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Developing a National Ground-Motion Database for Australia: Insights from the Magnitude 5.9 Woods Point Earthquake

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Abstract

In this paper, we present our ongoing work on the development of a national ground-motion database for Australia. Specifically, we focus on data recorded from the 21 September 2021 magnitude 5.9 Woods Point, Victoria, earthquake and showcase the procedure followed to process the recorded ground-motion data. We describe the process of collecting data and metadata followed by processing. The result is a set of high-quality ground-motion records suitable for engineering analysis. From the processed data, we calculate key engineering ground-motion parameters that provide critical insights for seismic hazard assessment and structural design applications. These parameters include peak ground acceleration, peak ground velocity, and spectral response values, among others. Finally, we compare the observed data from the 2021 Woods Point earthquake with predictions from selected ground-motion models. These models were previously used in the 2023 National Seismic Hazard Assessment of Australia. Our analysis provides a valuable benchmark for evaluating the performance of these models and highlights potential areas for improvement in ground motion modelling in the region.

Keywords: Ground-Motion Database, Seismic Hazard Assessment, 2021 Woods Point Earthquake

1 Introduction

Ground motion databases are essential resources for seismic hazard assessment and engineering design, providing the empirical data necessary for developing and validating ground motion models (GMMs). In Australia, the need for a comprehensive and high-quality ground motion database has become increasingly evident, especially in the wake of recent seismic events. The 21 September 2021 moment magnitude (M_W) 5.9 Woods Point earthquake, recorded by both national and regional networks, presents a valuable opportunity to assess the performance of automatic ground motion processing algorithms. This processing is crucial for filtering out noise, correcting instrumental response, and standardising the data, ensuring it accurately reflects ground motion in physical units. Additionally, it enables the extraction of key engineering parameters, making the data suitable for seismic hazard assessment and engineering applications. This event also allows us to explore and establish robust procedures for developing a ground motion database that is suitable for seismic hazard assessment and engineering applications. This paper presents ongoing efforts to develop a national ground motion database for Australia, with a focus on the data recorded during this significant event.

2 Ground Motion Data

For the 2021 M_W 5.9 Woods Point earthquake, we compiled a ground motion database containing 366 time-series, either originally in or converted to the standard MiniSEED format. The time-history data are raw, represented in "counts," which is proportional to the voltage measurements from the sensors. These data were collected from 97 monitoring stations, operated by national and regional networks, at epicentral distances ranging from 60 km to 2,200 km. Figure 1 shows the distribution of the recording stations. A variety of sensors, including short-period, broadband seismometers, and accelerometers, were used at the stations included in this study. For each station, the instrument transfer function was calculated based on the sensor and digitizer specifications, obtained from the EarthScope Consortium data centre or nominal technical specifications. All metadata, including the instrument transfer functions, are stored in StationXML format. Additionally, each station was assigned a time-averaged shear-wave velocity in the upper 30 m (V_{S30}) by taking the weighted average of available site-specific (Ebrahimi et al. 2023; Kayen et al. 2015) or proxy V_{S30} estimates (McPherson 2017; Wald and Allen 2007), prioritising site-specific values where available. The assigned V_{S30} values range from 144 m/s (soft soil conditions) to 1,140 m/s (hard rock conditions).

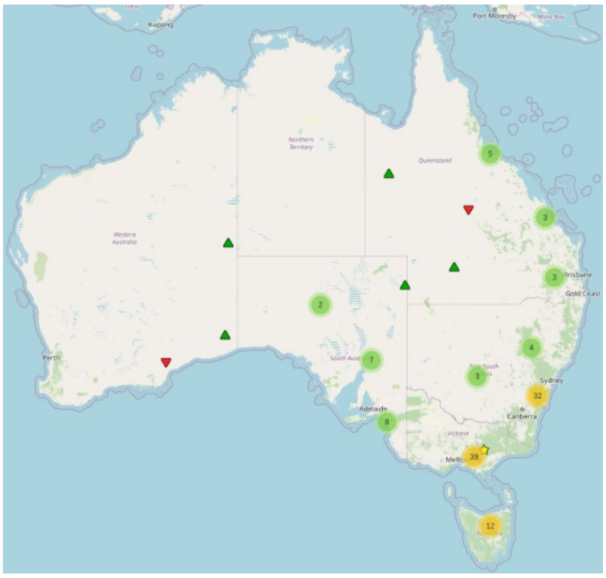

Figure 1. Spatial distribution of the recording stations for the 2021 Woods Point earthquake. Stations are represented by triangles, with green indicating stations that passed quality checks and red indicating those that failed. In areas where stations are closely spaced, they are aggregated into a circle, with the number inside indicating the count of nearby stations. The "green" color indicates that all the stations within the cluster are passed while "orange" indicates that some of the stations in the cluster did not pass the quality checks. The earthquake's epicentre is marked by a yellow star.

3 Ground-Motion Processing

Ground motion records are processed using “gmprocess” software. “gmprocess“ is a Python-based software tool developed by the U.S. Geological Survey’s (USGS) to automate the processing of ground motion data recorded by seismic instruments during earthquakes (Thompson et al. 2024). The tool takes raw seismic data (e.g., time series recorded in counts) and applies various steps, including time-series quality checks, baseline adjustment, filtering, and conversion to physical units (like acceleration, velocity, or displacement). Table 1 provides a brief description of the quality control measures, along with the number of records that failed to meet each criterion.

Table 1. “gmprocess” quality control measures, along with the number of records that failed to meet each criterion.

Quality measure	Description	Number of failed records
Co-location check	Check if the station is equipped with co-located sensors, prefer accelerometers over velocity sensors	5
Clipping check	Check if the record is clipped following Kleckner et al. (2022) algorithm	14
Signal window duration check	Check if the signal window duration captures the generic, magnitude dependent ground-motion record duration	2
Number of traces in a stream check	Check whether a stream contains the expected number of traces (i.e. 2)	18
Sample rate check	Check whether a record sample rate exceeds the minimum sample rate (i.e. 20 Hz)	14
Number of horizontal components check	Check if both horizontal components are present in the stream	1
Velocity ratio check	Check for the presence of abnormally large values in the tail velocity	2
Signal-to-Noise Ratio (SNR) check	Check whether the seismic signal is significantly (i.e. by order of 3) stronger than the background noise	23

As listed in Table 1, many records were “automatically” identified as clipped and were therefore rejected. We also conducted a visual inspection to confirm the presence of clipping in these records (e.g. Figure 2). This suggests that at those recording stations, the amplitude of ground motion exceeded the recording instrument’s dynamic range, resulting in the signal being "cut off" or "clipped”. This prevents the accurate calculation of key ground motion parameters, such as peak ground acceleration (PGA), velocity (PGV), and displacement (PGD). The records that passed all quality measures were then bandpass-filtered with corner frequencies set to achieve a minimum Signal-to-Noise Ratio (SNR) of 3.0 and were subsequently used to compute engineering ground-motion parameters, including peak ground motion metrics and the acceleration response spectrum.

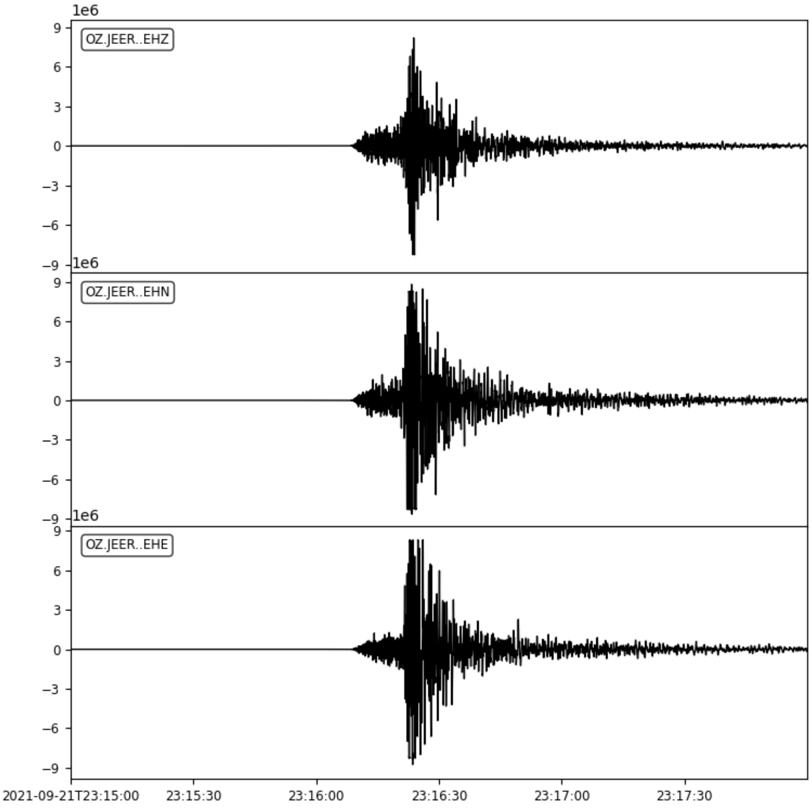

Figure 2. Recorded ground motion at the OZ.JEER station, located 95 km away from the epicentre. The station is equipped with a short period sensor with a 1-second natural period. Clipping effects are evident on the horizontal components.

4 Comparison with Ground Motion Models

We evaluate the goodness-of-fit to the compiled ground-motion data for 15 GMMs considered in NSHA23 (Allen et al. 2023). For each GMM and each supported spectral period, we compute the normalised residual as:

$$\mathrm{R_{norm}} = \frac{(\log(\mathrm{SA_{obs}}) - \log(\mathrm{SA_{pre}}))}{\sigma}$$

where:

$\mathrm{SA_{obs}}$: Observed spectral acceleration at the given period;

$\mathrm{SA_{pre}}$: predicted spectral acceleration value at the given period;

σ : corresponding standard deviation as indicated by the candidate ground-motion model at period of interest.

If the data perfectly matches the model predictions, the normalised residuals should follow a standard normal distribution, i.e. $N(\mu = 0, \sigma = 1)$. We then fit a normal distribution to the normalised residuals and compute the Kullback-Leibler (KL) distance, also called KL divergence, to measure the difference between the fitted normal distribution and the ideal standard normal distribution:

$$\mathrm{D_{KL}}(\mathrm{P}||\mathrm{Q}) = \int \mathrm{p(x)} \log \frac{\mathrm{p(x)}}{\mathrm{q(x)}} \, \mathrm{dx}$$

where p and q denote the probability density functions of the "true" distribution (standard normal distribution) and the "guess" distribution (fitted normal distribution to the normalised residuals), respectively. The KL divergence indicates how much information is lost when approximating p with q. A larger KL distance implies a poorer fit of the candidate GMM.

Figure 3 shows the computed KL distances for selected GMMs at representative periods of 0.05 sec and 1.0 sec. The results suggest that, for the 2021 Woods Point earthquake, the model by Atkinson and Boore (2006) fits data better at both representative periods compared to other selected GMMs. It also suggests the overall good performance of the Australian specific models. The performance of GMMs may be period-dependent and can vary significantly from short-period ground motion (0.05 sec) to longer periods (1.0 sec). For example, the performance of the NGA-East model (Goulet et al. 2021) improves significantly from 0.05 sec to 1.0 sec, while the opposite is true for the Zhao model that is adjusted for the Swiss seismic hazard model (Edwards and Fäh 2013).

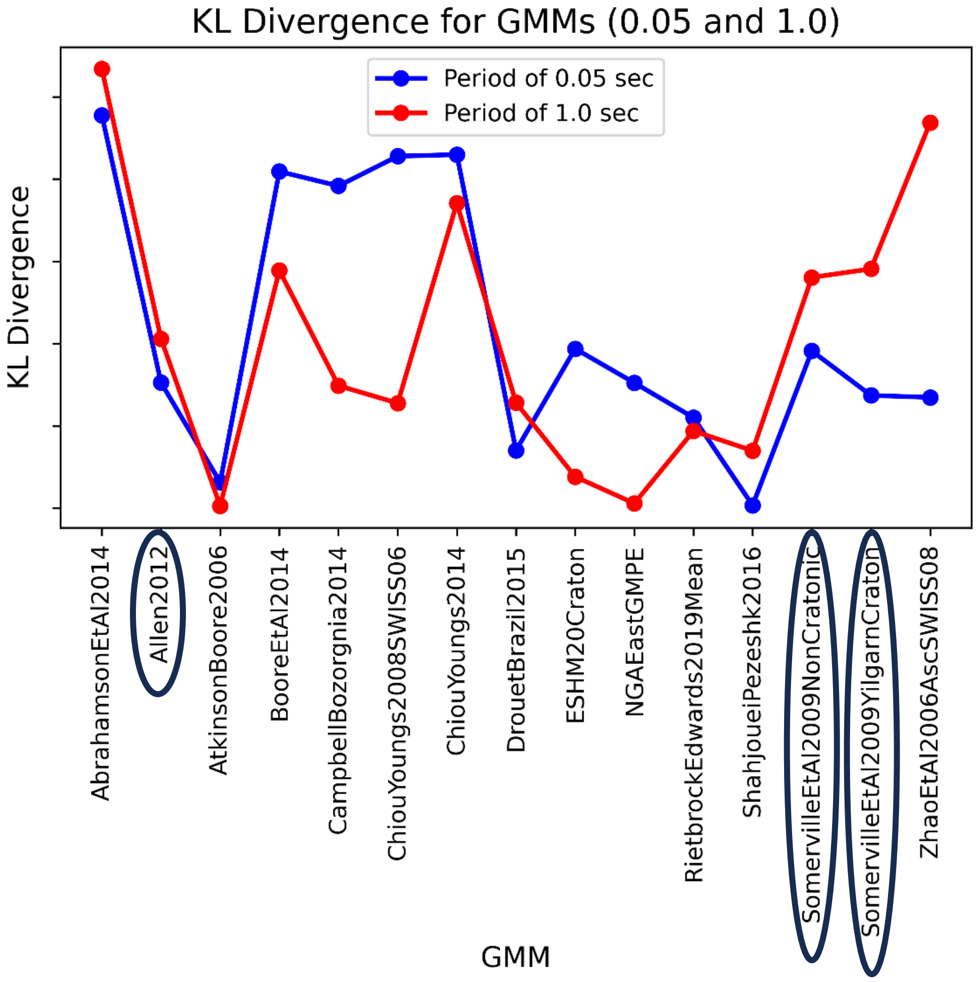

Figure 3. KL distances calculated for the selected GMMs. For definitions and key characteristics of the GMMs, please refer to Allen et al. (2023). The blue and red curves represent KL values at periods of 0.05 sec and 1.0 sec, respectively. The Australian specific models are highlighted by an oval drawn around them.

We should also emphasize that the number of available observation points may affect the accuracy of the normal distribution parameters fitted to the residuals, potentially biasing the computed KL distances. In this study, we qualitatively verified the ranking suggested by the KL distance by generating plots similar to Figure 4, which compares a GMM's mean and one standard deviation boundaries at the period of interest with observed spectral accelerations at the same period. In this figure, the model predictions are for a generic rock site with V_{S30} of 760 m/s, and the observations are normalised to rock site conditions. Consistent with the computed KL distances, Figure 4 shows that the mean NGA-East model fits the data better than the Zhao et al. model, and its performance improves at a period of 1.0 sec compared to 0.05 sec.

It is important to note that the KL distance results (Figure 3) represent the overall performance of the models across the entire range of observed distances for a single event. This broad view may obscure critical aspects of model performance, such as the ability to accurately predict near-field ground motions, which can have a greater impact for hazard. For instance, in Figure 4, at a period of 0.05 seconds, while the NGA-East model outperforms Zhao et al. overall, both models appear to fit the data well at shorter source-to-site distances of less than 150 km.

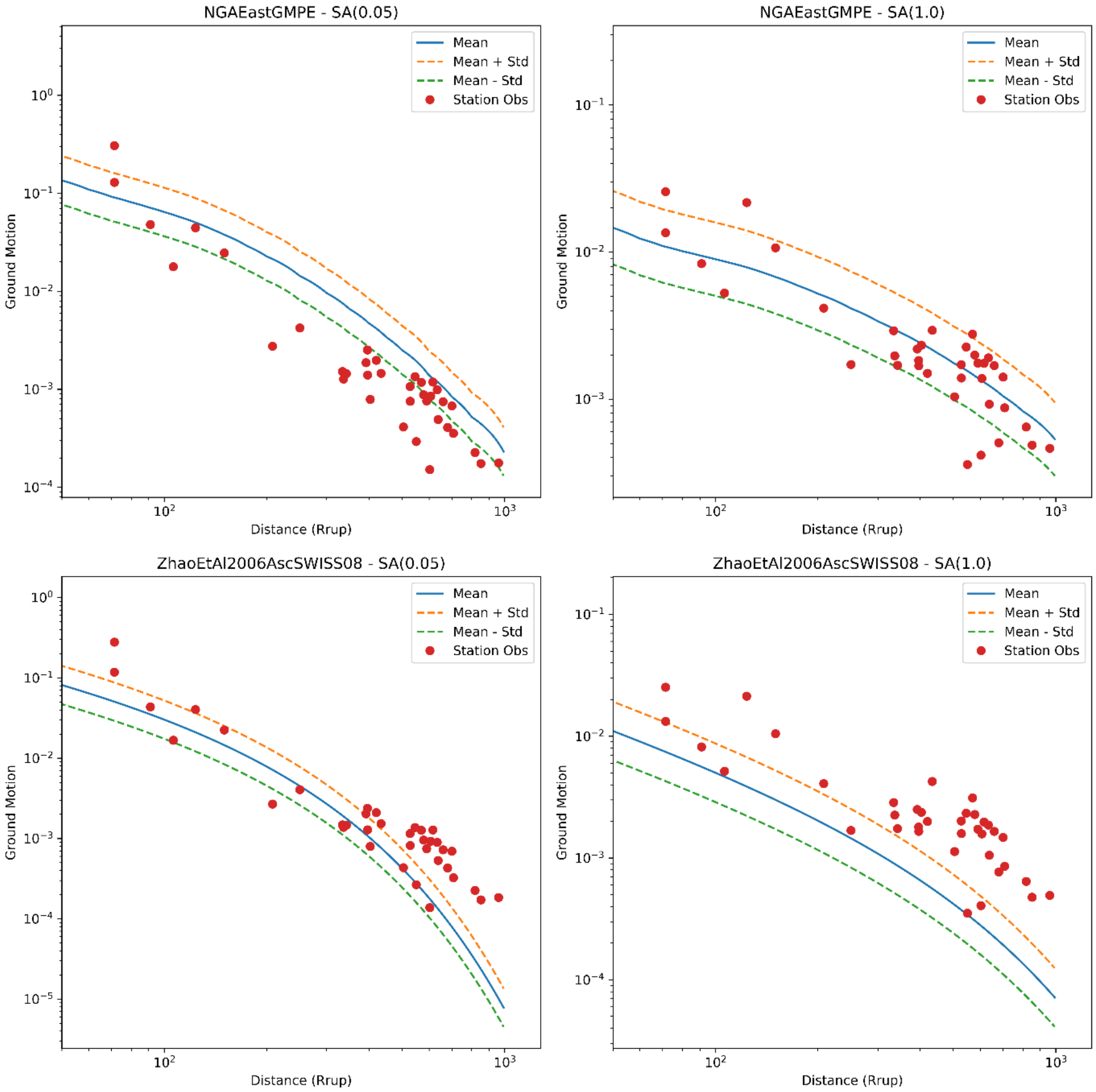

Figure 4. Comparison of observed spectral accelerations at periods of 0.05 sec and 1.0 sec with the NGA-EAST ground-motion model (top row) and the Zhao et al. model (bottom row). Solid and dashed curves represent the mean and one standard deviation boundaries predicted by the ground-motion models for the 2021 Woods Point event. Observations, normalized to generic rock site conditions, are shown as circles.

5 Conclusion

The development of a national ground-motion database for Australia, showcased through the analysis of the M_W 5.9 Woods Point earthquake, provides crucial insights for seismic hazard assessment and structural design. By processing high-quality ground-motion data, we were able to derive key engineering parameters, such as peak ground acceleration, velocity, and spectral response values. These data, along with a comparison of observed ground motions with existing GMMs, highlight the strengths and limitations of current models. The KL divergence analysis, demonstrated through visual comparisons, appears to be an effective quantitative measure for evaluating the overall performance of ground motion models. However, additional data and more comprehensive analysis are needed to verify the performance of GMMs, particularly in near-field regions. The presented results in this study should be interpreted with care as many of the selected GMMs do not support predictions for source-to-site distances larger than 1000 km. This ongoing work underscores the importance of refining GMMs for more accurate seismic hazard assessments in Australia.

Finally, it is known that there can be considerable inter-event variability in ground motions between earthquakes of a similar magnitude. Based on recent work of Allen (in prep), it is observed that the M_W 5.9 Woods Point earthquake possesses higher than average Brune (1970) stress drop. Consequently, GMMs developed for average Australian earthquakes may not perform well—particularly at short periods—for this event. Therefore, when selecting GMMs for seismic hazard assessments, it is important to consider the variability in potential ground motions from a range of earthquakes collectively.

6 References

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