BEFORE THE CANTERBURY REGIONAL COUNCIL
AND THE ASHBURTON DISTRICT COUNCIL

IN THE MATTER of the Resource Management Act 1991

A N D

IN THE MATTER of resource consent applications by Rangitata Diversion Race Management Ltd to the Canterbury Regional Council and Ashburton District Council for resource consents for the construction, operation and maintenance of the Klondyke Water Storage Facility, its associated water takes from and discharges to the Rangitata River, and all associated activities

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STATEMENT OF EVIDENCE OF GRAEME HAYNES McVERRY

Qualifications and experience

1. My name is Graeme Haynes McVerry.

2. I am a Principal Scientist at the Institute of Geological and Nuclear Sciences Limited (GNS Science), working as an engineering seismologist in the Natural Hazards Division. I have been employed by GNS Science since its inception in 1992, and before that by one of its predecessors, DSIR Physical Sciences, since 1974.

    2.1 I hold degrees of Bachelor of Engineering (Engineering Science) with first class honours, Master of Engineering (First Class Honours), both from the University of Auckland, and Doctor of Philosophy (Ph. D.) in Applied Mechanics from the California Institute of Technology (Caltech), Pasadena, California, USA.

    2.2 I am a Life Member of the New Zealand Society of Earthquake Engineering, and was awarded with my co-authors the 1994 E.R. Cooper Memorial Medal of the Royal Society of New Zealand for the publication of the best piece of original research work carried out in New Zealand in physics or engineering in a three-year period. I am currently a member of the Earthquake Engineering Research Institute (USA), and an associate member of the Seismological Society of America.

2.3 I have been involved in seismic hazard estimation since 1981. I served on Standards New Zealand committees that produced New Zealand Standards *NZS4203:1992* known as the *Loadings Standard* and *NZS1170.5:2004 Structural Design Actions Part 5: Earthquake actions – New Zealand*, as well as its Amendment No 1 of September 2016. I am currently a member of the committee preparing NZS1170.5 Amendment No 2. I had principal responsibility for writing *Section 3 Site Hazard Spectra* of NZS1170.5, as well as contributing to other sections.

2.4 Along with other GNS Science staff, I developed the 2000 National Seismic Hazard Model of New Zealand (NZNSHM; Stirling et al., 2002) that serves as the basis for the spectra and zone factor maps in the NZS1170.5:2004 Standard. I was co-author of the publications describing the 2000 model, and the 2012 paper (Stirling et al., 2012) describing the 2010 update of the NZNSHM.

2.5 I was responsible for developing the McVerry et al. (2006) ground-motion prediction equations (GMPEs) that form a key component of both the 2000 and 2010 NZNSHMs. I led the project team involving GNS Science staff and leading US specialists in this field.

2.6 I have produced consulting reports specifying earthquake ground motions, referred to as seismic hazard studies or seismic hazard assessments, for the assessment or design of a wide range of structures: hydro-electric and irrigation dams; offshore platforms; base-isolated buildings; high-rise buildings; bridges; power stations and electrical substations; oil storage tanks; an irradiation plant; a nuclear reactor; and port facilities. My project experience in this field spans many major projects in New Zealand and some overseas.

2.7 I have been involved in seismic hazard studies for the design or performance re-assessment of many dams and water storage ponds, including: proposed Waimea Dam; Waimakariri Irrigation Ponds as a subconsultant to DamWatch; many hydro-electric dams for ECNZ and its successors Genesis, Meridian and Mighty River Power (now called Mercury Energy), such as Benmore Dam, Upper Waitaki power scheme, Karapiro Dam and other Waikato River Dams, the proposed

Mokihinui River hydro development, Lower Waitaki (Project Aqua) preliminary assessment, and other projects such as the proposed Kapiti Coast bulk water supply dam, rebuilding of Matahina Dam, and its recent assessment, Patea Dam; Wairau Hydro-Electric scheme, Opuha Dam reconstruction, Dillmans power scheme, Watercare Dams, proposed Omaka Dam, Waipori Dam, Bankhouse developments, Wairau Valley, Te Marua Lakes refurbishment, Whangaehu hydro-electric power scheme, Manapouri power scheme and lake control re-assessment; and Lake Coleridge water scheme.

3. In preparing my evidence I have read and complied with the code of conduct for expert witnesses contained in Part 7 of the Environment Court of New Zealand Practice Note 2014. Except where I state that I am relying on the evidence of another person, this statement of evidence is within my area of expertise. I have not omitted to consider material facts known to me that might alter or detract from the opinions expressed.

4. In preparing this evidence, I have read the sections of the *Klondyke Storage Proposal Engineering Report* by MWH (now Stantec) dated August 2016 relevant to seismic design motions. I have also read the draft consent conditions proposed by the Canterbury Regional Council and the Ashburton District Council (Eleventh daft (10th of March till the 20th of March 2017). From a summary of submissions supplied by Mr Cole Burmeister of Enspire Consulting Limited, I have identified and read the following submissions referring to aspects of seismic hazard assessment for the Klondyke storage ponds: 31195 on behalf of Save the Rivers by Mr Keith Gunn; 31220 on behalf of Rangitata South Irrigation Limited by Mt Ian Morten; 31247 on behalf of Rangitata Water Limited by Ms Lia Smith; 31252 by Mr John Stack;31256 on behalf of Early Family Trust by Ms Prudence Steven QC; 31262 on behalf of Te Runanga o Arowhenua and Te Runanga o Ngai Tahu by Ms Kara Edwards. I have also read the Section 42A Officer's Report by Ms Natalia Ford of the Canterbury Regional Council, have noted paragraphs 71 and 72 of the Section 42 Planning Report from Ashburton District Council relating to the GNS Science November 2017 "Seismic Hazard Assessment", and read drafts of evidence by my GNS Science colleague Mr David Barrell and by Stantec New Zealand engineer Mr Steven Woods.

Scope of evidence

5. I have been asked by Rangitata Diversion Race Management Limited (RDRML*)* to address the assessment of design earthquake ground-shaking levels at the site of the proposed Klondyke Water Storage Facility (Klondyke Storage Pond) to satisfy the requirements of the 2015 *New Zealand Dam Safety Guidelines* (NZSOLD, 2015), which will be referred to as the NZSOLD 2015 Guidelines.

6. My evidence first discusses the size, mechanisms and types of earthquakes (paragraphs 7 to 10), measures of earthquake ground motions and structural responses (paragraphs 11 to 16) and background information on seismic hazard analysis (paragraphs 17 to 23). Technical terms are marked in bold where they are first explained. The evidence specific to the Klondyke Storage Pond commences in paragraph 24, in which I identify the reports on which the evidence is based. Then follows a summary of the recommended motions for the design of the proposed Klondyke Storage Pond (paragraphs 29 to 32). The remainder of the evidence covers the basis for these recommendations, including: requirements of the NZSOLD 2015 Guidelines regarding earthquake design motions (paragraphs 33 to 37), and requirements (paragraph 38) additional to those of the 2000 Guidelines; seismicity inputs to the hazard analysis (paragraph 39); site ground conditions (paragraphs 40 to 41); logic trees for ground-motion prediction equations (GMPEs) (paragraphs 42 to 45); hanging-wall factors (paragraphs 46 to 48); mean spectra and uncertainty from the GMPE logic trees (paragraph 49); epistemic uncertainties in the fault modelling (paragraphs 50 to 51); deterministic scenario spectra (paragraphs 52 to 54); and recommended vertical spectra (paragraphs 56 to 61). Then follow brief comments on issues from submissions and the officers' reports relevant to the seismic design motions (paragraphs 62 to 67), before presentation of the conclusions (paragraphs 67 to 75).

Size, mechanisms and types of earthquakes

7. Earthquakes are characterised by their size, their mechanism of movement and their type, which refers to the geological context of the earthquake location.

8. The size of an earthquake is measured by its **magnitude**. The original magnitude scale, called the **Richter magnitude**, and sometimes **local magnitude**, is denoted by the

symbol M_L, and is determined from the amplitude of earthquake waves recorded on a seismograph. It loses precision as a measure of size the larger the earthquake. A better measure of earthquake size, and one which is used in all seismic hazard science, is called **moment magnitude**, denoted as M_W or just M. It is also calculated from seismometer readings, and provides a better measure of the amount of energy released at the source of the earthquake. Magnitude scales are logarithmic, such that an earthquake of magnitude 6 releases approximately 32 times more energy than one of magnitude 5. The moment magnitude Mw is directly related to the logarithm of the **seismic moment** M_0. Seismic moment is proportional to the product of the average displacement of the earthquake source and its rupture area, and is thus amenable to estimation from both geological and instrumental observations. Moment magnitude is the measure used in this evidence, both to describe the size of an earthquake and to estimate the strength of ground shaking expected from it.

9. The **mechanism** of fault movement, sometimes referred to as source mechanism, earthquake mechanism, fault mechanism or focal mechanism, is related to the orientation of the fault plane on which an earthquake occurs and the direction in which movement takes place on it. The terms strike and dip together describe the orientation of the fault, while the direction of movement in relation to fault orientation is classified from a list of four categories.

9.1. The **strike of a fault** is the direction taken by the line of the fault, when viewed from above. Strike is usually measured in degrees from north.

9.2. The **dip of a fault** is the inclination of the fault surface measured in degrees, where 0° is horizontal and 90° is vertical.

9.3. The four categories of direction of movement, also known as sense of movement or sense, are strike-slip, reverse, normal (as illustrated in Figure 1) and oblique.

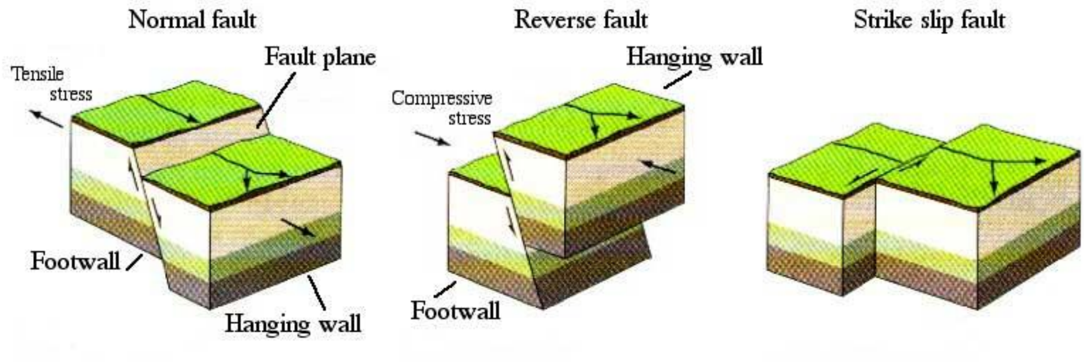
9.4. A **strike-slip fault** is one with its movement horizontal along the strike of the fault. In other words, the movement is sideways.

9.5. A **reverse fault** is one in which the movement is up on one side and down on the other, with the overlying block (**hanging wall**) riding up the underlying block (**foot wall**). Such a movement is a result of compression.

9.6. A **normal fault** movement is also up-down, but with the hanging wall slipping down with respect to the footwall. It occurs as a result of tension.

9.7. An **oblique fault** (not shown in Figure 1) has a combination of strike-slip and reverse or normal movement.

9.8. The mechanism is one of the parameters, along with its location and depth, that determines the type of an earthquake.



http://www.geosci.usyd.edu.au/users/prey/Teaching/Geos-2111GIS/Faults/Sld002c.html

Figure 1: Normal, reverse and strike-slip faults and hanging and foot walls (from http://www.geosci.usyd.edu.au/users/prey/Teaching/Geos-2111GIS/Faults/Sld002c.html)

10. In New Zealand, there is a three-fold classification of earthquake type, comprising subduction interface, subduction slab and crustal, related to the tectonic setting of New Zealand, summarised in Figure 2. New Zealand is located across the boundary of the Pacific and Australian plates, with the nature of the plate boundary changing through the country. Subduction occurs south-eastward beneath Fiordland and north-westward beneath the north-eastern South Island and eastern North Island. Crustal earthquakes characterise the remainder of New Zealand, as illustrated in the cross-section (vertical slice) in Figure 3.

10.1. **Subduction interface earthquakes** occur on the boundary where the offshore oceanic crust compresses against continental crust, with the denser oceanic crust dipping under the lighter continental crust in a process known as **subduction**.

10.1.1. In the Hikurangi subduction zone, extending from north-east of East Cape to offshore of Marlborough, the Pacific plate subducts under the Australian plate. The plate boundary interface lies beneath Wellington at depths of 20 to 30 km, as indicated by the solid line on the plate interface in Figure 3.

10.1.2. In the Fiordland subduction zone, a different arrangement of types of crust means that oceanic crust of the deep offshore part of the Australian plate subducts southeast under the continental crust of New Zealand on the Pacific Plate.

10.2. **Subduction slab earthquakes** occur within the down-going slab source zone within the subducting plate, i.e. the Pacific Plate in Figure 3, beneath the crust and subduction interface.

10.3. The proposed Klondyke Storage Pond site lies about 350 km away from either the Hikurangi or Fiordland subduction zones, meaning that subduction zone earthquakes are relatively minor contributors to seismic shaking hazard at Klondyke.

10.4. **Crustal earthquakes** occur at relatively shallow depths (<25 km) in continental crust rocks of Zealandia, which underlies all of the New Zealand landmass and shallow parts of the surrounding seas. All of the faults recognised onland in New Zealand are crustal faults. The crustal earthquakes collectively span the full range of earthquake mechanisms.

10.4.1. A region of oblique convergence linking the two subduction zones is dominated by the Alpine Fault but also includes other major predominantly strike-slip faults with some reverse movement in the Axial Tectonic Belt (Figure 2).

10.4.2. There are also zones of predominantly reverse faulting, in the north-western and south-eastern South Island, including around the location of the proposed Klondyke Storage Pond.

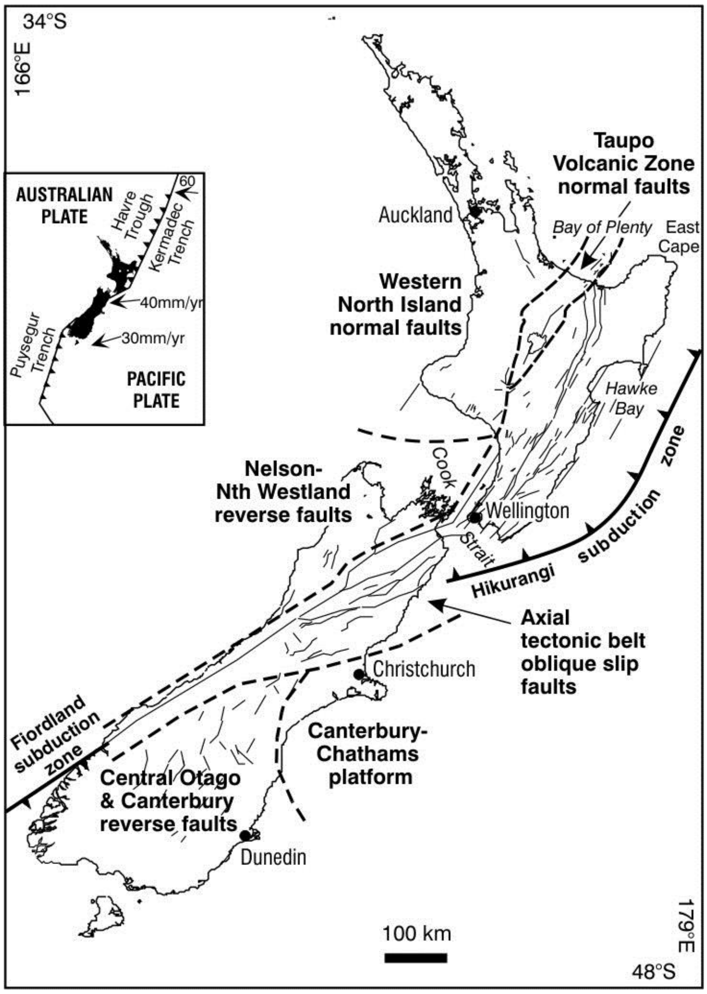


Figure 2: The plate tectonic setting of New Zealand, with the Pacific plate subducting north-east under the Australian plate in the Hikurangi subduction zone, and the Australian plate subducting under the Pacific plate in the Fiordland subduction zone in the south-west. The predominant faulting mechanism regimes for the various regions are also shown. The proposed Klondyke storage pond is in the Central Otago and Canterbury region of reverse faults. From McVerry et al. (2006).

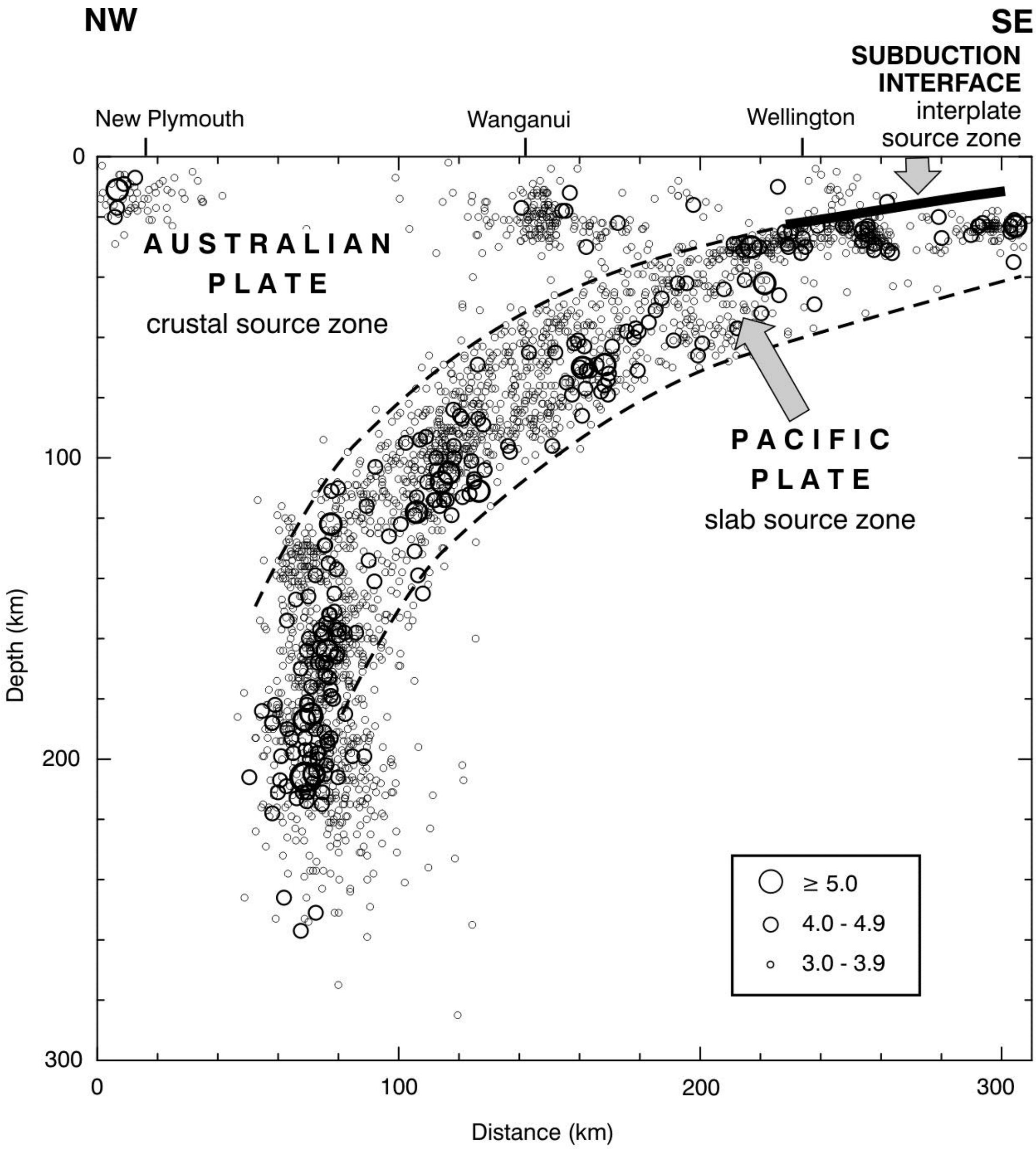


Figure 3: Vertical profile showing the distribution of earthquake locations beneath the southern North Island, and illustrating the settings of crustal, subduction interface and subduction slab earthquake types. From McVerry et al. (2006).

Measures of earthquake ground motions and structural responses

11. The strength of earthquake ground motions at a particular location depends not only on the magnitude of the earthquake, but also on many other factors such as the type of earthquake, the distance of the site from the earthquake source, the geological properties of the travel path of the earthquake waves and the geological nature of the ground immediately beneath the site (local site effects).

12. Effects of earthquake ground motions can be classified in terms of many measures: three common ones are Modified Mercalli Intensity, peak ground acceleration, and the acceleration response spectrum. The first relates to the observed effects of shaking on people or the immediate environment. The second is a physical measure of severity of motion, measured instrumentally for observed earthquakes or estimated analytically from seismic hazard models. The third relates to the response of built structures to earthquake motions. Peak ground acceleration and 5% damped acceleration response spectra are the measures generally used in seismic design, and are the quantities that are specified in this evidence.

13. **Peak ground acceleration (PGA)** is the maximum acceleration experienced by the ground, often expressed in earthquake engineering in units of "**g**", the acceleration produced by gravity when an item is dropped, with a numerical value of 9.8 m/s^2 (or 9.8 N/kg in terms of force per unit mass). PGA is a measure of motion that is useful for rigid structures and is often used as the basis for design in geotechnical engineering.

14. Structural responses to earthquake ground motions are commonly addressed through the **acceleration response spectrum** which is a measure of the maximum acceleration of simple elastically-responding structures to a particular earthquake motion. It assesses the maximum response as a function of natural period for a particular damping value, usually 5% of critical damping.

    14.1. The maximum acceleration response of a structure is usually different from the peak ground acceleration to which it is subjected. The acceleration response of a structure is important because it is directly related to forces imposed on it. The maximum response for simple structures depends on their natural period and damping. The response of more complex structures can be modelled as the sum of the responses of a series of simple structures, with clearly defined mathematical procedures to decompose the complex structure into its constituent simple structures ("modal decomposition"). The **natural period** of simple structures (or the **fundamental mode period** of complex structures) is that at which they vibrate if deflected horizontally and then released. The natural period depends on the ratio of the structure's mass and stiffness. Light, stiff structures have short periods of vibration, while heavy, flexible structures have longer periods. Rigid structures have a natural period of zero, and have the same motion as the ground. Short-period structures generally amplify the PGA. The degree of amplification or reduction depends on the damping, with higher damping generally reducing the peak response acceleration. Sufficiently long-period structures have peak accelerations lower than the PGA, because their inertia and flexibility allows them to remain close to stationary while the ground vibrates at much shorter periods than their natural period.

14.2. The acceleration response of a simple linear-elastic structure increases in proportion to its top displacement with respect to the ground. As the displacement increases, the acceleration begins to increase more slowly with displacement, with this change becoming noticeable at the yield point. Beyond yield, the displacement increases with slight increase in acceleration.

14.3. The maximum response of nonlinear structures can be approximated by factoring the maximum response of an elastically-responding structure by a factor depending on the **ductility** (the ratio of the maximum displacement/yield displacement, a measure of the displacement beyond yield).

14.4. The maximum response of complex structures can be found by appropriate combination of their modal responses.

14.5. For these reasons, the elastic acceleration response spectrum is a convenient engineering representation of the strength of earthquake motions, and is frequently the basis for calculating the design responses of both elastically- and nonlinearly-responding structures.

15. Ground-motion prediction equations (discussed in paragraph 19) often define acceleration response spectra with 5% damping, and 5% damped acceleration response spectra are common products of seismic hazard analysis. The PGA is the zero-period point on an acceleration response spectrum.

16. Earthquake engineering design in regard to structural response is mainly concerned with horizontal earthquake motions. This is because structures usually have inherent vertical strength to resist vertical earthquake motions from the requirement to support

their own weight, while structures not specifically designed for earthquake motions (or strong wind loadings in the case of taller structures) often possess little inherent horizontal strength. Seismic hazard studies generally concentrate on horizontal earthquake motions. There are few models available for estimating vertical motions, and, if required, they are often estimated by scaling horizontal motions. GNS Science has no models for specifically estimating vertical earthquake motions, other than by the scaling of estimated horizontal motions.

Background information on seismic hazard analysis

17. In performing seismic hazard assessment for a given location, there are two main components: the seismicity model and the ground-motion prediction equations.

18. The **seismicity model** gives the occurrence rate (usually represented by its inverse, the **average recurrence interval**) of future earthquakes which may produce motions at the location of interest. The model includes fault sources and distributed seismicity sources. The distributed seismicity model used for the Klondyke Pond seismic hazard assessment is discussed briefly in paragraph 39.1 of this evidence, and the fault source model in more detail in the evidence of my colleague Mr David Barrell.

19. A **ground-motion prediction equation (GMPE)** is an expression for estimating the strength of shaking expected at a given location from a specified earthquake.

    19.1. The strength of motion depends on factors such as the earthquake magnitude, the distance of the location of interest (site) from the earthquake source, the type of earthquake and the ground conditions at the site.

        19.1.1. There is a wide variability in the strength of motions experienced at a given distance for a given magnitude of earthquake, so GMPEs are probabilistic, defining the probabilities of exceeding any level of motion at a site from a specified earthquake.

        19.1.2. GMPEs are usually expressed in terms of the 50th-percentile motions and a measure of the scatter about the 50th-percentile motion.

19.1.3. A measure of scatter is the **standard deviation**, which is the square root of the **variance**. The **variance** is the mean of the square of the difference from the expected value of the motion.

19.1.4. The probability distributions for PGAs and response spectral accelerations are usually **log-normal**, i.e., the logarithm of their values follows a normal distribution.

19.1.5. A common measure of the scatter for log-normal acceleration distributions is the standard deviation of the logarithm of the acceleration.

19.1.6. Alternatively, the log-normal distributions of PGA and response spectral accelerations at a site for a specified earthquake are often specified in terms of their 50th- and 84th- percentile values.

19.1.7. In statistical terms, the 84th-percentile level corresponds to one standard deviation above the median for a normal (or log-normal) distribution.

19.1.8. The **percentile level** corresponds to the percentage probability that the associated motions are *not* exceeded if a specified earthquake occurs. At the 50th-percentile level, half the motions are expected to lie below the estimated level, and half above. At the 84th-percentile level, 84 percent of the motions are expected to lie below that level, and only 16 percent (about one in six) above it.

19.1.9. For log-normal distributions, the mean (average) motions exceed the 50th-percentile (median) values.

19.1.10. The GMPEs and related input parameters are discussed in paragraphs 40 to 49 of this evidence.

20. Two distinct forms of seismic hazard analysis were performed for the Klondyke Storage Pond study: probabilistic seismic hazard analysis and deterministic or scenario analysis

(paragraphs 21 and 22). The *NZSOLD 2015 Guidelines* recognise roles for both forms of analysis, as discussed in paragraph 36 of this evidence. Consideration of uncertainties in both the seismicity models and GMPEs is required for both forms of analysis, as discussed in paragraph 37 of this evidence. In the following paragraphs, all mention of 'earthquake' refers to possible future earthquakes in relation to seismic hazard analysis.

21. In **probabilistic seismic hazard analysis (PSHA)**, all possible future earthquakes represented in the seismicity model are accounted for, and the ground-motions modelled probabilistically. The estimated contributions of all earthquakes to the rate of exceedance of a specified level of earthquake motion are summed to obtain the overall **average exceedance rate**. The inverse of the average exceedance rate is referred to as the **return period** for that level of motion**.** Return periods refer to levels of shaking, while recurrence intervals (paragraph 15) refer to earthquake occurrences.

21.1. The rate of exceedance of a ground-motion intensity level for a specified earthquake depends on both the rate of the earthquake occurrence and the probability of that earthquake producing motions exceeding the specified level of shaking motions at the site of interest if the earthquake occurs. Thus the overall rate of exceedance may include contributions from frequent low-to-moderate magnitude earthquakes which individually have low probabilities of exceeding the shaking level, and rare large-magnitude earthquakes which have much higher probabilities of exceeding a given level of shaking if they do occur.

21.1.1. Modelling uncertainties may be considered by performing these calculations for multiple combinations of seismicity models and/or GMPEs, or through sensitivity analyses for key parameters.

21.1.1.1. Combinations of multiple seismicity and/or GMPE models may be handled through a logic tree approach. **Logic-trees** give weighted combinations of various models, with the models and their weights represented by tree-like structures. Each option at each level is indicated by a separate branch and has a weight assigned at that level. The weights assigned at each level represent assigned probabilities of the option being correct, so add to 1.0. The weights are assigned by judgement, usually by a team rather than an individual. Every combination of models can be followed through (the end-member branches may be more like twigs for complicated multi-level logic trees), and the overall weight calculated for that specific combination of models. The overall weight for each combination of options is obtained by multiplying the weights at each level on the way to the end-member branch (e.g. 0.2*0.185 for the top end-member branch in Figure 4). An example of a logic-tree structure for calculating the hazard rates for every GMPE branch for a single fault source representation is indicated in Figure 4 for a major dam.

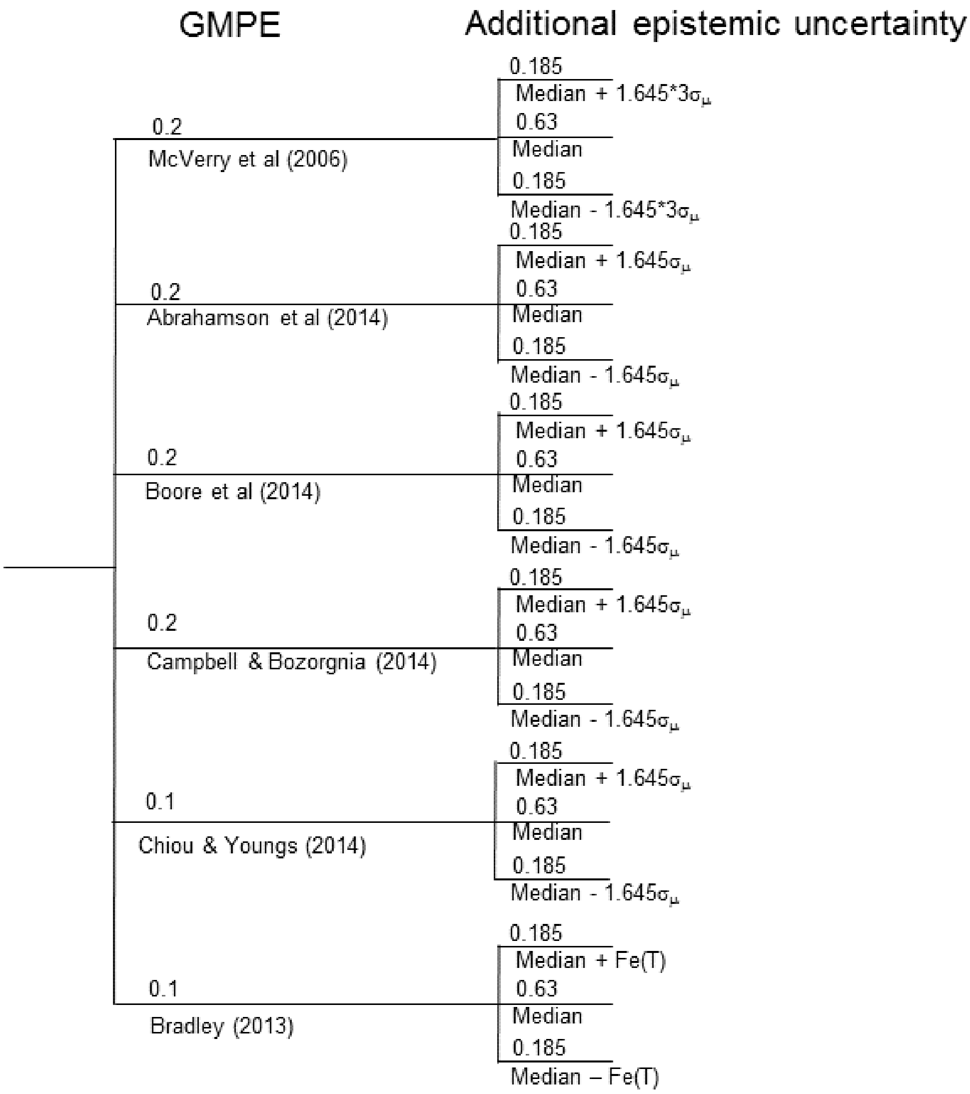


Figure 4: An example of a GMPE logic tree, indicating multiple GMPE options at the top level, and a second level with alternative ways of treating the GMPEs, together with the weights applied at each level.

21.2. The results from the probabilistic analyses for the Klondyke Storage Pond are presented in paragraphs 32 and 49 of this evidence.

22. A **deterministic or scenario seismic hazard analysis** relates to the motions expected in a specific earthquake. The aim of scenario analysis is to identify the earthquake likely to produce the strongest earthquake motions at the location of interest if it should occur. This often involves considering several scenarios to obtain the one giving rise to the strongest motions.

22.1. Although commonly referred to as a deterministic analysis, this type of analysis still contains probabilistic elements. The deterministic approach recognises that there may be variability in the motions experienced at the same location from two earthquakes of the same size on the same fault. The degree of recognition of this variability depends on the percentile level for which the analysis is performed. Scenario spectra for the Klondyke Storage Pond are presented for the 84^{th}-percentile level, as required by the NZSOLD 2015 Guidelines.

22.2. In addition, uncertainties in appropriate models are considered by using weighted means of the results from multiple GMPEs.

22.3. The deterministic scenario analyses are presented in paragraphs 52 to 54 of this evidence.

23. Both the probabilistic and deterministic approaches can at times lead to unrealistically high estimates of ground motions. The inclusion in the probabilistic analysis of contributions from all earthquakes, including some at levels of shaking that have very low probabilities of exceedance if that earthquake occurs, can at times lead to very high estimates of ground motions for long return periods, beyond what can reasonably be expected for any scenario (usually assessed at the 84^{th}-percentile level). Alternatively, major but low-activity faults may give rise to high scenario motions, but with very low exceedance rates. Both PSHA and scenario analyses are used to counter these extreme estimates.

Reports forming the basis for my evidence

24. My evidence is based on material related to the proposed Klondyke Storage Pond provided to Rangitata Diversion Race Management Limited by GNS Science in a consultancy report, namely:

    McVerry GH, Barrell DJA, Abbott ER. 2017. Seismic hazard assessment for the Klondyke Storage Pond. Lower Hutt (NZ): GNS Science. 39 p. (GNS Science consultancy report 2017/160).

    This report will be referred to as the GNS 2017 Report.

    24.1. I was involved in recommending the GMPEs used in this study; scoping and overseeing the seismic hazard calculations performed by my colleague Ms Elizabeth Abbott, using fault and distributed seismicity models provided by GNS Science geologists and seismologists; and recommending ground-shaking hazard values for design of the storage pond and appurtenant structures.

    24.2. Ms Abbott has been largely responsible for the implementation and application at GNS Science of the OpenQuake seismic hazard software developed as part of the major international Global Earthquake Model (GEM) project (GEM, 2017) that GNS Science now uses in place of its older in-house software. A CV setting out her qualifications and experience is attached in Appendix A.

    24.3. Evidence from my GNS Science colleague Mr David Barrell provides an overview of active fault structures in the region as potential sources of earthquakes and related ground deformation; his complementary evidence covers those aspects of the GNS 2017 Report that lie outside my field of expertise, specifically in sections 2.2 and 2.3 of that report.

25. GNS Science undertook an earlier seismic hazard assessment for the site of the proposed Klondyke storage scheme in 2014, namely:

    Stirling MW. 2014. Seismic design spectra for Klondyke Pond, Canterbury. Lower Hutt (NZ): GNS Science. 16 p. (GNS Science consultancy report 2014/82).

This report will be referred to as the GNS 2014 Report.

25.1. The GNS 2014 Report satisfied the requirements of the 2000 *New Zealand Dam Safety Guidelines* (NZSOLD, 2000), and was used to inform an earlier stage of the Klondyke Storage Pond resource consent application.

25.2. I had only a minor involvement in the 2014 study through discussions with Dr Stirling on smoothing of spectra and selection of SEE spectra, at that time referred to as MDE (Maximum Design Earthquake) spectra.

26. Since the 2014 work was undertaken the publication of the NZSOLD 2015 Guidelines means that more detailed seismic hazard assessments are required for dams, as discussed in paragraph 20 of this evidence. In my opinion this renders the seismic hazard recommendations of the GNS 2014 Report no longer adequate for the current requirements.

27. In my opinion the GNS 2017 Report satisfies the requirements of the NZSOLD 2015 Guidelines and supersedes the GNS 2014 report.

28. I have not carried out a site visit, as it was not necessary for my contributions to the hazard assessment.

Summary of recommended motions

29. Peak ground accelerations (PGAs) and seismic response spectra for 5% damping are presented for horizontal and vertical earthquake motions at the site of the proposed Klondyke Storage Pond that are appropriate for Operating Basis Earthquake (OBE) and Safety Evaluation Earthquake (SEE) motions as defined in the NZSOLD 2015 Guidelines. Requirements of the NZSOLD 2015 Guidelines for OBE and SEE motions are discussed in paragraphs 34 and 35 of this evidence.

30. The recommended motions are based on consideration of both deterministic ("scenario") estimates for Controlling Maximum Earthquake (CME) motions (defined in

paragraph 30.2.1) and probabilistic estimates for return periods ranging from 150 years to 10,000 years.

30.1. As required by the NZSOLD 2015 Guidelines (Module 3, Section 4.3.3, page 20) for high potential impact classification (PIC) dams such as the proposed Klondyke Storage Pond, epistemic uncertainties in both the earthquake source modelling and GMPEs were considered.

30.1.1. **Epistemic uncertainties** are those resulting from variations between models and incomplete data for the definitive specification of the models.

30.2. As the proposed Klondyke Storage Pond site is on the hanging wall of the Hutt-Peel 2017 fault, appropriate hanging-wall factors for the individual fault-site geometries were applied for all faults in estimating the PGAs and spectra, as discussed in paragraph 48.

30.2.1. The hanging wall is the zone that lies above the rupture plane of a dipping fault (see Figure 1). Ground-shaking is generally stronger on the hanging-wall than foot wall, as discussed in paragraph 47 of this evidence.

31. The representations of some of the faults that most influence the estimated seismic hazard in the region have changed since the GNS 2014 Report. The representation of the faults is described in the evidence of my GNS Science colleague, geologist Mr David Barrell.

32. The mean probabilistic horizontal spectra are listed in Table 1. The horizontal PGA values and their associated average magnitudes are listed in Table 2.

32.1. The horizontal results presented for the proposed Klondyke Storage Pond are for the larger of two randomly-oriented but orthogonal horizontal components. This is, in my experience and opinion, consistent with New Zealand structural design practice. The design motions specified in the New Zealand Standard NZS1170.5:2004 (Standards New Zealand 2004) were developed from seismic hazard studies using the seismic hazard model of Stirling et al. (2002) in terms of the larger horizontal component.

32.2. The 150-year spectrum corresponds to the OBE motions, and the 10,000-year spectrum is recommended for the SEE motions. The NZSOLD 2015 Guidelines (Module 3, Section 4.3.3, page 20) limit the SEE spectrum to no stronger than the mean 10,000-year spectrum rather than the stronger deterministic spectrum for the 84^{th}-percentile motions from a magnitude M_w 7.5 earthquake on the Hutt-Peel 2017 fault source.

32.3. The horizontal PGA values are 0.21g for the OBE and 0.87g for the SEE, with the associated 5% damped acceleration response spectra peaking at 0.51g and 1.99g, respectively.

32.4. The 500-year and 2500-year results are included in Tables 1 and 2 because they were requested for the GNS 2017 Report, but they are not needed for specifying the OBE and SEE motions. These return periods are often used for appurtenant structures such as those governed by New Zealand Standard NZS1170.5:2004 (Standards New Zealand, 2004, 2016).

Table 1 The mean peak ground acceleration and 5% damped larger horizontal component acceleration response spectra SA(T) for periods T up to 3s for 150-, 500-, 2500-, and 10,000-year return period motions for the proposed Klondyke Storage Pond. The OBE motions correspond to the 150-year spectrum and the SEE motions to the 10,000-year spectrum.

Mean 5% damped acceleration response spectra SA(T) (g)				
T(s)	**150 years (OBE)**	**500 years**	**2500 years**	**10,000 years (SEE)**
0 (PGA)	0.21	0.33	0.57	0.87
0.075	0.32	0.52	0.88	1.32
0.1	0.39	0.63	1.05	1.56
0.15	0.48	0.75	1.23	1.77
0.2	0.51	0.81	1.32	1.89
0.25	0.51	0.81	1.34	1.94
0.3	0.50	0.79	1.34	1.99

0.35	0.47	0.76	1.31	1.99
0.4	0.45	0.72	1.27	1.98
0.5	0.41	0.67	1.19	1.90
0.75	0.32	0.52	0.95	1.60
1	0.24	0.42	0.79	1.39
1.5	0.16	0.29	0.57	0.99
2	0.12	0.21	0.42	0.74
3	0.074	0.13	0.27	0.46

Table 2 PGA values and corresponding average magnitudes for the proposed Klondyke Storage Pond for each of the requested return periods.

		Return periods (years)			
		150	**500**	**2500**	**10,000**
Klondyke Storage Pond	**PGA (g)**	0.21	0.33	0.57	0.87
	Average magnitude	6.3	6.3	6.5	6.9

Requirements of the NZSOLD 2015 Guidelines

33. The NZSOLD 2015 Guidelines require consideration of two levels of earthquake motions, the Operating Basis Earthquake (OBE) and the Safety Evaluation Earthquake (SEE) motions. The performance requirements and level of motions are defined for both the OBE and SEE motions.

34. The performance requirements of the NZSOLD 2015 Guidelines (Module 3, Sections 4.3.1 and 4.3.2, page 19) are that at the OBE level of motion “the dam and appurtenant structures remain functional and that the resulting damage is minor and easily repairable” (NZSOLD, 2015;), while at the SEE level of motion “there is no uncontrolled release of the impounded contents” but “damage to the structure may have occurred”.

35. The NZSOLD (2015) Guidelines define the **OBE motions** as those with an annual exceedance probability (AEP) of 1/150, also referred to as a return period of 150 years. The OBE definition and performance requirements are unchanged from the 2000 Guidelines.

36. The NZSOLD Guidelines (2000 and 2015) allow the SEE ground motions to be defined either probabilistically or deterministically. These two forms of seismic hazard analysis are discussed in paragraphs 20 to 23 of this evidence.

36.1. **Probabilistically-defined SEE motions** for High Potential Impact Classification (PIC) dams, such as the dam for the proposed Klondyke Storage Pond, correspond to the mean 1 in 10,000 AEP (also referred to as 10,000-year return period) ground motions. The mean is taken across all the possible results from the logic trees. As the 2000 NZSOLD Guidelines did not require consideration of multiple GMPEs or epistemic uncertainties in the earthquake source model, only a single estimate was required from studies undertaken to satisfy those Guidelines with no need to consider the distribution of alternative results.

36.1.1. The NZSOLD 2015 Guidelines adopt the higher mean rather than 50^{th}-percentile values as the recommended level for the probabilistic estimates.

36.2. Alternatively, the **deterministic scenario SEE motions** may be taken at the 84^{th}-percentile level for the Controlling Maximum Earthquake. The scenario motions need not exceed those derived by the probabilistic approach.

36.2.1. The **Controlling Maximum Earthquake (CME)** is defined as "the maximum earthquake on a seismic source that is capable of inducing the largest seismic demand on a dam" (NZSOLD 2015 Guidelines, Module 3, Section 4.3.1, page 19).

Aleatory variability and epistemic uncertainties

37. A requirement of the NZSOLD 2015 Guidelines (Module 3, Section 4.3.3, page 20) that did not appear in the 2000 Guidelines is that "Epistemic uncertainties associated with earthquake sources and ground motion prediction equations should be considered".

37.1. Although "epistemic uncertainties" aren't defined in the *Guidelines*, they correspond to one of two items discussed in the description for uncertainty in the Glossary to the 2015 *Guidelines* (Objectives & Principles, page 21):

37.1.1. "**Uncertainty** – Result of imperfect knowledge concerning the present or future state of a system, event, situation or population under consideration. The level of uncertainty governs the confidence in predictions, inferences or conclusions. In the context of dam safety, uncertainty can be attributed to (i) inherent variability in natural properties and events, and (ii) incomplete knowledge of parameters and the relationships between input and output values."

37.1.2. The first type of uncertainty above is often referred to as "**aleatory variability**", and is accounted for in GPMEs by defining motions in terms of probabilistic distributions.

37.1.3. The second type of uncertainty related to incomplete knowledge is referred to as "**epistemic**". Paragraphs 42 to 44 and 50 to 51 discuss how this uncertainty was accounted for in the GNS 2017 report.

37.2. In the GNS 2017 Report, the requirements for considering epistemic uncertainties in GMPEs were addressed by using GMPE logic trees (i.e., by weighted combinations of the various models, with the models and their weights given in a tree-like structure, with branches associated with each option, as explained in paragraph 21.1.1.1 of this evidence). The specific logic tree for crustal GMPEs used in the Klondyke study is discussed in paragraph 37 of this evidence.

37.3. Epistemic uncertainties in the fault locations, segmentation, parameters and the possibility of multi-segment ruptures were considered through sensitivity analyses of the probabilistic hazard spectra and estimation of deterministic spectra for various fault-rupture scenarios as alternatives to the probabilistic hazard spectra. Various representations of the faults in the region around the Klondyke Storage Pond are discussed in the evidence of Mr David Barrell.

Differences between NZSOLD 2000 and 2015 Guidelines

38. The SEE requirements of the NZSOLD 2015 Guidelines for high PIC dams, as discussed above, are similar to the 2000 requirements, but are more comprehensive in two ways.

38.1. The NZSOLD 2015 Guidelines specify the 84th-percentile level for the scenario motions. The percentile level was previously undefined, although the 84th-percentile level was recommended in the Mejia et al. (2001) paper that was often used to interpret the NZSOLD 2000 Guidelines. The effects of this change are limited by the retention of the maximum requirement in terms of the 1 in 10,000 AEP motions.

38.2. A new requirement is to explicitly consider “epistemic uncertainties”, needing consideration of multiple GMPEs and multiple representations of the earthquake sources.

Seismicity inputs to the hazard analysis

39. The site-specific inputs to the hazard assessment include a seismic source model made up of two components that, in combination, provide the locations, magnitudes and recurrence intervals of earthquakes that affect the site. The two components are a model of distributed seismicity derived from historical seismicity, and a geologically-based model of active fault sources in the region surrounding the site.

39.1. In the **distributed seismicity component**, earthquakes are distributed across a three-dimensional grid to provide a smoothed representation of historical seismicity. The distributed seismicity model used for the GNS 2017 Report is described in Stirling et al. (2012), which is derived from the nationwide Geonet historical seismicity catalogue available from https://www.geonet.org.nz/data/types/eq_catalogue .

39.1.1. The distributed seismicity model provides the rates of earthquakes in 0.1° by 0.1° (approximately 11 km longitude north-south by 7 km latitude west-east) cells of 20 km depth, spread across 5 layers centred at depths of 10 km, 30 km, 50 km, 70 km and 90 km. The two deeper layers only occur in regions containing deep slab earthquakes. The rates for each layer are determined from the numbers of historical earthquakes by fitting Gutenberg-Richter (1944) frequency-magnitude relations. According to the **Gutenberg-Richter relation**,

$$\log_{10} N(M) = a - b\,M$$

where N(M) is the number of earthquakes of magnitude M or larger and a and b are fitted parameters associated with the total number of earthquakes and their decay with magnitude, respectively. The parameter b is usually close to 1, meaning that the rate of earthquakes decays by about a factor of 10 for a unit increase in magnitude. The parameter b was fitted for five regions characterised by earthquakes with similar mechanisms. The smoothed value of the rate parameter a was calculated for each grid point by weighting the number of earthquakes in its layer by a factor that decayed exponentially with distance from the grid point. To avoid double-counting earthquakes represented by the fault model, a maximum magnitude for the distributed seismicity was taken as 7.2. More detail is given in Stirling et al. (2012)

39.2. The geologically-based representation of active fault sources used in estimating the seismic hazard at the site is discussed in the evidence of my GNS Science colleague Mr David Barrell. In consultation with other fault geologists within GNS Science, he reassessed and modified fault sources for the region within about 50 km of the Klondyke Storage Pond from their representation in the NZNSHM.

Site conditions

40. Earthquake motions depend on the ground conditions at the site. Those at the site of the proposed Klondyke Storage Pond were taken as New Zealand Standard 1170 Site Class D Deep or Soft Soil (Standards New Zealand 2004, 2016), using the evaluation given in the GNS 2014 Report. That evaluation was performed by the author of the GNS 2014 Report, Dr Mark Stirling, who is now Chair of Earthquake Science in the Department of Geology at the University of Otago.

40.1. Dr Stirling's assessment was based on a site visit and an interpretation of the 2007 QMAP Aoraki geological map (Cox & Barrell, 2007) that includes the proposed storage pond location.

41. Some of the GMPEs used for estimating the earthquake motions characterise site conditions in terms of the average shear-wave velocity to 30 metres depth (V_s30), which was not provided in the 2014 study.

41.1. In the 2017 study, V_s30 was taken as 250 m/s, the default value for Site Class D given in Table 2 of Bradley (2013). This value in turn is taken from Table A1 of Boore and Atkinson (2008) as the geometric mean for a set of sites that exhibits a range of V_s30 values from 180m/s to 360 m/s.

41.2. The default Vs30 value was used because V_s30 is a very difficult parameter to measure for deep gravel sites such as that at the proposed Klondyke Storage Pond. Measurements of V_s30 require either velocity measures from boreholes of this depth or greater, or inversion for the profile of shear-wave velocity with depth from surface wave measurements of ambient noise or waves generated on the surface through sledge-hammers, shakers or dropping of weights. Downhole methods are costly, while modelling of velocities from surface-wave measurements can be difficult, particularly if the shear-wave velocities change gradually with depth rather than with distinct velocity differences across layer boundaries. Shear-wave velocities estimated from surface-wave measurements often lead to non-unique profiles. These difficulties are discussed by Teague et al. (in press), for example.

41.3. Class D combines both deep and soft soil sites that have site periods longer than 0.6s.

41.4. A V_s30 value of 250 m/s is typical for soft soil sites, but may be an under-estimate for a deep gravel site, such as the proposed Klondyke Storage Pond site.

41.5. A decrease in V_s30 generally decreases PGA values and short-period spectral values up to about the peak of the spectrum or somewhat longer periods, but increases response spectral accelerations for longer periods.

41.5.1. The effect of V_s30 on the estimated spectra for the Klondyke Storage Pond site is demonstrated in Figure 5 by comparing the recommended spectra (solid curves) calculated using V_s30=250m/s with those obtained using Vs30=300m/s (dashed curves). The higher V_s30 value increases the PGA estimates slightly (by a maximum of 7% for the 10,000-year spectrum, shown by the blue curves) and the short-period values (by 8% at 0.3s at the peak of the 10,000-year spectrum), but reduces long-period spectral values (by 4%, 10% and 12% at 1s, 2s and 3s, respectively, for the 10,000-year spectrum).

41.6. Consequently, use of the default V_s30 value of 250 m/s may over-estimate the spectra at the proposed Klondyke Storage Pond site for periods longer than about 0.2s to 0.7s, depending on the return period, but may produce modest (<10%) under-estimates of PGAs and values at the peak of the spectra.

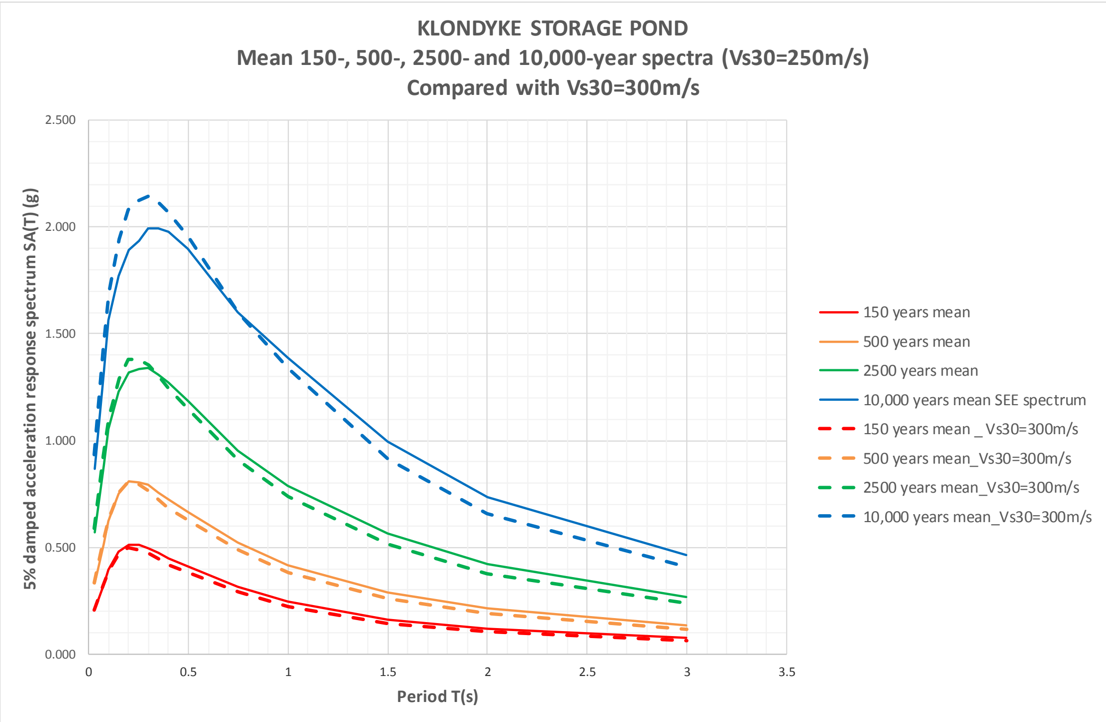


Figure 5: The effect of V_s30 on the estimated spectra for the Klondyke Storage Pond site is demonstrated by comparing the recommended spectra (solid curves) calculated using V_s30=250m/s with those obtained using Vs30=300m/s (dashed curves). The higher Vs30 value

increases the estimates slightly for PGA and short spectral periods, but reduces long-period spectral values.

41.7. In my opinion, adoption of the Bradley's recommended default V_s30 value of 250m/s for Class D for the Bradley GMPE is acceptable for this project in the absence of site-specific data. The effects on the spectra of the higher V_s30 values that are likely for this deep gravel site are modest.

41.8. Logic trees for ground-motion prediction equations

42. The effects of uncertainty in the GMPEs were included by using logic trees (explained in paragraph 21.1.1.1) to combine the estimates the ground-motions produced from two GMPE sets, one for crustal earthquakes and the other for subduction zone earthquakes.

42.1. The proposed Klondyke Storage Pond is distant from both New Zealand subduction boundaries, in Fiordland and off the east coast from north-east of East Cape to Marlborough, with a shortest distance of about 350 km to both.

42.2. Consequently, subduction earthquakes contribute little to the seismic hazard at the site of the proposed Klondyke Storage Pond.

43. Table 3 lists the GMPEs and their weights used for crustal earthquakes. The GMPEs are a combination of the New Zealand-developed McVerry et al. (2006) and Bradley (2013) models, and three 2014 models from the NGA West-2 project (Gregor et al., 2014) in the United States.

Table 3 GMPEs and associated weights selected for use with sources classified as Active Shallow Crust.

Active Shallow Crust	
GMPE	**Weight**
Abrahamson et al. (2014)	0.2
Boore et al. (2014)	0.2
Campbell and Bozorgnia (2014)	0.2
Bradley (2013)	0.25
McVerry et al. (2006)	0.15

44. A similar table for the GMPEs and their weights used for subduction zone earthquakes is given in the GNS 2017 report. Subduction zone earthquakes are a small contributor to the estimated hazard at the proposed Klondyke Storage Pond site, so that table is not repeated here.

45. There are several measures that GMPEs use for PGAs and horizontal spectral accelerations. For consistency, it is necessary to convert the results for all the GMPEs used to the same measure. The NGA West-2 GMPEs use a measure called SaRotD50, the Bradley (2013) GMPE uses SaGMRotI50, and the global subduction zone models use SaGM. The measure used in the GNS 2017 Report for the Klondyke Pond is the larger horizontal component, Salarger, as used by the McVerry er al. (2006) GMPE. Accordingly, to obtain results for all GMPEs in terms of Salarger, it was necessary to use three different conversion factors for the GMPEs selected, namely for the ratios Salarger/SaRotD50, Salarger/SaGMRotI50, and Salarger/SaGM. The conversion factors implemented by GNS Science in the OpenQuake software are given by Equation 2 of Boore and Kishida (2017), in which different coefficients are specified for each factor. Boore and Kishida derived all three conversion factors from the same very large set of data, comprising over 21,000 pairs of horizontal component response spectra from the NGA West database (Ancheta et al. 2014). The factors used are shown in Figure 6.

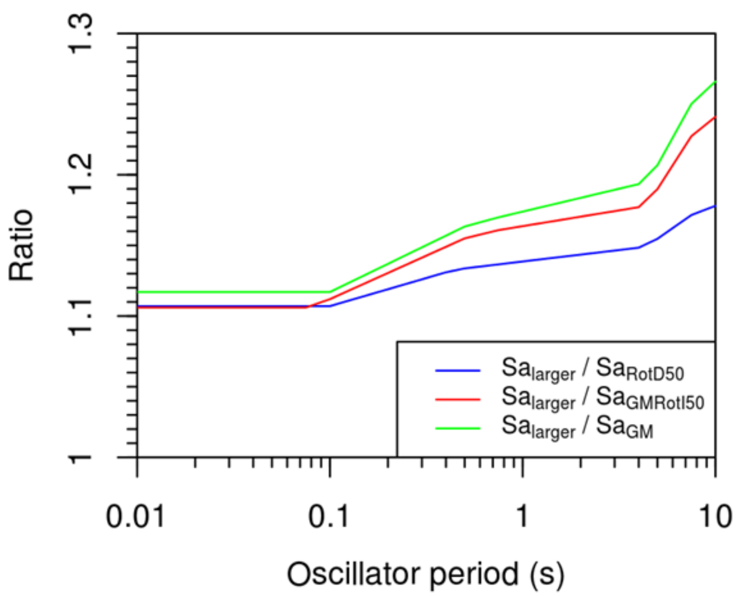


Figure 6: Conversion factors of Boore and Kishida (2017) for Sa_{larger} / Sa_{RotD50}, which is used for the NGA West-2 models, Sa_{larger} / $Sa_{GMRotI50}$, which is used for the Bradley (2013) model, and Sa_{larger} / Sa_{GM}, which is used for the global subduction zone models.

Hanging-wall factors

46. The proposed Klondyke Storage Pond site is on the hanging wall of the Hutt-Peel 2017 fault, i.e., on the side that lies above the dipping fault plane (explained in paragraph 9 and Figure 1), to the north-west for this fault.

47. A site on the hanging-wall side of a fault will generally experience stronger motions from rupture of the fault than a site on the foot-wall at the same shortest distance. This results from the hanging-wall site having a shorter average distance to the fault plane than the foot-wall site (shown in Figure 7) and from amplification effects as the wedge of material between the fault plane and surface tapers as the dipping fault approaches the surface.

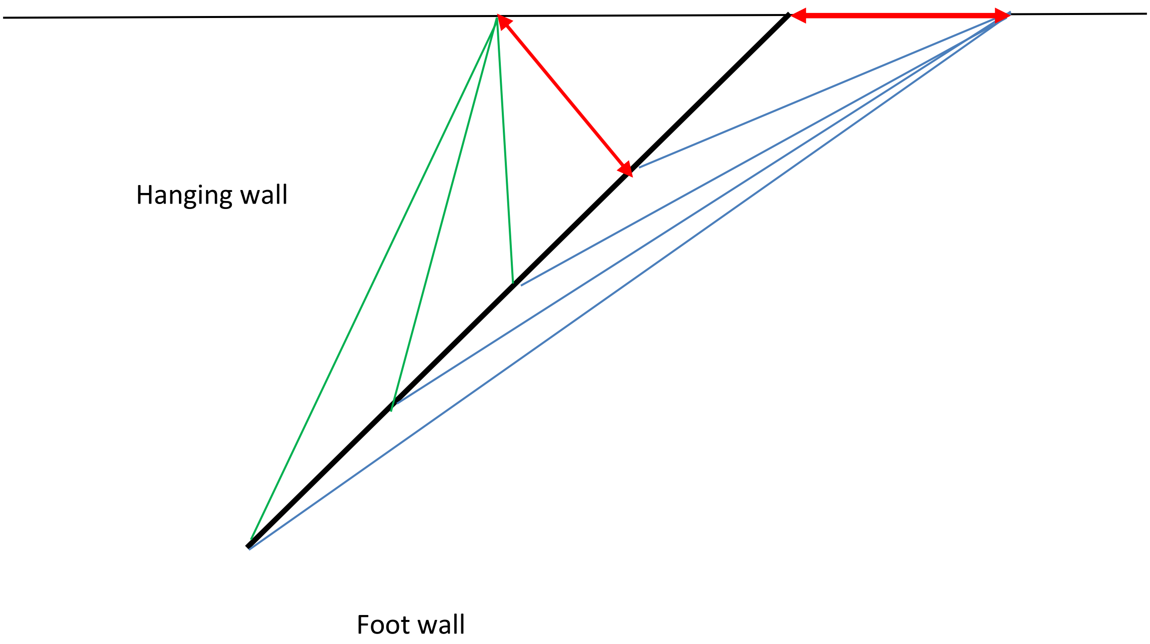


Figure 7: A vertical section through a reverse fault showing two sites on the ground surface at the same shortest distance (indicated by red lines with arrows) from a fault plane (inclined black line) on the hanging wall and foot wall. The green lines indicate the generally shorter distances of the hanging wall site than the distances of the foot wall site (blue lines) from other points on the fault plane.

48. The GNS Science seismic hazard software accounts for hanging-wall effects for all the crustal GMPEs used for the Klondyke Storage Pond. The software applies appropriate hanging-wall factors for the individual fault-site geometries for all faults.

48.1. For the NGA West-2 and Bradley (2013) GMPEs, hanging-wall effects are accounted for in the GMPE expressions themselves, either through the choice of distance measure or through explicit hanging-wall factors.

48.2. For the McVerry et al. (2006) GMPE, hanging-wall effects were accounted for in the GNS 2017 report by applying the hanging-wall term from the Abrahamson et al. (2014) GMPE. In my opinion, use of the Abrahamson et al. hanging-wall factors for the McVerry et al. GMPE is appropriate because the two GMPEs are similar in character. The McVerry et al. GMPE was modified from an earlier generation of the Abrahamson at al. GMPE, namely the Abrahamson & Silva (1997) GMPE.

Mean spectra and epistemic uncertainty from the GMPE logic tree

49. The mean spectra calculated from the GMPE logic tree, as listed in Table 1, are shown in Figure 8 for return periods of 150, 500, 2500 and 10,000. Figure 8 also shows the 50^{th}-percentile and 84^{th}-percentile probabilistic spectra calculated for these return periods to demonstrate the effect of epistemic uncertainty in the GMPEs on the hazard estimates.

49.1. The 50^{th}-percentile spectra for each return period are similar to the mean spectra.

49.2. The 84^{th}-percentile spectra are up to 32% larger around the peaks than the mean spectra for the same return periods, although typically larger than the mean spectra by about half this amount.

49.3. The requirements of the NZSOLD 2015 Guidelines are satisfied by recommending the mean 150-year spectrum for the OBE motions and the mean 10,000-year spectrum for the SEE motions.

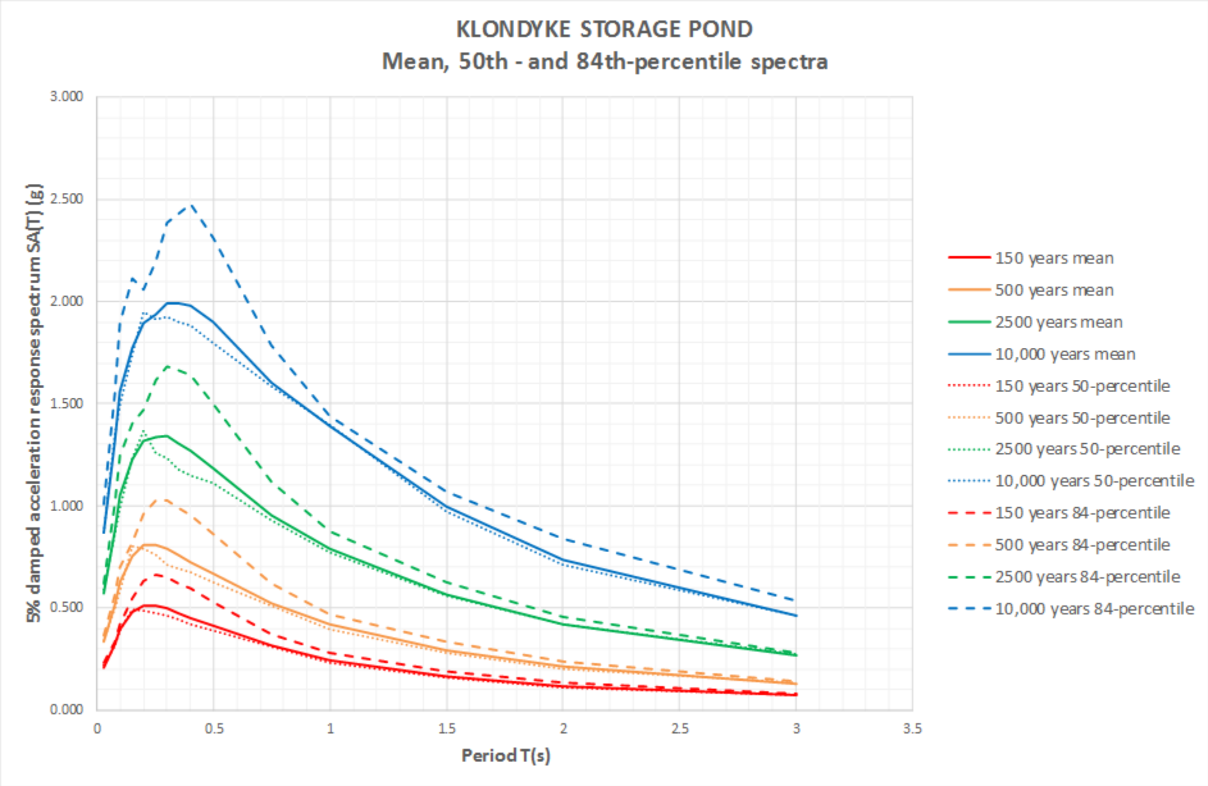


Figure 8: The mean 5% damped larger horizontal component acceleration response spectra SA(T) for periods T up to 3s for 150-, 500-, 2500- and 10,000-year return period motions for the proposed Klondyke Storage Pond. The 50th– and 84th-percentile spectra are also shown. PGA is plotted at 0.03s.

Epistemic uncertainties in fault modelling

50. The hazard results provided in the GNS 2017 report considered the effects of epistemic uncertainties in the magnitudes and recurrence intervals of six fault sources within 35 km of the site of the proposed storage pond.

    50.1. These uncertainties were addressed through two sensitivity runs for the probabilistic calculations in addition to that for the adopted magnitudes and recurrence intervals.

51. Consideration of the uncertainties in the fault parameters listed in Table 2.2 of the GNS 2017 report produced a maximum increase with respect to the preferred spectra of 23% for a spectral period of 1s for the 10,000-year return period.

51.1. The changes from the modification of the fault parameters are weaker at short periods (up to about 0.5s-0.75s) than those going from the mean to the 84th-percentile GMPE spectra. At longer periods, the results are more sensitive to the fault parameters than to the selection of GMPE.

Deterministic scenario spectra

52. The probabilistic hazard spectra presented in the preceding paragraphs are now compared with deterministic scenario spectra to arrive at the recommended Safety Evaluation Earthquake (SEE) motions for the Klondyke Storage Pond.

53. As an alternative to the spectra derived probabilistically, the NZSOLD 2015 Guidelines allow deterministic scenario-based SEE ground motion parameters, to be estimated at the 84th-percentile level for the Controlling Maximum Earthquake (CME) (paragraph 36.2.1 of this evidence), with the proviso that they need not exceed the mean 10,000-year motions derived probabilistically.

53.1. The dual probabilistic and deterministic criteria of the NZSOLD 2015 Guidelines are to ensure that the SEE motions are not taken as unreasonably strong to cater for motions from a fault source that has a very long recurrence interval, of tens of thousands of years or more.

53.2. The NZSOLD 2015 Guidelines (Module 3, Section 4.3.1, p19) cite ICOLD Bulletin 148 and Mejia at al. (2001) as the source for the SEE ground motion parameters. Mejia et al. in turn states that the 10,000-year return period arises in Canadian, United States and NZSOLD (2000) guidelines. It also notes “that a mean AEP of 1/10,000 is accepted for seismic design of critical facilities, such as nuclear power reactors and liquefied natural gas plants, in regions of moderate to low seismicity such as the Eastern United States”.

54. Consideration of magnitudes and fault-to-site distances lead to the identification of a magnitude M_w 7.5 earthquake on the Hutt-Peel 2017 fault as the CME. The hazard estimates are calculated at a specific geographic point, defined by latitude/longitude values to two decimal places. The adopted calculation point is 43.84°S/171.27°E, which lies in the north-western part of the proposed pond footprint. This modelled fault

source is at a shortest distance of about 2½ km from the hazard estimation point. Considering the perimeter of the footprint, the shortest distance from the modelled fault source to any part of the pond footprint is about 1 km.

54.1. The results of the hazard analyses also showed that M_w 7.5 earthquakes on the Hutt-Peel 2017 fault contribute about half the exceedances of the 10,000-year PGA level.

54.2. Figure 9 shows that the 84th-percentile spectrum for this scenario earthquake exceeds that for other fault sources. It thus forms the candidate scenario spectrum for the SEE motions.

54.3. However, Figure 9 also shows that this scenario spectrum exceeds the mean 10,000-year hazard spectrum at the hazard estimation point. Those parts of the pond lying as close as 1 km to the modelled fault source would experience even greater exceedance of the 10,000-year spectrum. Thus this scenario spectrum is eliminated as a candidate for the SEE motions, according to the criteria of the NZSOLD 2015 Guidelines, as stated in paragraph 53.

54.4. Accordingly, the probabilistically-determined mean 10,000-year spectrum is recommended to represent the Safety Evaluation Earthquake (SEE) motions.

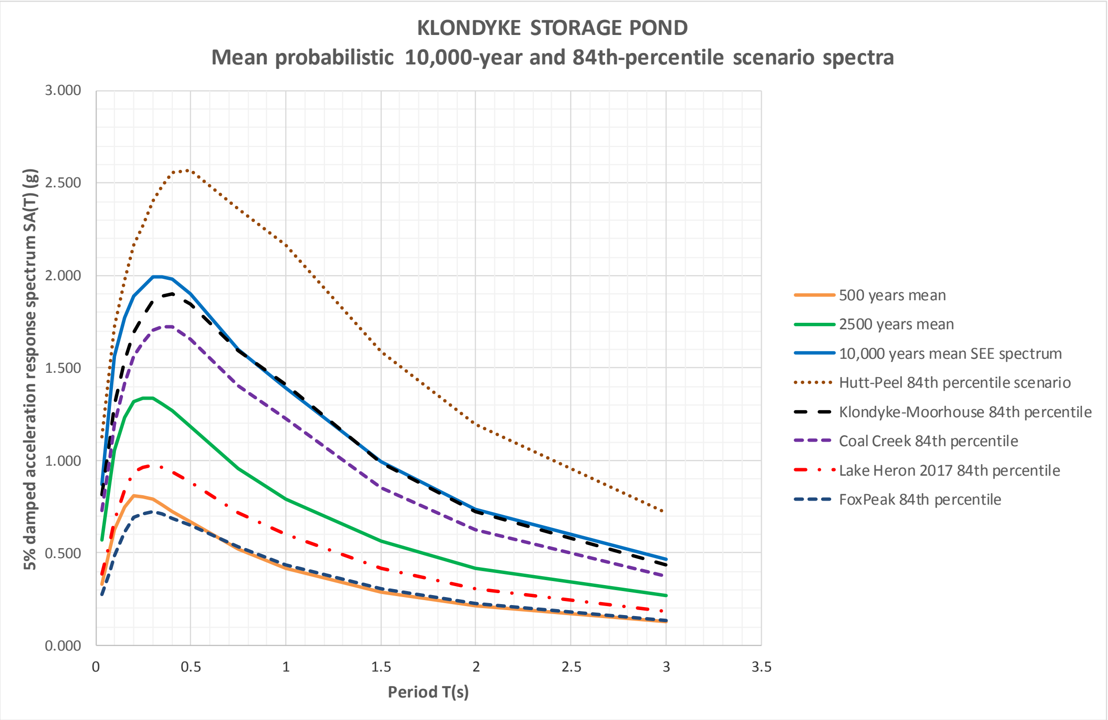


Figure 9: Mean probabilistic spectra and the 84th-percentile deterministic spectra for the Hutt-Peel 2017, Klondyke-Moorhouse, Coal Creek, Lake Heron 2017 and Fox Peak 2017 sources. The 10,000-year spectrum (solid blue curve) is recommended for the SEE motions. PGA is plotted at 0.03s.

Comparison with GNS 2014 Report

55. The recommended SEE spectrum for the larger horizontal component in the GNS 2017 Report generally considerably exceeds the recommended SEE spectrum from the 2014 GNS report (Figure 10), requiring an increase in the design motions. The effect of this increase on the design for the Klondyke Pond is addressed in the evidence of Mr Steven Woods of Stantec New Zealand.

    55.1. The increase in the SEE spectrum results from the combination of (i) using different fault source models; (ii) using multiple GMPES rather than the single one that was allowable in 2014; and (iii) satisfying the NZSOLD 2015 Guidelines by evaluating candidate scenario spectra for the SEE motions at the 84th-percentile level.

    55.2. The requirement to consider 84th-percentile scenario motions rather than the 50th-percentile level that formed the basis for the recommended SEE motions in 2014 raised the scenario candidate spectrum for the SEE motions from below to above the mean 10,000-year spectrum, the maximum level required to be considered in terms of the NZSOLD 2015 Guidelines. Thus the recommended SEE spectrum changed from one that was scenario-based to one that was derived probabilistically.

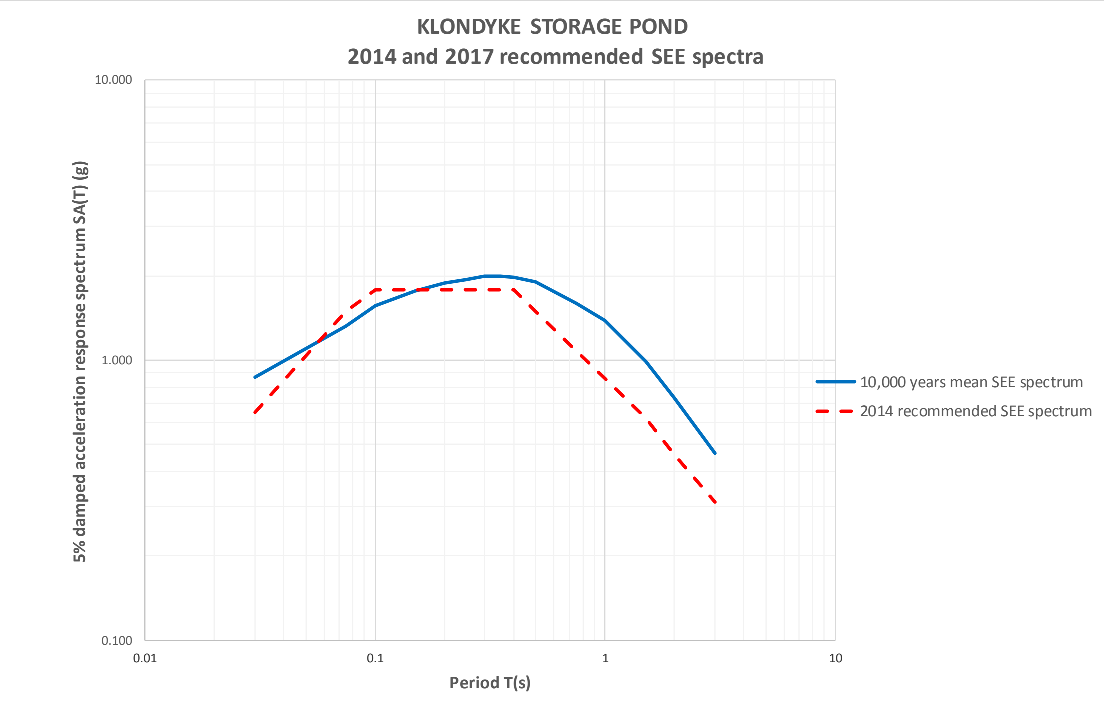


Figure 10: The recommended SEE spectrum from the GNS 2017 report, corresponding to the probabilistic 10,000-year spectrum (solid blue curve), generally exceeds the scenario-based SEE spectrum (red dashes) recommended in the GNS 2014 report.

Recommended vertical spectra

56. The NZSOLD 2015 Guidelines (Module 3 Section 4.3.3 subheading Seismic Analysis Methodologies, p21) require consideration of vertical motions only for concrete dams and for embankment dams with very steep slopes. Nevertheless, I was requested to supply estimates of vertical motions as part of scope for the seismic hazard study, so have included them in my evidence for completeness. The evidence of Mr Steven Woods (paragraph 6.41) states that interaction of horizontal and vertical accelerations will be used in a three-dimensional model to refine estimates of the deformation of the pond embankments for assessment of the synthetic liner and the secondary soil liner.

57. It is not common to consider vertical earthquake motions in engineering design (see paragraph 16 of this evidence). Consequently, there are few GMPEs available for vertical motions. The combination of GMPEs used in the hazard study do not produce vertical response spectra.

58. Instead vertical spectra were constructed from the recommended horizontal spectra using the equations given in NZS1170.5 Amendment 1 (Standards New Zealand, 2016).

58.1. As explained in its commentary clause C3.2, the equations of Amendment 1 are appropriate where the hazard is dominated by near-fault motions, as they are for the proposed Klondyke Storage Pond.

59. The vertical spectra are presented in Table 4 and plotted with the horizontal spectra in Figure 11.

60. Characteristic of deep soil sites at near-source locations, the vertical spectra recommended for the proposed Klondyke Storage Pond have strong PGAs and spectral peaks, but they are short-period in nature and fall below the associated horizontal spectra for periods longer than about 0.2s.

61. Engineering design documents provide rules for the combination of horizontal and vertical motions. Their combination is beyond my brief, and also requires knowledge of structural response parameters to extract the appropriate values from the horizontal and vertical spectra. Accordingly, any comment on this aspect lies outside my role of providing seismic hazard estimates for the project.

Table 4 Vertical spectra SAv(T) produced from the recommended horizontal spectra SA(T) for 150-, 500-, 2500-, and 10,000-year return period motions for the proposed Klondyke Storage Pond.

Vertical Spectra for Klondyke Storage Pond SAv(T) (g)				
T(s)	**150 years**	**500 years**	**2500 years**	**10,000 years**
PGA	0.31	0.50	0.86	1.31
0.03	0.48	0.76	1.29	1.93
0.05	0.59	0.94	1.58	2.34
0.075	0.59	0.94	1.58	2.34
0.1	0.59	0.94	1.58	2.34
0.15	0.59	0.94	1.58	2.34
0.2	0.48	0.76	1.27	1.89
0.25	0.40	0.64	1.08	1.60
0.3	0.35	0.56	0.94	1.39

0.35	0.31	0.50	0.84	1.24
0.4	0.28	0.45	0.76	1.12
0.5	0.24	0.38	0.64	0.95
0.75	0.18	0.28	0.47	0.70
1	0.14	0.23	0.38	0.57
1.5	0.11	0.17	0.28	0.42
2	0.085	0.13	0.23	0.34
3	0.063	0.099	0.17	0.25

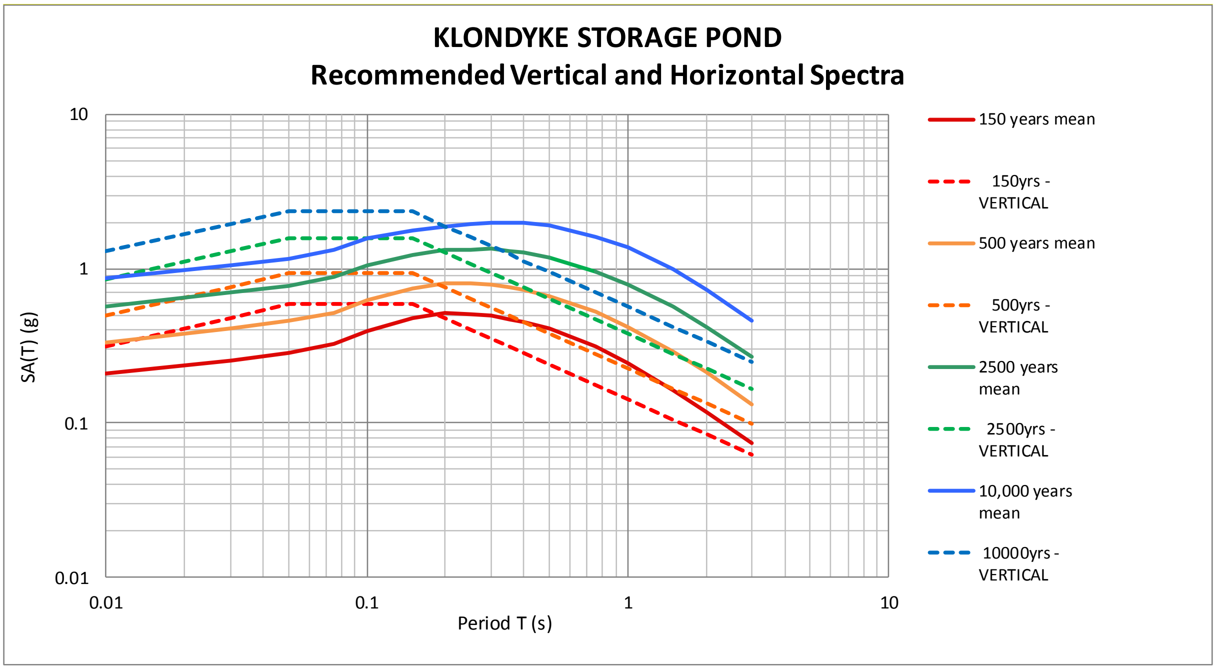


Figure 11: Vertical spectra (dashed) compared with horizontal spectra (solid) for 150-, 500-, 2500-, and 10,000-year return period motions for the proposed Klondyke Storage Pond. PGA is plotted at 0.01s.

Submissions

62. I have identified items in submissions 31195 (Save the Rivers Mid Canterbury), 31220 (Rangitata South Irrigation Limited), 31247 (Rangitata Water Limited), 31252 (Mr John Stack), 31256 (Early Family Trust) and 31262 (Ngai Tahu) that touch on seismic hazard issues.

63. Submissions 31195, 31220, 31247, 31256 and 31262 all mention dam break issues.

63.1. It is outside my expertise to comment on how the engineering design addresses survival of the dam without uncontrolled release of the reservoir in this level of motion. Also, it is outside my expertise to comment on the dam-break analyses carried out to cater for the situation if the dam should be breached. These matters are, however, addressed in the evidence of Mr Woods and Mr Fletcher of Stantec.

63.2. However, I can confirm that the GNS 2017 Report addresses two aspects of the dam-break concerns by recommending Safety Evaluation Earthquake (SEE) motions, and discussing that there has been no discernible fault displacement through the proposed pond site over the last 18,000 years. My evidence has discussed the SEE motions, as summarised in the following subparagraphs, while the evidence of my GNS Science geologist colleague covers the lack of discernible fault displacement.

63.3. The SEE motions recommended in the GNS 2017 Report satisfy the requirements of NZSOLD 2015 Guidelines in that they are the estimated mean 1 in 10,000 AEP ground motions. According to the NZSOLD requirements, the SEE motions for High PIC dams (such as the Klondyke Storage Pond) need not exceed this level (Module 3, Section 4.3.3, p20).

63.4. The derivation of the 1 in 10,00 AEP (10,000-year) motions is discussed in detail in the preceding paragraphs of my evidence.

64. Submissions 31252, 31256 and 31262 mention faults.

64.1. The modelling of faults is discussed in Section 2 of the GNS 2017 Report.

64.2. Most aspects of the fault modelling from that report are covered in the evidence of Mr David Barrell. Mr Barrell's evidence includes discussion of why not all fault traces are explicitly represented by the modelled faults, as raised in submission 31252 by Mr Stack.

64.3. The basis for assigning magnitudes, as raised in Submission 31256 on behalf of Early Family Trust, is discussed in Section 2.1 of GNS Report 2017. Magnitudes for the modelled faults are assigned from equations for magnitude in terms of fault length and width. The expression used in GNS Report 2017 is that given in Stirling et al. (2008), which was originally derived as part of a consultancy study for the Waitaki hydro-electric system (Berryman et al., 2002). The expressions were subsequently used in assigning magnitudes to most faults in GNS Science's National Seismic Hazard Model (Stirling et al., 2012).

Officer's reports

65. I have read the Section 42A Officer's Report by Natalia Ford of the Canterbury Regional Council (CRC), the Section 42A Planning Report prepared on behalf of Ashburton District Council by Nicholas Boyes of Planz Consultants Limited, and the report by Tim Morris of Tonkin & Taylor Limited who was engaged by CRC to review aspects of hazards, design and construction in relation to the proposed storage pond, including the GNS 2017 report.

65.1. The GNS 2017 Report is discussed in paragraphs 197 to 199 of Ms Ford's report and paragraphs 71 and 72 of Mr Boyes report.

65.2. Paragraph 199 of Ms Ford's report repeats the comment on the GNS 2017 report by Mr Morris that "the assessment is appropriate to provide a perspective on seismic hazards relevant to the project for the project resource consent stage", although noting that "a number of matters may require further work as part of the detailed design."

65.3. Paragraphs 71 and 72 of Mr Boyes' report provide a summary of findings of the GNS 2017 report regarding earthquake faults in the vicinity of the storage pond and ground deformation and fault rupture issues.

65.4. I have no disagreement with any of the content of the Officer's Reports regarding matters covered in my evidence.

Conditions

66. Regarding the Conditions recommended in the Officer's Reports, I have identified none in the Ashburton District Council report by Mr Boyes that pertain to seismic hazards. The CRC Recommended Conditions for resource consent CRC170657 include one that

relates to seismic design, namely Condition 5, which states "*The Dam shall be investigated, designed, constructed, commissioned, operated and maintained in accordance with the New Zealand Dam Safety Guidelines (May 2015 including any amendment or update or replacement edition) (hereafter referred to as the Guidelines) published by the New Zealand Society On Large Dams as pertains to a High Potential Impact Category (PIC) dam*." I agree with this condition regarding aspects of the Guidelines dealing with seismic hazard assessment and related design parameters.

67. My evidence relates to the seismic assessment as presented in the GNS 2017 Report. I confirm that I believe that the assessment of seismic design motions in that report satisfy the requirements of the NZSOLD 2015 Guidelines and thus are consistent with that aspect of the recommended Conditions.

Conclusions

68. In my opinion, the horizontal and vertical acceleration response spectra recommended in the GNS 2017 report for the proposed Klondyke Storage Pond satisfy the requirements of the 2015 NZSOLD Guidelines for OBE and SEE motions.

69. The new recommendations replace those of the earlier GNS 2014 Report in recognition of the more comprehensive requirements of the NZSOLD 2015 Guidelines compared to the previous NZSOLD 2000 Guidelines.

70. The modelling of faults in the 2010 NZNSHM within about 50 km of the dam site was also reviewed, and the revisions were incorporated in the hazard estimates performed for the 2017 GNS study.

71. Requirements of the 2015 NZSOLD Guidelines to consider epistemic uncertainties in the GMPEs were addressed by using the weighted combination of five GMPEs for crustal earthquakes: three from the international NGA-West2 project and two incorporating New Zealand data.

72. Epistemic uncertainties in the fault source modelling were addressed through two sensitivity runs for the probabilistic calculations in addition to that for the preferred magnitudes and recurrence intervals.

73. The CME was determined to correspond to rupture of the Hutt-Peel 2017 fault in an M_w 7.5 earthquake possibly as close as a distance of about 2½ km to the location within the proposed Klondyke storage pond site for which the hazard estimates were calculated, and as little as only about 1 km from that part of the storage pond nearest to the fault source.

74. The deterministic spectrum at the 84th-percentile level for this earthquake scenario exceeded the mean 10,000-year hazard spectrum, thus eliminating this spectrum as a candidate for the SEE motions, according to the criteria of the 2015 NZSOLD Guidelines.

75. Consequently, the SEE motions are recommended as the probabilistically-determined mean 10,000-year spectrum, which is the maximum level that needs to be taken for the SEE motions in terms of the NZSOLD Guidelines 2015.

76. The recommended SEE spectrum for the larger horizontal component in the GNS 2017 study generally considerably exceeds the recommended SEE spectrum from the GNS 2014 Report.

77. The NZSOLD Guidelines requires consideration of vertical motions only for concrete dams and for embankment dams with very steep slopes. Nevertheless, the brief for the hazard study included vertical PGAs and spectra, so I have provided them in this evidence for completeness. Like many GMPEs, those considered in the hazard study lacked expressions for vertical motions. Consequently, the recommended vertical PGAs and response spectra were derived using the equations given in NZS1170.5 Amendment 1 (Standards New Zealand, 2016). The commentary to Amendment 1 states that these equations are appropriate for locations like the proposed Klondyke Storage Pond where the hazard is dominated by near-fault motions.

Dr Graeme McVerry
28 March 2018

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APPENDIX A Curriculum Vitae: Elizabeth Abbott

Academic Qualifications 2014 MSc (Geological Science - Seismology), Miami University of Ohio 2012 BA (Earth and Planetary Science), Harvard
Professional positions held 2015 - present Seismic Hazard Specialist, GNS Science 2014 - 2015 Marketing Analyst, Datameer 2014 - 2014 Model Product Management Intern, Risk Management Solutions (RMS) 2013 - 2014 Graduate Research Assistant, Miami University of Ohio

Present research/professional speciality
Performing site-specific seismic hazard analyses for consultancy projects (buildings, dams, roading structures).
Leading the transition to OpenQuake at GNS (since 2016) including:
• Implementing and applying OpenQuake to New Zealand and international seismic hazard analyses at GNS
  o Investigate treatment of input parameters (ie. site condition parameters such as NZS site class, Vs30)
  o Investigate variations in GMPE interpretation of input parameters and the extent of GMPE variation with regards to NZ structural design standards
  o Understand how the OpenQuake engine functions and can be adjusted to fulfil GNS and NZ requirements
  o Identify OpenQuake functions that can be modified or need to be developed to fulfil GNS and NZ needs
  o Development of post-processing tools to assist in the visualisation and interpretation of OpenQuake outputs
• Benchmarking results produced by OpenQuake and GNS' legacy fortran code for seismic hazard analyses
  o Investigate the structure of each program's code
  o Endeavour to understand how different parameters and input values are interpreted by and used in each program
  o Identify potential sources of discrepancies between the results of each program
• Development of an organizational structure and system for use of OpenQuake at GNS
  o Work with Records team on data management of source models, GNS-modified GMPEs, guidelines/help information
  o Design and write guidelines and instructions for use of OpenQuake at GNS, including settting up and running OpenQuake, as well as post-processing OpenQuake output
  o Write documents to supplement existing manuals and help material from OpenQuake to improve GNS understanding of the program, answer questions from new users, and document the knowledge gained through the implementation, application, and benchmarking exercises.

Total years research experience 6 years
Peer reviewed journal articles **Abbott, E.R.**; Brudzinski, M.R. 2015. Shallow seismicity patterns in the northwestern section of the Mexico Subduction Zone. *Journal of South American earth sciences, 63:* 279-292; doi: 10.1016/j.jsames.2015.07.012

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Dam Safety Intelligence: Unlocking the 2015 New Zealand Dam Safety Guidelines 2017 (Wellington, New Zealand). Attendee.
Taiwan-Japan-New Zealand Seismic Hazard Assessment Meeting 2017 (Tainan, Taiwan). Presenter: Seismic Hazard and Risk Products in New Zealand.
New Zealand Society for Earthquake Engineering Annual Meeting 2017 (Wellington, New Zealand). Attendee.
New Zealand Society of Large Dams Symposium & Workshop 2017 (Wellington, New Zealand). Attendee.
New Zealand Society for Earthquake Engineering Annual Meeting 2015 (Rotorua, New Zealand). Attendee.
Taiwan-Japan-New Zealand Seismic Hazard Assessment Meeting 2015 (Wellington, New Zealand). Attendee.
American Geophysical Union Fall Meeting 2011 (San Francisco, United States). Presenter.
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