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# A Referenced Empirical Framework for Regional adjustment of Ground-Motion Models in the Indian Himalayas

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## Abstract

This study evaluates and develops regionally adjusted Ground Motion Models (GMMs) for the Himalayan region using a reference-based empirical approach. Owing to the tectonic complexity of the Himalaya and the limited availability of strong-motion data, the direct application of global GMMs may introduce systematic bias. To address this, regional adjustment factors are derived by utilizing a dataset of 724 recordings from 189 earthquakes recorded at 197 stations, covering moment magnitudes $M_w \geq 2.0$ and hypocentral distances ($R_{hypo}$) up to 400km. Three adjusted models are proposed: (1) fully parameterized model incorporating magnitude, distance; (2) constrained model enforcing compatibility at near-source distances (< 10 km); (3) simplified model based on linear distance-dependent correction. Model performance is evaluated for peak ground acceleration (PGA) and spectral acceleration (SA) at periods up to 2.0s. Results indicate that the constrained model improves agreement with regional observations while maintaining near-source stability, whereas the simplified model achieves comparable performance with reduced complexity. Both adjusted models outperform the reference global GMMs, particularly at intermediate distances, underscoring the importance of region-specific calibration and demonstrating the effectiveness of the proposed adjustment framework for PSHA applications in data-limited regions. In addition, we provide a data-driven framework for implementing these adjusted GMMs within PSHA workflows in the Indian context, enabling more reliable hazard estimates where regional strong-motion datasets remain sparse.


## Introduction

Probabilistic Seismic Hazard Analysis (PSHA) provides a framework for estimating the likelihood that earthquake ground motions will exceed specified intensity levels at a site over a given time period. A key component of PSHA is the Ground Motion Models (GMMs), which relate ground-motion intensity measures (IMs), such as peak ground acceleration (PGA) and spectral acceleration (SA), to earthquake source, path, and site characteristics, including magnitude, source-to-site distance, faulting style, and local site conditions. In tectonically active regions with dense strong-motion networks (e.g., California, Japan, and New Zealand), GMMs have been developed using extensive high-quality datasets covering wide ranges of magnitude, distance, and site properties. Advances in instrumentation, data processing, and metadata quality have enabled latest GMMs to incorporate refined distance metrics (e.g., rupture and Joyner-Boore distances) and improved representation of near-source effects,

leading to enhanced statistical stability, better-constrained epistemic uncertainty, and more physically consistent modeling of attenuation and site response. A major advancement in empirical ground-motion modeling was achieved through the Pacific Earthquake Engineering Research Center Next Generation Attenuation (PEER-NGA) projects. The NGA-West1 initiative produced a suite of GMMs based on a large, uniformly processed strong-motion database and standardized definitions of magnitude, distance metrics, site parameters ($V_{S30}$), and faulting style, significantly improving model robustness and consistency (Power et al., 2008; Abrahamson et al., 2008; Boore and Atkinson, 2008; Campbell and Bozorgnia, 2008; Chiou and Youngs, 2008). These models form basis of contemporary seismic hazard and engineering applications worldwide. However, NGA-West1 GMMs are primarily calibrated for shallow crustal earthquakes in active tectonic regions, particularly western North America, and can exhibit systematic bias when applied to regions with differing tectonic regimes, stress conditions, and attenuation characteristics. Later, NGA-West2 program expanded the strong-motion database and introduced refinements to magnitude and distance scaling, nonlinear site response, hanging-wall effects, basin-depth terms, and improved treatment of epistemic uncertainty (Bozorgnia et al., 2014). Subsequent developments have further advanced source and path characterization through regionally calibrated attenuation models and mixed-effects regression frameworks (Abrahamson and Bhasin, 2020; Kuehn and Abrahamson, 2020; Parker et al., 2022). These developments have exposed limitations of the traditional ergodic assumption, motivating partially and fully non-ergodic GMMs that explicitly separate source, path, site variability and account for spatial correlation in ground motion (e.g., Lin et al., 2011; Bayless & Abrahamson, 2019; Kuehn et al., 2020).

Within Indian context, seismic hazard is dominated by the tectonically active Himalayan arc, one of the world's most seismically active regions, formed by the ongoing convergence and under thrusting of the Indian Plate beneath the Eurasian Plate (Bilham, 2019). The densely populated Indo-Gangetic plains south of the Himalayan front are particularly vulnerable due to their proximity to major seismogenic sources and the presence of deep alluvial basins capable of significantly amplifying ground motions (Bollinger et al., 2006; Nath et al., 2005). Despite this, PSHA studies in the Indian subcontinent largely rely on global GMMs developed for well-instrumented active tectonic regions, including NGA-West1, NGA-West2, and models derived from RESORCE and KiK-net datasets. Although several region-specific GMMs have been proposed for the Indian Himalayas (e.g., NDMA, 2010; Nath and Thingbaijam, 2011; Bajaj and Anbazhagan, 2019; Ramkrishnan et al., 2019; Sreejaya et al., 2022), their applicability is

often constrained by sparse strong-motion data and limited magnitude-distance coverage. Consequently, the widespread use of global GMMs implicitly assumes that Himalayan seismotectonic and wave-propagation characteristics are comparable to those of the host regions (California, Europe and Japan) used for model development, and also model-embedded aleatory and epistemic variability adequately represents uncertainty in the target region. However, ground-motion scaling and attenuation are known to vary significantly across tectonic environments due to differences in crustal structure, regional attenuation, stress-drop characteristics, and site response (Boore, 2003; Atkinson, 2004; Weatherill et al., 2020; Kotha et al., 2020). As a result, host-region GMMs frequently exhibit systematic bias when applied outside their calibration domain. Recent advances within the NGA framework emphasize the importance of explicitly accounting for regional path and site effects (Abrahamson and Bhasin, 2020; Kuehn and Abrahamson, 2020), yet such approaches remain largely absent from PSHA studies in India. This highlights the need for regionally appropriate GMMs, either through the development of new models and ground-motion simulations or through systematic, data-driven adjustment of existing global models. Hence, the applicability of global GMMs must be critically evaluated prior to their use in Indian hazard assessments. The data-driven adjustments in the published global GMM remains a preferred approach globally for seismic hazard analysis (Bradley et al., 2024; Moschetti et al., 2025).

Traditional GMMs are generally developed using three approaches: (i) purely empirical, (ii) stochastic simulation, and (iii) hybrid empirical techniques. Empirical GMMs rely on regression of observed ground motions and are most effective in well-instrumented regions. Stochastic simulation models provide an alternative for data-sparse regions by explicitly modeling source, path, and site effects, though their performance depends on assumed source and attenuation parameters (Atkinson and Boore, 1995, 2006, Boore 2003; Yenier and Atkinson, 2015, Omkar et al., 2026). Hybrid approaches combine empirical models with simulation-based adjustments (Campbell, 2003; Pezeshk et al., 2011). When observational data are insufficient for fully empirical model development, the referenced empirical approach (Atkinson, 2008) offers a practical solution by anchoring a host GMM and deriving region-specific adjustment factors directly from empirical residuals. While conceptually related to hybrid methods, the referenced empirical approach is entirely data-driven and assumes comparable source-scaling behaviour between host and target regions, such that residual trends primarily reflect regional path and site effects. Its effectiveness has been demonstrated in several data-constrained regions, including eastern North America, Hawaii, and Puerto Rico

(Atkinson, 2008, 2010; Atkinson and Boore, 2011; Atkinson and Motazedian, 2013; Hassani and Atkinson, 2015). In the Himalayan region, recent efforts to compile indigenous strong-motion datasets, particularly the Indian Ground Motion (IGM) database (Sharma et al., 2025), have improved data availability for PSHA. However, recordings remain sparse especially for large magnitudes ($M > 6$) and near-source distances ($\leq$ 20km) and often lack key metadata required by modern GMMs. To address these limitations, this study adopts a referenced empirical approach to develop regionally calibrated GMMs. Unlike stochastic simulations, which rely on poorly constrained source, path, and site parameters and may yield non-unique solutions in tectonically complex settings (Sharma et al., 2024), this approach derives adjustments directly from observed ground motions. The adjustments are anchored to widely used global GMMs, including Abrahamson and Silva, 2008 (AS08), Abrahamson et al., 2014 (ASK14), Boore et al., 2014 (BSSA14), Campbell and Bozorgnia, 2014 (CB14), Chiou and Youngs, 2014 (CY14).

Thus, the primary objective of this study is to derive empirical adjustment factors (AFs) for PGA and SA across multiple periods, enhancing the regional applicability of global GMMs for the Indian Himalayan region. While this approach partially mitigates epistemic uncertainty associated with regional differences in attenuation and site response, the focus of this work is restricted to the development and evaluation of robust regional adjustments; a comprehensive treatment of uncertainty lies beyond the scope of the present study. Nevertheless, the adjusted models are readily compatible with probabilistic frameworks and can be used to better represent regional ground-motion characteristics in Indian PSHA. Accordingly, this paper is structured as follows: (1) comparative evaluation of global GMMs against existing Himalayan GMMs; (2) detailed description of the adjustment methodology used for deriving the referenced empirical adjustment; (3) evaluates the performance of the adjusted models using regional observations; and (4) a data-driven framework for application of the adjusted GMMs for seismic hazard analysis in Indian context through their distance-scaling characteristics. A weighted ensemble of the adjusted models is subsequently developed based on their relative agreement with the observations, and its performance is evaluated. This provides an integrated assessment of the regional applicability of the adjusted models while accounting for variability among the individual host-model formulations.

## Ground-motion database and Selection Criteria

This study utilises the strong-motion dataset compiled by Sharma et al. (2025) within the IGM database, which represents the most comprehensive publicly available collection of strong-motion records from the Indian subcontinent, with a particular emphasis on the Himalayan region. From this database, we selected 724 recordings from 189 earthquakes, recorded between 1986 and 2018 at 197 seismic stations. The dataset spans moment magnitudes, M or $M_w \geq 2.0$ and hypocentral distances, $R_{hypo} \leq 400$km, providing adequate coverage of the magnitude-distance space relevant for ground-motion modeling and seismic hazard analysis, with a representative site condition of $V_{S30} = 400$ m/s adopted in this study. The inclusion of low-magnitude events ($M_w \geq 2.0$) improves constraints on magnitude scaling and attenuation at short distances by increasing data density in the near field, thereby enhancing the statistical stability of the regression analysis. Figure 1 shows spatial distribution of earthquake epicenters and recording stations, along with major fault traces, with epicenters scaled by magnitude, facilitating visualization of both their geographic distribution and variation in event size.

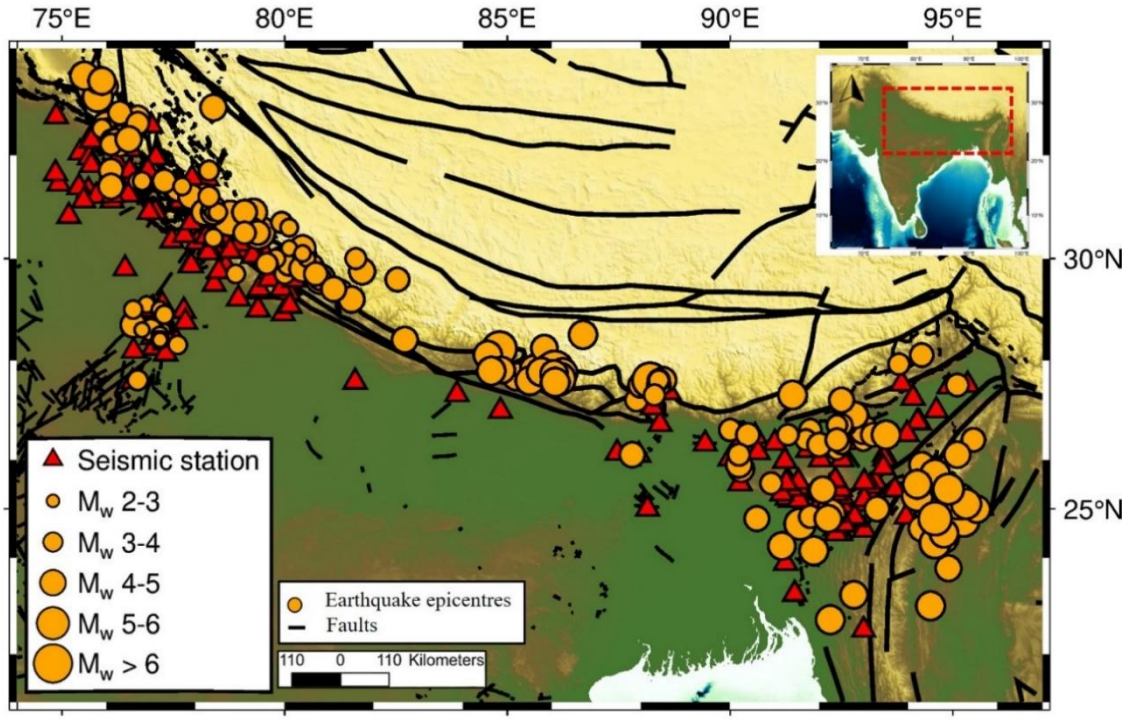



***Figure 1. Spatial distribution of earthquake epicenters (orange circles) and seismic stations (red triangles) recorded by multiple seismic networks from 1986 to 2018. Circle sizes correspond to earthquake magnitudes, with larger diameters indicating higher magnitudes.***

Figure 2 (a) illustrates the distribution of $M_w$ and $R_{hypo}$, showing a pronounced concentration of recordings within ~200 km, with progressively fewer recordings at larger distances. Figure 2 (b) illustrates the corresponding depth distribution, indicating that the majority of events are

shallow, with depths < 20km, and a limited earthquakes occurring at depths > 50km. Consistent with other regional datasets, a key limitation is the paucity of large-magnitude ($M_w$ > 6) events recorded at near-source distances (<100km).

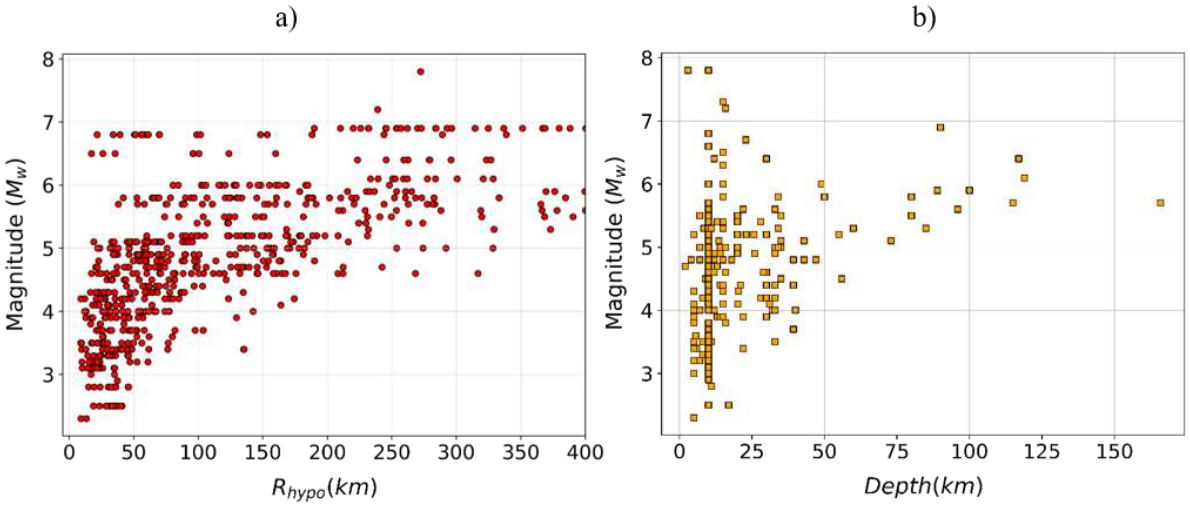



***Figure 2. (a) Moment magnitude ($M_W$) and hypocentral distance ($R_{hypo}$) distribution of ground-motion records used in the study, and (b) Moment magnitude and depth distribution of events.***

Although, NGA-West models are formulated using rupture-based distance measures such as $R_{JB}$ and $R_{rup}$, $R_{hypo}$ is used in the present study because detailed finite-fault parameters are unavailable for a substantial proportion for the considered earthquakes. For the present dataset, major differences between Rhypo and rupture distance are not expected, and any systematic effect of this choice would appear in the residuals. $R_{hypo}$ is also consistent with several GMMs developed for the Indian region (e.g., Sharma, 1998; Raghu Kanth and Iyengar, 2007; Nath et al., 2009; Anbazhagan et al., 2013; Kumar et al., 2015). Site characterization is another important consideration. Although $V_{S30}$ values are reported for several stations in the adopted database, the source documentation does not consistently state whether they were measured directly or inferred from proxies, and the recordings come from multiple networks with different site-characterization approaches. To avoid the uncertainty of mixing estimation methods, a common reference $V_{S30}$ of 400 m/s was adopted for all NGA-West models instead of the station-specific values. This provides a uniform basis for comparison and evaluating the relative performance of the models. Further, the IGM database provides a comprehensive set of ground-motion intensity measures, including peak ground acceleration, velocity, and displacement, as well as spectral acceleration over a broad frequency range (0.01-10 Hz). For the present analysis, the study specifically utilizes PGA and SA consistent with standard practice in GMM development and seismic hazard analysis.

## Comparison of global NGA-West GMMs with the Himalayan GMMs

Although numerous GMMs have been developed worldwide, PSHA in India has largely relied on NGA-West models as reference frameworks across diverse tectonic settings (e.g., Nath et al., 2005; NDMA, 2010; Nath & Thingbaijam, 2012; Kumar et al., 2017; Bajaj and Anbazhagan, 2019). Given the relatively sparse Indian strong-motion network compared to well-instrumented regions such as California and Japan, studies have increasingly adopted modified or regionally calibrated NGA-West models to better represent local seismic and site conditions. However, direct application of these global models in the Himalayan region without regional calibration can introduce significant epistemic and aleatory uncertainties (Sharma et al., 2024) and lead to biased ground-motion estimates. Validation studies (e.g., Nayak et al., 2011) show that NGA-West models often misrepresent ground-motion amplitudes in the Indian context, particularly at large magnitudes and short distances, owing to the distinct tectonic characteristics of the Himalayan collision zone shallow thrust faulting, higher stress drops, and stronger high-frequency radiation. Limited site characterization and strong geological variability further reduce the reliability of NGA-West site terms, underscoring the need for region-specific adjustments. This section therefore presents a comparative evaluation of five NGA-West models (AS08, ASK14, BSSA14, CB14, CY14) and five Himalayan GMMs (NDMA10; Sharma and Haribhandhu, 2012 (SHK12); Anbazhagan et al., 2013 (AKS13); Harbindu et al., 2014 (HGS14); BA19) across a range of magnitudes and source-to-site distances for PGA and SA, thus allowing consistent comparison across IMs.

Although the full analysis spans SA up to 2.0s, results are illustrated for PGA and SA at 1.0s (in supplementary) for four representative magnitudes (M=3.5, 4.5, 5.5, 6.5), highlighting key inter-model differences. Only models valid within the corresponding magnitude ranges are shown. The selected representative magnitudes were defined based on the distribution of the available recordings. The observations were grouped into four magnitude bins: the $M_w = 3.5$ scenario includes all recordings from earthquakes with $M_w < 4.0$; $M_w = 4.5$ scenario includes recordings from earthquakes with $4.1 \leq M_w \leq 5.0$; the Mw = 5.5 scenario includes recordings with $5.1 \leq M_w \leq 6.0$; and the $M_w = 6.5$ scenario includes all recordings from earthquakes with $M_w > 6.0$. These representative scenarios were selected based on the distribution of the available dataset to ensure that all recordings were included in the evaluation while providing a clear comparison of model performance across different magnitude ranges. Figure 3 compares variation of PGA with distance, showing that Himalayan GMMs do not fully represent the corresponding NGA-West behaviour, particularly for $M \geq 4.5$ at near-source (<

10km) and far-field (> 100km) distances. Himalayan models also display greater variability in spectral shape (reflecting larger epistemic uncertainty), whereas NGA-West models show smoother and more consistent attenuation. Among Himalayan models, SHK12 and HGS14 agree most closely with NGA-West predictions at short distances (< 50km), while NDMA10 and AKS13 show large variability at very short distances (< 10km). BA19 broadly follows NGA-West but tends to overpredict PGA beyond ~10km and exhibits inconsistent attenuation, suggesting possible overfitting.

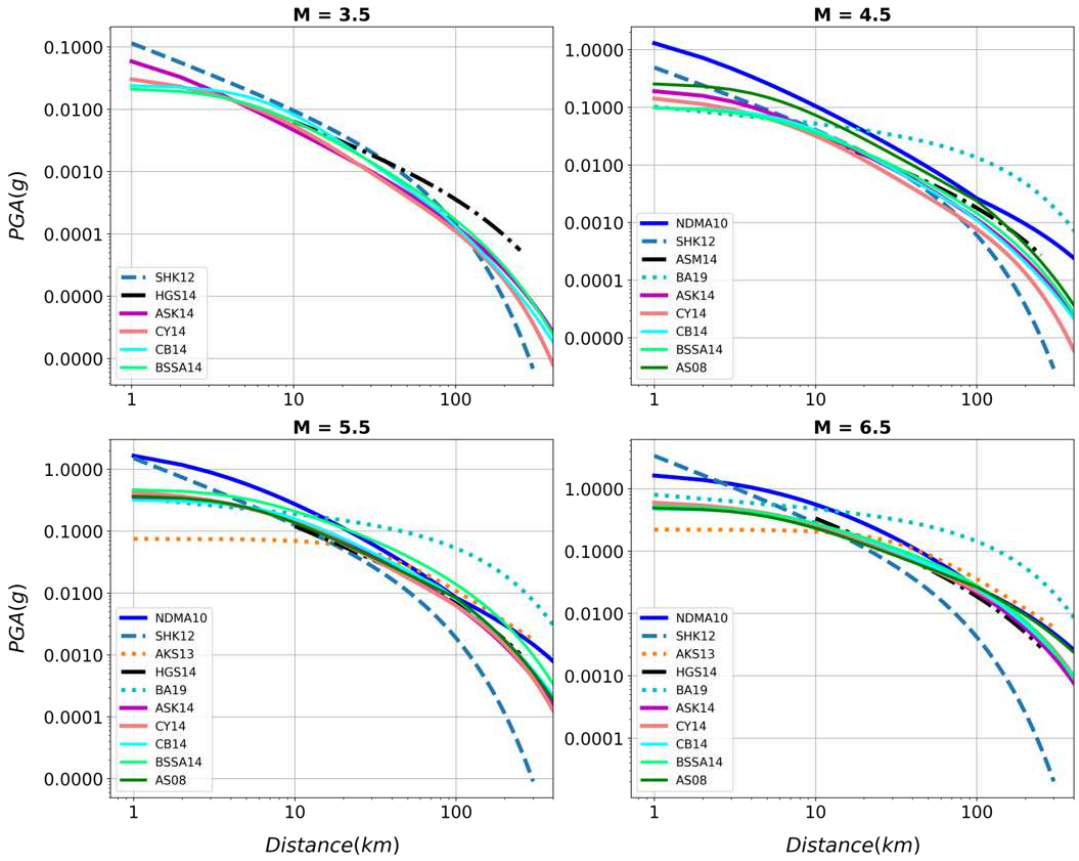



***Figure 3. Comparisons of NGA-West with selected Himalayan GMMs for peak ground acceleration (PGA) with respect to distance for four magnitude scenarios M = 3.5, 4.5, 5.5 and 6.5.***

Also, Figure S.1 (in Supplementary Material) illustrates the distance-scaling behaviour of SA at T = 1.0s showing noticeable differences in spectral shape and distance decay, particularly at larger magnitudes. Himalayan models exhibit greater scatter and inconsistent attenuation patterns, whereas NGA-West models display smoother and more systematic trends. These contrasts highlight the influence of regional source, path, and site effects and demonstrate the limitations of directly applying global models without calibration. Overall, the comparison reinforces the need for empirically constrained, regionally adjusted GMMs that better capture

the seismological characteristics of the Indian region. An additional comparison of aleatory variability shown in Figure 4, was conducted as a function of period. The period-dependent standard deviation indicates that NGA-West models exhibit a relatively narrow variability band, whereas Himalayan GMMs show substantially larger spread, particularly at short periods. This dispersion reflects epistemic differences in datasets, functional forms, and treatment of regional effects. Some of the Himalayan GMMs exhibit very small values of aleatory variability that essentially reflects a problem often encountered with smaller datasets and over-fitting of the models. This is the main reason that we have such larger differences between the models in terms of both median (Figure 3) and aleatory variability (Figure 4).

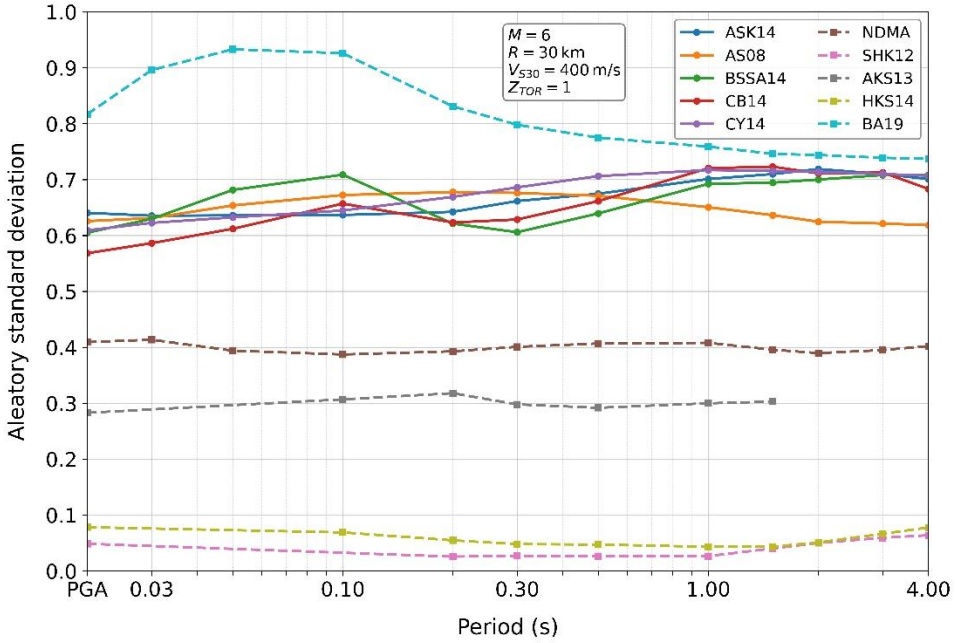



***Figure 4. Comparison of period-dependent aleatory standard deviation predicted by NGA-West ground-motion models (solid lines) and Himalayan models (dashed lines).***

The consistent departure of Indian models from the NGA envelope indicates that aleatory variability inferred from global datasets is not directly transferable to the Indian tectonic setting, underscoring the need for regionally constrained estimates for seismic hazard applications.

## Reference-Based Empirical Adjustment Methodology

The study adopts a referenced empirical approach following Atkinson (2008) to develop a regionally calibrated GMM for the Himalayan region. The method utilizes the well-constrained magnitude scaling and near-source behaviour of a data-rich host GMM, while introducing

region-specific empirical adjustments to distance attenuation using recorded ground motions. This framework is particularly effective where strong-motion data are insufficient for fully empirical model development. It assumes that magnitude scaling and near-source distance dependence are broadly transferable, with regional differences primarily controlled by path-related attenuation. These effects are quantified through residual analysis relative to the host GMM, enabling recalibration of distance-dependent attenuation while preserving the original magnitude scaling. The procedure begins with the selection of an appropriate reference model and application region, forming the basis for subsequent regional adjustment. Each step is discussed below:

**Step 1: Selection of Host and Target Regions**: Five widely used NGA-West GMMs (AS08, ASK14, BSSA14, CB14, and CY14) are adopted as host models, while the Himalayan region as the target region for regional calibration. AFs are derived independently for each host model to account for inter-model variability and to assess the consistency and robustness of the regional corrections.

**Step 2: Computation of Residuals**: To evaluate the suitability of the selected host models, a residual analysis is performed using the available Indian strong-motion dataset. For each IM, total residuals are computed as:

$$\textbf{Residual} = \ln(Y_{obs}) - \ln(Y_{pred}) \quad (1)$$

in which $Y_{obs}$ represents the observed IM whereas $Y_{pred}$ represents the corresponding median prediction from the selected GMMs. The analysis provides a quantitative assessment of how well each selected model reproduces regional ground-motion scaling. Figure 5 presents the residual analysis for the selected NGA-West models, illustrating residual trends as a function of (a) magnitude and (b) distance. Consistent patterns across models indicate systematic regional differences in magnitude scaling and distance attenuation, particularly at larger magnitudes and distances where data are limited. The persistence of these trends highlights the need for region-specific empirical adjustments prior to applying NGA-West models in the Himalayan region. Also, AS08 has been superseded by ASK14 but is retained in our current analysis as it exhibits stable, nearly unbiased magnitude scaling and systematic distance-dependent residual behaviour, making it suitable for deriving robust adjustment factors.

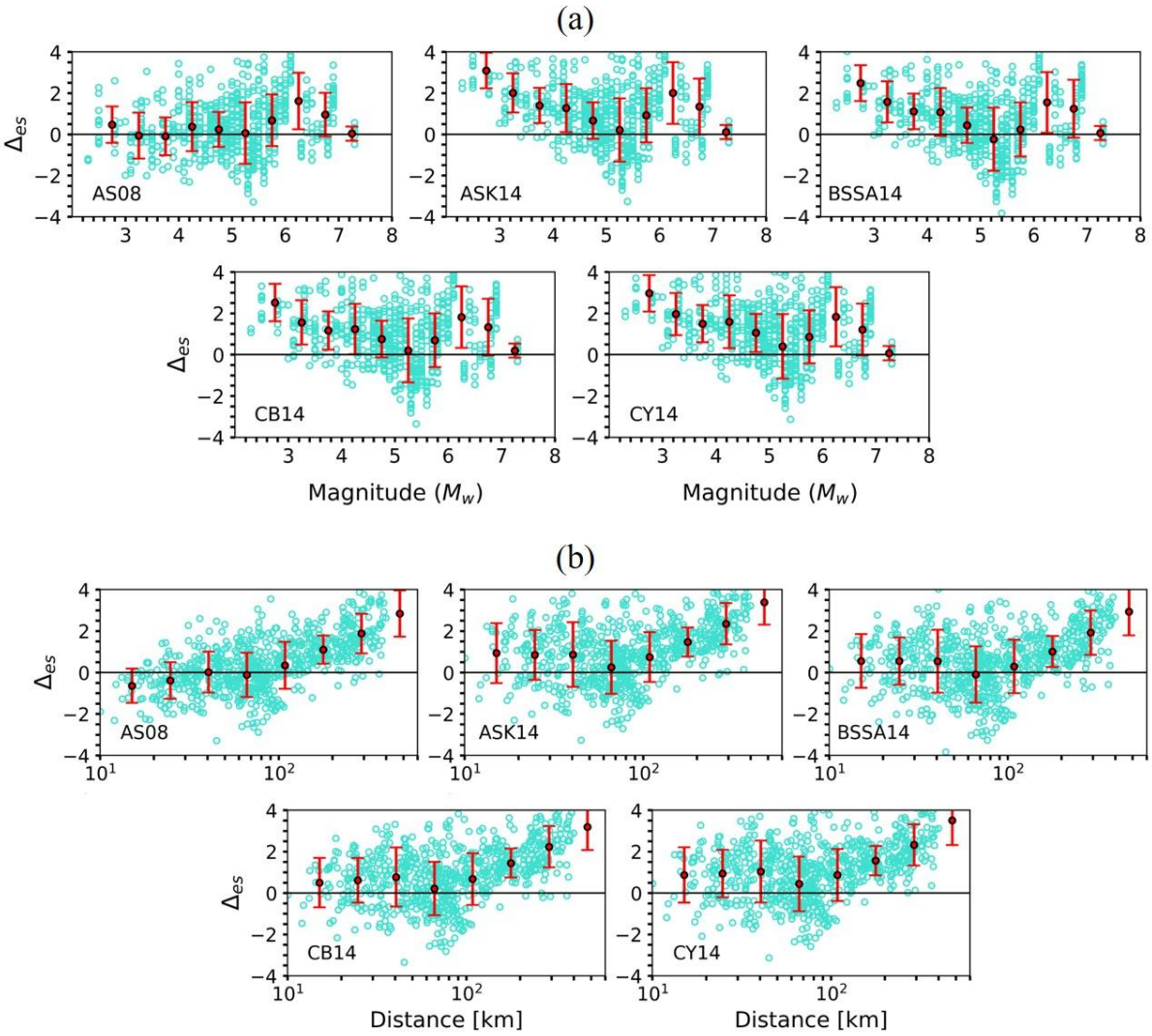



***Figure 5. Total Residuals (ln $Y_{obs}$ − ln $Y_{pred}$) for Peak Ground Acceleration (PGA) plotted against (a) moment magnitude ($M_W$) and (b) distance for five NGA-West Ground Motion Models (GMMs). Red points mark the mean value, and vertical lines in each magnitude bin show one standard deviation.***

In the present study, we restricted the residual analysis to total residuals and considered it only as an initial check of the model performance and regional trends. We limited the residual analysis to this initial check and did not perform a separate decomposition into between-event and within-event residuals, as such decomposition requires a sufficient number of records per event and per station to yield statistically robust estimates of these terms.

**Step 3: Selection of Adjustment Functional Form**: An empirical adjustment function is fitted to the residuals to quantify systematic deviations between observed Himalayan ground motions and host GMM predictions. Several functional forms are tested, including linear and logarithmic distance terms and combined magnitude-distance parameterizations, to capture

both near-source behaviour and regional attenuation. Each functional form is evaluated using iterative nonlinear regression to assess their ability to represent near-source effects and attenuation characteristics, statistical performance (comparisons of Akaike Information Criterion and Bayesian Information Criterion) and complemented by visual inspection of residual trends. Regression is performed independently at each spectral period, yielding period-specific adjustment coefficients that reflect the frequency-dependent nature of regional scaling while limiting overfitting. The final empirical AFs for AS08 and NGA-West2 models were obtained from the best-performing functional forms. Since AS08 originates from the NGA-West1 framework, its AFs were derived separately, as a common functional form did not adequately capture the behaviour of NGA-West2 models; thus, adjustments were estimated independently for AS08 and the NGA-West2 set.

For AS08, the adopted adjustment is expressed as:

$$\ln(AF) = C_0 + C_1 * M * \ln\left(\text{sqrt}\left(R_{hypo}^2 + h^2\right)\right) + C_3 * R_{hypo} \quad (2)$$

$$\text{where, } h = 10^{(-0.405 + 0.235*M)}$$

For the remaining NGA-West2 models, the adjustment takes the form:

$$\ln(AF) = C_0 + C_1 * M * \ln\left(R_{hypo} + h\right) + C_2 * R_{hypo} \quad (3)$$

$$\text{where, } h = M^2$$

here, M-moment magnitude, $R_{hypo}$-hypocentral distance, and h- magnitude-dependent term.

**Step 4: Final Adjusted GMM**: Using the period-specific coefficients obtained in Step 3, empirical AFs are applied to the selected host GMM predictions to construct a regionally calibrated model for the Himalayan region. For each spectral period, the corresponding AF is applied multiplicatively to the host model outputs, yielding regionally representative ground-motion estimates, hereafter referred to as the Adjusted GMM. It is expressed as:-

$$Y_{\text{Adjusted GMM}} = Y_{\text{Host model GMM}} \times AF \quad (3)$$

Here, $Y_{\text{Host model GMM}}$ denotes NGA-West IMs and AF is the empirically derived regional adjustment factor. These AFs independently across spectral periods captures frequency-dependent regional effects resulting in regionally calibrated ground-motion predictions.

**Step 5: Model Validation Using Observed Ground Motions:** In the final step, the adjusted GMM is systematically validated against the observed dataset and with predictions from the NGA-West models. So, we again carried out the residual analysis to assess the adjusted model's performance for source-to-site distance for IMs. These evaluations quantify the degree to which the regional adjustments improve agreement with observations, reduce systematic bias, and maintain physically consistent magnitude scaling and attenuation behaviour.

Thus, this study presents a methodological advancement in ground-motion modeling for the Indian context, addressing challenges posed by sparse instrumental data and complex seismotectonic conditions. By adopting a referenced empirical framework, it expands the range of predictive models available for India and strengthens the basis for logic-tree implementation in PSHA. The approach also highlights systematic mismatches between global formulations and regional observations, identifying attenuation and scaling features requiring adjustment. Validation results indicate that the adjusted models provide a more reliable representation of Himalayan ground motions than unmodified NGA-West models.

## Evaluation of the adjusted GMM

This section provides a systematic evaluation of the empirically adjusted GMM based on regional modifications to selected NGA-West host models. Results are structured into three subsections focusing on:

(1) General model performance across all distances and magnitude scenarios,
(2) Near-source Ground motion characteristics within 0-10km, and
(3) Interpretability and Simplification of the Distance Term ($C_2R$).

For each IM, magnitude-distance binned comparisons are performed to contrast host-model predictions and the adjusted GMM against observed strong-motion data, enabling quantitative evaluation of bias reduction and regional agreement across magnitude, distance, and spectral domains. Although adjustments were developed for SA up to 2.0s, detailed evaluation is shown for PGA in the main text, while corresponding results for SA at T = 1.0s are provided in the Supplementary Material for all each section to maintain clarity and focus.

**(1) General model performance across all distances and magnitude Scenarios:** This subsection evaluates the overall performance of the adjusted GMM. We imposed no constraints, allowing the intrinsic behaviour of the selected AF to be examined over the

complete attenuation domain. This approach enables a direct evaluation of (i) agreement between adjusted predictions and observed strong-motion data, and (ii) systematic departures from the original host models. The results provide a quantitative measure to capture regional attenuation characteristics and reproduce observed Himalayan ground-motion trends. Figure 6 illustrates the performance of the adjusted GMM for PGA across the full distance range for four magnitude scenarios (M = 3.5, 4.5, 5.5, and 6.5). Dotted curves denote host GMM predictions (AS08, ASK14, CY14, CB14, and BSSA14), solid curves their empirically adjusted counterparts, and orange circles the observed strong-motion data. At M = 3.5, the host models show substantial dispersion and systematic misfit, particularly at short to intermediate distances; the adjustments markedly reduce this spread and improve alignment with observations. At M = 4.5 and 5.5, amplitude differences and inter-model variability especially in the far-field are effectively reduced by the adjustments, which converge toward a common decay trend consistent with the data. At M = 6.5, despite sparser recordings, the adjusted models remain anchored to the observations and preserve physically reasonable attenuation behaviour, in contrast to the wider spread of the host models. Overall, the empirical adjustments systematically reduce bias and inter-model scatter across all magnitude scenarios, improving agreement with regional observations.

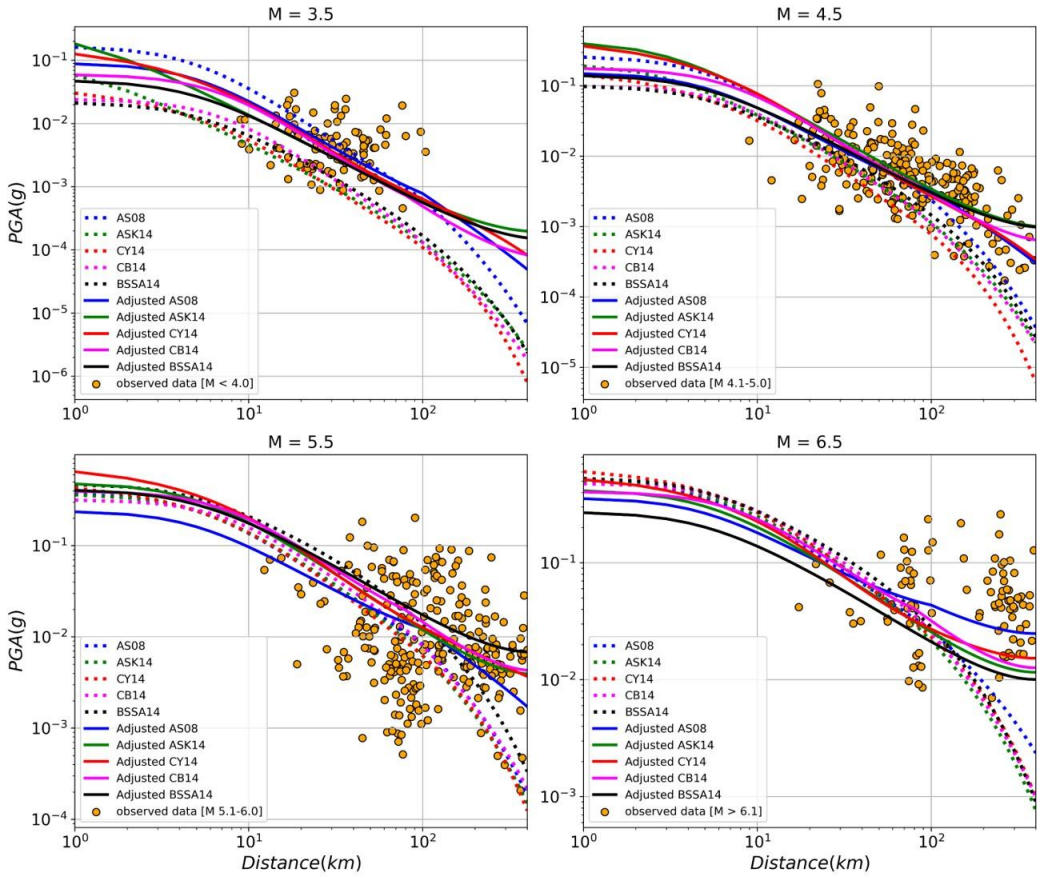


***Figure 6. Comparison of Adjusted GMM and selected Host GMMs with observed ground motion at PGA with no constraint across four magnitude scenarios. The observed ground motion data (yellow circles), the selected Host models (dashed line), and the adjusted GMM (dotted line).***

Figure S.2 (Supplementary Material) presents the comparison at T = 1.0 s. The host NGA-West models exhibit notable dispersion and systematic bias, particularly at near-to-intermediate distances. The empirically adjusted GMM reduces amplitude bias and inter-model scatter, yielding stable predictions and smoother long-period scaling across magnitude scenarios while preserving physically consistent distance attenuation. Overall, the adjustments improve host GMM performance across a broad range of magnitudes and distances, with improvements most evident at moderate magnitudes and intermediate to large distances. Physically consistent attenuation trends are maintained even for larger events despite limited data availability. The regression coefficients ($C_0$, $C_1$, $C_2$) and corresponding predictions are summarized in Table S.1 (in Supplementary Material). Figure 7 further demonstrates the effectiveness of the adjusted models through residual diagnostics. Compared with the systematic trends observed previously (Figure 5b), the residuals show a marked reduction in bias, with distributions that are more symmetric about zero and binned means remaining close to zero across the distance range. The absence of distance-dependent bias indicates that the adjustments effectively capture the dominant regional path characteristics. Consequently, the adjusted models show improved agreement with observed ground motions, confirming that the primary discrepancies present in the unadjusted case have been largely mitigated.

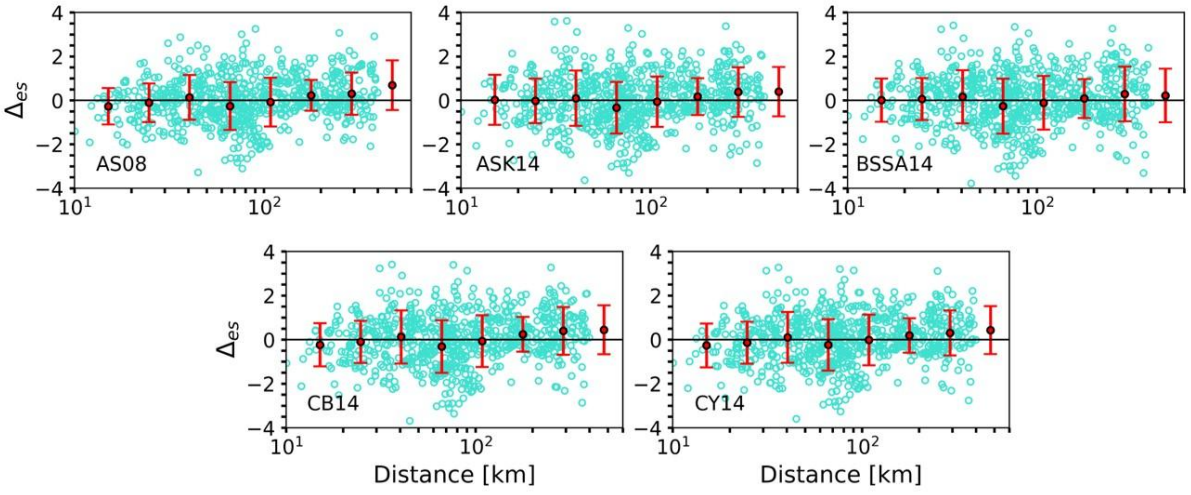



***Figure 7. Total Residuals (ln $Y_{obs}$ − ln $Y_{pred}$) for Peak Ground Acceleration (PGA) plotted against distance for adjusted five NGA-West Ground Motion Models. Red points mark the mean value, and vertical lines in each magnitude bin show one standard deviation.***

**(2) Near-source Ground Motion characteristics within 0-10km:** This subsection evaluates model performance within the near-source distance range (0-10km), where ground-motion behaviour is most complex and predictive uncertainty is highest. Strong-motion recordings within this range remain extremely sparse in India, limiting robust residual estimation. Accordingly, the adjusted model is constrained to follow the host GMM behaviour within 10km, ensuring physical stability and avoiding unrealistic corrections in a data-poor regime. Beyond 10km, where data coverage improves, adjustment factors are derived directly from regional observations, preventing unstable extrapolation while maintaining physically consistent predictions across the full distance range. Figure 8 illustrates PGA distance scaling with the imposed near-source constraint, ensuring that the adjusted models closely follow host-model behaviour within 0-10km where regional data are sparse. Beyond 10km, improved observational coverage allows the adjusted models to depart from the host predictions and align more closely with the recorded ground motions, better capturing regional attenuation trends. For M = 3.5, the adjustment yields only modest improvement at intermediate distances. For moderate magnitudes (M = 4.5-5.5), the adjustments become more pronounced beyond 10km, with the adjusted curves more consistently tracking the central tendency and decay of the observations. At larger magnitudes (M = 6.5), the improvement is strongest at intermediate to far distances, where the adjusted models avoid excessive attenuation while remaining stable near-source due to the constraint. Overall, the adjusted GMM provides the most reliable representation for moderate-to-large events where data support is strongest.

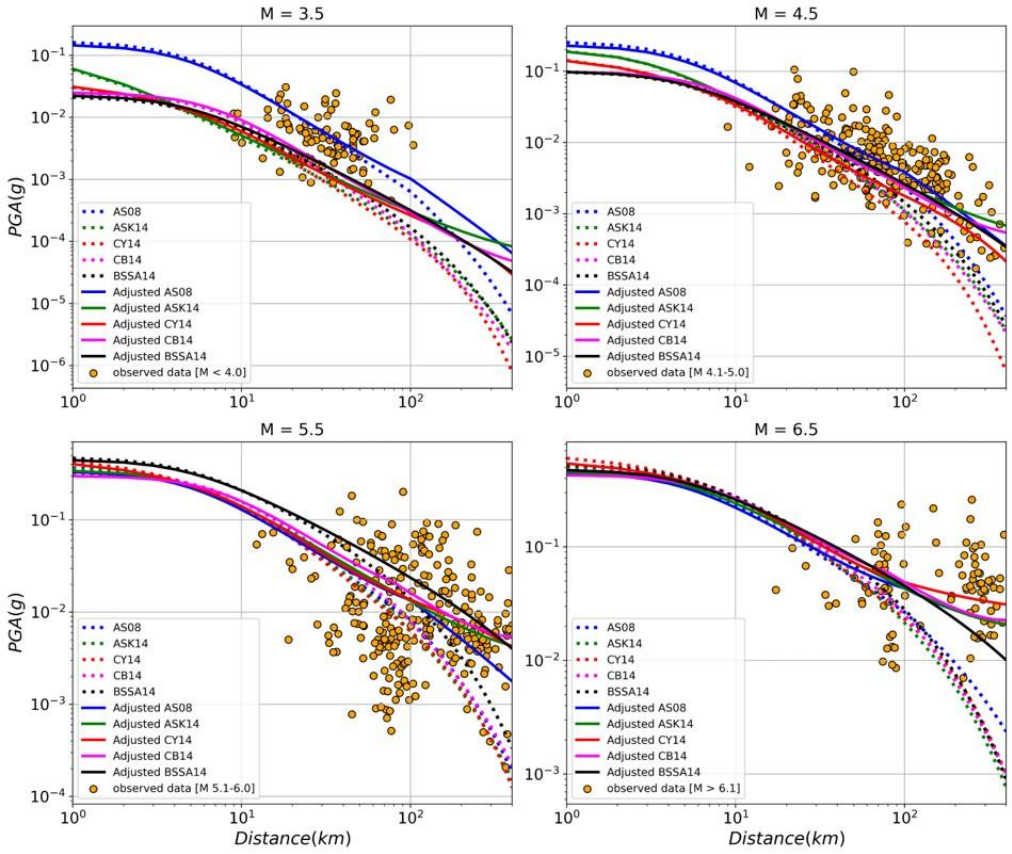



***Figure 8. Comparison of Adjusted GMM and selected Host GMMs with observed ground motion at PGA with constraints within 0-10km distance across four magnitude scenarios. The observed ground motion data (yellow circles), the selected Host models (dashed line), and the adjusted GMM (dotted line).***

Figure S.3 (in Supplementary Material) evaluates the constrained adjusted GMMs for SA at T = 1.0s. The adjustments reduce inter-model variability and improve agreement with observed Himalayan strong-motion data, particularly beyond 10km where observational constraints are stronger. The adjusted models exhibit smoother, physically consistent distance attenuation for moderate-to-large magnitudes while maintaining stable near-source behaviour under the imposed constraint. Overall, the results confirm the effectiveness of the constrained adjustment in enhancing regional consistency and reducing excessive attenuation present in several host models. As summarized in Table S.2 (in Supplementary Material), the regression coefficients ($C_0$, $C_1$, $C_2$) show systematic variation with spectral period. The magnitude-scaling term $C_1$ remains close to zero across periods, indicating weak sensitivity of the adjustment factor to event magnitude. This reflects the imposed near-distance constraint, which suppresses source-related contributions and shifts the regression toward path-controlled attenuation behaviour. Consequently, the adjustments are primarily governed by distance-dependent effects at larger ranges, where path influences dominate the ground-motion response. Figure 9 illustrates the

residuals after applying the constrained adjustment. Consistent with Figure 7, the residuals are more symmetrically distributed about zero, and distance-binned means remain close to zero across the range, indicating removal of systematic distance-dependent bias while preserving near-source stability. The constrained formulation avoids exaggerated short-distance corrections observed in the unconstrained case by anchoring model behaviour within 0-10 km, achieving a balanced representation of near-field consistency and far-field attenuation. Overall, the residual trends confirm that the constrained distance-term adjustment effectively captures dominant regional path effects, yielding more robust and physically interpretable ground-motion predictions.

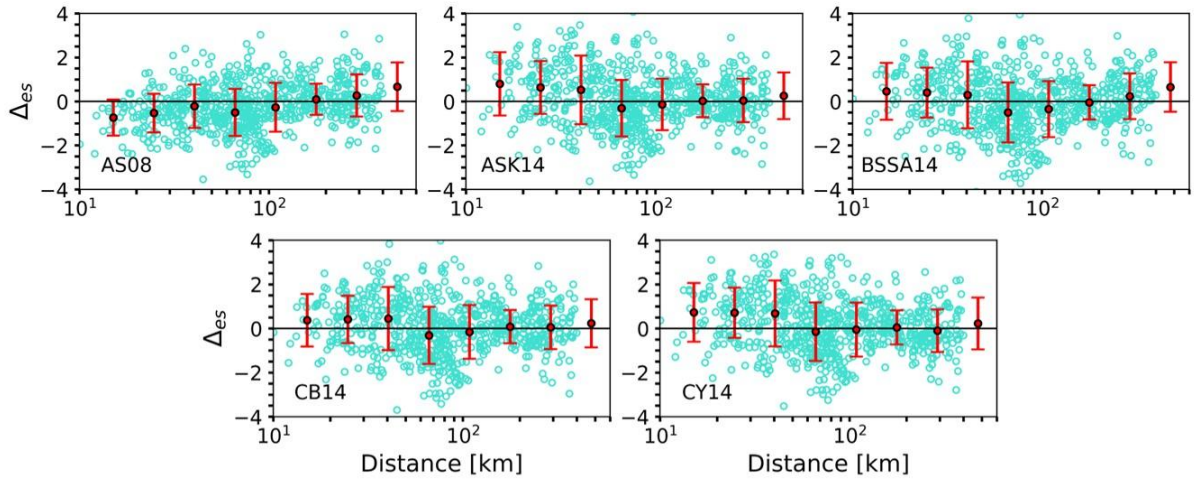



***Figure 9. Total Residuals (ln $Y_{obs}$ − ln $Y_{pred}$) for Peak Ground Acceleration (PGA) plotted against distance for adjusted five NGA-West Ground Motion Models with constraints within 0-10km distance. Red points mark the mean value, and vertical lines in each distance bin show one standard deviation.***

**(3) Interpretability and Simplification of the Distance Term:** This subsection evaluates model interpretability under limited regional data and the imposed near-source constraint. With the 0-10km constraint applied, the estimated magnitude-scaling term consistently approached zero, indicating that magnitude dependence is not the primary source of mismatch between host predictions and regional observations. Systematic deviations instead occur mainly in distance attenuation, highlighting the dominance of path effects. A simplified formulation retaining only the linear distance term ($C_2$R) was therefore tested, yielding stable and physically meaningful predictions without additional magnitude-scaling or depth-proxy terms. These findings suggest that increased functional complexity offers limited benefit in data-limited settings, and that a simplified formulation enhances robustness and interpretability. Figure 10 presents the PGA distance scaling under the $C_2$R

constraint for the considered magnitude scenarios. For M = 3.5, the adjusted models closely track the host models at short distances and show minimal divergence at larger distances, consistent with the weak magnitude influence when near-source behaviour is constrained. At moderate magnitudes (M = 4.5-5.5), the adjustments become more evident beyond approximately 10 km, resulting in improved agreement with the observed PGA distribution and reduced inter-model variability. Across most distances, the adjusted models reproduce the overall attenuation trend, indicating that path-controlled scaling alone adequately captures the observed behaviour without explicit magnitude modification. At higher magnitude (M = 6.5), the models remain stable at intermediate to large distances, avoiding excessive decay while maintaining consistency with observations.

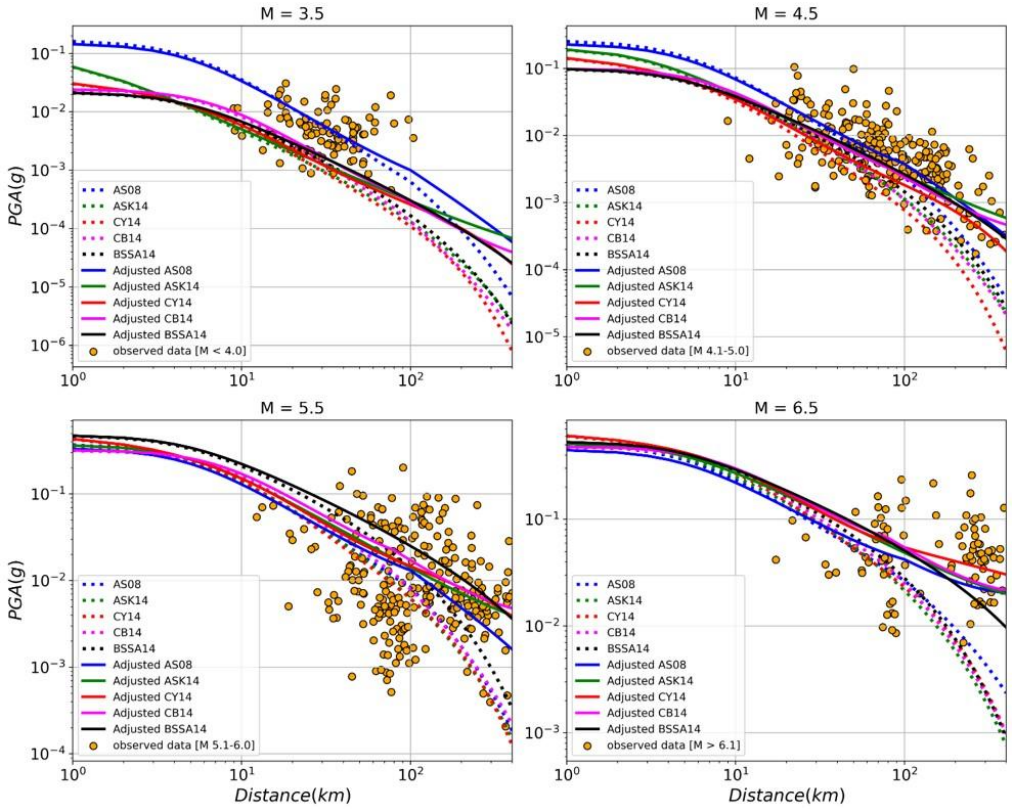
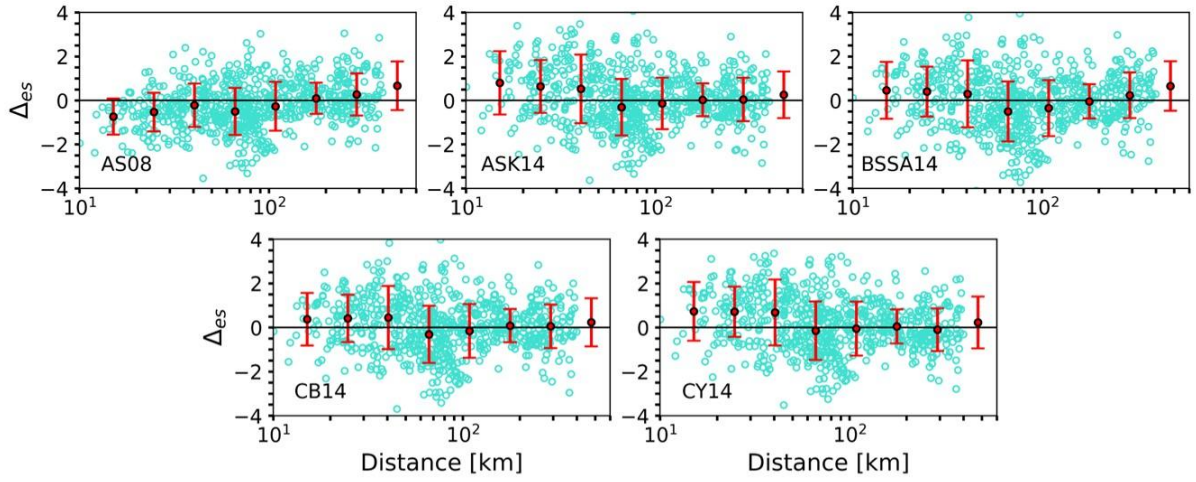



***Figure 10. Comparison of Adjusted GMM and selected Host GMMs with observed ground motion at PGA with distance constraint (only $C_2R$ term) across four magnitude scenarios. The observed ground motion data (yellow circles), the selected Host models (dashed line), and the adjusted GMM (dotted line).***

Figures S.4 (in Supplementary Material) shows distance scaling at T=1.0 s under the simplified $C_2R$ adjustment. At lower magnitudes, the adjusted models remain anchored to host predictions at short distances, with limited divergence at larger distances due to the imposed near-source constraint. For moderate to large magnitudes, improvements become evident beyond ~10 km,

where the adjusted curves align more closely with observed SA and reduce inter-model variability. The results indicate that, once near-source behaviour is constrained, path-controlled adjustment alone captures the principal regional characteristics of SA. Overall, the distance-only formulation yields smoother and more physically consistent attenuation at intermediate to far distances, avoiding the excessive decay exhibited by some host models. More broadly, the analysis demonstrates that increased functional complexity does not necessarily improve predictive capability or physical realism; a parsimonious formulation using only a linear distance term reproduces the dominant attenuation behaviour of the dataset with comparable, and in some cases superior, performance to more complex alternatives. The simplified approach offers improved numerical stability and reduces susceptibility to overfitting. Nevertheless, this reduction in functional complexity entails an inherent trade-off, as certain region-specific effects that might otherwise be represented explicitly may instead be absorbed into the aleatory variability. Despite this, the regression coefficients presented in Table S.3 (in supplementary material) demonstrate the robustness and consistency of the $C_2R$ term, confirming it as the primary control on attenuation behaviour in the Indian context. Overall, by avoiding unnecessary parameterization, the simplified formulation enhances interpretability and provides a reliable basis for regional seismic hazard assessment. Figure 11 presents the residuals obtained after applying the constrained adjustment to the distance-scaling ($C_2R$) term. The residuals are more uniformly distributed about the zero-mean reference line, and the distance-binned averages remain close to zero across the full distance range. This behaviour indicates that the constrained distance-term modification effectively reduces systematic distance-dependent bias while maintaining stability in the near-source region. Notably, the imposed constraint prevents unrealistically large corrections at short distances that may arise in unconstrained adjustments. Overall, the reduction in residual trends demonstrates that the constrained formulation captures the dominant regional path effects, resulting in more robust and physically interpretable ground-motion predictions for the Indian dataset.




515

516 ***Figure 11. Total Residuals (ln $Y_{obs}$ − ln $Y_{pred}$) for Peak Ground Acceleration (PGA) plotted against distance for***
517 ***adjusted five NGA-West Ground Motion Models with distance constraint. Red points mark the mean value, and***
518 ***vertical lines in each distance bin show one standard deviation.***

519 The empirical adjustment functions were developed directly from the observed data, and the
520 final adjustment model was selected based on its ability to best represent the overall trend of
521 the recorded earthquake data rather than by imposing a predefined attenuation shape. The
522 observed concavity at larger distances is therefore data-driven and reflects the characteristics
523 of the available dataset, particularly the limited number and uneven distribution of recordings
524 in the far-distance range. Since the regression procedure gives equal importance to all available
525 observations, the fitted model naturally follows the dominant pattern present in the data, even
526 where the physical attenuation trend may appear less intuitive. Particularly for the $M_w$ = 6.5
527 scenario (Figure 8), the adjusted models exhibit greater divergence in attenuation behaviour
528 than the original NGA-West host models. We would like to clarify that this divergence arises
529 from the empirical adjustment procedure, which is entirely constrained by the observed strong-
530 motion dataset rather than by imposing any predefined attenuation shape. For all magnitude
531 scenarios considered in this study, the original NGA-West host models generally underpredict
532 the observed ground-motion amplitudes for the Himalayan dataset. Consequently, the
533 adjustment factors are required to compensate for these systematic differences between the
534 host-model predictions and the observations. At larger magnitudes (e.g., $M_w$ = 6.5), these
535 discrepancies become more pronounced, resulting in larger empirical corrections and,
536 consequently, greater divergence among the adjusted models. Thus, the concave-up behaviour
537 observed in several adjusted models at larger distances primarily reflects the characteristics of
538 the available dataset, particularly the sparse and distance-limited recordings at $M_w$ = 6.5. The
539 regression therefore attempts to represent the dominant trend within the available observations,

and the resulting attenuation shape is influenced by this uneven data distribution. In contrast, the lower-magnitude datasets ($M_w$ = 3.5, 4.5, and 5.5) contain a different spatial distribution of recordings, leading to different adjustment trends. It is important to note that these empirical adjustments are intended to capture the relative prediction bias of the host models rather than to fully characterize the total uncertainty in ground-motion attenuation. The apparent concavity at larger distances should therefore be interpreted with caution, particularly for higher-magnitude cases where observational constraints are limited, and alternate approaches to address this situation when applying such adjustments are discussed in the later section.

## Applicability of Adjusted NGA-West Models in the Indian Context

To evaluate the applicability of the adjusted host models, a systematic performance-based weighting framework was implemented following the empirical adjustment procedure outlined in the preceding sections. Model performance was quantified using the log-likelihood (LLH) metric (Scherbaum et al., 2009; Kale and Akkar, 2013; Mak et al., 2017; Sunny et al., 2021), which has become a standard tool for evaluation and ranking of GMMs. The LLH assesses the probability of observing the recorded ground motions given the model predictions, assuming normally distributed residuals, thereby simultaneously accounting for both systematic bias and aleatory variability. Lower LLH values indicate improved agreement between predicted and observed motions, making it particularly effective for comparing the relative performance of competing models. Table S.4 (in Supplementary Material) summarizes the LLH values obtained for the different adjusted models, separately for the three adjustment approaches considered in this study, for PGA. The LLH values were transformed into normalized weights representing the relative contribution of each adjusted model to the ensemble prediction. Models showing better agreement with the observations were assigned larger weights, and the weights were normalized such that their sum was equal to unity. The normalized weights were then applied to the corresponding adjusted median PGA predictions to construct the composite regional ground-motion model. Specifically, for each magnitude and distance scenario, the ensemble PGA was calculated as the weighted sum of the PGA predictions from the five adjusted models:

$$\mathbf{PGA = w_1 * PGA_1 + w_2 * PGA_2 + w_3 * PGA_3 + w_4 * PGA_4 + w_5 * PGA_5} \quad \mathbf{(5)}$$

where $PGA_i$ represents the median PGA predicted by the $i^{th}$ adjusted NGA-West model and $w_i$ is its corresponding normalized weight.

This procedure was applied independently for each adjustment and magnitude scenario. The resulting weighted ensemble therefore combines the predictions of the individual adjusted models according to their relative agreement with the Indian strong-motion observations, while reducing dependence on any single host-model formulation. Figure 12 presents the distance-scaling characteristics of PGA obtained from the weighted ensemble of the adjusted NGA-West2 models for the three adjustment approaches considered in this study: (a) no constraint, (b) constraint within 0-10km, and (c) distance constraint using only the $C_2R$ term. The ensemble predictions are shown for representative magnitudes of M=3.5, 4.5, 5.5, and 6.5, while the observed Indian strong-motion recordings are grouped into four magnitude ranges $M < 4$, $4 \leq M < 5$, $5 \leq M < 6$, and $M \geq 6$ and plotted against hypocentral distance. In all three adjustment schemes, the ensemble curves exhibit a systematic decrease in PGA with increasing distance, together with consistent magnitude scaling, such that larger-magnitude scenarios produce higher predicted ground-motion amplitudes. The predicted attenuation trends generally encompass the distribution of the observed recordings over the available distance range, although appreciable scatter is evident in the observations, particularly at larger distances. Differences among the three adjustment schemes are most apparent in the near-source and intermediate-distance ranges, reflecting the influence of the imposed constraints on the distance-dependent adjustment. Overall, the weighted ensemble predictions provide a consistent representation of the observed regional PGA attenuation and demonstrate that the adjusted models capture the principal magnitude- and distance-dependent characteristics of Indian strong-motion data.

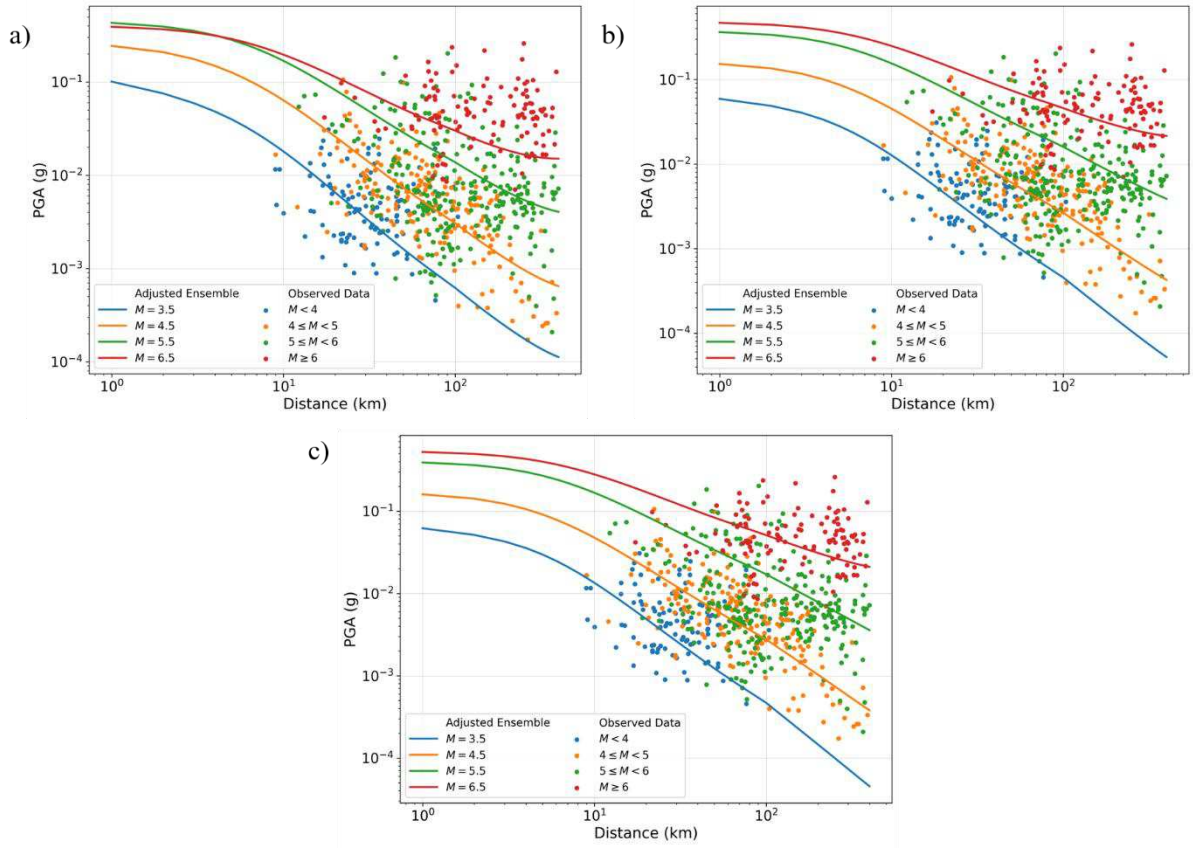



***Figure 12. Distance scaling of peak ground acceleration (PGA) predicted by the weighted adjusted ground-motion models with a) no constraint b) constraints within 0-10km distance c) distance constraint (only $C_2R$ term) for representative magnitudes (M = 3.5, 4.5, 5.5, and 6.5), compared with observed Indian strong-motion recordings binned by magnitude ranges. Solid curves denote the adjusted model predictions, while colored symbols represent observed PGA values at corresponding distances.***

These results demonstrate that the adjusted NGA-West models, when combined through an objective performance-based weighting scheme, provide a robust and interpretable framework for representing ground-motion attenuation in the Indian region. The resulting models offer a practical basis for regional seismic hazard applications, particularly in contexts where indigenous strong-motion datasets remain limited, yet regional adaptation of global models can substantially improve predictive reliability.

## Conclusion

This study develops regionally adjusted GMMs for the Himalayan region using a referenced empirical adjustment framework to address limitations of applying global models to tectonically distinct settings. Adjustments were derived for NGA-West host models for PGA and SAs using 724 recordings from 189 earthquakes. The adjusted models capture regional attenuation characteristics while preserving the functional forms of the host GMMs.

Performance was evaluated across multiple magnitude scenarios to examine distance scaling behaviour. Although AS08 lies outside its formal validity range at $M \approx 3.5$, it was retained for comparison due to stable residual behaviour and consistency with observations. Applicability is limited to periods $\leq 2.0$s, as sparse long-period data lead to increased model divergence beyond this range. Overall, the results demonstrate that regional GMM adjustments can be achieved through empirical corrections anchored to well-validated global host GMMs. Assessment through residual analysis and comparison across multiple IMs shows the evaluation of three adjustment strategies highlighting a trade-off between flexibility and robustness: fully parameterized formulations offer limited improvement and may become unstable with sparse data, whereas constrained approaches enhance physical consistency. The linear distance adjustment ($C_2R$) consistently captures the dominant regional attenuation behaviour, indicating that path-related distance scaling is the primary source of deviation from global models in the Indian Himalaya in the current dataset with very few recordings from moderate to larger magnitude events $M > 6.0$. These findings support the use of parsimonious, host-model-anchored adjustments as a reliable basis for seismic hazard applications in data-limited regions.

Following development and assessment, a practical framework for implementing the adjusted models in seismic hazard analysis was proposed using LLH-based ranking and weighting. The results demonstrate that NGA-West models, when regionally adjusted and combined through performance-based weights, provide a robust and interpretable representation of ground-motion attenuation in the Indian Himalaya. The resulting composite models offer a suitable basis for PSHA in data-limited regions where adaptation of global models improves predictive reliability. The selection of NGA-West models was motivated by their global adoption, extensive validation, strong data constraints, and broad magnitude-distance coverage, developed for seismically active shallow crustal regions with tectonic characteristics broadly comparable to those of the Indian region. This study does not seek to identify a single optimal host GMM; rather, the approach can be adopted for other host models as well, and similar adjustments could be considered for pan-European GMMs in future work. From an application perspective, the adjusted models are readily integrated within logic-tree frameworks, improving regional representativeness relative to unmodified global formulations. Future work should extend this approach toward partially non-ergodic formulations, refined treatment of epistemic and aleatory variability, and incorporation of additional site-response parameters and

simulation constraints to support development of hybrid regional GMMs for seismic hazard assessment in India.

## Funding Declaration

The authors declare that no funding was received for the conduct of this study or the preparation of this manuscript.

## Data Availability

Datasets related to this article were developed within the database IGM flat-file produced and is made available via the figshare repository DOI: 10.6084/m9.figshare.29530823. We used PyGMT (Tian et al., 2024) to plot the figures. We used OpenQuake to compute the residuals and IMs for NGA-West models.

## Competing Interests

The authors declare that there are no conflicts of interest or competing interests.

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