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Selection of Ground-Motion Models for National Seismic Hazard Assessment of Australia

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Abstract

One of the key challenges in assessing earthquake hazard in Australia is in understanding the attenuation of ground-motion through the stable continental crust. There are now a small number of ground-motion models (GMMs) that have been developed specifically to estimate ground-motions from Australian earthquakes. These GMMs, in addition to models developed outside Australia, are considered here for use in the updated national seismic hazard assessment of Australia. An updated and extended suite of ground-motion data from small-to-moderate Australian earthquakes are used to assess the suitability of the candidate models for use in the Australian context. Recorded spectral intensities are compared with those predicted by the GMMs. Both qualitative and quantitative approaches are considered for such comparisons. The goodness-of-fit results vary significantly among different GMMs, spectral periods and distance ranges; however, overall, the Australian-specific GMMs seem to perform reasonably well in estimating the level of ground shaking for earthquakes in Australia.

Keywords: ground-motion model; seismic hazard assessment; Australia.

1 Introduction

In recent years, the number of ground-motion models (GMMs) has increased significantly due to the improvement and expansion of global and regional seismic networks. Douglas (2018) summarizes the characteristics of 440 GMMs for the prediction of peak ground acceleration (PGA) and 282 models for the prediction of elastic response ordinates. Given the number of available models, several studies have attempted to define selection criteria to shortlist GMMs, such as the tectonic region type, magnitude type, spectral period range, magnitude and distance ranges and calibration of site effects (e.g., Cotton *et al.*, 2006; Bommer *et al.*, 2010; Stewart *et al.*, 2011; Stewart *et al.*, 2015). Such criteria are considered in the pre-selection of candidate GMMs for the 2018 National Seismic Hazard Assessment (Ghasemi and Allen, 2018). However, the availability of high-quality ground-motion records, together with the advancement of the model development techniques make most of the modern GMMs pass initial selection criteria. In this way, the hazard modeller requires to select a representative suite of GMMs representing the range of ground-motion amplitudes in the target region from a long list of candidate models.

In this paper, we present the preliminary results for assessing model performance of 279 GMMs that pass the pre-selection criteria, using ground-motion database compiled for earthquakes in the cratonic regions of western and central Australia (Ghasemi and Allen, 2021). First, we review the compiled database and selected GMMs followed by introducing the methodology for assessing predictive model performance. The goodness-of-fit results for the selected GMMs are then presented. Finally, we discuss the results and outline areas for future study.

2 Ground-Motion Database

Recently Ghasemi and Allen (2021) compiled a ground-motion database for earthquakes in cratonic regions of western and central Australia. In this database, data are mainly recorded by Australian National Seismograph Network (ANSN), complemented with data from temporary deployments, and covering the period of 1990 to 2019. We added raw and processed time-series data for earthquakes in the period of 2020 to 2022 into the compiled database. For an example, we added the ground-motion data recorded for the M_W 5.3 Marble Bar earthquake-in particular those data recorded by temporary Pilbara array directly on top of the epicentre (Yuan, 2017). For available ground-motion data the corresponding engineering ground-motion parameters are also computed and stored in the database.

To select GMMs for seismic hazard assessment, we used a subset of the database that includes 240 records with hypocentral distances less than 300 km recorded from earthquakes with $M_W \geq 4.0$. The far-field records as well as records from smaller events are of low engineering significance and are not included in our model evaluation. We assumed the local site condition of the recording stations as “engineering rock” with a time-averaged shear-wave velocity to 30 m (V_{S30}) of 760 m/s. Figure 1 shows the distribution of the selected records with respect to magnitude and distance.

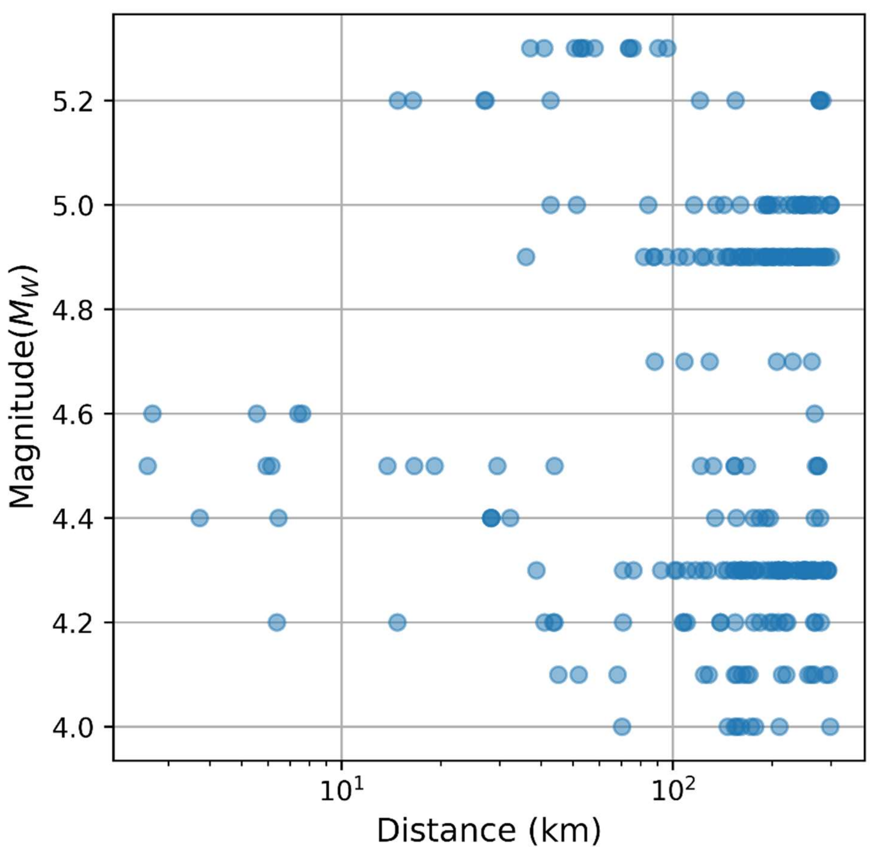

Figure 1. The magnitude versus hypocentral distance distribution of the selected records.

There is a clear gap in the data distribution with no record from moderate to large earthquakes with M_W > 5.3. Such earthquakes have the largest potential for damage and can drive seismic hazard estimates at longer return periods at many Australian localities (e.g. Stephenson, 2020) (e.g., Stephenson et al., 2020). Most data are recorded at hypocentral distances between 30 and 300 km from earthquakes with magnitudes in the range of 4.0 to 5.3. Hence, the performance of the candidate ground-motion models can only be verified within aforementioned distance and magnitude ranges.

3 Candidate Ground-Motion Models

Australian continent is comprised of very old crust, and is located far from active plate boundaries. The continent is characterised by relatively low rates of seismicity and is classified as stable continental region, similar to central and eastern North America (Johnston, 1994) . Nevertheless, it is shown by previous studies that some of the GMMs developed for active tectonic regions such as California appear to approximate moderate magnitude Australian ground-motions well at short source-receiver distances (e.g. Allen *et al.*, 2011 and Ghasemi and Allen, 2018). In this study, we selected, in total, 279 GMMs that are implemented in the OpenQuake-engine hazard library (Pagani *et al.*, 2014). Among the selected models, 60 models are developed for stable continental crust and 219 models for active shallow crust tectonic setting. All the selected models have physically based functional forms with terms modelling the magnitude scaling, geometrical spreading and anelastic attenuation as functions of moment magnitude, and source-to-site distance measure. Also, all the selected GMMs support predicting 5%-damped spectral acceleration (SA) at the periods of 0.1, 0.2, 0.5, and 1.0 second.

4 Residual Analysis

The performance of the selected GMMs is evaluated against compiled ground-motion database for earthquakes in western and central Australia. For each observation, i.e., computed spectral acceleration at period of interest, and for each candidate GMM, the residual is calculated as the difference between the natural logarithm of observation and prediction by the model. For each GMM, the mean value of all the computed residuals is then computed and plotted as a goodness-of-fit (GOF) measure. In this way, the positive mean value indicates that the corresponding GMM, in overall under predicts the observations while the opposite holds for the negative mean values.

Figure 2 shows the heat map of the mean values of residuals computed for the selected GMMs at the periods of 0.1, 0.2, 0.5, and 1.0 second. The GMMs (y-axis) are sorted based on the mean values of residuals at period of 0.1 sec. From this figure, there is significant variability in the level of ground motions predicted by the selected GMMs for the same dataset. Such inter-model variability clearly highlights the importance of capturing the epistemic uncertainty in seismic hazard assessments (SHAs). Furthermore, in Figure 2, the performance of GMMs appears to be period dependent. This may favour period dependent ranking of ground motion models for SHA studies in Australia; however, we believe this may not be a proper and practical approach as similar dependencies are also observed for other exploratory parameters such as magnitude and source-to-site distance (e.g., Figure 3).

We note that the quantitative GOF measures (e.g., Figure 2) reflect the overall performance of the model against the entire data which may undermine some desirable features of the model. For example, Allen (2012) model predicts normalised SA(0.1) recorded at distance range of 30-100 km reasonably well, while generally under-predicting the data recorded outside of this range (Figure 3a). Consequently, the overall mean value of this model is biased as most of the data is recorded at distances larger than 100 km.

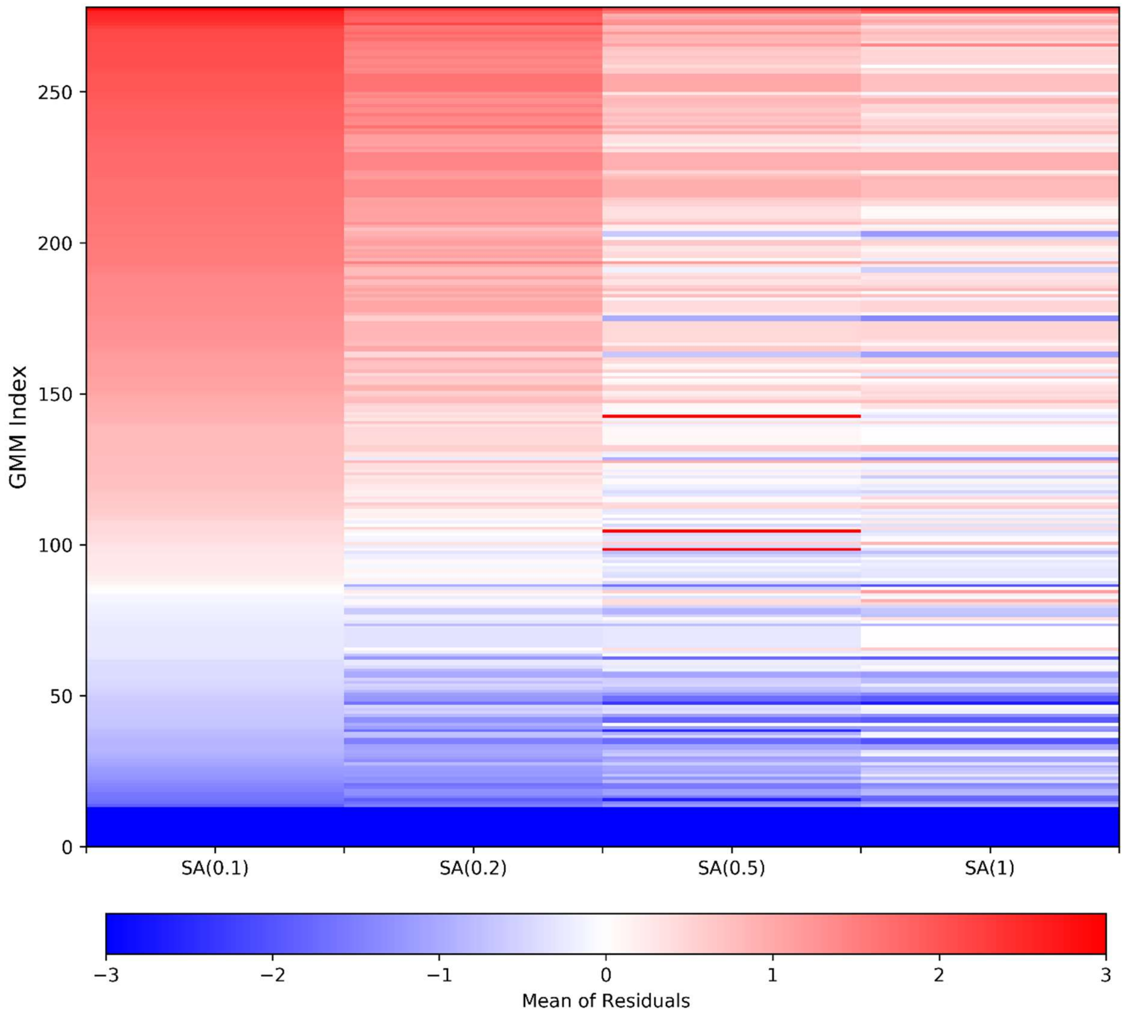

Figure 2. The heat map of the mean values of residuals (ln Observed – ln Predicted) computed for the selected GMMs at spectral acceleration periods of 0.1, 0.2, 0.5, and 1.0 second. Models that are represented by red colours overestimate observed ground-motions, while blue colours underestimate the data.

To further explore the utility of the candidate GMMs, similar plots as Figure 3 are produced for each of the GMMs. Figure 3a, as an example, compares the observed spectral accelerations at 0.1 sec with the Allen (2012) model that is originally developed for the southeastern Australian region. To help with the visualisation of the model fit, the observed spectral accelerations, shown as filled circles, are normalised to a reference earthquake with M_W 4.0 occurring at depth of 5.0 km. The normalized data are calculated using the model being tested. The mean and one standard deviation boundaries predicted by ground-motion model for the reference event are shown as solid and dashed curves respectively. It can be seen that, overall, the Allen (2012) model fits the data reasonably well in the distance range of 30-100 km, with most of the observations bounded within one standard deviation of the predicted mean curve. Figure 3b shows the histogram of the normalized residuals of the selected model. The normalised data residuals should follow the standard normal distribution, i.e., N (μ = 0, σ = 1), if data perfectly matches the model predictions. In this figure the standard normal distribution (red curve) is compared with the curve fitted to the normalised residuals (black curve). It can be seen that generally, the Allen (2012) model under-predicts the observations, and the scatter in the observations, measured by standard deviation of the fitted normal distribution, is comparable with that from the ground-motion model. The scatter plots of the residuals with respect to magnitude and distance are presented in Figure 3c-d, respectively. The red solid lines in these graphs are best fitting least-squares lines, calculated in order to detect any possible trends in the distribution of the residuals with respect to magnitude and distance. Based on this limited dataset, there is a significant positive trend in the distribution of the residuals suggesting that the performance of the model is distance dependent. The apparent magnitude dependence may be real, or a consequence of the non-uniform distance distribution of the dataset. Note that such dependencies would not be reflected in the quantitative GOF measures such as mean values presented in Figure 2.

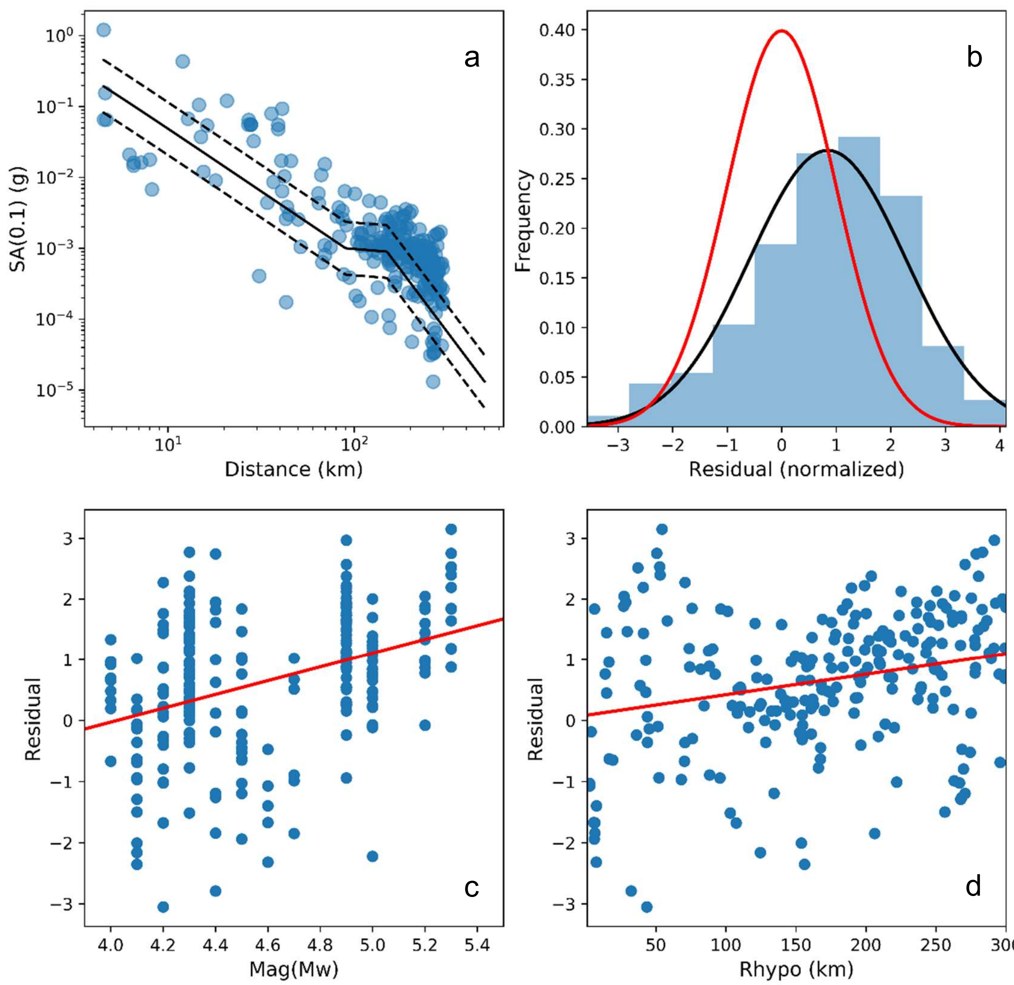

Figure 3. a) Comparison of the observed spectral accelerations at period of 0.1 sec with the ground-motion model of Allen (2012) derived for southeastern Australia. The observations are normalised to the reference ground motion with M_W4.0 occurring at depth of 5.0 km. The mean and one standard deviation boundaries predicted by ground-motion model for the reference event are shown as solid and dashed curves respectively. b) Histogram of the normalised residuals. Comparison between fitted normal distribution (black curve) and standard normal distribution (red curve) are also presented. c-d) Distribution of the ground-motion model's residuals with respect to magnitude and distance. The fitted lines to the residuals are shown as red lines.

Figure 4 shows the model fit of NGA-East (Goulet *et al.*, 2021) and Somerville et al. (2009) GMMs to the observed spectral accelerations at period of 0.1 sec and 1.0 sec. The Somerville et al. (2009) model is developed for the Yilgarn Craton, and is suggested for the Proterozoic and Achaean regions of central and western Australia, same as the region of the compiled dataset of this study; however, we note that most of the compiled data are from earthquakes with $M_W < 5.0$ that is outside of the recommended magnitude range of this model (i.e. M_W 5.0-7.5). Several studies have shown that ground-motion models should not be extrapolated to magnitudes outside the range supported by the model due to magnitude-scaling problems (e.g. Bommer *et al.*, 2007). The NGA-East model is developed for central and eastern North America that, like Australian crust, is classified as stable continental region (Johnston, 1994). The magnitude and distance range of the compiled dataset is within the recommended range of NGA-East model.

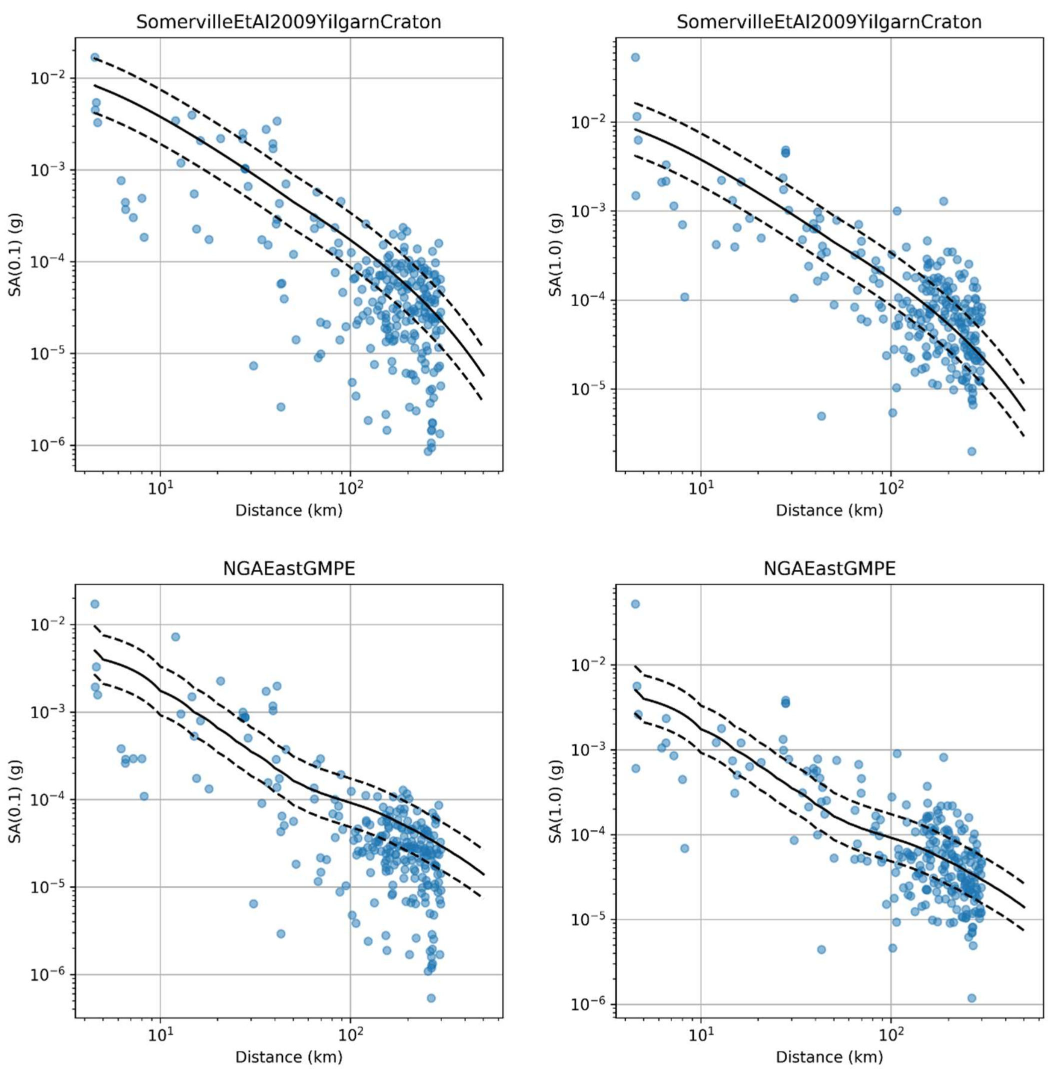

Figure 4. Comparison of the observed spectral accelerations at period of 0.1 sec and 1.0 sec with the ground-motion model of Somerville et al. (2009) cratonic crust model (top row), and NGA east model (bottom row). The observations are normalised to the reference earthquake with M_W4.0 occurring at depth of 5.0 km. The mean and one standard deviation boundaries predicted by ground-motion model for the reference event are shown as solid and dashed curves respectively.

In Figure 4, at any distance, a significant scatter can be observed in the distribution of the recorded ground motions. This can be partially due to not considering exploratory variables such as local site condition, focal mechanism, etc.; however, it may also indicate quality issues such as problems with the instrument response information, level of background noise, etc. Overall, it can be seen in Figure 4 that both GMMs fit data reasonably well at period of 1.0 sec. Also, both models over-predict observations at period of 0.1 sec that is more apparent for data points at distances larger than 100 km.

5 Concluding Remarks

In this study we pre-selected and analysed 279 candidate ground-motion models that may be considered for an update to the Australian National Seismic Hazard Assessment. The selected models are available in the OpenQuake-engine hazard library (Pagani *et al.*, 2014), and are developed for either stable continental crust or for active shallow crust tectonic setting.

To verify the performance of ground-motion models, we compiled a ground-motion database for earthquakes in the cratonic regions of western and central Australia. Currently the database includes 240 records with hypocentral distances less than 300 km recorded from earthquakes with $M_W \geq 4.0$. We observed significant variability in the level of ground motions predicted by the selected GMMs for the compiled dataset. Such inter-model variability clearly highlights the importance of capturing the epistemic uncertainty in seismic hazard assessment (SHA) studies. It also shows the value of the recorded data to guide the selection process of GMMs to obtain a representative suite of models that can model the expected range of ground motions.

Overall, the results show that the performance of the candidate GMMs may vary with magnitude, distance, and period. However, we note that the performance of the GMMs can only be verified within the magnitude and distance range of the database and can be also biased due to the relatively small number of available data. Hence, the results of this study should be interpreted with great caution.

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