Australian Earthquake Engineering Society
2024 National Conference, 21-23 November 2024
Adelaide, South Australia

Seismic Hazard to Australian Dams from Proximal Faults: Comparison of Deterministic and Probabilistic Ground Motions

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Abstract

This study assesses seismic hazard exposure for ANCOLD-registered dams across Australia, emphasizing ground motion intensities from deterministic and probabilistic models. Using the Australian Neotectonic Features Database (NFD), we identified 216 faults within 100 km of 428 dams, with 31 dams situated within 1 km of fault traces. Deterministic ground motion models (GMMs) were applied to estimate peak ground acceleration (PGA) and pseudo-spectral acceleration at 1.0 s (PSA[1.0 s]) for maximum moment magnitude ($M_{w,max}$) events, yielding hazard levels frequently exceeding those from the 2023 National Seismic Hazard Assessment (NSHA23) probabilistic model. Results indicate that deterministic ground motion intensities provide critical insights for high-consequence dams, especially those close to relatively high-slip-rate faults. Enhanced fault characterization and the integration of deterministic and probabilistic models are recommended to improve dam safety frameworks.

Keywords: seismic hazard; ground motion; ANCOLD; dams.

1 Introduction

The seismic design of dams in Australia has evolved substantially, as historical events and global advances in seismic hazard research underscored the need for improved infrastructure resilience. Initially, many Australian dams were constructed without seismic design considerations due to a perception of low seismicity. However, earthquakes such as the 1968 Meckering event highlighted potential vulnerabilities (McCue, 1995). In response, seismic guidelines were progressively adopted, with the Australian National Committee on Large Dams (ANCOLD) defining performance criteria for two primary seismic conditions: Operating Basis Earthquake (OBE) and Safety Evaluation Earthquake (SSE). The OBE is that level of ground motion at the dam site for which only minor damage is acceptable, and the SEE is the recommended maximum level of ground motion for which the dam should be designed or analysed. The Maximum Credible Earthquake (MCE), on the other hand, is the largest reasonably conceivable earthquake magnitude that is considered to be possible along a recognised fault or within a geographically defined tectonic province, under the presently known or presumed tectonic framework (ANCOLD, 2019). Because this study focuses on assessing the impact of proximal faults to dams, we employ MCE (determined from fault scaling laws) instead of SSE in our analysis.

To comprehensively understand seismic hazard to dams, ANCOLD encourages using both probabilistic and deterministic models, with high-consequence dams especially requiring stringent seismic assessments. The 2023 National Seismic Hazard Assessment (NSHA23) (Allen et al., 2023), provides annualized ground motion estimates like peak ground acceleration (PGA) and pseudo-spectral acceleration (PSA) at specified exceedance probabilities (e.g., 1 in 5,000 annual exceedance probability [AEP]). While NSHA23 provides a standardized hazard estimate at a national scale, it is not a replacement for site-specific seismic hazard studies for critical infrastructure.

In this study, deterministic ground motion models (GMMs), by contrast, can estimate ground motion intensities specifically for a given maximum moment magnitude ($M_{w,max}$) events along known faults (it is noted these GMMs contain a probabilistic component for uncertainty). Setting deterministic models to the 85th percentile ground motion estimates, per ANCOLD guidance, provides an upper-bound ground motion level that is particularly relevant for high-consequence dams. This study employs deterministic GMMs that have been used in NSHA23 with specific logic tree weights obtained through structured expert elicitation (Griffin et al., 2020; Allen et al., 2023), adapted for the Australian tectonic setting to capture regional differences between Cratonic and non-Cratonic areas.

This paper evaluates deterministic and probabilistic ground motion estimates for ANCOLD-registered dams near faults listed in the Australian Neotectonic Features Database (NFD). By comparing deterministic ground motion intensities with NSHA23 probabilistic values, this study aims to illuminate the seismic hazard profiles for dams in fault-proximal areas, underscoring the value of integrating both deterministic and probabilistic models in hazard assessment.

2 Data

Data for this study include:

i) ANCOLD Registry of Large Dams: https://ancold.org.au/wp-content/uploads/2023/04/Australia-2015-update-as-at-January-2022-with-disclaimer-1.xlsm.

ii) Australian Neotectonic Features Database (NFD): https://www.ga.gov.au/applications/neotectonic-features-database.

iii) Fault source model used in NSHA23: https://ecat.ga.gov.au/geonetwork/srv/api/records/76fef341-dcb8-42c7-9691-ff73ced58fd4.

Using ArcGIS Pro, fault traces within a 100 km radius of ANCOLD dams were identified and mapped (see Fig. 1). Fault-dam distances were calculated as the shortest Euclidean distance between each dam's centroid and the nearest fault trace. For critical proximities (distances < 1 km), a positional uncertainty of ± 250 m was applied to account for discrepancies in fault and dam mapping precision, resulting in a reduced set of 216 faults out of an initial 409 (Clark et al., 2011).

Fault parameters, including $M_{w,max}$, average displacement (AD), maximum displacement (MD), and recurrence intervals (RI), were derived using regional earthquake scaling relationships (Yang et al., 2021; Leonard, 2014; Somerville, 2021; Moss et al., 2022). Slip rate (SR) estimates used in NSHA23 supported recurrence interval estimates for events along faults near dams, although significant epistemic uncertainties remain due to variable fault activity histories and limited constraints on geological slip rates (Clark et al. 2020). Fig. 1 shows the NFD fault traces and ANCOLD-registered dams considered in this study. More detailed information can be found in Quigley et al. (2024) and references therein.

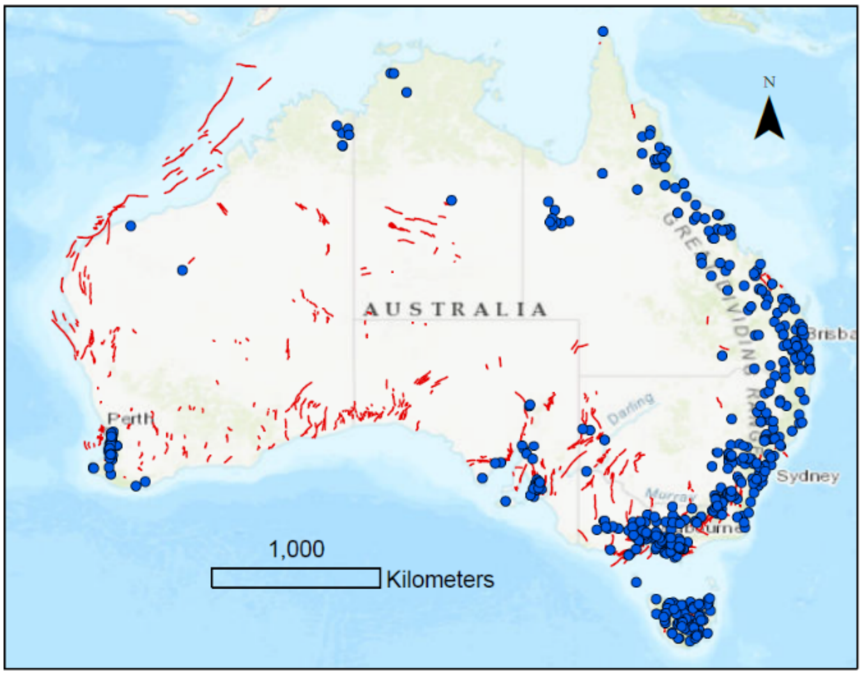

Figure 1: NFD fault traces (red lines) and ANCOLD-registered dams (blue circles) considered in this study.

3 Ground Motion Analysis

To estimate ground motion intensities in the event of $M_{w,max}$ on dam proximal faults (i.e., deterministic approach), we used $M_{w,max}$ and dam-fault distances as inputs into the same set of GMMs (with the relative weights unchanged as well to avoid any additional uncertainties, see Table 1) that were used in NSHA23 (Allen et al., 2023). To conduct a study of this scale we make many generalizations. As most dams can be considered more susceptible to short-period ground motions (e.g. Zimmaro and Ausilio [2020]), we selected the PGA and PSA[1.0 s] instead of other intensity measures for utilization in these analyses. We estimated the PGA and PSA[1.0 s] values under Cratonic and non-Cratonic conditions depending on the geological setting of the dam. For all dam sites we assume a general NEHRP B/C rock site (i.e., V_{S30} = 760 m/s). The GMM outputs are converted into 85th percentile intensities, as suggested in the ANCOLD guidelines for Extreme Consequence Dams. We acknowledge that a diversity of dam types, geometries and heights, designs, ages, site and foundation conditions are present in the ANCOLD database; our results are not intended to replace site-specific, dam-specific analysis.

Table 1. GMMs and associated weights for Cratonic and Non-Cratonic conditions for deterministic ground motion calculations (Allen et al. 2023)

Model	Cratonic	Non-Cratonic	Reference
A12	0.24	0.29	Allen (2012)
AB06	0.13	0.15	Atkinson and Boore (2006)
D15	0.14	0.17	Drouet (2015)
ESHM	0.10	0	Weatherill et al. (2020)
NGAE	0.09	0.10	Goulet et al. (2017)
S09YC	0.16	0	Somerville et al. (2009)
S09NC	0.14	0.29	Somerville et al. (2009)

Probabilistic ground motions for dam locations were estimated from the NSHA23 (Allen et al., 2023). NSHA23 is calculated on a grid of sites, and PGA and PSA[1.0 s] hazard values with a

1/5,000 annual exceedance probability (AEP) from this grid were interpolated to dam locations. NSHA23 uses combinations of several ground motion models weighted in separate logic trees for Cratonic and non-Cratonic Australia. Maximum magnitudes on faults in NSHA23 were defined using a combination of structured expert judgement (varying for different neotectonic domains; Griffin et al., 2018; 2020) and area-based earthquake scaling relations (Leonard, 2014; used in the case that fault dimensions were too small to host the $M_{w,max}$). As recommended in ANCOLD 2019 for Extreme Consequence Dams, we use 85th percentile NSHA23 PGA and PSA[1.0 s] values for comparison purposes. We compare deterministic intensities for $M_{w,max}$ from GMMs against probabilistic intensities for 1/5000 AEP from NSHA23 for different fault slip rate.

We calculate the fractional ratio of deterministic $M_{w,max}$ intensity values from GMMs to probabilistic NSHA23 intensity values and take log10 of this ratio for better illustration purpose. Positive values ($M_{w,max}$ GMM intensity > NSHA23 intensity) indicate scenarios where deterministic 85th percentile intensities for a given dam (i.e., proximal fault-based ground motion hazard) exceed the 1/5000 AEP derived from NSHA23 (i.e., 85th percentile probabilistic ground motion hazard including faults, seismicity). We only take the maximum positive value of $M_{w,max}$ intensity vs. NSHA23 intensity for each dam and plot the ratio (i.e. $M_{w,max}$ GMM intensity / NSHA23 intensity) considering other factors towards seismic hazard (e.g., slip rate).

4 Results

Fig. 2 shows the ratio plot of PGA and PSA[1.0 s] between deterministic and probabilistic ground motions. Fig. 3 shows the ratio distribution map with fault traces for PGA. Key aspects of the ground motion analysis include:

- For the 4055 considered fault-dam combinations, approximately 88% (n = 3579) yield 85th percentile deterministic $M_{w,max}$ PGA estimates ≥ 0.1 g, and the number for PSA[1.0 s] is 70% (n = 2844).
- For the 428 scenarios for dams with maximum ground motion intensities (428 dams), approximately 94% (n = 402) yield 85th percentile deterministic $M_{w,max}$ PGA that exceed the 85th percentile NSHA23 PGA with 1/5000 AEP, and the number for PSA[1.0 s] is 99% (n = 422).
- There are 341 instances (11 faults) where $M_{w,max}$ PGA are ≥ 0.1 g and estimated fault slip rates are ≥ 100 m / Myr (i.e., 0.1 mm/yr), and the number for $M_{w,max}$ PSA[1.0 s] is 299 (11 faults). These faults could be prioritised for further research.
- There are 29 dams (6.5% of 428 dams) where: (i) the 85th percentile deterministic $M_{w,max}$ PGA ≥ 0.1 g; (ii) the $M_{w,max}$ PGA is greater than the corresponding NSHA23 1/5,000 AEP PGA, and (iii) the fault contributing to this hazard has an estimated slip rate ≥ 100 m / Myr.
- There are 32 dams (7.5% of 428 dams) where: (i) the 85th percentile deterministic $M_{w,max}$ PSA[1.0 s] ≥ 0.1 g; (ii) the $M_{w,max}$ PSA[1.0 s] is greater than the corresponding NSHA23 1/5,000 AEP PSA[1.0 s], and (iii) the fault that contributes to this hazard has an estimated slip rate ≥ 100 m / Myr.

There are 241 dams with the same criteria but lowering the slip rate to ≥ 10 m / Myr for PGA and 285 for PSA[1.0 s]. Given the potential for large (perhaps even exceeding an order of magnitude) temporal variations and associated uncertainty in slip rates for some faults (only few faults have good geological constraints on slip rates) (Clark, et al., 2016), rigorous studies of proximal faults could be considered as part of due diligence PSHA for these dams.

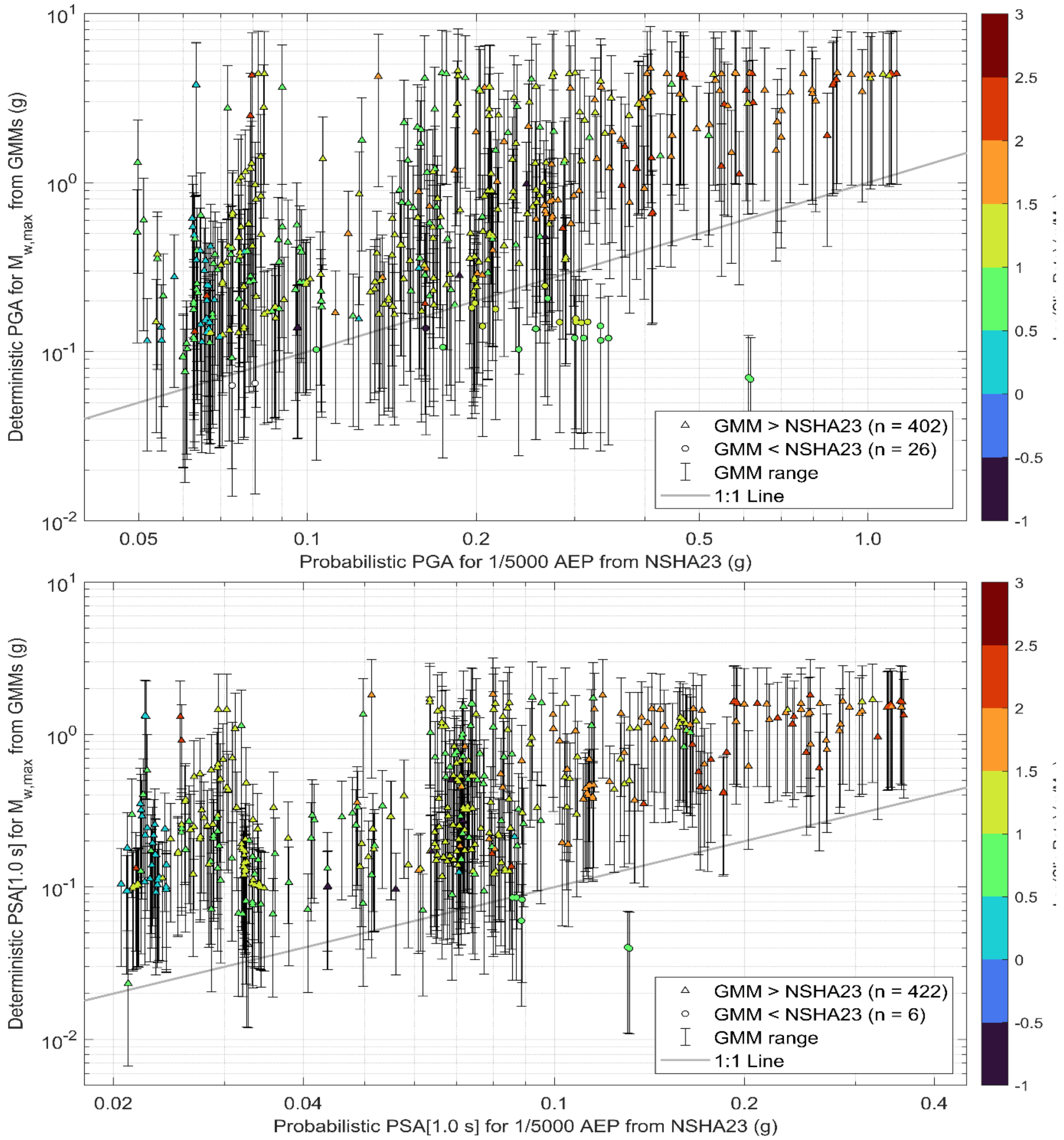

Figure 2. GMM intensity vs NSHA23 intensity coded for slip rate (a) $M_{w,max}$ PGA, (b) $M_{w,max}$ PSA[1.0 s]. The x-axis indicates the 85th percentile ground motion level from the NSHA23 model, and y-axis shows the 85th percentile ground motion level from the GMMs. The error-bar indicates the full range of the deterministic ground motions.

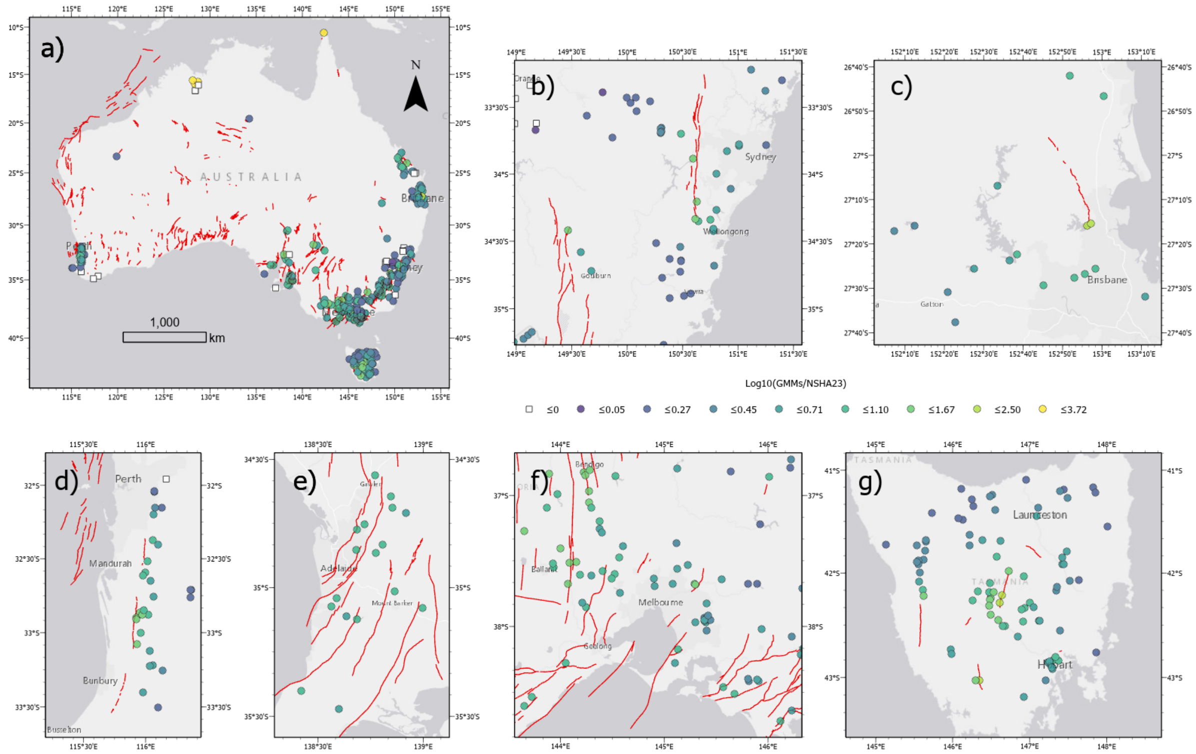

Figure 3. GMM/NSHA23 intensity ratio distribution with fault traces for $M_{w,max}$ PGA

5 Conclusions

This study underscores the importance of integrating deterministic and probabilistic ground motion assessments for ANCOLD-registered dams, with deterministic $M_{w,max}$ estimates frequently exceeding NSHA23 probabilistic values, especially for faults with high slip rates. Deterministic models capture significant hazard potential, particularly relevant for dams located near major fault lines.

Future work would focus on: (i) Enhanced Fault Mapping: High-resolution LiDAR mapping and fault-trace analyses to improve positional accuracy; (ii) Paleoseismic Studies: Trenching and subsurface analyses to better understand fault recurrence and segmentation patterns; and (iii) Advanced PFDHA Models: Developing tailored displacement hazard models to suit Australia's unique tectonic environment.

An integrated approach combining deterministic and probabilistic methods will enhance the seismic resilience framework for dams, offering a robust response to both regional and site-specific seismic challenges.

6 Acknowledgments

This research was funded by the Australian Government National Emergency Agency (NEMA) Disaster Ready Fund (Project DRF 40204) and by AuScope (Project 3.128) via the National Collaborative Research Infrastructure Strategy (NCRIS). We acknowledge Trevor Allen for providing the ground motion calculations.

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