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Seismic and Geohazard Assessment for a Pumped Hydroelectric Scheme in South Australia

Luke Johnstone[1], Tim Mote[2] and Jack Pappin[3]

1. Graduate Engineering Geologist, Transport and Resources, Arup, NSW 2000.
   Email: Luke.Johnstone@arup.com

2. Associate Principal, Transport and Resources, Arup, NSW 2000.
   Email: Tim.Mote@arup.com

3. Arup Fellow, Email: Jack.Pappin@hotmail.com

Abstract

A probabilistic seismic hazard analysis (PSHA) was carried out to support the design and geohazard assessment for a proposed pumped hydroelectric energy scheme in South Australia.

The tectonic setting of the site is considered stable continental crust on the eastern edge of the Gawler Craton, yet eastward is the transition into the Flinders Ranges, a zone of high seismic activity associated with a number of active faults expressing uplift.

Following ANCOLD guidance, explicit consideration of neotectonic faults in the PSHA was followed to develop design basis ground motions. Neotectonic features within 50km of the site were characterised and a number of faults are modelled as active sources in the PSHA. The uncertainty of the Torrens Lineament, a major tectonic structure that defines the eastern edge of the Gawler Craton, is modelled probabilistically in the PSHA. Both soil and topographic effects on ground motions were considered for the upper and lower reservoirs.

1 INTRODUCTION

The proposed Cultana Seawater-sourced Pumped Hydro Energy Scheme (CSPHES) is a 225 megawatt pumped hydro energy storage project using seawater near Port Augusta in South Australia. The project has potential to provide enough energy to power over 120,000 homes for around eight hours during periods of peak energy demand (Energy Australia, 2019). The CSPHES will require construction of an upper reservoir, penstock, powerhouse, power transmission, lower reservoir structures and seawater outfall.

A Probabilistic Seismic Hazard Analysis (PSHA) was carried out to support the design and geohazard assessment for this proposed pumped hydroelectric energy scheme. The assessment considered both seismic hazards such as ground motions, active faulting, and liquefaction, and a PSHA to derive design ground motions.

This assessment provides site-specific seismic hazard input to support design and application of (ANCOLD) Guidelines for Design of Dams and Appurtenant Structures for Earthquake for the project (ANCOLD, 2019).

The PSHA developed response spectra for annual probabilities of exceedance (APE) of interest and magnitude-distance de-aggregation showing source zone contributions.

2 MODEL DEVELOPMENT

2.1 Tectonic Setting

Regional seismotectonic setting: The site is located in a stable continental region, on the tectonically stable Indo-Australian plate, far from the earthquake-generating plate boundaries. The Indo-Australian plate is bounded to the south by a mid-ocean ridge system. To the north and east, the plate boundary is complex, including segments of continent–continent collision, continent–arc collision and subduction (Hillis & Reynolds, 2003). This collision generates far-field stresses within the continent and reactivates older faults and structures.

Local seismotectonic setting: The continental-scale stresses identified above are modified by heterogeneities of the crust and pre-existing tectonic structures. These include ancient fault zones, regions of enhanced crustal heat flow, volcanic intrusions and topography, and the contrasting structural strengths of blocks defined by geology and tectonic boundaries (Hillis & Reynolds, 2003; Rajabi et al., 2016). In the upper 10km of Earth’s crust, stresses are partitioned further by the presence and thickness of sedimentary basins, the hydrostatic pressures within them, their geometry, and their relationship with surrounding tectonic blocks (e.g. Zhao & Muller, 2003).

The site is located on the east of an ancient stable section of continental crust. This stable section of crust, the Gawler Craton is made of metamorphosed sediments, volcanics and intrusives. East of the site, the basement rocks are gently folded and faulted forming the Torrens Hinge Zone, a transition into the highly deformed Adelaide Geosyncline on the east of the Spencer Gulf.

Tectonic history: The region has undergone a series of tectonic stress-derived events (McAvaney et al., 2014). Uplift of the Cultana Inlier and initial activation of the Cultana fault occurred between 1600 and 541Ma. During the Marinoan (635 to 541Ma) the Cultana Fault was reactivated as a reverse fault.

The Wilkatana, Depot Creek and Crystal Brook Faults were primarily activated during the Delamerian Orogeny (~515 to 480Ma), when the Adelaide Geosyncline was formed by folding and faulting bounded on the west by the Torrens Hinge Zone.

Separation of Australia from Antarctica ~10Ma resulted in the current stress regime and reactivation of the structures. There have since been five marine transgressions and regressions in the Pirie Basin and lacustrine, lagoonal and marine deposition from the Late Eocene to present.

Current stress regime: The site sits west of the Flinders Range stress province (Hillis & Reynolds, 2000). The Flinders Ranges stress province is characterised by east - west compressive stress and expressed by north – south features. Historic seismicity near the site (see Figure 1) is concentrated to the east of the Spencer Gulf in the Adelaide Geosyncline (Allen, 2018). Seismicity in the Gawler Craton is less common however a number of historical events have occurred along the coast 10-50km inland of the Spencer Gulf. The northern extent of this seismicity is the Roopena and Randel Faults. In the Torrens Hinge Zone underlying and north of the gulf there is little seismicity.

2.2 Regional Neotectonic Features

In Australia, Neotectonic features are faults that have undergone displacement under the current stress regime (5 to 10Ma, Sandiford et al., 2004) and may have the potential for displacement in the future (Clark et al., 2011). The ANCOLD earthquake design guidance directs consideration of neotectonic faults in development of earthquake design basis ground motion

Neotectonic features from the Geosciences Australia (GA) Neotectonic Features Database (Clark, 2012) were examined and included in the PSHA as active sources. These include:

The Wilkatana North, Wilkatana South, Depot Creek Knickpoint and Cobble Faults are a series of fault splays forming the western bound of the Flinders Ranges (see Figure 1). Their upward splaying geometry suggests the segments merge into a single fault at depth and have been modelled as a single feature. Analysis by Quigley et al. (2006) places the slip rate on Wilkatana North as 0.051 mm/year, Wilkatana South as 0.036 mm/year.

The Nectar Brook fault and Crystal Brook Fault form the western bound of the Flinders Ranges to the south of the Wilkatana Fault. The slip rate on these features has been assumed from Somerville et al. (2008) at 0.15 mm/year.

Southeast of the site are the Roopena/Randell Faults which form the northern extent of the Roopena Fault Zone. These are parallel reverse/strike slip faults trending NNE – SSW. Trenching and dating of sediments by Crone et al. (2003) identifies events on the Roopena Fault. From these a slip rate of 0.08 mm/year has been estimated.

In addition to the faults identified in the GA Neotectonic Features Database the Torrens Lineament is included as an active source. The Torrens Lineament is a major tectonic structure directly east of the site delineating the eastern edge of the Gawler Craton. The Cultana Fault, mapped 15 km south of the site, is assumed to be a component of the lineament and confines its location. Here it is near vertical and does not show neotectonic activation. To the north deep seismic lines confine the location of the Torrens Hinge Zone, of which the Torrens Lineament is the western bound. North of the site the Torrens Liniments orientation and dip make it susceptible to reactivation in the current tectonic regime, as it may have a similar orientation and dip adjacent to the site it has been included in the PSHA. It is modelled as a possible neotectonic feature similar to the Randell and Roopena Fault splays to the south.

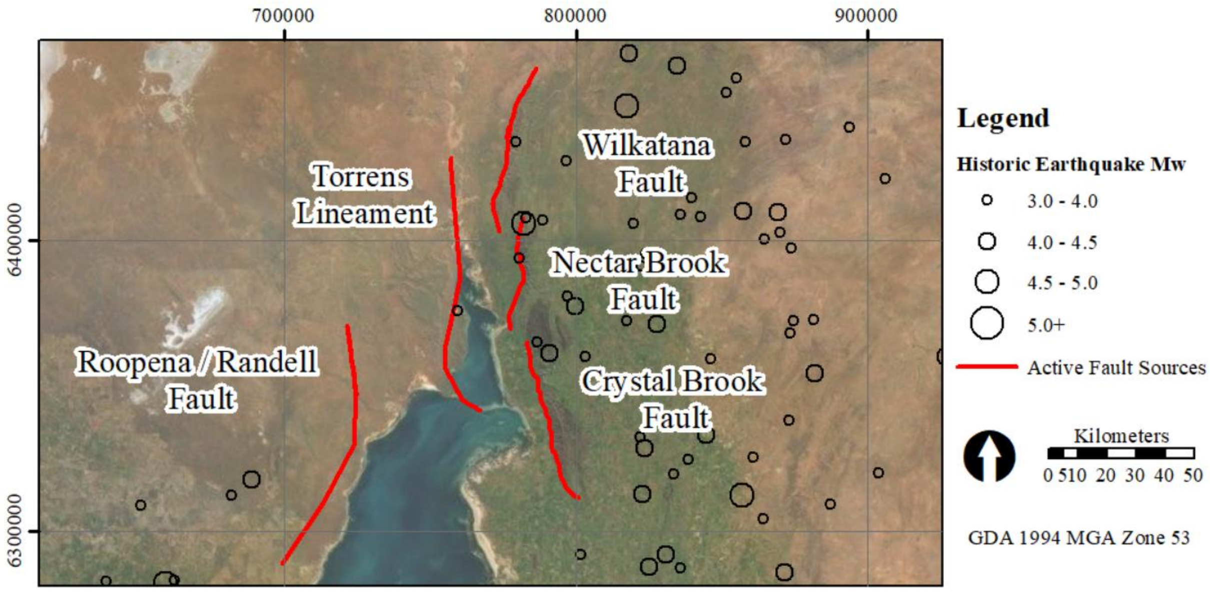

Figure 1 Active fault sources in PSHA and historic events (Allen, 2018)

2.3 Local Faults

Local faults from published mapping and site-specific geologic mapping were considered for Pleistocene activity and inclusion into the PSHA. These included:

To the north of the site a small fault was shown on geologic maps adjacent to a quarry. Field mapping and geomorphological analysis of this and similar features in the region in combination with high angle beds in the faulted block showed that this feature is a historic block slump of the mesa slope.

At the lower site, a gouge zone overlain by young sediments was encountered during the ground investigation, characterised by gouge and breccia with angular clasts in an altered sandy clay matrix and secondary mineralisation, chlorite and quartz.

This triggered a more detailed paleoseismic study of boreholes and trenches, which proved this to be a block slump.

As these features were not a driven by tectonic stresses they were not included as active fault sources in the PSHA.

3 PROBABILISTIC SEISMIC HAZARD ANALYSIS

Derivation of design ground motions follows the PSHA method originally proposed by Cornell (1968) and modified to include uncertainty through the logic tree method. The PSHA combines seismic source zoning, earthquake recurrence and ground motion models (Mote et al., 2017) to produce 'hazard curves' in terms of level of ground motion and an associated annual frequency of being exceeded.

This PSHA builds on the Arup Australian national source model developed by Mote et al. (2017). In the analysis, background seismicity, nearby neotectonics faults are modelled, site sub soil class is identified and topographic scaling applied to the results of the upper reservoir.

The PSHA presented here uses Arup's in-house computer program, Oasys SISMIC, to calculate the annual frequency or rate at which specified hazard values are likely to be exceeded at a site due to areal and fault sources. The program is able to directly model slip rates, characteristic earthquakes and maximum credible events based on fault geometry using the Youngs & Coppersmith (1985) procedures. SISMIC has been verified using the Pacific Earthquake Engineering Research Center test cases (Thomas et al., 2010).

Earthquake catalogue: The catalogue used is detailed in Mote et al. (2017), including instrumental and historical records. The data was cleaned using recommended declustering method number 3 in Burbidge (2012) and converted to moment magnitude (M_W) using Scordilis (2006).

Areal source zones: A seismotectonic model has been developed following the Neotectonic Domains of Clark et al. (2012) by Mote et al. (2017). The domains describe areas with similar characteristics, broadly separated into cratonic and non-cratonic. The site lies within Domain 1b. The rate of occurrence of earthquakes in each area zone is described in terms of magnitude recurrence. Domain 1b has a seismic activity (a-value) of 0.38 and a recurrence rate (b-value) of 0.95. A minimum magnitude of M_W 4.5 and a maximum of M_W 7.3 has been adopted.

Active fault sources: Neotectonic faults are explicitly modelled using the additive moment model. These features are presented in Table 1.

Table 1 Parameters active fault sources.

Neotectonic Fault	**Site to Source Distance (km)**	**Slip Rate (mm/yr) [Weight]**	**Dip (°)**	**Length (km)**	**Depth (km)**	**Mmax (M_W)**
Wilkatana	16	0.03 [0.15] 0.05 [0.70] 0.10 [0.15]	45	60	20	7.5
Nectar Brook	21	0.07 [0.15] 0.15 [0.70] 0.30 [0.15]	65	38	20	7
Crystal Brook	38	0.07 [0.15] 0.15 [0.70]	65	64	20	7.2

Neotectonic Fault	Site to Source Distance (km)	Slip Rate (mm/yr) [Weight]	Dip (°)	Length (km)	Depth (km)	Mmax (M_W)
		0.30 [0.15]				
Ropena & Randell	39	0.06 [0.20] 0.08 [0.70] 0.15 [0.10]	45	88	20	7.3
Torrens Lineament	1	0.06 [0.20] 0.08 [0.70] 0.15 [0.10]	92	92	20	7.3

Logic tree: A weighted logic tree to capture the influence of epistemic uncertainty has been modified from Mote et al. (2017). Variations in a-value, b-value, maximum magnitude, GMPE and slip rate is encapsulated.

4 RESULTS

4.1 Ground Motions

The results of the PSHA are presented in terms of peak ground acceleration (PGA) (see Table 2) and uniform hazard response spectra for APEs of 1/500 and 1/2500 (see Figure 2). Site scaling factors may be applied due to amplifying or de-amplifying site conditions assigned following AS1170.4 (2018). Following Eurocode 8 which references EN 1998-5:2004, simplified topographic amplification factors are applied to ground motions at slopes.

Table 2 PSHA, AS1170.4 (2018) and NSHA18 (Allen, 2018) PGA (g).

Source	1/500 APE	1/2500 APE	1/10000 APE
Arup PSHA (excluding faults)	0.07	0.16	0.18
Arup PSHA (including faults)	0.11	0.36	1.04
AS1170.4	0.11	0.19	NA
NSHA18	0.03	0.09	NA

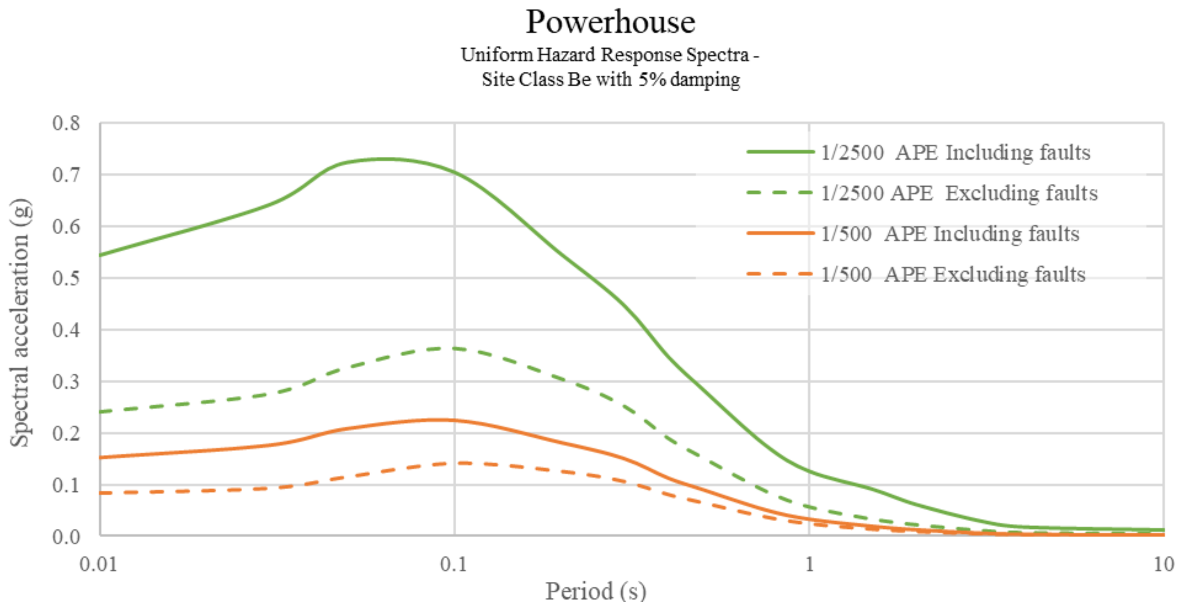

Figure 2 Final Model Uniform Hazard Response Spectra for the Powerhouse, Site class Be with 5% damping.

4.2 Magnitude-Distance De-Aggregation

The 1/2500 APE de-aggregation of PGA ground motions (see Figure 3) shows contribution from both the background seismicity, the far field Flinders Ranges faults and the Torrens Lineament. The 1/10000 APE de-aggregation of PGA ground motions (see Figure 3) shows significant contribution from the Torrens Lineament, far-field Flinders Ranges faults and little contribution from background seismicity. At 1/2500 APE the dominant source of ground motions is the Flinders Ranges Faults and at 1/10000 APE the Torrens Lineament is dominant.

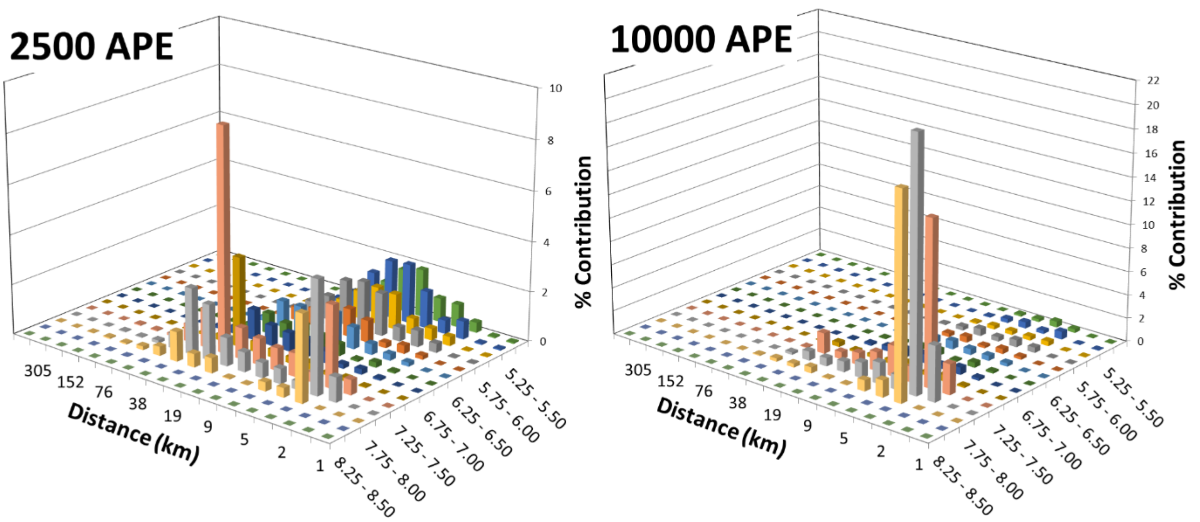

Figure 3 De-aggregation of PGA (period of 0) at APEs of 1/2500 and 1/10000 for site sub soil class Be

5 CONCLUSIONS

A seismic hazard investigation was conducted for a site in South Australia following the methodology developed by Mote et al. (2017). The inputs were a combination of areal zones built from historic seismic records governed by recurrence curves and neotectonic faults governed by slip rate. The neotectonic faults identified in literature include the Flinders Ranges Faults, the Roopena Fault Zone faults and the Torrens Lineament.

During the early phase of ground investigation, neotectonic features were assessed for Pleistocene displacement. A possible neotectonic feature was identified and targeted with a subsequent paleoseismic study including mapping, boreholes and trenching. The feature was identified the feature as a fault define the basal plane of a block slump.

The PSHA results (see Section 4) show that including the active fault sources calculates a larger hazard value at smaller APE. This agrees with the ANCOLD requirement for inclusion of neotectonics faults in analysis in order to better capture uncertainty at a smaller APE. When comparing the model to AS1170.4 (2018), the calculated results are significantly lower at shorter return periods and higher at longer return periods. When comparing the model to NSHA18, the calculated results are significantly higher. This is due to the inclusion of the Torrens Lineament which, when modelled has the capability to produce large ground motions at long return periods.

De-aggregation of the model results shows that with increasing APE seismicity from the modelled faults have an increasing influence on PSHA results over background seismicity. While both the Flinders Range Faults and the Torrens Lineament have a significant contribution at the 1/2500 APE, at 1/10,000 the Torrens Lineament has a greater influence due to proximity.

The results of the PSHA and ground investigation discounted liquefaction, lateral spread and fault rupture as geohazards on site.

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