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Evaluating deterministic and probabilistic seismic hazard assessments for the tunnel design in Sydney: Insights and comparisons

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ABSTRACT: This paper evaluates the application of Deterministic Seismic Hazard Analysis (DSHA) for tunnel design in the low-seismic context of Sydney and compares its outcomes with National Probabilistic Seismic Hazard Assessments (NSHA18 and NSHA23) and the AS1170.4 design standard. While DSHA is valuable in regions with recognised active faults, its use in Sydney—where no active faults have been identified—can significantly overstate hazard levels.

The study shows that PSHA-derived ground motions are substantially lower than those from DSHA and AS1170.4, indicating that AS1170.4 provides a conservative basis for design in this region. In particular, DSHA scenarios involving the Lapstone Structural Complex produce unrealistically high ground motions, despite the fault being classified as inactive under international and ANCOLD guidelines.

The findings support the use of PSHA informed by NSHA23, which, when paired with appropriately selected deterministic scenarios and the conservative provisions of AS1170.4, offers a more realistic and economically justifiable approach to infrastructure design in Sydney's low-seismicity environment.

1 INTRODUCTION

Section 6.4 in Austroads Guide to Road Tunnels (2021) (AGRT) has those definitions for different seismic design events based on performance-based design principles:

- After the design return period event (sometimes referred to in other countries as maximum design earthquake MDE), the tunnel should be usable by emergency traffic, although damage may have occurred, and some temporary repairs may be required. Permanent repair to reinstate the design capacities for both static and seismic loading should be feasible.
- After an event with a return period significantly less than the design value (sometimes referred to in other countries as operating design earthquake ODE), damage should be minor, and there should be no disruption to traffic.
- After an event with a return period significantly greater than the design return period event (the maximum considered earthquake MCE), the tunnel should not collapse, although damage may be extensive. It should be usable by emergency traffic after temporary repairs and should be capable of permanent repair, although a reduced capacity for further seismic events may be acceptable, given this is a highly infrequent event.

The definitions for ODE, MDE, and MCE are adapted from international practices, particularly from countries where maintaining tunnel operability post-earthquake is critical due to realistic threats such as aftershocks, emergency response, and commuter demands. These definitions are applicable across all seismic regions, with their relevance becoming more pronounced in areas of moderate to high seismicity, such as New Zealand, where the magnitude and frequency of seismic events are greater.

While Sydney is located in a low-seismicity region where seismic loading may not typically govern tunnel design, this does not preclude the application of AGRT. The definitions of MDE, ODE, and MCE remain valid and are determined by return periods, regardless of seismicity level. However, in such regions, the differences between return period events are relatively small, and the probability of a disruptive earthquake is low. As a result, designing for post-earthquake operability, such as continued emergency traffic use, may be considered overly conservative or economically disproportionate to the actual risk. Of course, this depends on the availability of the application of the probability of exceedance.

However, AGRT does not define the design earthquakes in terms of probability of exceedance or return periods.

In this paper, the author conducts a Deterministic Seismic Hazard Analysis (DSHA) for the Sydney region, using the ground motion model developed by Somerville et al. (2009) for the Sydney Basin. The results are compared with those from the National Seismic Hazard Assessments (NSHA) 2018 and 2023, alongside the requirements outlined in AS 1170.4, which is applicable to all structures, including tunnels. The active faults in the Sydney area are identified for the DSHA application or selection. The probability of exceedance or return periods has been discussed and recommended.

2 PSHA HAZARD CURVE AND COMPARISON WITH AS1170.4

Following the release of the 2018 Probabilistic Seismic Hazard Assessment (PSHA18), Geoscience Australia, in collaboration with the broader Australian seismology community, developed the 2023 National Seismic Hazard Assessment (NSHA23). This updated assessment is intended for incorporation into the upcoming 2024 edition of Standards Australia's Structural design actions, Part 4: Earthquake actions in Australia (AS 1170.4–2024).

Seismic hazard curves provide the annual probability of exceeding a given ground motion level. Hazard curves calculated on AS1170.4 Site Class Be are calculated for the localities listed in Table 3.2 of the AS1170.4–2024 (Standards Australia, 2024), and additional sites.

Figure 1 summarises a comparison of mean seismic hazard curves for the NSHA18 and the NSHA23, and shows the annual probability of exceedance against Peak Ground Acceleration (PGA) for Sydney. The annual probability of exceeding a given PGA level (in g) for Sydney on AS1170.4 Site Class Be (equivalent to VS30 = 760 m/s). The plots compare the mean NSHA18 and NSHA23 hazard curves. The 5^{th} - 95^{th} percentile curves are shown for the NSHA23, while the AS1170.4 - 2024 Z value is plotted together with the hazard floor value of 0.08g as used in the AS1170.4 - 2024. The rationale for the changes in hazard between the NSHA18 and NSHA23 is discussed in (Allen et al., 2023).

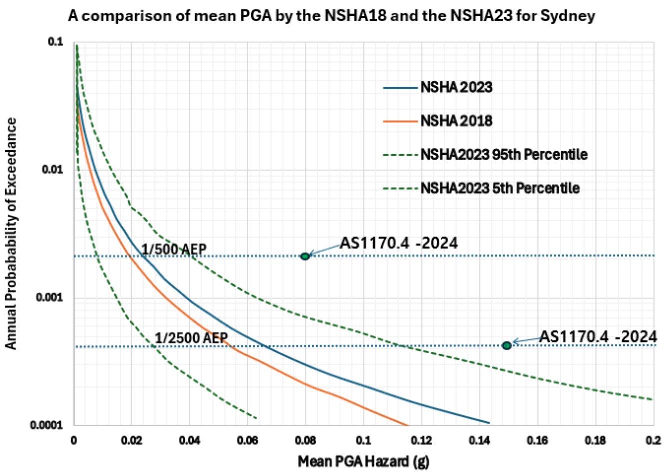

Figure 1 Comparison: mean PGA by NSHA18 and NSHA23

As can be seen in Figure *1*. The PGA obtained by either PSHA18 or PSHA23 is much lower than the PGA obtained by AS1170.4 (2024) for the Sydney region.

Table 1 below compares PGAs using different models.

Table 1. The difference in PGA by different models

AEP	PGA (g)		
	NSHA18	NSHA23	AS1170.4
1/475	0.021	0.026	0.08
1/2475	0.056	0.07	0.144

To evaluate the conservatism of each model, a Deterministic Seismic Hazard Analysis (DSHA) based on the ground motion model by Somerville et al. (2009) is conducted for further comparison and comment purposes. For DSHA purposes, we need to review the seismic scenarios in the Sydney Basin.

3 EARTHQUAKE SCENARIOS IN SYDNEY

The Sydney Basin is underlain by a thick sequence of sedimentary rocks deposited during the Permian to Triassic periods, roughly between 290 and 200 million years ago. Situated well within the stable interior of the Australian tectonic plate, the basin typically experiences low levels of seismic activity, especially in comparison to areas located near active plate boundaries. Nevertheless, seismicity within the basin is not evenly distributed, with relatively higher activity observed in its southern and western regions.

Allen et al. (2011) published the geographical distribution of past earthquake events within the basin. The Geoscience Australia recorded earthquake activity shows:

1. No earthquakes greater than magnitude three have been recorded within 20 km of Sydney's Tunnels.
2. The strongest earthquake ever recorded in the Sydney Basin had a magnitude of 5.6.

Paleo-seismic research by Clark (2010) indicates that the LSC is capable of producing earthquakes with moment magnitudes (Mw) of up to 7.5, although such events are expected to recur only every 1 to 2 million years.

In addition to the LSC, other fault systems within the Sydney Basin may also exhibit seismic activity. Berryman et al. (2009), using geological and seismological data gathered from regional mining and tunnelling projects, assessed the likelihood of moderate-magnitude earthquakes occurring along these faults. Their analysis suggests that individual faults could generate events ranging from Moment Magnitude (M_w) 5.0 to 6.0, with recurrence intervals spanning several million years. Collectively, these findings indicate that the overall seismic hazard for tunnels in the Sydney region is low, due to the region's low seismicity and limited potential for strong ground shaking. Nevertheless, a higher moment M_w is conservatively assumed in the following DSHA to account for uncertainties and ensure robustness in the design approach.

For deterministic seismic hazard assessment (DSHA) in tunnel design, two representative earthquake scenarios are commonly considered:

- A M_w 7.5 event originating from the LSC, situated 20–50 km from the Sydney CBD.
- A hypothetical Mw 5.5 earthquake occurring 20 km from the city.

Although these scenarios represent extreme cases, they are treated as maximum credible earthquakes (MCE) within current seismic hazard frameworks (Clark, 2010; Berryman et al., 2009).

4 DSHA MODEL AND COMPARISON

The two scenarios in the above section involved DSHA. The analyses are based on the model of Somerville et al. (2009). The 5%-damped uniform hazard horizontal acceleration response spectra for Class B – Rock (Vs30 = 760m/s) are shown in Figure 2 also compares the uniform hazard spectra within the DSHA results for M_w of 5.5 and 7, PSHA23, and AS1170.4. As we can see, the DSHA spectra for M_w of 7.5 are significantly higher than those for M_w of 5.5 and AS1170.4.

Table 2 gives the PGA comparison. M_w=5.5 DSHA obtains a PGA of 0.06, and for M_w=7.5, DSHA gets the PGA of 0.2. Compared with AS1170.4, PGA is 0.08 for the case of the 10% in 50 years (AEP of 1/475 - Probability factor kp of 1). PGA is 0.144 for the case of the AEP of 1/2475 (Probability factor kp of 1.8). AS1170.4 does not explicitly include seismic magnitude in its assessment.As a scenario-based DSHA, the results by DSHA are governed by magnitude (Mw) selection. Through the comparison in

Table 2, PGA by DSHA for M_w of 7.5 is much higher than the minimum PGA value in AS1170.4 (2024). Is the DSHA overestimating the seismic hazard in the Sydney region? Or should the selected seismic with an M_w of 7.5 not be included in the Sydney Basin seismic analysis? As we know, the DSHA does not apply to the inactive faults. DSHA only applies to active faults because it assumes a fault can generate a future earthquake of maximum credible magnitude. Inactive or ancient faults are excluded because they are not expected to rupture again within relevant engineering timescales. Now, we face the question: What is an Active Fault? Or what is the criterion for determining whether faults are active?

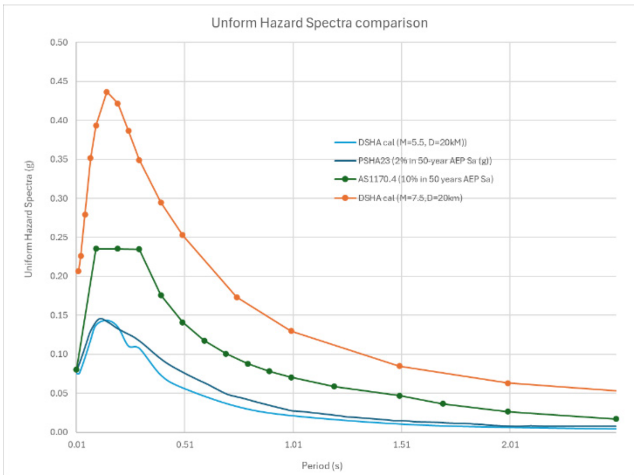

Figure 2. Uniform Hazard Spectra comparison

Table 2. Deterministic Seismic Hazard Analysis for Sydney

PGA (g)			
DSHA		AS1170.4	
		AEP=1/475	AEP=1/2475
Mv=5.5	0.078	0.08	0.144
Mv=7.5	0.2		

5 WHAT IS AN ACTIVE FAULT?

The terminology is from the Australian National Committee on Large Dams (ANCOLD) Guidelines for Design of Dams and Appurtenant Structures for Earthquake, which is adapted from the International Commission on Large Dams (ICOLD - 2016):

– An active fault is defined as a fault, reasonably identified and located, known to have produced historical earthquakes or showing evidence of movements in Holocene time (i.e. in the last 11,000 years) and large faults that have moved in the latest Pleistocene time (i.e. between 11,000 and 35,000 years ago).

– A Neotectonic fault is a fault, not active as defined above, that experienced displacement under conditions imposed in the current crustal stress regime, and hence may move again in the future.

In the ANCOLD commentary, the very long faults that have moved repeatedly in Quaternary time (the last 1.8 million years) are not included as active faults, as they would be too conservative for use in the deterministic analysis approach. However, these faults are included in PSHA as Neotectonic faults.

These are both active faulting areas along plate tectonic boundaries, whereas most of continental Australia apart from the north adjacent to PNG, is a tectonically inactive craton/plate that is far removed from subduction zones.

Based on the NZ definition (Litchfield et al., 2013), a fault zone is classified as active if there is evidence, or inferred evidence, for ground surface displacement in the past 125,000 years (Late Pleistocene, i.e. since the peak high stand of the last interglacial period, marine isotope stage 5e).

In the USA, the California Department of Water Resources, Division of Safety Dams (DSOD) oversees more than 1,200 existing dams. Fraser and Chief (2001) provide fault activity descriptions used by DSOD for their dam safety assessments:

– Active: Faults with proven displacement in the last 35,000 years.
– Inactive: Faults with confidently located traces that are consistently overlain by unbroken geologic materials 35,000 years or older.
– Conditionally Active: A fault that has been active in Quaternary time (about the last 2.6 million years), but its displacement history during the last 35,000 years is not known well enough to determine its activity or inactivity. Conditionally active seismic sources are considered active for dam safety evaluations. Following the definitions above, the author conservatively considers an active fault as a fault that has moved in the past 125,000 years.

6 DETERMINE THE DSHA RESULT IN THE LOW SEISMIC ACTIVITY ZONE OF SYDNEY

The seismic scenario described in Section 3 occurred within the thick sedimentary sequence of the Sydney Basin, composed of Permian–Triassic aged rocks (approximately 290–200 million years old). As outlined in Section 4, DSHA is typically applied to active faults, which are assumed to be capable of rupturing at any time. In this context, a fault is generally considered active if there is evidence of movement within the past 125,000 years. Based on the assessment results in Section 5, faults with no evidence of movement within this timeframe may be treated as inactive for design purposes, given the low likelihood of reactivation within a typical infrastructure design life of 100 to 150 years.

However, this does not imply that faults with long recurrence intervals are disregarded. For the purpose of this DSHA, and in the absence of definitive evidence confirming inactivity, these faults are conservatively treated as "active" to ensure that potential seismic hazards are not underestimated in the subsequent analysis.

Including these "active" faults by DSHA would skew engineering design and economic feasibility, leading to unnecessarily conservative outcomes.

As discussed in scenario 2 of Section 3. The LSC is approximately maximum earthquake magnitudes ~M_w7.5 might occur on the LSC with an average frequency of between 1 and 2 million years. It can be treated as an inactive fault. DSHA in Sydney should exclude the magnitudes of M_w 7.5.

In the region of very low to low seismic activity, our knowledge of faults and their activity is derived from NSHA23, and there are no active faults in the Sydney basin. Therefore, we selected a DSHA check for a reasonable nearby earthquake (Mw = 5.5 and D = 20km) for AS1170.4 Site Class Be, as shown in Table *3* below. The results show that the 84th percentile of DSHA is similar to PSHA at 2,475 years return. Refer to Figure *2* above, where hazard values are calculated to Sa (3.01 s), but are truncated to Sa (2.5 s) for plotting clarity.

Table 3. Selected DSHA output in Sydney (Mv=5.5, D=20km)

Baseline: 5% Damping				
T (s)	PSa Median for 5% damping	PSa Median + 1.σ for 5% damping	PSa Median - 1.σ for 5% damping	Sd Median for 5% damping
0.01	0.07803	0.15306	0.03978	0.00019
0.02	0.07495	0.14730	0.03814	0.00074
0.03	0.08035	0.15950	0.04048	0.00180
0.05	0.09613	0.19479	0.04744	0.00597
0.075	0.11794	0.24367	0.05709	0.01647
0.1	0.13753	0.28592	0.06615	0.03414
0.15	0.14377	0.29726	0.06953	0.08030
0.2	0.13576	0.27865	0.06615	0.13481
0.25	0.11072	0.22647	0.05413	0.17179
0.3	0.10793	0.22170	0.05255	0.24114
0.4	0.07340	0.15174	0.03550	0.29152
0.5	0.05720	0.11949	0.02738	0.35498
0.75	0.03330	0.07084	0.01565	0.46496
1	0.02162	0.04622	0.01011	0.53671
1.5	0.01081	0.02309	0.00506	0.60394
2	0.00649	0.01386	0.00304	0.64469
3	0.00306	0.00655	0.00143	0.68375
4	0.00180	0.00381	0.00085	0.71431
5	0.00118	0.00250	0.00056	0.73228
7.5	0.00049	0.00103	0.00023	0.68216
10	0.00026	0.00055	0.00013	0.65576

7 CONCLUSIONS

This paper has examined the application of Deterministic Seismic Hazard Analysis (DSHA) in the low-seismicity context of the Sydney region and compared its outcomes with those from National Probabilistic Seismic Hazard Analyses (NSHA18 and NSHA23) and the current design standard AS1170.4 (2024). While DSHA offers valuable insights for regions with well-defined, active faults, its application in areas with low seismicity, such as Sydney, must be approached with caution.

The comparative analysis shows that PGA values derived from NSHA (both 2018 and 2023 updates) are significantly lower than those stipulated in AS1170.4, suggesting that the current standard may be conservative for Sydney's seismic environment. Moreover, the DSHA results, particularly for the Mw of 7.5 scenario sourced from the Lapstone Structural Complex (LSC), produced ground motions exceeding those from both AS1170.4 and PSHA. However, considering that the LSC has an estimated recurrence interval of 1 - 2 million years and lacks evidence of movement within the past 125,000 years, it should be classified as an inactive fault under international and ANCOLD guidelines. Including such a scenario in DSHA overstates the actual seismic hazard and may lead to overly conservative designs.

Furthermore, the assessment confirms that no active faults have been identified within or near the Sydney Basin according to modern criteria. The DSHA scenario based on the Mw of 5.5 event at 20 km distance aligns reasonably with the upper-bound results from PSHA at the 2,475-year return period. This supports the view that for the Sydney region, where there are no currently recognised active faults, AS1170.4 provides a reasonable conservative solution for seismic design.

In conclusion, while DSHA remains a useful tool in regions with recognised active faults, its application in low-seismicity areas like Sydney, where no active faults have been identified, should be limited. For infrastructure such as road tunnels in the Sydney Basin, seismic design based on PSHA, informed by the latest NSHA23 data and consistent with the conservative approach of AS1170.4, provides a more realistic, reliable, and economically justifiable solution.

8 ACKNOWLEDGEMENT

This paper is in memory of our deceased colleague, geologist Richmond Beetham, in New Zealand. He undertook the geological part of the PSHA work for this project. The author recognised and appreciated his contribution to the project.

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