the earthquake. It is important to note that earthquakes with magnitudes less than 4.0 and records captured at only one or two stations were omitted (i.e., less than 3 stations), as they may introduce bias arising from localized site effects or potential instrumental inconsistencies. Ensuring a minimum of three recordings per event enhances the generalizability and stability of the regression model, adhering to standard GMPE development practices.

Table 1. Earthquakes considered for the study area NE part of India.

EQ locations	D (km)	Date	Lat	Lon	M	N
Assam-Meghalaya Border	39.3	15/02/09	26	90.2	4.4	5
Nagaland-Mayanmar Border	10	24/02/09	25.9	94.3	4.8	3
Mayanmar-Manipur Border	22	11/08/09	24.4	94.8	5.6	12
Mayanmar-Manipur Border	85	30/08/09	25.4	94.8	5.3	5

Mayanmar- Manipur Border Bhutan	100	03/09/09	24.3	94.6	5.9	9
Kokrajhar	5	29/10/09	27.3	91.4	5.2	5
Myanmar India Border Bhutan	100	29/12/09	24.5	94.8	5.5	6
Meghalaya -Assam- Border	20	11/09/10	25.9	90.2	5	3
Myanmar- India- Border	30	04/02/11	30	94.6	6.4	7
India- Nepal Border	10	04/04/11	29.6	80.8	5.7	24
Sikkim- Nepal- Border	26	03/06/11	27.5	88	4.9	4
Sikkim- Nepal Border	10	18/09/11	27.6	88.2	6.8	13
Assam	20	11/05/12	26.6	93	5.4	3
Nagaland	50	01/07/12	25.7	94.6	5.8	3
Kohima- Nagaland	35	14/07/12	25.5	94.2	5.5	3
Sonitpur- Assam	35	02/10/12	26.9	92.8	5.1	3
Myanmar- India Border	89	09/01/13	25.4	94.9	5.9	6
Assam	16	16/04/13	26.3	92	4.6	4
Assam (Karbi)	20	06/11/13	26.5	93.5	5.5	4

In total, 114 data entries were used, spanning moment magnitudes from M_w 4.2 to 6.8 and hypocentral distances ranging from 30 km to 900 km. As mentioned in the earlier section also, Figure 2 shows the extend of magnitude and hypocentral distances range used in the study. Previous studies faced challenges due to sparse datasets and limited distance coverage, often relying on simulations or combining data from regions with similar tectonic settings. However, the current dataset provides sufficient coverage up to 900 km, making it well-suited for developing region-specific GMPEs for NE India using only recorded data. Although fewer records were available at distances beyond 900 km, the dataset was deemed sufficient for regression analysis, with a minor trade-off in accuracy at the farthest distances. Rather than introducing synthetic data which earlier studies showed could lead to significant over or under-prediction of PGA, this study proceeds with real data to improve predictive reliability, particularly within the hypocentral distance range most relevant for regional hazard assessment.

3 FORMULATION OF THE NEW REGION-SPECIFIC GMPEs

The finalized dataset comprised 114 strong-motion recordings from 21 earthquake events, covering a range of hypocentral distances between 30 km and 900 km. This comprehensive dataset includes observed Peak Ground Acceleration (PGA) values, the names and geographic coordinates (latitude and longitude) of the recording stations, as well as detailed earthquake parameters, such as origin date and time, epicenter

coordinates, focal depth, and moment magnitude (M_w). The hypocentral distance (X) between each earthquake epicenter and the corresponding recording station was computed and incorporated into the dataset.

In addition to M_w , generalized moment magnitude values (M_{wg}) were derived from the seismic moment (M_0) of each event. This was undertaken to develop Ground Motion Prediction Equations (GMPEs) specifically in the M_{wg} scale, which has not been previously attempted for the North-eastern region of India. Accordingly, this study develops GMPEs in both M_w and M_{wg} scales through nonlinear multiple regression framework, with the objective of improving the accuracy and regional applicability of attenuation models for this tectonically intricate region.

A commonly used form of predictive ground motion relationship, incorporating magnitude, distance, and other influencing parameters, is expressed as follows (Kramer, 1996):

$$Y = Z(M, R, B) \quad (1)$$

where, Y is the ground motion parameter of interest (such as PGA or PGV), M is the earthquake magnitude, R represents the source-to-site distance, and B is a set of additional variables that may account for factors such as the earthquake source characteristics, wave propagation path, and local site conditions.

The generalized form of the GMPE is thus expressed as Equation (2):

$$\log(PGA) = Z_1(M) + Z_2(R) + Z_3(T) + Z_4(F) + \varepsilon \quad (2)$$

where, $\log(PGA)$ is PGA, $Z_1(M)$ denotes functional dependence on earthquake magnitude, $Z_2(R)$ captures the effect of source-to-site distance, $Z_3(T)$ accounts for the influence of the tectonic environment, $Z_4(F)$ reflects the impact of fault type and ε represents the uncertainty in the predicted ground motion, encompassing model errors and unmodeled effects.

Several earlier studies, including those by Das et al. (2025b), Gogoi et al. (2023), Ramkrishnan et al. (2020), Anbazhagan et al. (2013), Baruah et al. (2009), Sharma (1998), Fukushima & Tanaka (1990), Joyner & Boore (1988), and, Campbell (1981) have adopted the generalized predictive relation as expressed in Equation (2). Following this well-established approach, the present study also employs Equation (2) as the foundational form for developing ground motion prediction equations (GMPEs).

Based on the multiple non-linear regression analyses conducted in this study, and utilizing the generalized regression framework presented in Equation (2), the following mathematical formulation has been obtained and used for further analysis:

$$\log(PGA) = D_1 + D_2 M + D_3 M^2 - D_4 \log(X) - D_5 [M \log(X)] + D_6 [\log(V_{S30})] + \varepsilon \quad (3)$$

where, $\log(PGA)$ describes, in base 10, the required PGA; M describes the magnitude of earthquake events; X describes, in base 10, the hypocentral distance in kilometres; V_{S30} (in base 10) denotes the average shear wave velocity in the top 30 m; D_1 , D_2 , D_3 , D_4 , D_5 , and D_6 are regression coefficients, and standard error is ε . This formulation does not incorporate the tectonic environment, $Z_3(T)$ or fault type, $Z_4(F)$, as focal mechanism information for many of the events is poorly constrained. Consequently, possible biases arising from uncertainties in focal mechanisms and earthquake event types are acknowledged in the GMPE development.

The regression coefficients and standard error were estimated using a MATLAB-based nonlinear regression

program developed in-house during the study and applied to the compiled dataset. The coefficients corresponding to the region-specific GMPEs, developed in both M_w and M_{wg} scales for the North-eastern region of India, are provided in Table 2. The PGA values considered for each event correspond to the maximum of the two horizontal components (i.e., EW and NS directions).

Table 2. Estimated regression coefficients of respective GMPEs.

Magnitude Scale	Regression Coefficients	Coefficient Values	Standard Error (E)
M_w	D_1	-4.995 ± 2.02	0.292
	D_2	0.299 ± 0.66	
	D_3	0.077 ± 0.08	
	D_4	-1.601 ± 1.05	
	D_5	0.396 ± 0.19	
	D_6	0.165 ± 0.17	
M_{wg}	D_1	-4.962 ± 1.64	0.290
	D_2	0.464 ± 0.49	
	D_3	0.055 ± 0.06	
	D_4	-1.300 ± 0.89	
	D_5	0.359 ± 0.16	
	D_6	0.176 ± 0.17	

To assess the performance of the proposed equations, the newly developed GMPEs were compared with several existing models formulated either for the Northeastern region of India or for tectonically analogous regions across the globe. The DC25 model proposed in this study exhibits strong potential to improve seismic hazard assessment and regional zoning, owing to its robust capability in accurately predicting ground motion over a broad spectrum of magnitudes and source-to-site distances.

Table 3. Summary of the existing GMPEs considered for the comparative analysis.

Existing GMPEs	Abbreviations	Magnitude Range	Distance Range (km)
Youngs et al. (1997)	Youngs97as	≥ 5.0	10 – 500
Youngs et al. (1997)	Youngs97af	≥ 5.0	10 – 500
NDMA (2010)	ndmaH-10 & ndmaNE-10	4.0 – 8.5	1 – 500
Nath et al. (2012)	Nath-12	4.8 – 8.1	≤ 100
Anbazhagan et al. (2013)	Anbu-13	4.3 – 8.7	≤ 300
Abrahamson et al. (2014)	ASK-14	3.0 – 8.5	0 – 400
Chiou & Youngs (2014)	CY-14	3.5 – 8.0	0 – 300
Campbell & Bozorgnia (2014)	CB-14	5.5 – 8.0	0 – 300
Singh et al. (2016)	SI-16	4.0 – 8.5	≤ 300
Bajaj & Anbazhagan (2019)	KT-19	4.0 – 9.0	10 – 750

Comparison shown in Figure 3 (a, b) shows that the DC25 model aligns closely with several widely accepted GMPEs in the global seismological community, such as Bajaj & Anbazhagan (2019), Anbazhagan et al. (2013), NDMA (2010), Campbell & Bozorgnia (2014), Abrahamson et al. (2014), Nath et al. (2012), Singh et al. (2016), Youngs et al. (1997). This consistency with internationally recognized models highlights the validity and robustness of DC25, reinforcing its suitability

for use in seismic hazard analysis. The model's reliable performance across both near-field and far-field conditions suggests that DC25 can serve as a dependable tool for estimating ground motion in a variety of seismic scenarios throughout the North-Eastern region of India.

4 MODEL VALIDATION AND COMPARATIVE EVALUATION OF GMPEs

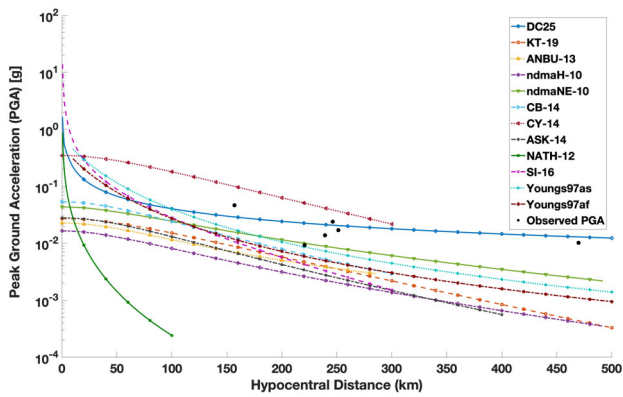
To assess the predictive capability of the newly developed GMPEs, the originally recorded ground motion data were compared with the predicted values generated by new models, along with a selected set of previously established GMPEs. This comparison was visualized through a series of plots, allowing for a clear evaluation of how well each model replicates observed seismic behavior. The list of GMPEs included in the comparative analysis is provided in Table 3.

It is significant to highlight that due to particular data and application limitations, several GMPEs designed for the North-eastern region were unable to be included in the comparison study. These include restricted applicability to specific magnitude or distance ranges, incomplete parameter sets, or the absence of essential data (e.g., V_{330} values or fault type information) necessary for uniform and consistent implementation across models. Despite these exclusions, the comparative framework remains robust and includes a representative set of widely accepted GMPEs relevant to the tectonic setting of the study area.

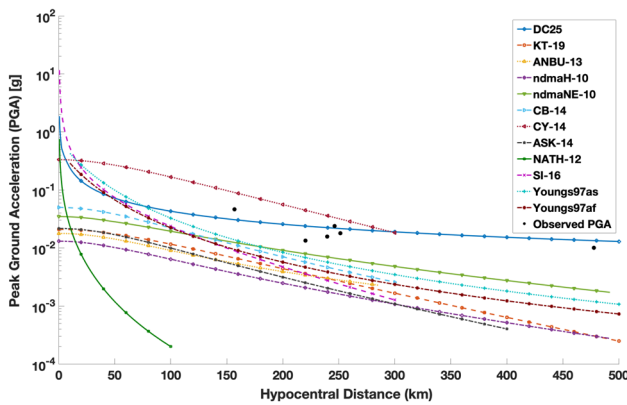
In this study, we adopted the validation approach followed by Anbazhagan et al. (2013), Ramkrishnan et al. (2020), Gogoi et al. (2023) and Das et al. (2025b), wherein Peak Ground Acceleration (PGA) data not included in the regression analysis are used to evaluate the predictive accuracy of the developed GMPEs. For this purpose, the 9th January, 2013, Myanmar–India Border Earthquake (M 5.9) was selected, as it lies within the North-eastern (NE) region of India and represents the complex tectonic regime of the Indo-Burma subduction zone which is a key seismotectonic domain influencing the seismic hazard in the region.

The validation involved comparing the observed PGA values recorded during this event with those predicted by the newly developed GMPEs, formulated in both M_w and M_{wg} scales. Additionally, the predicted values were evaluated against selected existing GMPEs to examine consistency and performance. A comparison with other earthquakes was also conducted, which showed that the DC25 model performs well. However, due to space constraints, all corresponding figures and results could not be included here.

The comparison, shown in Figure 3 (a, b), demonstrates the capability of the developed GMPEs to accurately capture the attenuation behaviour and ground motion characteristics for this significant event in NE India. This independent validation highlights the applicability of the proposed models for future seismic hazard analysis in the region.



(a)



(b)

Figure 3. Comparison of the predicted PGAs derived from the DC24 equation, existing GMPEs, and the observed recordings for the 9th January, 2013, Myanmar–India Earthquake (M 5.9) in: (a) the M_w scale and (b) the M_{wg} scale.

5 CONCLUSIONS

Following are the major conclusions of the study stated as below:

- The Ground Motion Prediction Equations (GMPEs) developed in this study are specifically designed for the Northeastern (NE) region of India, a seismically active area located at the junction of the Himalayan arc and the Indo-Burma subduction zone. These models are derived from strong-motion records of earthquakes with moment magnitudes ranging from 4.2 to 6.8, and hypocentral distances extending up to 900 km, using data from seismic events that occurred between 2009 and 2013.
- A nonlinear multiple regression analysis was performed to derive the regression coefficients and quantify residuals. Model validation was carried out using an independent earthquake event from the region that was the January 9, 2013, Myanmar-India Border Earthquake (M 5.9); which was not part of the training dataset. This event, located within the Indo-Burma tectonic domain, provides a realistic test case for evaluating model performance in the NE context. The comparison of observed vs. predicted PGA values confirms that the developed GMPEs perform better than many existing models in accurately estimating ground motion in this complex seismotectonic setting. Minor discrepancies due to sparse data at large distances

are acknowledged and will be addressed through future dataset expansion.

- Previous research, including Das et al. (2019), has indicated that the conventional M_w scale tends to underestimate the earthquake energy for small to moderate magnitude events (M 3.0–7.5), especially within subduction and collisional tectonic environments such as Northeast India. To overcome this limitation, the present study develops a new GMPE in the generalized moment magnitude (M_{wg}) scale, encompassing events within the magnitude range of M 4.2–6.8. This first-of-its-kind model for NE India exhibits superior predictive performance, especially for smaller and moderate magnitude events, enhancing the region’s seismic hazard modeling capabilities.
- The M_{wg} -based GMPE marks a pioneering development in seismic hazard analysis, representing the first such model developed globally for the NE Indian region. In parallel, the newly derived M_w -based GMPE, built exclusively from observed data, demonstrates broader applicability across distance and magnitude ranges while achieving lower residuals compared to existing GMPEs. Both models strengthen efforts in risk mitigation, seismic hazard mapping, and earthquake-resistant design specific to NE India.
- This study focuses on developing Ground Motion Prediction Equations (GMPEs) for Peak Ground Acceleration (PGA) at T = 0 seconds, owing to its critical engineering relevance and extensive availability in recorded datasets. Due to the scarcity of reliable spectral acceleration (SA) data at longer periods for the Northeastern region of India, the present model is confined to PGA. Future research will aim to extend the model to predict SA across multiple periods, thereby enhancing its applicability for performance-based engineering and advanced seismic risk evaluation.

Overall, the development of region-specific GMPEs for Northeast India presented in this study represents a significant step forward in addressing the long-standing gaps in seismic hazard modeling for this tectonically complex region. Beyond the technical advancements, the study underscores the importance of regionally calibrated models in capturing the ground motion behavior more realistically than globally or generically derived equations. By aligning ground motion modeling with the local seismotectonic context, the work not only enhances scientific understanding but also contributes meaningfully to public safety and infrastructure resilience. As seismic risk continues to rise with increasing urbanization in vulnerable areas, the insights gained from this research offer a timely and essential foundation for improved hazard preparedness and policymaking.

Moving forward, the integration of multidisciplinary approaches and newer datasets will further elevate the predictive accuracy and utility of such models, ultimately aiding in the development of earthquake-resilient communities across Northeast India.

6 ACKNOWLEDGMENT

The authors extend their heartfelt thanks to Dr. Ranjit Das, Assistant Professor at Universidad Católica del Norte, Chile, for his insightful and constructive guidance throughout the planning and preparation of this manuscript.

7 REFERENCES

- Abrahamson, N.A., Silva, W.J., and Kamai, R. 2014. Summary of the ASK14 ground motion relation for active crustal regions. *Earthquake Spectra* 30, 1025–1055.
- Anbazhagan, P., Kumar, A., and Sitharam, T.G. 2013. Ground motion prediction equation considering combined dataset of recorded and simulated ground motions. *Soil Dynamics and Earthquake Engineering* 53, 92–108. Available at: <https://doi.org/10.1016/j.soildyn.2013.06.003>
- Bajaj, K., and Anbazhagan, P. 2019. Determination of GMPE functional form for an active region with limited strong motion data: application to the Himalayan region. *Journal of Seismology* 22, 161–185. Available at: <https://doi.org/10.1007/s10950-017-9701-1>
- Baruah, S., Baruah, S., Gogoi, N.K., Erteleva, O., Aptikaev, F., and Kayal, J.R. 2009. Ground motion parameters of Shillong plateau: one of the most seismically active zones of northeastern India. *Earthquake Science* 22, 283–291. Available at: <https://doi.org/10.1007/s11589-009-0285-2>
- Bureau of Indian Standards. 2016. *Criteria for earthquake resistant design of structures—general provisions and buildings. Part 1 (IS 1893:2016)*. New Delhi: BIS, 1–39.
- Campbell, K.W., and Bozorgnia, Y. 2014. NGA-West2 ground motion model for the average horizontal components of PGA, PGV, and 5% damped linear acceleration response spectra. *Earthquake Spectra* 30, 1087–1115.
- Campbell, K.W. 1981. Near-source attenuation of peak horizontal acceleration. *Bulletin of the Seismological Society of America* 71, 2039–2070.
- Chiou, B.S.J., and Youngs, R.R. 2014. Update of the Chiou and Youngs NGA model for the average horizontal component of peak ground motion and response spectra. *Earthquake Spectra* 30, 1117–1153.
- Das, A., Das, T., Chaudhuri, C.H., and Choudhury, D. 2024. Integrated study on buried pipelines, co-seismic landslides, and magnitude conversion for 2023 Türkiye earthquake. *Engineering Geology* 337, 107599. Available at: <https://doi.org/10.1016/j.enggeo.2024.107599>
- Das, R., and Das, A. 2025. Limitations of Mw and M scales: compelling evidence advocating for the Das Magnitude Scale (M_{wg})—a critical review and analysis. *Indian Geotechnical Journal* 1–19. Available at: <https://doi.org/10.1007/s40098-024-01147-6>
- Das, R., Menesis, C., and Urrutia, D. 2023. Regression relationships for conversion of body wave and surface wave magnitudes toward Das magnitude scale, M_{wg} . *Natural Hazards* 117, 365–380.
- Das, R., Sharma, M.L., Wason, H.R., Choudhury, D., and Gonzalez, G. 2019. A seismic moment magnitude scale. *Bulletin of the Seismological Society of America* 109, 1542–1555.
- Das, A., Das, R., and Choudhury, D. 2025a. Improved regional earthquake magnitude scaling relations for the Indian subcontinent. *Natural Hazards Review* 26(4), 04025048. Available at: <https://doi.org/10.1061/NHREFO.NHENG-2332>
- Das, A., Das, R., and Choudhury, D. 2025b. Ground motion prediction equations for the Himalayan region based on earthquake data using conventional and random forest approaches. *Natural Hazards* 121, 22095–22119. Available at: <https://doi.org/10.1007/s11069-025-07678-2>
- Fukushima, Y., and Tanaka, T. 1990. A new attenuation relation for peak horizontal acceleration of strong earthquake ground motion in Japan. *Bulletin of the Seismological Society of America* 80, 757–783.
- Gogoi, A., Baruah, S., and Sharma, S. 2023. Regression analysis on ground motion parameters for the earthquakes ($M_w \geq 4.0$) in NE India with special emphasis on 3 Jan 2016 M6.7 Tamenglong earthquake. *Physics and Chemistry of the Earth, Parts A/B/C* 129, 103316. Available at: <https://doi.org/10.1016/j.pce.2022.103316>
- Gupta, I. 2017. Uniformly processed strong motion database for Himalaya and Northeast Region of India. *Pure and Applied Geophysics* 175, 829–863. Available at: <https://doi.org/10.1007/s00024-017-1703-y>
- Hanks, T.C., and Kanamori, H. 1979. A moment magnitude scale. *Journal of Geophysical Research: Solid Earth* 84(B5), 348–2350.
- Joyner, W.B., and Boore, D.M. 1988. Measurement, characterization, and prediction of strong ground motion. *Proc. Earthquake Engineering and Soil Dynamics II, Am. Soc. Civil Eng. Geotech. Eng. Div. Specialty Conference*, 27–30.
- Kanamori, H. 1977. The energy release in great earthquakes. *Journal of Geophysical Research* 82, 2981–2987.
- Khattri, K.N. 1987. Great earthquakes, seismicity gaps and potential for earthquake disaster along the Himalaya plate boundary. *Tectonophysics* 138, 79–92. Available at: [https://doi.org/10.1016/0040-1951\(87\)90067-9](https://doi.org/10.1016/0040-1951(87)90067-9)
- Kramer, S.L. 1996. *Geotechnical Earthquake Engineering, Vol. 3*. Prentice Hall, New York, 71–72.
- Nath, S.K., Thingbaijam, K.K.S., Maiti, S.K., and Nayak, A. 2012. Ground-motion predictions in Shillong region, northeast India. *Journal of Seismology* 16, 475–488. Available at: <https://doi.org/10.1007/s10950-012-9285-3>
- Nath, S.K., Vyas, M., Pal, I., and Sengupta, P. 2005. A seismic hazard scenario in the Sikkim Himalaya from seismotectonics, spectral amplification, source parameterization, and spectral attenuation laws using strong motion seismometry. *Journal of Geophysical Research: Solid Earth* 110(B1).
- National Disaster Management Authority. 2010. *Development of probabilistic seismic hazard map of India*. Technical report, Government of India. Available at: <http://www.ndma.gov.in/images/pdf/Indiaphafinalreport.pdf>
- Pallavi Joshi, S., Das, R., and Bairwa, A.K. 2023. Earthquake disaster database system in assessment and prediction of seismic hazard. *Sādhanā* 48(4), 225.
- Parvez, I.A., Sutar, A.K., Mridula, M., et al. 2008. Coda Q estimates in the Andaman Islands using local earthquakes. *Pure and Applied Geophysics* 165, 1861–1878. Available at: <https://doi.org/10.1007/s00024-008-0399-4>
- Ramkrishnan, R., Sreevalsa, K., and Sitharam, T.G. 2020. Strong motion data based regional ground motion prediction equations for northeast India based on non-linear regression models. *Journal of Earthquake Engineering* 1–21. Available at: <https://doi.org/10.1080/13632469.2020.1778586>
- Sharma, M.L. 1998. Attenuation relationship for estimation of peak ground horizontal acceleration using data from strong-motion arrays in India. *Bulletin of the Seismological Society of America* 88, 1063–1069.
- Singh, N.M., Rahman, T., and Wong, I.G. 2016. A new ground-motion prediction model for Northeastern India (NEI) crustal earthquakes. *Bulletin of the Seismological Society of America* 106, 1282–1297. Available at: <https://doi.org/10.1785/0120150180>
- Youngs, R.R., Chiou, S.J., Silva, W.J., and Humphrey, J.R. 1997. Strong ground motion attenuation relationships for subduction zone earthquakes. *Seismological Research Letters* 68, 58–73. Available at: <https://doi.org/10.1785/gssrl.68.1.58>