

# NEOTECTONIC FAULT SIGNIFICANCE

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## ABSTRACT

This paper presents a sensitivity analysis on the significance of neotectonic faults at various slip and distance scenarios to seismic hazard ground motion estimates. The analysis implements neotectonic faults into an exemplar probabilistic seismic hazard analysis (PSHA) with no prior known neotectonic faults by iterating 15 hypothetical neotectonic distance-slip scenarios combining, five site-to-fault distances (5, 10, 20, 50, and 80 km) with three slip rate scenarios (~ 1 m/Myr, 10 m/Myr, and 100 m/Myr). The results show the relative increase in calculated ground motion through the addition of the distance-slip fault scenario as a percentage to the baseline hazard (no faults) to demonstrate the significance of neotectonic faults to seismic hazard in an Australian critical infrastructure design context. The sensitivity analysis provides insights to inform decision making in support of more detailed paleoseismological studies following initial desk study/screening level assessments of neotectonic faults near a site.

## 1 INTRODUCTION

Australia is often perceived as a seismically stable region due to its intraplate setting within the Australian tectonic plate, far from active plate boundaries. However damaging earthquakes do occur and almost all earthquakes, especially larger ones, occur on existing faults.

Accounting for ground motions from earthquake recurrence intervals on known active faults is a fundamental step in probabilistic seismic hazard analysis (PSHA). In tectonically active regions, a fault is typically considered active if it has moved within the Holocene epoch (approximately the last 11,700 years) or within the Late Pleistocene epoch (approximately 35,000 years ago). Australia has a relatively low number of Holocene active faults compared to tectonically active regions.

In an Australian seismotectonic context “Neotectonic” faults are faults that have demonstrable or probable movement during the current crustal stress field orientation which started in the Pliocene and late Miocene (i.e., the past 5-10 million years) and may have the potential for displacement in the future (Clark et al. 2011; Sandiford et al. 2004). Neotectonic faults are important sources in Australian seismic hazard assessments because they represent recent tectonic activity in the region. They reflect the present-day tectonic stress regime and are interpreted as more likely to rupture again, making them a locus of future earthquake recurrence. As such, neotectonic faults that could significantly contribute to the design basis ground motions for critical infrastructure should be identified and be accounted for.

Over the past two decades, research into understanding neotectonic faulting and incorporation into Australia’s current state of seismic hazard assessment has progressed. The Geoscience Australia National Seismic Hazard Assessment (NSHA18 Allen et al, 2018, NSHA23 Allen et al 2023) incorporated neotectonic faults. The ANCOLD (2019) Guidelines for Design of Dams and Appurtenant Structures for Earthquake requires ... *neotectonic faults that could significantly contribute to the ground motion for the dam should be identified and be accounted for in the seismic hazard assessment.*

Numerous recent studies have shown the significance of neotectonic faults to critical infrastructure in Australia through paleoseismic field investigations (e.g., Clark et al., 2021, Ninnis and Clark, 2019, and Mote et al., 2021, and Griffin et al., 2024). While the incorporation of neotectonic features is acknowledged in the current state of practice, the level of effort required to adequately characterise neotectonic faults to understand their significance to ground motions has not yet been mainstreamed. In regions with low rates of tectonic activity and landscape development (e.g. Australia), fault activity characterization is difficult (McMoran and Hull, 2013). Assessing the location and activity of neotectonic faults can be technically challenging, time intensive, and affect design and construction schedules.

This paper will present a sensitivity analysis of the impact to design basis ground motions from adding hypothetical single neotectonic fault scenarios to an exemplar PSHA with no prior neotectonic faults. The analysis will iterate through 15 hypothetical neotectonic distance-slip scenarios combining: five site-to-fault distances (5, 10, 20, 50, and 80 km) with three slip rate scenarios (~ 1 m/Myr), 10m/Myr, and 100m/Myr) to estimate the relative increase in calculated ground motions as a percentage over the baseline hazard (no faults) at three select annual exceedance probabilities (AEP).

## 2 NEOTECTONIC ASSESSMENT BACKGROUND

An Australia-wide assessment of active faulting based on neotectonics data was initiated by Clark et al. (2011) and expanded into the Geoscience Australia Neotectonic Feature Database (NFD) (Clark and McPherson, 2012). The data were derived from the analysis of Digital Elevation Models (DEMs), aerial photos, satellite imagery, geological maps, and paleoseismic

studies. At the time of this paper the catalogue contains 406 neotectonic features, (neotectonics.ga.gov.au). Verifying these features as neotectonic faults (or not) is an ongoing process. The catalogue is not a complete representation across Australia, as such site-specific seismic hazard assessments need to identify and account for neotectonic faults, accordingly.

Several recent studies highlight and provide insight into the significance of neotectonic faults. Sommerville et al. (2017) summarised conditions under which identified neotectonic faults contribute significantly to seismic hazard in Australia and states that ground motion levels decrease rapidly with increasing closest distance from a fault. They found identified faults rarely dominate the probabilistic hazard if they are 20 km or more from the site. Ninis and Clark (2019) presented a paleoseismic study which identified 2 or 3 M7.0 earthquakes on the Avonmore Scarp in last ~80,000 years, highlighting their significance to hazard estimation. Clark et al. (2021) presented a paleoseismic study for the Meadow Valley Fault and found that potentially damaging ground motions might be generated out to distances of 50-70km from the fault, but noted uncertainty in the likelihood that the fault might generate significant ground motions within a time frame relevant to infrastructure stability. Griffin et al. (2024) presented a paleoseismic study showing three earthquakes on Jindabyne Thrusts since ~40,000 years ago that are significant to critical infrastructure in the Snowy Mountains. Quigley et al. (2024) showed there are 216 NFD fault traces within 100 km of 428 ANCOLD dams and suggested that detailed analyses of fault-based hazard may be particularly relevant for dams within 20 to 30 km of faults with sufficient length (e.g.,  $\geq 20$ -30 km) to produce  $M \geq 6.7$  to  $> 7.0$  earthquakes and sufficiently high slip rates (e.g.,  $\geq 0.1$  mm/yr) to potentially contribute to seismic hazard at time-scales commonly of interest for critical infrastructure (e.g.,  $\leq 1:5,000$  to  $1:10,000$  AEP). Ninis et al. (2018) provided a methodology to incorporate bedrock faults that are aligned favourably with the current stress regime with slip rates of 1 to 2 m/Myr. In their study 11 total faults, over distances from 10 to 60 km were added to a PSHA to show a 10 to 20% increase in peak ground acceleration (PGA) across a range of AEPs.

A recurring theme in all of these studies is the value of the more rigorous paleoseismic studies, be it field or desk-based, to reduce uncertainty and add confidence into the assessment of neotectonic faults that could have significant impact to design basis ground motions estimates.

### 3 SENSITIVITY ANALYSIS

#### 3.1 METHODOLOGY

The sensitivity analysis methodology involved developing an exemplar PSHA for a location in Northern NSW/Southern Queensland, where no neotectonic faults in the current Geoscience Australia NFD are identified (Figure 1). It is important to note that in this area, the NFD is not complete and there are many mapped regional bedrock faults that are favourably aligned with the current stress regime to allow reactivation.

The exemplar fault parameters (e.g. maximum magnitude) were based on typical neotectonic faults located in eastern Australia with three mean slip rate scenarios ( $\sim 1$  m/Myr,  $\sim 10$ m/Myr, and  $\sim 100$ m/Myr). The slip rates scenarios were selected to represent orders of magnitude of ground deformation. For reference, a 1 m/Myr slip rate is arguably the lower limit of recognisable fault displacement expression given erosion rates, and a 100 m/Myr slip rate is comparable to active slip rates in high seismicity areas (e.g. a Pleistocene rupture). In line with the typical PSHA methodology, the slip rate scenarios were implemented with weighted distributions across upper, preferred, and low estimates, to capture epistemic uncertainty.

The PSHA model followed the ANCOLD (2019) guidelines and incorporated inputs from NSHA23 (Allen et al., 2023). A full detailed description of the PSHA implementation is beyond this paper. The key model components are summarised below:

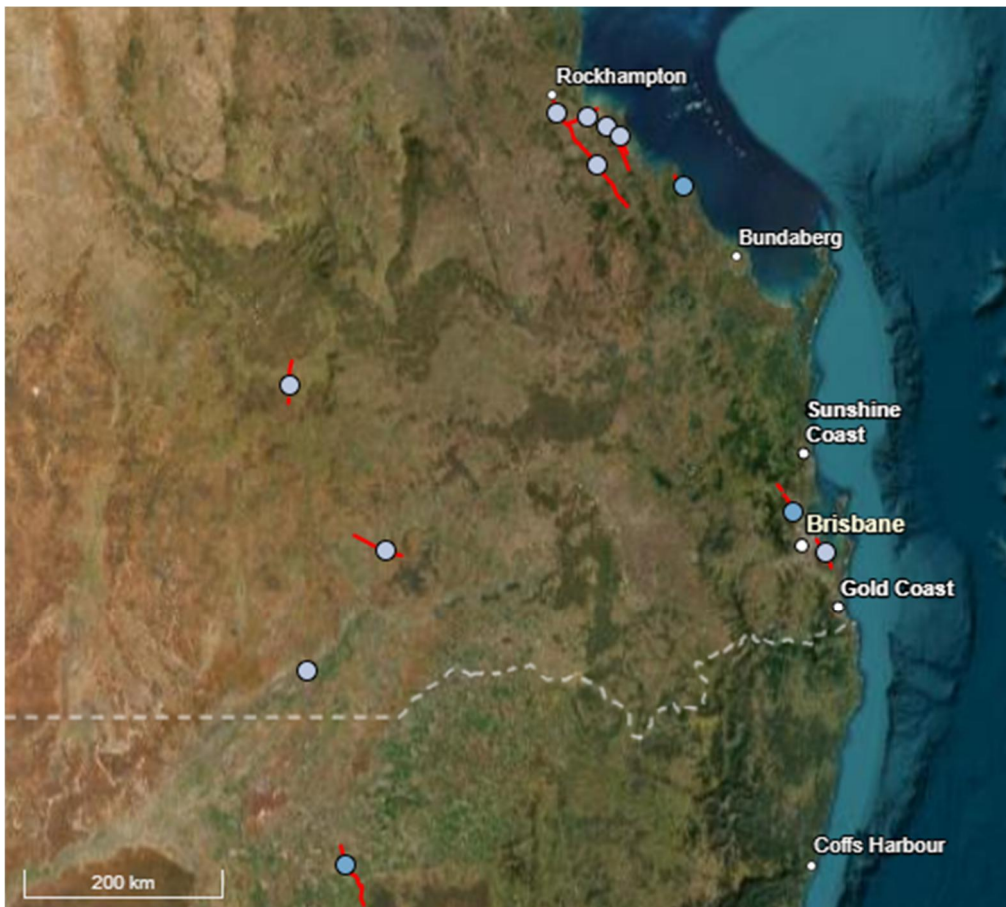
- Site  $V_{s30}$  of 760 m/s.
- NSHA23 earthquake catalogue.
- Three seismotectonic models; two distributed seismicity/areal-source models (GHD site-specific and AUS6) and one smoothed seismicity models (RF23). Both AUS6 and RF23 implementations were extracted from NSHA23.
- Ground motions prediction equations applied for non-cratonic Australia.
- Faults were added to baseline model with no consideration of double counting between fault and areal sources.
- The hypothetical fault characterisation including length, dip, seismogenic depth was used to calculate a maximum magnitude distribution is summarised in Table 1.
- b-values distribution was adopted from the local site-specific areal source zone
- Neotectonic faults were modelled with an exponential magnitude recurrence model (i.e., Gutenberg - Richter) with a minimum magnitude of M5.0. While many Australian PSHAs apply weighted exponential and characteristic magnitude recurrence models to capture uncertainty, implementing only the exponential model in this study is considered conservative.

The model was run to develop baseline ground motions (e.g. no neotectonic fault contributions). The model was then re-run, iteratively, with a single neotectonic fault added to the model for 15 hypothetical distance-slip scenarios: five site-to-fault distances (5, 10, 20, 50, and 80 km) with the three slip rate scenarios (Low, Moderate, High).

Results were computed for three AEP (1:475, 1:2000, and 1:10,000) representing typical design basis AEP for critical infrastructure over three ground motion parameters (PGA with spectral periods of 0.2 s and 1.0 s). For reference the baseline PGA at a 1:10,000 AEP for the exemplar site is ~0.1g.

**Table 1: Neotectonic Fault Characterisation**

| Length (km) | Fault Type | Dip Angle (weight) | Depth (weight) | Mmax Mw (weight) |
|-------------|------------|--------------------|----------------|------------------|
| 170         | Reverse    | 60 (0.2)           | 10 (0.2)       | 7.2(0.2)         |
|             |            | 65 (0.6)           | 15 (0.6)       | 7.3(0.6)         |
|             |            | 70 (0.2)           | 25 (0.2)       | 7.4(0.2)         |

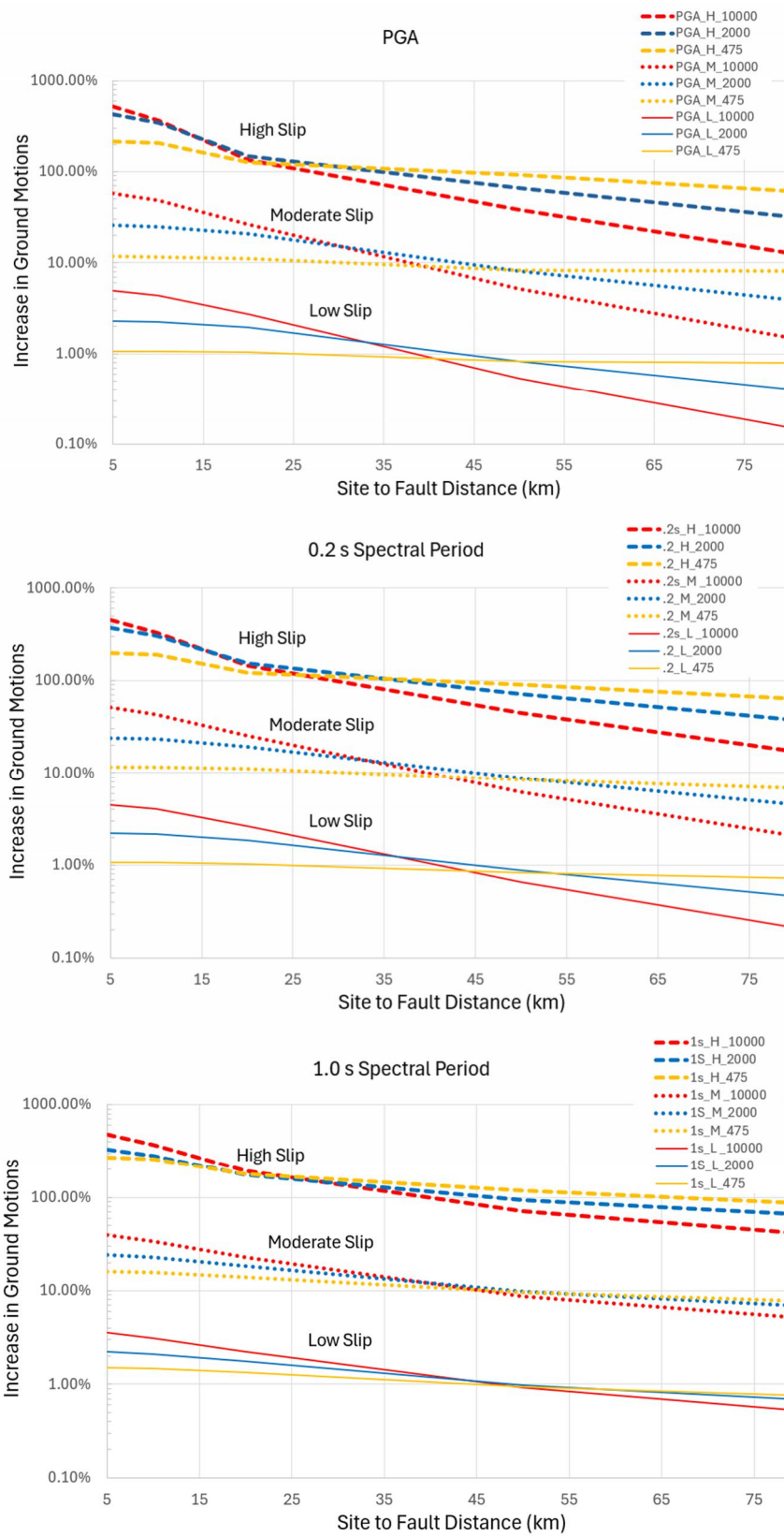


**Figure 1:** Extract from Geoscience Australia NFD for Northern NSW/Southern Queensland highlighting the sparsity of neotectonic faults (red) identified in the region ([www.neotectonics.ga.gov.au](http://www.neotectonics.ga.gov.au))

### 3.2 SENSITIVITY RESULTS

The sensitivity results are presented in Figure 2 for three ground motion parameters (PGA, 0.2 s, and 1.0 s) and three AEPs (1:475, 1:2,000, and 1:10,000).

Each line represents the relative increase in calculated ground motions through the addition of the distance-slip fault scenario as a percentage to the baseline hazard (no faults). The percentage increase is shown in log scale on the y-axis and distance from site-to-fault on the x-scale. The three slip scenarios are delineated by line style (Low Slip = solid, Moderate Slip = dotted, High Slip = dashed). The three AEP scenarios are separated by colour (1:475 AEP = orange, 1:2,000 AEP = blue, 1:10,000 = red).



**Figure 2:** Relative percentage increase in ground motions from fault distance-slip scenarios. PGA (top), 0.2 s (middle), 1.0 s (bottom). The three slip scenarios are delineated by line style (Low Slip = solid, Moderate Slip = dotted, High Slip = dashed). The three AEP scenarios are separated by colour (1:475 AEP = orange, 1:2,000 AEP = blue, 1:10,000 = red).

## 4 DISCUSSION

The sensitivity results show a similar pattern across all ground motions parameters and AEPs. As expected, adding neotectonic fault scenarios with increasing slip, from Low to High Slip, corresponds to larger increases in relative ground motions to the baseline, respectively.

The Low Slip scenarios have little increase to ground motions across all scenarios. They only increase the baseline hazard by a few percent when the site-to-fault distance is less than ~10km at 1:2,000 and 1:10,000 AEPs.

The High Slip scenarios increase the baseline hazard ground motions by over 100% for all ground motions parameters and AEPs for distances less than ~25 km. As expected, the High Slip scenarios are over 2 x the baseline hazard. The 1.0 s results show this increase out to ~45 km, reflecting the influence in ground motion from large earthquakes at distance.

The Moderate Slip scenarios report an increase typically between 10% and 100% out to distances of 45km.

Across all slip scenarios, at 1:475 AEP the relative change in ground motions with increasing distance is expressed with a relatively flat line (comparable change across all distances) compared to a steeper slope at 1:10,000 AEP where the relative increase drops off faster with distance. This steeper slope for 1:10,000 AEP reflects the greater contribution from the baseline (e.g. background) seismicity at these lower probabilities (e.g., long return periods).

Consideration of these exemplary results can start to provide insight into what slip rate scenarios on potential neotectonic faults at known distances will contribute significantly to ground motion estimation at a site. While state of practice guidance directs accounting for neotectonic faults that could significantly contribute to the ground motion, there is no explicit commentary on what significant contribution means. For example, taking a 10% increase as an arbitrary threshold for engineering significance, these exemplar results can be interpreted to provide insight on contribution of faults and support decision making and justification for more detailed characterisation of neotectonic faulting through paleoseismological investigations.

- A High Slip scenario contributes significantly (e.g. >10%) to the ground motions at all distances and AEPs. While the contribution drops with distance for PGA, at 1.0 s the increase in ground motions is still significant. This highlights the importance of identifying and confidently quantifying slip rates for these neotectonic faults.
- A Moderate Slip scenario contributes significantly (e.g. >10% - 100%) to ground motions at site-to-fault distances less than 45 km. The contribution is more significant in the lower probabilities. This highlights the importance of identifying and confidently accounting for neotectonic faults within 45km.
- A Low Slip scenario fault increases the ground motions less than the 10% arbitrary threshold. This suggests that these low slip neotectonic faults are not significant to the ground motion estimates (assuming a 10% threshold of significance).

These insights can be used to inform decision making to support more detailed paleoseismological studies following initial desk study/screening level assessments of potential neotectonic faults near a site. As often is the case, the significance of a potential neotectonic fault needs to be communicated, and often quantified, to decision makers to justify the investment in increased effort.

Notably, as a single exemplary PSHA, the analysis presented here has inherent site-specificity with its geographical location as well as the implementation of the PSHA model (e.g. site Vs30, local areal sources, fault characterization, ground motion models, etc.). It is not intended as a generalization for all of Australia.

## 5 SUMMARY

Although the incorporation of neotectonic faults is now standard in the current state of Australian seismic hazard assessment practice, the level of effort required to adequately characterise neotectonic faults to understand their significance in contributing to ground motions has not yet been mainstreamed.

A sensitivity analysis was carried out by iteratively adding 15 hypothetical neotectonic distance-slip scenarios, five site-to-fault distances (5, 10, 20, 50, and 80 km) with three slip rate scenarios, to an exemplar PSHA with no previous mapped neotectonic faults.

The results show a relationship between distance-slip scenarios on neotectonic faults and an increase in estimated ground motions. For this exemplar, it reiterates the significance of neotectonic faults with slip rates more than ~100 m/Myr, shows that slip rates of ~10m/Myr can significantly increase ground motions at distances less than ~50km, and neotectonic faults with slip rates of 1m/Myr have little contribution. This sensitivity analysis has inherent site-specificity in its geographical location as well as details in the implementation of the PSHA model. More work is needed to expand the analysis to adequately capture a range of seismotectonic settings in Australia and support broader understanding of neotectonic fault significance to

critical infrastructure ground motions. Nevertheless, these insights can start to help inform decision making in support of more detailed paleoseismological studies following initial desk study/screening level assessments of potential neotectonic faults near a site.

The findings of this study and other paleoseismic studies on neotectonic faults can be used to develop guidance on the requirements of paleoseismic assessments for critical infrastructure in Australia.

## 6 ACKNOWLEDGEMENTS

The author wishes to thank Dr Brendan Duffy and Dr Narges Khajavi for their valuable discussions on neotectonic faulting and assessment practice in Australia. Comments from an anonymous reviewer were very much appreciated.

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