Detailed Seismic Hazard assessment of Mt Bold area: comprehensive site-specific investigations on Willunga Fault

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Abstract: *The Mt Bold Dam, located in the Mt Lofty Ranges in South Australia, is a 54 m high concrete arch-gravity dam that impounds Adelaide's largest reservoir. The dam site is located less than 500 m from a suspected surface rupture trace of the Willunga fault.*

Preliminary assessments indicate that Mt Bold Dam is likely to be the dam with the highest seismic hazard in Australia, with the Flinders Ranges-Mt Lofty region experiencing earthquakes of sufficient magnitude to generate shaking damage every 8-10 years on average. Prior evidence suggests that the Willunga Fault is likely capable of generating M 7-7.2 earthquakes.

As part of the South Australia Water Corporation (SA Water) portfolio of dams, Mt Bold Dam is regularly reviewed against the up-to-date dam safety guidelines and standards. SA Water commissioned GHD to undertake detailed site-specific geophysics, geotechnical and geomorphological investigations, and a detailed site-specific Seismic Hazard Assessment (SHA) of the Mt Bold Dam area. The results of this investigation will be used to inform decisions related to planned upgrade works of the dam.

Geomorphological mapping of Willunga Fault, detailed geological mapping, analysis of airborne lidar data, geophysical seismic refraction tomography and seismic reflection surveys, and paleoseismic trenching and luminescence dating of faulted sediments was conducted to obtain input parameters for the site-specific SHA. Discrete single-event surface rupture displacements were estimated at ~60 cm at dam-proximal sites. The mean long-term recurrence interval (~37,000 yrs) is exceeded by the quiescent period since the most recent earthquake (~71,000 yrs ago) suggesting long-term variations in rupture frequency and slip rates and/or that the fault is in the late stage of a seismic cycle. The length-averaged slip rate for the entire Willunga Fault is estimated at 38 ± 13 m / Myr. Shear wave velocity (Vs30) of the dam foundations was estimated based on geotechnical data and geological models developed from geophysical surveys and boreholes drilled through the dam and into the foundation rock. The nearest seismic refraction tomography (SRT) lines were correlated with the boreholes and those velocity values used in the Vs30 parameter determination. All relevant input parameters were included into seismic hazard analysis with comprehensive treatment of epistemic uncertainties using logic trees for all inputs.

Deterministic Seismic Hazard Analysis (DSHA) confirmed that the controlling fault source for the Mt Bold Dam site is Willunga Fault, which is located very close to main dam site (420 m to the West).

For more frequent seismic events (1 in 150, 1 in 500 and 1 in 1,000 AEP), the probabilistic analysis indicates that the main seismic hazard on the dam originates from the area seismic sources (background seismicity). Based on deaggregation analysis from the site specific Probabilistic Seismic Hazard (PSHA), the earthquakes capable of generating level of ground motion for the 1 in 10,000 AEP event can be expected to occur at mean distances of approximately 22 km from the dam site (with the mean expected magnitude at Mt Bold Dam site estimated at Mw > 6).

For less frequent (larger) seismic events, the contribution of the Willunga Fault to the seismic hazard of Mt Bold Dam can be clearly noted with Mode distance in the 0-5 km range, which indicates that most of the seismic hazard events larger than the 1 in 10,000 AEP comes from the Willunga Fault. The Mode magnitudes of the events are expected to be Mode Magnitude at Mw= 6.6 for a segmented Willunga Fault scenario, and Mw= 7.2 for a non-segmented fault scenario.

Consideration was also given to the upcoming update of the ANCOLD Guidelines for Earthquake, which calls for the determination of the Maximum Credible Earthquake (MCE) on known faults for the Safety Evaluation Earthquake (SEE) of "Extreme" consequence category dams. The MCE for Mt Bold Dam was estimated from the DSHA; in terms of acceleration amplitude, the MCE event approximately equals the 1 in 50,000 AEP seismic events.

Keywords: *Willunga Fault, Kapetas Fault, Seismic Refraction Survey, Seismic Reflection Survey, Geomorphological Analysis, Seismicity, Seismic Hazard, Uniform Hazard Spectra.*

Introduction

SA Water engaged GHD Pty Ltd (GHD) in September 2010 to undertake Stage 1 of the safety review of Mt Bold Dam in accordance with ANCOLD Guidelines on Dam Safety Management (2003). This stage was completed in July 2012.

SA Water subsequently engaged GHD in November 2012 for Stage 2 of the safety review, which comprised intrusive and nonintrusive dam foundation investigations, a detailed nonlinear structural analysis of the dam wall and a detailed risk assessment. The main outcomes of this phase were documented in the final report for Stage 2 issued in November 2015. Stage 2 of the Safety review included the following geological and geotechnical investigation phases:

- Phase 0: Geological mapping, in November 2012 (not originally designated as Phase 0)
- Phase 1: Initial drilling in dam, dam surroundings and auxiliary spillway, in February 2013
- Phase 2: Drilling in dewatered spillway basin, in April 2013.

In March 2016 SA Water engaged GHD to conduct "Further Geological and Geotechnical Considerations for Mt Bold Dam". This project was conducted as a first tier to address outstanding geotechnical matters arising from the Stage 2 Dam Safety Review, and included a scoping workshop that served as the basis for the present "Phase 3 - Geological Investigations of Mt Bold Dam".

On 24th October 2016 SA Water engaged GHD to conduct the present "Phase 3 - Geotechnical Investigations Mt Bold Dam.

Objectives

The objective of Phase 3 investigations was to refine the knowledge of the geological and geotechnical conditions of the Mt Bold Dam area and its surroundings for the purpose of obtaining all relevant foundation and seismic hazard information required for subsequent phases of the design of the dam upgrade. To that end, the main targets of the proposed investigations are:

- To gain a better understanding of the site-specific "ground model"
- To gain a better knowledge of the material parameters of the foundation
- To gain a better knowledge of the potential foundation defect-controlled failure mechanisms in the dam abutments
- To identify depths for suitable foundations for the proposed saddle dam and a potential new dam
- To refine the seismic hazard of the area to account for nearby fault activity

Review of regional seismicity

Prior to commencing a site-specific analysis of the potential fault activity and seismicity close to the dam, a desk-top review of the latest published and unpublished records for the Mt Lofty Ranges was undertaken.

The study area extended approximately 100 km north, south, east and west of the Mt Bold Reservoir (Figure 1). This 200 km x 200 km area recorded a substantial number of seismic events over the last 175 years, which allowed for forecasting of future frequency-local magnitude (ML) distributions.

Data for the study was retrieved from the South Australian Resources Information Gateway (SARIG) published by the Department of The Premier and Cabinet (2016). This resource is widely considered to be the most complete record of South Australian earthquakes publicly available, containing greater than four times the number of events listed in the Geoscience Australia (GA) database under the same geographical and temporal constraints. The GA database contains a gap in the seismic record from early 1898 to 1954, during which no events are listed (Geoscience Australia, 2016).

Frequency-magnitude relationship

Gutenberg-Richter (G-R) scaling (Gutenberg and Richter, 1956) was used to estimate earthquake frequency-local magnitude (ML) distributions for the study area. The G-R relationship takes the form:

$$\log_{10} \mathrm{N} = \mathrm{a} - \mathrm{bM}$$

Where N is the number of earthquakes exceeding magnitude M, and a and b are constants. Using 402 recorded earthquakes with local magnitudes in the range 1.1 ≥ ML ≥ 4.6, the G-R coefficients were determined as: a = 159.29 ± 13.34 and b = 0.860 ± .012. Extrapolation of this relationship to higher magnitudes result in regional earthquake recurrence interval estimates for ML 7.0 of 6,500 ± 1,800 years and ML 7.5 of 17,700 ± 5,200 years.

Catalogue "de-clustering" was also undertaken, which removes the potential bias associated with fore- and after-shocks in the earthquake record. This reduced the number of earthquakes in the catalogue to 358 and the preferred exponential least squares fit to G-R scaling yielded a= 151.34 ± 9.72, and b = 0.864 ± 0.009 for earthquakes with local magnitudes (ML) between 1.1 and 4.6. Extrapolation of this relationship to higher magnitudes results in regional earthquake recurrence interval estimates for ML 7.0 of 7,400 ± 1,500 years and ML 7.5 of 20,000 ± 4,400 years.

Rupture length – magnitude relationship

Analysis of active faults in the study area was undertaken using surface rupture lengths from the updated neotectonic catalogue and from the latest Geoscience Australia.

Empirical regressions indicate that at least 20 faults capable of generating an earthquake of local magnitude ML ≥ 6.0 and between seven and eleven faults capable of generating ML ≥ 7.0 earthquakes lie less than 100 km from the Mt Bold Dam.

ML 7.0 earthquake recurrence intervals (RI) on individual faults are estimated as 46,000 ± 14,000 to 82,000 ± 25,000 years if regional recurrence intervals are uniformly distributed across all known faults and periodic rupture recurrence is assumed. This estimate is consistent with other independently derived estimates of RI from paleo-seismic trenching and topographic data, suggesting that historical seismicity may be representative of long-term earthquake recurrence in this region.

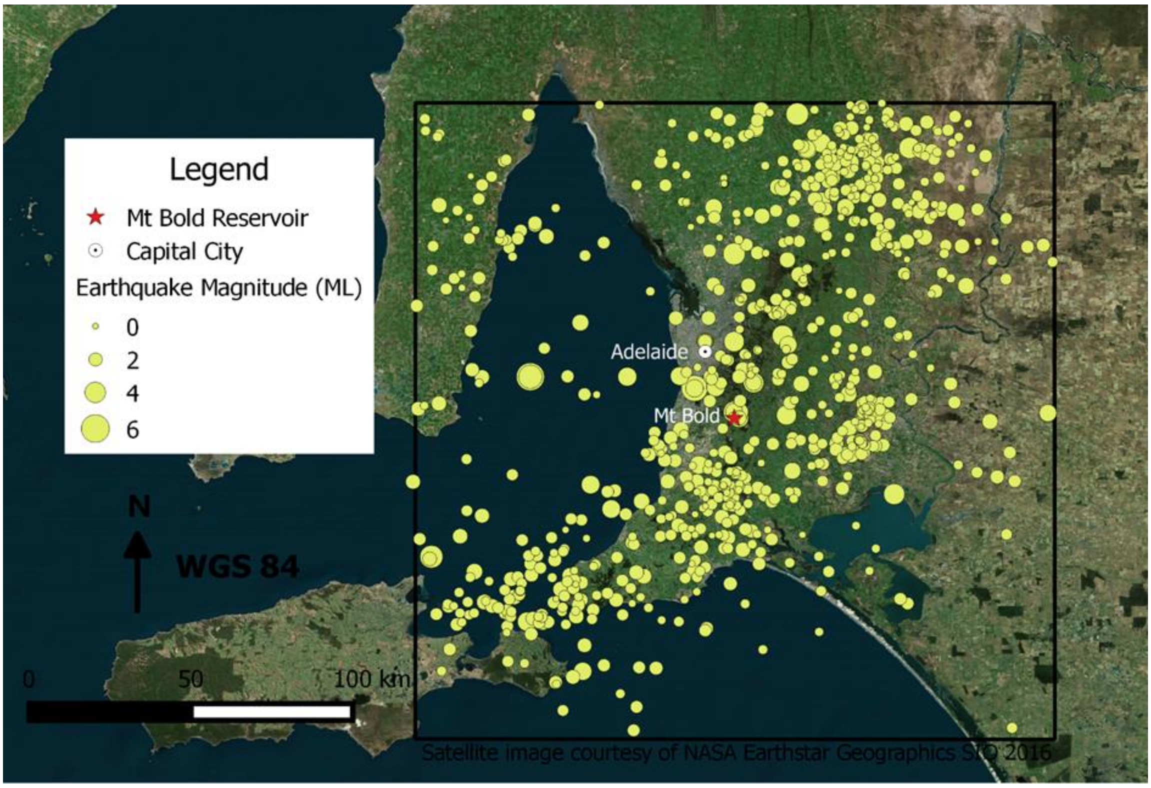

Figure 1 Aerial extent of the earthquake records assessed

A preferred estimate of moment magnitude (M_w) of 7.1 to 7.2 for the Willunga Fault, based on this review of regional historical seismicity data, yields a RI range of 29,000 ± 9,000 to 77,000 ± 23,000 years. The field and laboratory work subsequently undertaken for this Phase 3 investigation was intended to provide better constraints on the magnitude and recurrence interval estimates for the Willunga Fault in the Mt Bold dam area.

Seismic Surveys (Refraction and Reflection)

The seismic refraction method is based on the measurement of the travel time of seismic waves (typically P-waves) refracted at the interfaces between different velocity subsurface layers. Seismic energy is provided by a source ('shot') located on the surface. For shallow applications this normally comprises a hammer and plate, weight drop or small explosive charge (explosives in a borehole or a blank shotgun cartridge). Energy radiates out from the shot point, either travelling directly through the upper layer (direct arrivals), or travelling down to and then laterally along higher velocity layers (refracted arrivals) before returning to the surface.

The energy is detected on the surface using a linear array (or spread) of geophones spaced at regular intervals. Shots are deployed at and beyond both ends of the geophone spread in order to acquire refracted energy as first arrivals at each geophone position.

Data is recorded on a seismograph. Travel-time versus distance graphs are then constructed and velocities calculated for the overburden and refractor layers. Depth profiles for each refractor are produced by an analytical procedure based on consideration of shot and receiver geometry and the measured travel-times and calculated velocities. The final output comprises a depth profile of the refractor layers and a velocity model of the subsurface.

Willunga Fault surveys

Eight SRT lines were surveyed across the inferred trace of the Willunga Fault in December 2016 at the locations shown on Figure 2, amounting to a total surveyed length of 1,195 m.

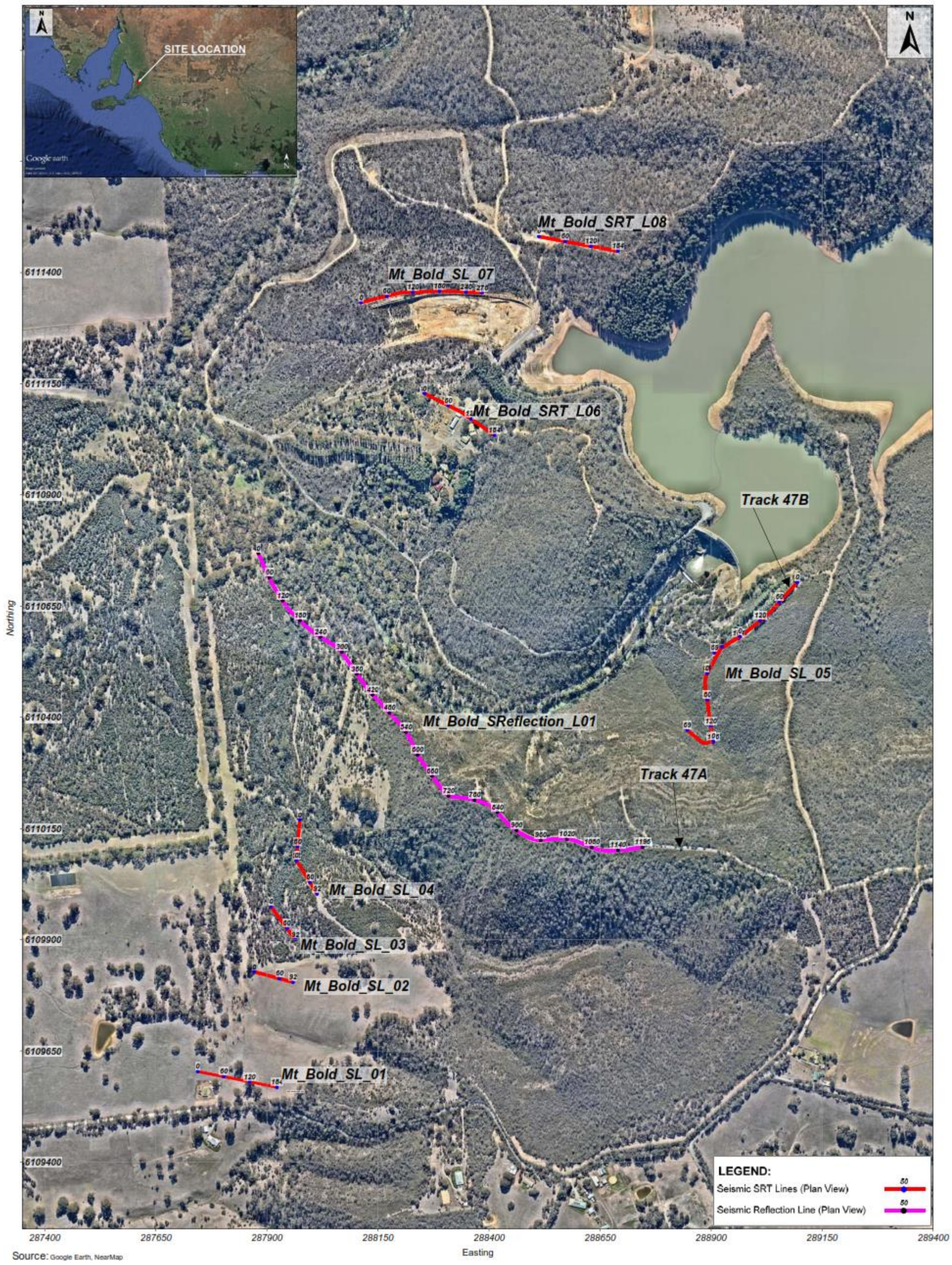

Figure 2 SRT and SRS line locations on the inferred Willunga Fault

Figure 3 illustrates an example of distinct velocity changes observed when traversing across the inferred line of the Willunga Fault. At this location, subsequent trench mapping confirmed that the position and dip of the inferred Willunga Fault correlate closely with the P-wave velocity anomaly, passing through point 5 at the surface.

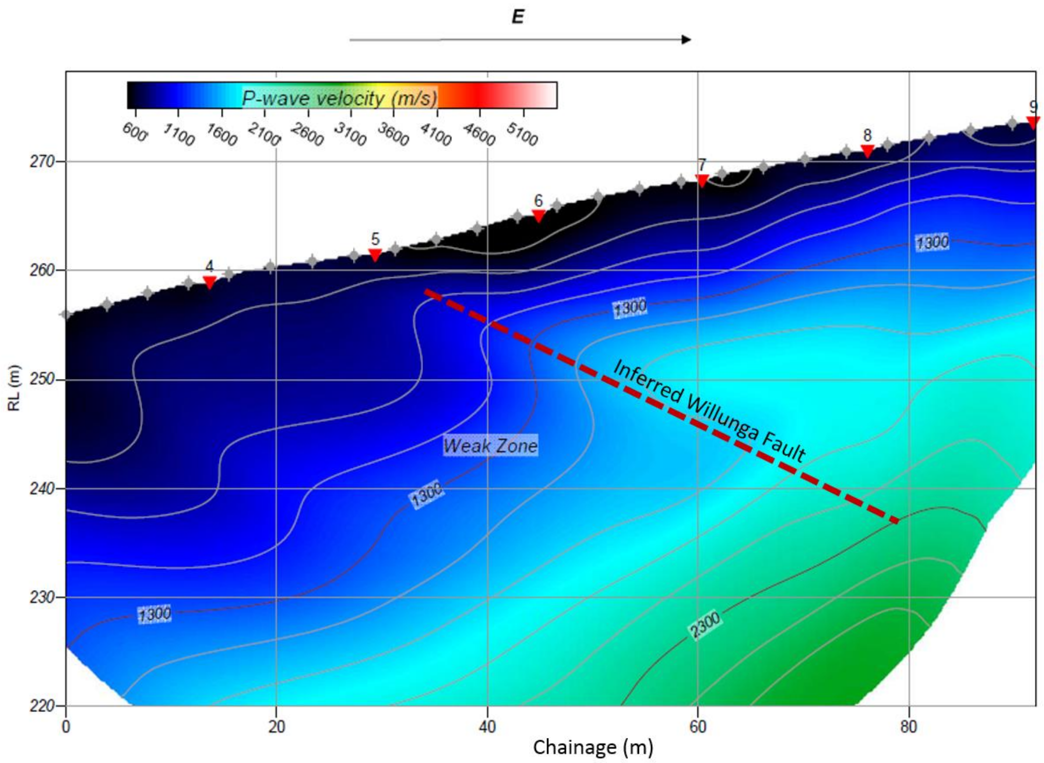

Figure 3 SRT line 02 across inferred Willunga Fault trace

Error! Reference source not found. below shows the results of the seismic reflection survey undertaken by GHD to confirm the location of the Willunga Fault, as well as to enhance the understanding of the Willunga Fault spatial position in relation to the Mt Bold Dam. The results clearly show the location and general dip of the Willunga Fault, in addition to traces of other structures within the area. Some of the traces towards end of seismic line changes coincide with the potential location of the mapped structure known as the “Kapetas Fault”.

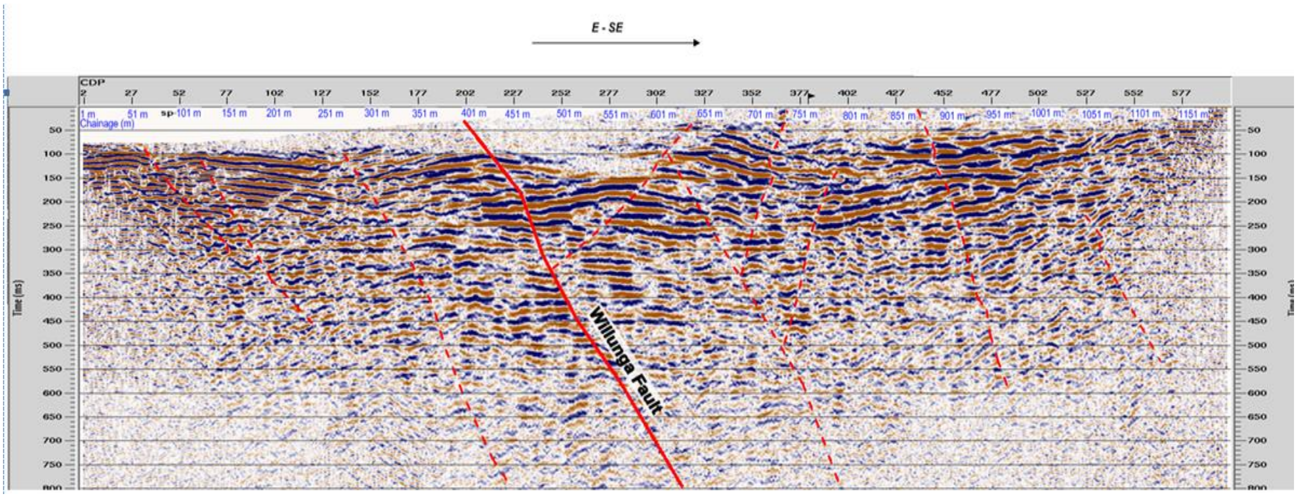

Figure 4 Seismic reflection Line across inferred Willunga Fault trace

Kapetas Fault zone surveys

A further 400 m of SRT survey was conducted on the left abutment downstream of the dam.
The surveys followed Track 47B for the first 184 m, the remainder following the former tramway, which had been manually cleared in preparation for the surveys. Due to the variable strike of the survey lines the surveys were broken into segments which results in discontinuities in the velocity profiles at the cut lines. In addition, the surveys were approximately parallel to the strike of the inferred Kapetas fault, meaning that distinct velocity discontinuities could not be readily correlated with possible fault locations at ground surface.
Nonetheless, because the SRT lines were sub-parallel to the inferred strike of the "Kapetas Fault" low angle velocity anomalies, that may represent the effects of low angle thrust faulting, can be seen at between 20 and 40 m depth on the tomograms.

Paleoseismic trenching results and implications for Willunga Fault rupture behaviour

Two paleoseismic trenches were excavated across the primary surface rupture trace of the Willunga Fault. A third trench was excavated across a valley fill sequence that overlies the surface rupture trace. Trench logging was conducted using hand-held and drone-acquired photomosaics assembled with Agisoft Photoscan software and mapped in the field on a Microsoft Surface. The Willunga Fault was observed in two of the trenches as a 40 to 50 degree east-dipping thrust fault that displaces phyllite bedrock over clay-rich colluvial sediments. Optically stimulated luminescence dating of the faulted and post-faulting sediments constrains the timing of the most recent earthquake to ca. 60,000 to 80,000 years ago, with a preferred most recent event age of 71±10 ka. The net dip-slip offset measured from stratigraphically correlative units present on both the faulted hangingwall and footwall is 60 ± 5 cm and the vertical vertical offset using a fault dip of 40^{o} is 39 ± 3 cm. It is likely that the total coseismic fault displacement at depth is greater than the displacement measured in the trenches and (given the granular nature of the sediments and the strongly fractured hangingwall bedrock) that coseismic displacements could include distributed folding in addition to the discrete faulting observed. For these reasons, the coseismic displacement is considered a minimum surface rupture displacement in the MRE. Adding an additional 100% to the discrete fault measurements results in an estimate of 120 cm total displacement across the fault zone (80 cm on a 40^{o} dipping fault).

Topographic profiles across the Willunga Fault at the trench site indicate 135 ± 20 m of cumulative vertical displacement. The inception of reverse faulting on analogous faults in the region is taken to be 5 to 10 Myr ago (Quigley et al., 2006). Combining these estimates with a range of Willunga Fault dip estimates yields a slip rate of 16 to 42 m / Myr in the Mount Bold area and the length-averaged slip rate for the entire Willunga Fault (incorporating 10 other topographic profiles) is 38 ± 13 m / Myr. Using incremental slip estimates of 60 cm and 120 cm yields recurrence intervals of 14,300 to 38,500 yrs and 28,600 to 77,000 yrs, respectively. A preferred (summative) RI for the Willunga Fault is thus proposed at 37,700 yr (+39,300, -18,500 yr). The mean long-term recurrence interval (~37,000 yrs) is exceeded by the quiescent period since the most recent earthquake (~71,000 yrs ago) although age overlap occurs at the upper bound of the mean value. This could be interpreted to indicate that the Willunga Fault is late in its seismic cycle (assuming periodic rupture behaviour) and / or earthquakes on the Willunga Fault exhibit temporal clustering and the fault is currently in a relatively quiescent period. Using surface rupture length and displacement-based scaling relationships, we estimate Willunga Fault rupture would result in a preferred Mw of 7.1-7.2 (±0.2) and a segmented rupture Mw estimate for the Mt Bold segment of 6.3 (±0.1). We estimate the probabilistic maximum credible earthquake = 7.35 ±0.2 for the entire Willunga Fault using the Monte Carlo sampling method outlined in Stahl et al. (2016).

Refined seismic hazard assessment

Approach

One of the main objectives of the present Phase 3 Geotechnical Investigation was to determine the impact of the potential activity of the Willunga Fault on the seismic hazard assessment of the Mt Bold Dam area. For this reason, as part of the present study GHD conducted a refined Seismic Hazard Assessment (SHA), incorporating the findings of the Phase 3 investigations that comprised geophysics surveys, trenching, hand augering, detailed geological mapping, the analysis of LiDAR data, a detailed geomorphological mapping of the Willunga Fault (the nearest, most influential, active tectonic feature), and fault activity dating.

The SHA study included both probabilistic and deterministic seismic hazard assessments, and the generation of probabilistic Uniform Hazard Spectra (UHS). The area sources were determined following the updated AUS5 seismogenic model of Australia by Brown & Gibson (2004).

Summary and conclusions of results and the refined SHA

A site specific Vs30 parameter for the dam foundations was estimated based on the available geotechnical information, geological models and geophysical survey undertaken on site. Boreholes drilled within dam foundations were also taken in consideration. The nearest seismic refraction tomography (SRT) lines were correlated with the boreholes and those velocity values used in the Vs30 parameter determination. The mean value of the site Vs30 parameter was estimated at 2,566 m/s, which classifies the site as a “hard rock” class site.

The seismic model in the study was derived using independently defined parameters (i.e. earthquake catalogue, declustering, magnitude unification, seismic activity parameters, depths, max min Mw coefficient b etc. based on the GA and SARIG earthquake catalogues available in public domain).

All relevant seismic hazard parameters were included in the analysis. with comprehensive treatment of epistemic uncertainties through application of logic trees for all input sources;

Figure 5 illustrates the logic tree with the parameters that were considered in the Willunga Fault source in the Mt Bold Dam SHA and the uncertainties that were treated through application of alternative parameters (each associated with an appropriate weight). Alternative fault geometry parameters, slip rate, magnitude values and recurrence models, as well as the six alternative attenuation equations were used in the SHA to treat epistemic uncertainties.

The same approach was used to treat uncertainties regarding the definition of seismicity in area source zones used in the analysis.

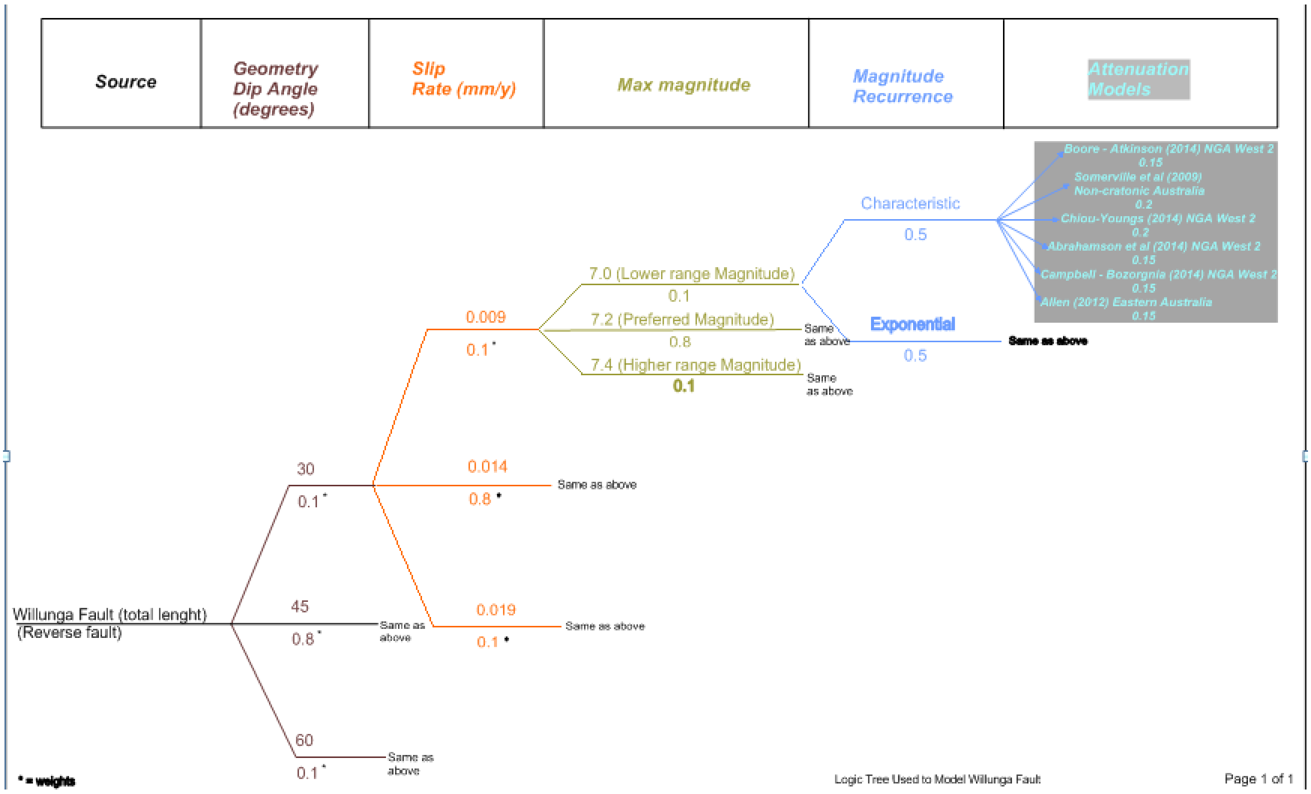

Figure 5 Logic tree Willunga fault source with parameters (Example)

Sensitivity of the computed hazard to alternative parameters was extensively tested prior to inclusion in the model and SH calculations. The parameters tested included: alternative sources and local faults with different parametric variations related to the activity of the faults; ground motion attenuation models tested at the most significant sources.

Testing of these attenuation models indicates that the hazards computed using the Somerville et al (2009) and Allen (2012) ground motion prediction models are consistently slightly higher than those computed using the other selected models in the shorter recurrence periods. A source of this discrepancy is that the models being calibrated to smaller Vs30 values than NGA 2014 West 2 GMPMs values (VS30 = 1500 m/s). The results of the sensitivity tests were later used to fine tune the model parameters specifically related to the application of the appropriate weights assigned to the selected multiple GMPMs.

To validate the site source model used in the study, calibration of the seismic hazard calculations was performed using the adopted seismic model with other local SHA in the site vicinity and mapped values of seismic hazards. The calibration was performed against the current version of GA Seismic Hazard Map of Australia and with a SHA performed for a site near Adelaide and with the SHA report for Mt Bold Dam undertaken by ES&S in 2013. The model used in the analysis predicts results very similar to those mapped by GA (Burbidge et al, 2012) and the results described in Leonard et al (2014), validating the seismic source model used in the analysis.

The conducted Deterministic Seismic Hazard Analysis (DSHA) confirmed that the controlling fault source for the Mt Bold Dam site is the Willunga Fault, which is located very close to the main dam site (420 m to the West of the dam).
For more frequent seismic events (1 in 150, 1 in 500 and 1 in 1,000 AEP), the probabilistic analysis indicated that the main seismic hazard for the dam originates from area seismic sources (background seismicity).

Based on deaggregation analysis from the site specific Probabilistic Seismic Hazard Assessment (PSHA), earthquakes capable of generating a level of ground motion for a 1 in 10,000 AEP event can be expected to occur at mean distances of approximately 22 km from the dam site (with the mean expected magnitude at Mt Bold Dam site estimated at Mw > 6).

For less frequent (larger) seismic events, the contribution of the Willunga Fault to the seismic hazard of Mt Bold Dam can be clearly noted with Mode distance in the 0-5 km range, which indicates that most of the seismic hazard events larger than the 1 in 10,000 AEP comes from the Willunga Fault. The Mode magnitudes of the events are expected to be Mode Magnitude at Mw= 6.6 for a segmented Willunga Fault scenario, and Mw= 7.2 for a non-segmented fault scenario.
The vertical spectra were also calculated for a number of return period events following the Gullerce & Abrahamson (2011) procedure for scaling of the horizontal UHS following the appropriate deaggregation scenarios.

As part of the Probabilistic Seismic Hazard Analysis (PSHA), uniform hazard spectra were generated for ten periods of return, from 150 to 65,000 years, as reproduced in Figure 6.

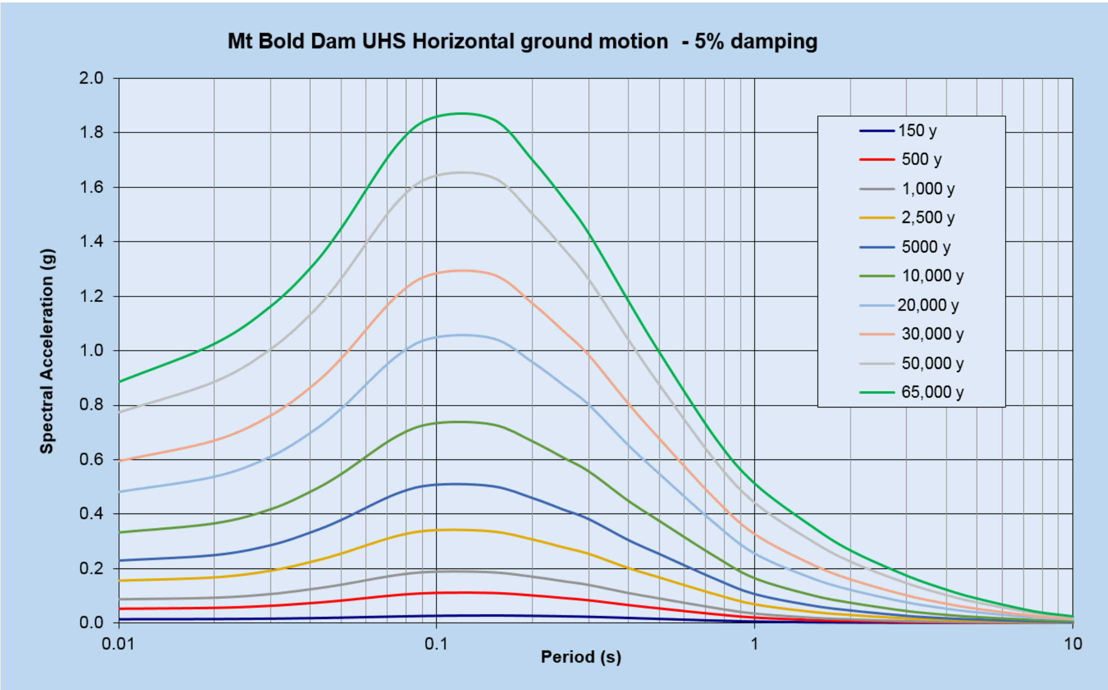

Figure 6 Probabilistic Uniform Hazard Spectra for Mt Bold Dam area

Based on the Probabilistic Seismic Hazard Analysis (PSHA), the main seismic hazard for the shorter return periods (150, 500 and 1,000 years) originates from the area seismic sources (Zone 1, Zone 2 and Zone 3), whilst the effects of the specific fault seismic sources are perceived at greater return periods.

The deaggregation analysis of the site-specific PSHA indicates that the 1:10,000 year return earthquake, for the Peak Ground Acceleration (PGA) period (0.01 s) and spectral acceleration (0.33 g), can originate at mean distances of approximately 17 km from the site, with a mean magnitude Mw for motion estimated at Mw 6.4.

The deaggregation analysis of the site-specific PSHA indicates that the 1:10,000 year return earthquake, for the current dam's fundamental period (0.18 s) and corresponding spectral acceleration (0.69 g), can originate at mean distances of approximately 17 km, with a mean magnitude Mw for motion estimated at Mw 6.5 (refer to Figure 7).

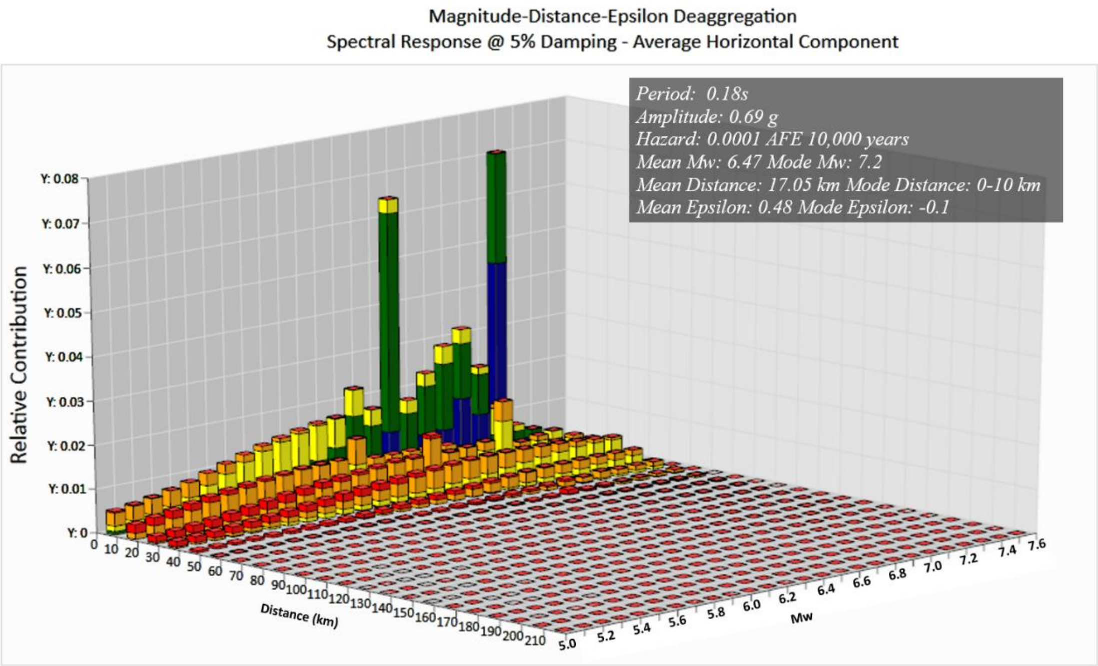

Figure 7 Deaggregation plot for 10,000 y earthquake and period 0.18s

The Deterministic Seismic Hazard Analysis (DSHA) clearly indicated that the controlling fault source for the Mt Bold Dam site is the Willunga Fault, which is located in close proximity to the main dam site (some 500 m to the west).

The DSHA also indicated that the mean MCE generated by the Willunga Fault is expected to produce a PGA of 0.78 g. At the structural period of interest for the current and potentially upgraded dam (at around 0.2 s), the mean MCE spectral acceleration reaches 1.54 g. A superposition of the response spectrum generated for the MCE on the UHS response spectra (refer to Figure 8) shows a similar acceleration amplitude to that of the probabilistic 50,000 year earthquake.

This approximate period of return for the MCE is similar to the Most Recent Surface Rupture Event (MRE) for the Willunga Fault of 60,000 to 80,000 years, and with the preferred Recurrence Interval (RI) of 37,700 years (from the paleo-seismic trenching), as described in Section **Error! Reference source not found.**.

The effects of the Willunga fault start to be clearly seen at return periods greater than the 10,000 years, with Mode Distance at the range 0 - 10 km (Willunga Fault) and Mode Magnitude at Mw 6.6 and Mw 7.2 (for the segmented and non-segmented Willunga Fault scenarios, respectively).

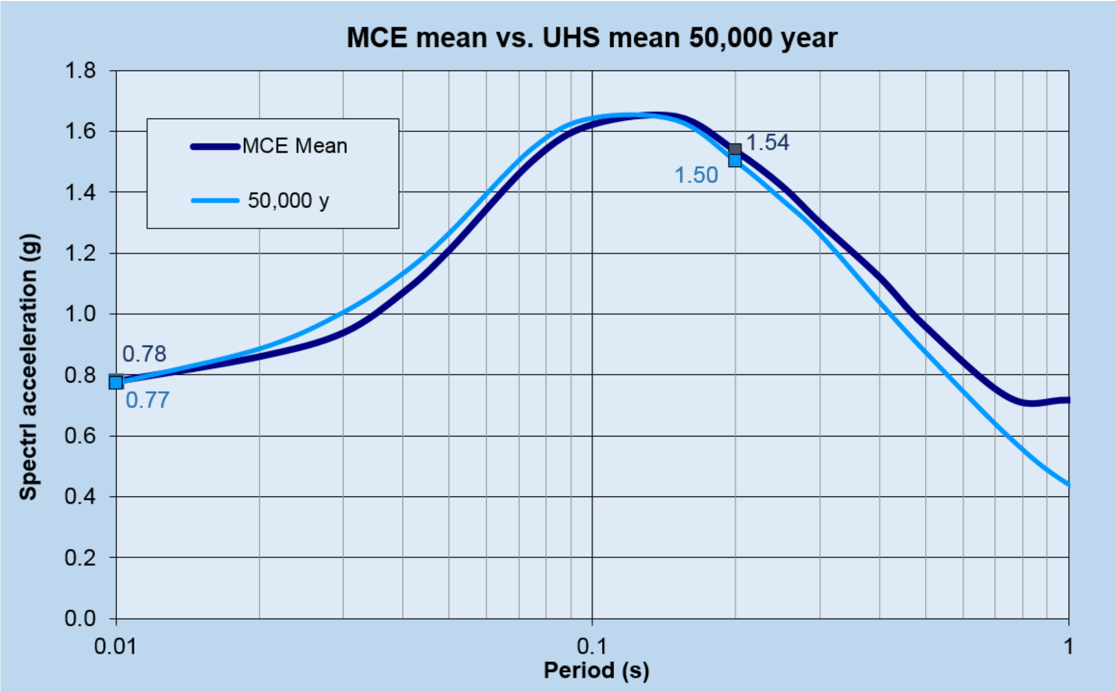

Figure 8 Comprison on mean MCE (from DSHA) and 50,000 year event (from PSHA)

At the structural period of interest for the dam wall (around 0.2 s), in both the 1,000 and 10,000 year cases the refined seismic hazard produced acceleration amplitudes that are almost half of the values estimated by ES&S in 2013.

The DSHA, driven by the activity of the nearby Willunga Fault, produced a MCE with an estimated period of return of 50,000 years.

The results of the present study indicate that for the structural period of the dam, say 0.2 s, the spectral acceleration of the 10,000 year earthquake is 0.67 g, while those for the MCE are 1.54 g (using the mean) and 2.35 g (using the 84th percentile).

It is recommended that SA Water wait for the official publication of the ANCOLD "Guidelines for Design of Dams and Appurtenant Structures for Earthquake", and use the official publication to adopt the design criteria for the upgrade of Mt Bold Dam. This applies to important issues pending resolution such as the use of the MCE as the design earthquake, and the compulsory use of three different seismic models for the SHA (that is two in addition to the AUS5 model employed in this study).

Since the seismic hazard of the Mt Bold Dam area is significant for Australian standards, and the design accelerations will be important regardless of the of the adopted seismic criteria, it is recommended that the detailed design of the upgrade of the dam be optimised by using a linear elastic time-history approach.

Similarly, in order to cover the seismic uncertainty, it may be appropriate to used five sets of accelerograms in the design phase of the dam upgrade.

Implications for future design of dam upgrades

The refinement of the Seismic Hazard Assessment of the Mt Bold Dam area, conducted as part of the present study, included probabilistic and deterministic approaches. The PSHA, using the AUS5 seismic model, produced mean response spectra for several periods of return ranging from 150 to 65,000 years. The DSHA, driven by the activity of the nearby Willunga Fault, produced a MCE with an estimated period of return of 50,000 years.

The draft of the ANCOLD "Guidelines for Design of Dams and Appurtenant Structures for Earthquake" (dated March 2017) is currently recommending the adoption of a Safety Evaluation Earthquake (SEE) based upon the Consequence Category of the dam. For an extreme category dam, as it is the case for Mt Bold Dam, the draft guideline recommends an SEE that is the largest between the 10,000 year period of return earthquake and the MCE. As it can be observed from the results of the present study, the implications of those recommendations are significant. As presented in Figure 9, for the structural period of the dam, say 0.2 s, the spectral acceleration of the 10,000 earthquake is 0.67 g, while those for the MCE are 1.54 g (using the mean) and 2.35 g (using the 84th percentile).

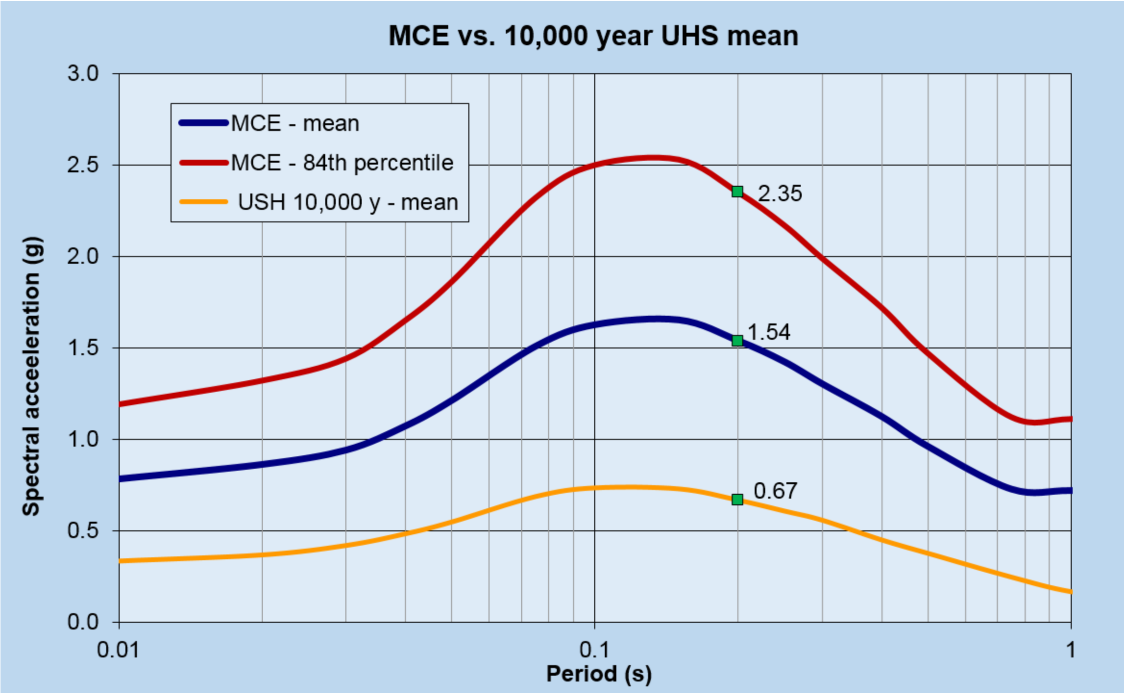

Figure 9 Comparison of MCE and 10,000 year UHS mean

Interestingly, at 0.2 s the mean MCE acceleration amplitude is 31% larger than that of the 10,000 year earthquake produced by ES&S in 2013 (1.17 g).
It is noted that the design criteria chosen by SA Water during the Upgrade Option Study was to employ the 20,000 year earthquake developed by ES&S in 2013 as the design earthquake (GHD, 2016), which has a spectral amplitude of 1.65 g. The preliminary seismic analysis conducted during the Upgrade Options Study showed that the 20,000 year earthquake, as developed by ES&S, was on the limit of feasibility for several of the options analysed. In other words, these preliminary seismic analyses indicated that, if the spectral acceleration of the design earthquake adopted for the upgrade of Mt Bold Dam is larger than 1.65 g, the success of the upgrade using conventional strengthening methodologies cannot be guaranteed.
Based on the discussion above, and with consideration to the future stages of the Mt Bold Dam project (i.e. refinement of upgrade options, and detail design of the selected upgrade option), the following is recommended:

- SA Water could wait for the official publication of the ANCOLD "Guidelines for Design of Dams and Appurtenant Structures for Earthquake", and use the official publication to adopt the design criteria for the upgrade of Mt Bold Dam. This applies to important issues pending resolution such as the use of the MCE as the design earthquake, and the compulsory use of three different seismic models for the SHA (that is two in addition to the modified AUS5 model employed in this study).
- Since the seismic hazard of the Mt Bold Dam area is significant for Australian standards, and the design accelerations will be important regardless of the of the adopted seismic criteria, the detailed design of the upgrade of the dam should be optimised by using a linear elastic time-history approach, rather than the more simplistic response spectrum analysis. Also, in order to deal more conservatively with the seismic uncertainty, it may be appropriate to used five sets of accelerograms in the upgrade design phase, instead of the three that are usually employed in safety reviews.

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