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Site-Specific Seismic Hazard Assessment Using Deterministic and Probabilistic Methods in Low-Seismicity Regions of NSW, Australia

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ABSTRACT: New South Wales (NSW) in Australia is a region of low seismicity, yet critical infrastructure projects increasingly require assessment for rare, high-consequence earthquake events. While the Australian Seismic Design Code (AS 1170.4–2007) provides design spectra for return periods up to 2,500 years, some infrastructure demands evaluation for up to 10,000-year events.

This paper presents a site-specific seismic hazard assessment for a major underground hydropower project in NSW, using both deterministic seismic hazard analysis (DSHA) and probabilistic seismic hazard analysis (PSHA). The analysis incorporates regional neotectonic faults, inactive paleo faults, and the latest National Seismic Hazard Assessment model (NSHA18). Deterministic scenarios address plausible near-field events, while probabilistic approaches cover a broad range of potential seismic sources and return periods, up to 10,000 years.

The comparison of DSHA and PSHA results demonstrates that probabilistic values control the seismic design at longer return periods, exceeding the requirements of AS1170.4. This study offers a robust methodology for tailoring seismic hazard assessments to the needs of large infrastructure in low-to-moderate hazard zones, providing a practical reference for similar projects across Australia.

KEYWORDS: Tunnel design, PGA, site-specific seismic hazard.

1 INTRODUCTION - SNOWY2 PROJECT BRIEF

The Snowy 2.0 pumped hydro project (Figure 1 and Figure 2), with a capacity of 2,000 MW, connects the existing Tantangara and Talbingo reservoirs via a system of 10.9 m diameter tunnels and an underground power station equipped with reversible pump-turbines. Energy is generated by harnessing approximately 1,000 metres of hydraulic head, allowing water to flow from the upper reservoir (Tantangara) to the lower reservoir (Talbingo). The reversible turbines also enable water to be pumped back upstream, creating a closed-loop pumped-storage system. This configuration allows repeated use of the same water to meet peak electricity demand, improving the overall efficiency of water resource utilisation.

The seismic design of the Snowy 2.0 infrastructure is governed by both national and industry-specific guidelines, namely:

- AS 1170.4–2007: Structural Design Actions, Part 4 – Earthquake Actions in Australia; and
- ANCOLD Guidelines for Design of Dams and Appurtenant Structures for Earthquake (May 2019).

While AS 1170.4 specifies a maximum earthquake return period of 2,500 years (as per Table 3.1 in AS 1170.4), the ANCOLD guidelines stipulate design considerations for events with return periods up to 10,000 years. As such, a site-specific seismic hazard assessment was undertaken for Snowy 2.0 to establish appropriate earthquake loading criteria. The project is required to demonstrate compliance with ANCOLD's seismic design principles and documentation requirements.

Figure 1 Snowy2 project – Power waterway plan

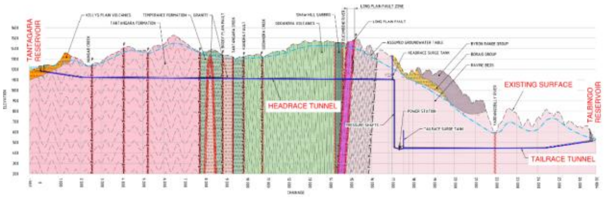

Figure 2 Snowy2 project – Power waterway long section

2 SITE-SPECIFIC DETERMINED SEISMIC HAZARD ANALYSIS FOR SNOWY2

A deterministic seismic hazard assessment (DSHA) was conducted for the SNOWY2 project. DSHA provides specific estimates of potential ground shaking at the site by considering data from identified active faults.

As is well known, the DSHA does not apply to 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.

2.1 *Magnitude selection for DSHA*

The concept of "active fault" follows the ANCOLD Guidelines for the Design of Dams and Appurtenant Structures for Earthquakes, which are based on ICOLD (2016). These guidelines define:

- An active fault is one that is clearly identifiable and has either produced recorded seismic events or shows signs of movement during the Holocene epoch (the past 11,000 years). This also includes major faults with activity dated between 11,000 and 5,000 years ago.
- A neotectonic fault is not considered active under the above criteria but has experienced displacement under the current stress regime of the Earth's crust, suggesting the potential for future movement.

Using these definitions, faults that may have last moved between 5 and 10 million years ago are not classified as active. None of the known faults in the Snowy region, including the Tantangara Fault near the reservoir intake, meet the criteria for active faults. The Tantangara Fault is therefore treated as a neotectonic structure with a negligible slip rate, consistent with the NSHA18 seismic model.

The NSHA18 integrates data on known shallow crustal faults and regional seismic sources across Australia. Comprehensive information regarding the NSHA dataset is provided by Allen et al. (2018a, 2018b). The seismic hazard parameters discussed in this report are derived from the NSHA18 seismic source models, which include fault sources, area sources, and smoothed gridded seismicity. The subduction zone component of NSHA18 was excluded from Coffey's analysis, as these sources lie over 1000 km to the north and have no significant impact on the seismic hazard at the Snowy 2.0 site. For this assessment, Coffey applied the NSHA seismic source model within a 500 km radius of Snowy 2.0. The model's reliability was assessed by comparing the peak ground acceleration (PGA) hazard curve from this study with that of the NSHA18 model at Canberra.

2.2 *DSHA results*

In a scenario-based DSHA, the results are governed by the magnitude (Mw) selection. Given the region's low seismicity, the understanding of fault activity relies primarily on the NSHA18 dataset. Consequently, a DSHA was performed to assess possible reservoir-induced events:

- Scenario 1 - magnitude Mw 3.5 at 1 km distance, and
- Scenario 2 - magnitude Mw 5.5 at 25 km - a plausible regional earthquake scenario.

Table 1 summarises the PGA comparison. The DSHA yields a PGA of 0.038g for the Mw 3.5 scenario and 0.047 g for the Mw 7.5 scenario. By contrast, AS1170.4 specifies a PGA of 0.08g for 10% in 50 years event (Annual Exceedance Probability (AEP) = 1/475, probability factor kp = 1) and 0.144g for the AEP = 1/2475 event (kp = 1.8). Note that AS1170.4 does not explicitly use earthquake magnitude as an input in its assessment.

Table 1 Deterministic Seismic Hazard Analysis for SNOWY2

DSHA		PGA (g)	
		AS1170.4	
		AEP=1/475 (0.002)	AEP=1/2475 (0.0004)
Mv=3.5	0.038	0.08	0.144
Mv=5.5	0.047		

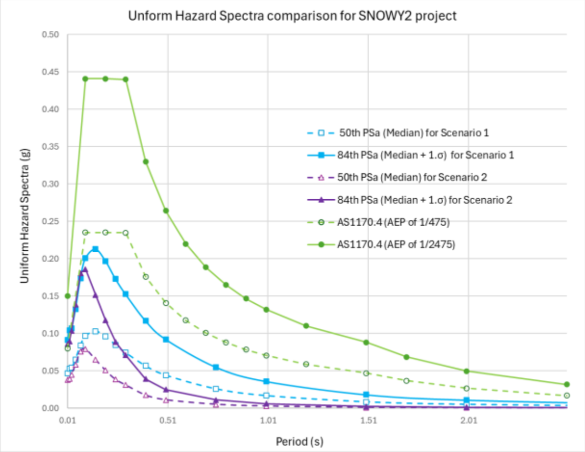

Figure 3 Uniform Hazard Spectra by DSHA and AS1170.4 for SNOWY2 project

Figure 3 shows the Uniform Hazard Spectra comparing AS1170.4 with the DSHA results for the two scenarios. AS1170.4 spectra are plotted for AEP = 1/475 (0.002) and AEP = 1/2475 (0.0004). The DSHA curves present the 50th-percentile and 84th-percentile spectral accelerations for each scenario. Results indicated that the 84th percentile ground motion values from the DSHA remain below those from the AS1170.4 for a 2,475-year return period, confirming that deterministic loads do not govern the seismic design for the SNOWY2 project. Refer to the discussion in the Section 3 and the results in the above, in a scenario-based DSHA, the results are governed by the magnitude (Mw) selection. Given the region's low seismicity, the understanding of fault activity relies primarily on the NSHA18 dataset. Consequently, a DSHA was performed to assess possible reservoir-induced events:

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2.3 *Earthquake action as per AS1170.4*

The example of 5%-damped uniform hazard horizontal acceleration response spectra (C(T)) as per AS1170.4 for Class B – Rock (IL3) is listed in Table 1. The detailed calculations were based on AS Equation 7.2(2), see below:

$$C(T) = k_p Z C_h(T) \tag{1}$$

Where k_p is the Probability factor defined by Table 3.1 AS1170.4; Z is the seismic hazard defined by Figure 3.2 (A) AS1170.4, and $C_h(T)$ is the spectra shape factor by Table 6.4 in AS1170.4.

The Elastic Response Spectra by AS1170.4 were presented in Figure 3.

The above Figure 3 compares the Hazard Spectra by DSHA and AS1170.4. Hazard values were calculated up to 4.0 s but truncated to 2.5 s for clarity.

After comparing the results in Sections 1 and 2, it is evident that DSHA does not govern the seismic design of the Snowy 2.0 project. The deterministic ground motion estimates are consistently lower than those derived from PSHA at relevant return periods. Therefore, the project's design is governed by the probabilistic seismic hazard outcomes, which will be discussed in the next section. Notably, the PSHA extends the PGA estimates beyond the limitations of AS1170.4, particularly for rare events with return periods exceeding 2,500 years, thereby providing critical input for high-consequence infrastructure design.

3 SITE-SPECIFIC PSHA FOR SNOWY2

Since the DSHA is not governing the design, a PSHA has been conducted for the SNOWY2 project. The results were provided to the geotechnical and structural design. This section presents the results of the site-specific Probabilistic Seismic Hazard Assessment (PSHA) conducted for the Tantangara intake (latitude 35.7926°S, longitude 148.6523°E), Talbingo intake (latitude 35.768741°S, longitude 148.3776°E), and the connecting tunnel alignment.

The analysis is based on the probabilistic method originally formalised by Cornell (1968). A logic tree framework was employed, incorporating four independent regional source models developed by Griffin et al. (2018). The structure and weighting of the logic tree were established through expert elicitation workshops. A total of 18 experts in seismic hazard assessment—representative of the broader Australian earthquake hazard community—participated in two workshops hosted by Geoscience Australia in March 2017. These efforts supported the development of the National Seismic Hazard Assessment 2018 (NSHA18) model, whose inputs and results are used in this study.

3.1 *Site Neotectonic faults*

Key components of the PSHA framework include:

- Ground Motion Prediction Equations (GMPEs) and their associated weights, as summarised in Table 5 of Allen et al. (2018b).
- Seismic source models, detailed in Tables 3 and 4 of Allen et al. (2018b).
- Fault source parameters, including magnitude–frequency distributions and potential episodic recurrence behaviour.
- Area (regional and background) source parameters, including Hypocentral depth ranges (Table 9, Allen et al. 2018b) and maximum magnitudes (Table 4, Allen et al. 2018a).

We consider faults within 50 km of the site from Geoscience Australia's National Fault Source Model used in NSHA18. The model lists 356 onshore and 23 offshore faults. These faults generated large earthquakes in the Neogene–Quaternary (past ~5–2.6 Ma to present), but none in the Snowy 2.0 area are known to be Holocene-active (last ~11,000 years). Neotectonic traces used are summarised in Table 2. All have low slip rates. For example, the nearest Tantangara Fault has an estimated slip of 62 m per million years (≈6.2 mm per 100 years, or ~0.062 mm/yr).

Table 2 Neotectonic fault attributes within 50km of Snowy 2.0

NAME	DISTANCE FROM THE SITE (KM)	LENGTH (KM)	DIP (KM) AND DIRECTION	LONG-TERM SLIP RATE (M/MILLION YEARS)
Tantangara Fault	<1	40	40(E)	62
Tumut Pond Fault	11	59	40(E)	62
Khancoban_Yellow Bog Fault	12	64	40(E)	93
Adaminaby Scarp	13	25	40(W)	16
Cotter Fault	13	54	40(W)	78
Khancoban-Yellow Bog Splay	17	30	40(E)	47
Buenba Splay	32	27	40(W)	16
Tom Groggin Fault	33	92	40(W)	62
Jindabyne Thrust	37	87	20(E)	117
Berridale Wrench Fault	40	48	60(SW)	7
Murrumbidgee Fault	43	69	40(W)	124
Michelago Scarp	45	42	40(W)	31

3.2 *Hazard Curve by Site-Specific PSHA*

The PSHA was performed for ground conditions corresponding to Subsoil Class B – Rock, as defined in AS 1170.4–2007. Assessments were carried out for the Tantangara intake, the Talbingo intake, and the underground powerhouse.

Hazard curves illustrate the variation of peak ground acceleration (PGA) with annual exceedance probability (AEP), which is the reciprocal of the return period. Figure 4 presents the 5%-damped PGA hazard curves for return periods ranging from 10 to 10,000 years at the key design locations.

Table 3 summarises the site-specific PGA values for selected return periods of engineering interest. The minimum design value of 0.08g, as required by AS 1170.4–2018, is also indicated. Site-Specific PGAS (5% Damped) are on the Ground Surface for Subsoil Class B (Vs30 = 760 m/s) at Different Return Periods.

Table 3 Site-Specific PGA by PSHA at different structural locations

LOCATION	RETURN PERIOD (YEARS)	PEAK GROUND ACCELERATION(g)
Talbingo intake	145	0.02*
	475	0.04*
	2,000	0.12
	10,000	0.27
Tantangara intake	145	0.02*
	475	0.04*
	2,000	0.15
	10,000	0.5
Powerhouse	145	0.02*
	475	0.04*
	2,000	0.13
	10,000	0.34

*min. 0.08 as required by AS1170.4

The results presented in Figure 4 and Table 3 indicates the following:

- Tantangara Intake: The seismic hazard is predominantly influenced by the nearby Tantangara Fault, located less than 500 m from the site, leading to relatively higher hazard levels compared to other locations. However, the magnitude of the seismic activity is only 3.
- Powerhouse and Talbingo Intake: These sites are located more than 17 km from the Tantangara Fault. Their seismic hazard is mainly governed by contributions from the Tumut Pond Fault and the Khancoban Yellow Bog Fault, located approximately 12 km away.

As can be seen in Figure 4, the PGA obtained by site-specific PSHA is much lower than the PGA obtained by AS1170.4 (2024) for the Snowy2 project when AEP is greater than or equal to 1/475. Whereas for AEP equal to 1/2475, the PGA by PSHA is much larger than AS1170.4. Specifically, for AEP less than 1/2475, AS1170.4 is out of its limitation.

Table 4 below are summaries of PGAS by PSHA at Tabingo Intake and compared with AS1170.4.

Table 4 PGA comparison between PSHA and AS1170.4

AEP	PGA (g)	
	PSHA	AS1170.4
1/145	0.02	0.08
1/475	0.04	0.08
1/2,475	0.19	0.014
1/5,000	0.31	N/A
1/10,000	0.5	N/A

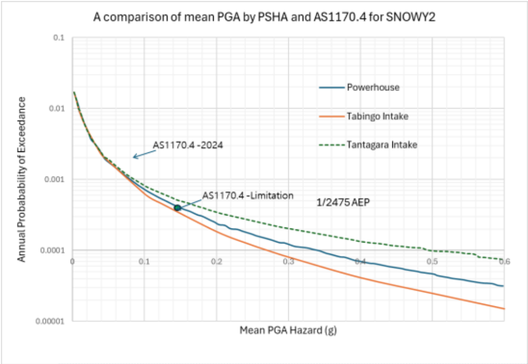

Figure 4 Hazard Curve at different design locations

3.3 *Spectra by site-specific PSHA for SNOWY2*

The 5%-damped uniform hazard horizontal acceleration response spectra for Class B – Rock (V_{s30} = 760m/s) are shown in Figure 5.

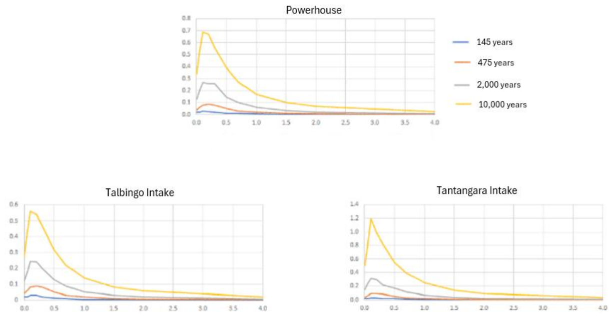

Figure 5 Uniform Hazard Spectra by PSHA for the SNOWY2 project

PSHA spectral results for return periods of 145, 475 and 10,000 years were used to develop site-specific design spectra for Talbingo Intake, Tantangara Intake and the Powerhouse. At each location, spectral ordinates at PGA (Sa at T = 0) and at selected periods (0.01–4.0 s) were extracted and used to calibrate the response-spectrum shape and scaling. The 10,000-year (AEP = 1/10,000) results were retained as an upper-bound sensitivity check where project criteria require more conservative demand estimates. Note that the use of the 10,000-year PSHA as an upper bound extends beyond the return-period scope of AS1170.4.

Epistemic uncertainty in PSHA arises from limited knowledge of seismic sources, magnitude–frequency relations, GMPE selection, and site-response modelling. To mitigate this, we used alternative source models and multiple weighted branches within a logic-tree, and retained long return-period results (AEP = 1/10,000) as a conservative sensitivity check. Remaining epistemic uncertainty should be managed for critical components by conservative detailing or targeted additional checks.

4 CONCLUSIONS

This study illustrates how site-specific deterministic and probabilistic seismic hazard analyses can be effectively applied to infrastructure projects in low-seismicity regions, using a major underground development in New South Wales as a representative case. While deterministic approaches offer valuable insights into plausible near-field earthquake scenarios, the probabilistic analysis, grounded in the 2018 National Seismic Hazard Assessment (NSHA18), provides a more comprehensive framework for evaluating seismic risks across a broad spectrum of return periods, including rare but potentially critical events with return periods up to 1-in-10,000 years.

The findings underscore that probabilistic seismic hazard analysis (PSHA) often yields higher spectral accelerations than deterministic methods for long-return-period events at the Snowy Mountain region. This reinforces the importance of incorporating probabilistic approaches in the seismic design of critical infrastructure, particularly where safety and long-term resilience are of paramount importance. Furthermore, the use of site-specific response spectra, tailored to local geological and seismotectonic conditions, offers a more accurate and realistic representation of seismic hazard than reliance on generic national code provisions alone. This ensures that infrastructure designs are not only robust and safe but also economically optimised, avoiding both under- and over-design.

By integrating deterministic and probabilistic methodologies, this approach bridges the gap between national standards and the nuanced demands of complex infrastructure projects. It enhances the ability of engineers and planners to make informed, risk-based decisions that account for both the likelihood and consequences of seismic events. In doing so, it contributes to the development of more resilient underground infrastructure, even in regions traditionally considered seismically quiet.

The methodology and insights presented in this study can serve as a practical reference for future infrastructure developments in regions with similar seismic conditions. Specifically, the design requirement of Annual Exceedance Probability (AEP) considered in this project extends beyond the limitations prescribed in AS 1170.4, highlighting the need for more tailored hazard assessments in certain contexts. As infrastructure projects increasingly intersect with diverse geological settings and evolving performance expectations, the adoption of such integrated hazard assessment frameworks will be essential in ensuring long-term safety, functionality, and sustainability.

5 ACKNOWLEDGEMENTS

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