Appendix C

Assessment of Probability of Dam Failure

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The probabilities of dam failure have been assessed using the event tree framework described by Foster, Fell, Davidson and Wan (2002)[1]. This involves breaking the process for each failure scenario into a sequence of phases that lead to formation of a breach.

C1.1 Dam Failure Scenarios

Table C.1 summarises the dam failure scenarios considered.

The event trees that were used to assess the probabilities of failure are presented for each failure scenario in Attachment C1. These have been developed using the Excel add-on program "PrecisionTree".

The following sections (C1.2 to C1.6) qualitatively discuss the basis for the conditional probabilities assigned to the branches in the event trees for each scenario. The estimated annual probabilities of dam breach for each scenario are summarised below in Section C1.7.

[1] Foster, Fell, Davidson and Wan (2002) *Estimation of the Probability of Failure of Embankment Dams by Internal Erosion and Piping Using Event Tree Methods*. ANCOLD Bulletin No. 121, 75-88.

Appendix C
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Table C.1: Dam Failure Scenarios Considered

Event Category	Loading Event	Failure Mode	Mechanism
Hydrological Events	Extreme Flood (ie Probable Maximum Flood, PMF)	Dam Breach	Flood Overtopping
			Flood Induced Piping
			Flood Induced Instability
			Spillway Failure
		Partial Loss of Storage	Flood Overtopping
	Flood During Construction	Partial Dam Failure	Flood Overtopping
Sunny Day Events	Moderate Earthquake (Operating Basis Earthquake, OBE)	Dam Breach	Earthquake Induced Piping
			Earthquake Induced Slope Instability
			Earthquake Induced Reservoir Landslide
			Foundation Liquefaction (Immediate Failure)
	Large Earthquake (Maximum Design Earthquake, MDE)	Dam Breach	Earthquake Induced Piping
			Earthquake Induced Slope Instability
			Earthquake Induced Reservoir Landslide
			Fault Rupture Causing Overtopping
			Fault Rupture Causing Piping
			Foundation Liquefaction (Immediate Failure)
	Normal Operating Condition	Dam Breach	Piping Through Dam
			Slope Instability
			Foundation Piping
			Reservoir Rim Instability

C1.2 Extreme Flood (PMF) Events

C1.2.1 Flood Overtopping

Overtopping

The dam will be designed to accommodate the PMF event by incorporating sufficient freeboard to store the inflow that exceeds the discharge capacity. This can be achieved because the catchment is small compared to the impoundment volume. Additional freeboard allowance will also be provided to accommodate wave action and embankment settlement.

Breach and Intervention

In the almost inconceivable circumstance that the design PMF is exceeded, the dam design should handle up to 300mm overtopping for short duration as it incorporates a wide crest and is constructed mainly from gravel materials.

There may also be some opportunity for intervention to avoid dam breach in this situation, given that the dam will be fully instrumented and is immediately adjacent to Coalgate.

C1.2.2 Flood Induced Piping

Initiation

A flood induced piping scenario involves initiation of piping due to reservoir levels outside the normal operating range of the storage. This scenario is expected to involve internal erosion within the upper part of the core that is not normally exposed to piezometric pressures. The core will be constructed from either weathered greywacke gravels or Tertiary sediments and both of these materials are expected to be moderately erodible.

Continuation

The dam will incorporate a fully intercepting filter designed to prevent excessive migration of material in the core arresting crack growth.

Progression

A Zone 2B ("crack filler") will be included upstream of the core to "clog" any crack that should develop in the core, preventing a crack from propagating back to the reservoir.

Breach and Intervention

The embankment shoulders will be constructed from sandy greywacke gravels, which will form a strong, well-drained fill, which will not be prone to sustaining excessively high piezometric levels.

The dam foundation comprises Tertiary age sediments overlain by glacial outwash gravels of various ages. The gravels will be left in-situ with seepage controlled by a foundation cut-off.

As a high hazard dam, a suitable monitoring system will be incorporated in the dam design and implemented during construction and operation of the dam. The monitoring system will conform with internationally accepted modern dam safety guidelines and will alert the operator to unexpected behaviour such as embankment deformation, elevated pore pressures or excessive seepage. If flood induced piping occurs (the likelihood of which is very low due to the modern, fully intercepting filter), the monitoring system will provide a means of detecting excessive seepage, to provide an opportunity for intervention prior to dam breach.

C1.2.3 Flood Induced Instability

Flood Surcharge Failure

This scenario involves embankment slope failure as a result of flood reservoir levels outside the normal operating range.

Breach and Intervention

The embankment shoulders will be constructed from sandy greywacke gravels, which will form a strong, well-drained fill and given the proposed embankment slope configuration, will not be prone to slope instability. Should the embankment experience deformation, it has a wide crest and sufficient freeboard, even during the PMF, that loss of freeboard due to slope failure is very unlikely.

In the unlikely event of embankment slope instability, there may be some opportunity for intervention to avoid dam breach in this situation, given that the dam will be fully instrumented and is immediately adjacent to Coalgate.

C1.2.4 Spillway Failure

Control Structure Failure

The control structure will be founded on rock (Tertiary sediments) and will be designed to accommodate the Maximum Design Earthquake. The structure is designed with a factor of safety of 3 making failure possible only if an undetected fault occurs that was not allowed for.

Spillway Slab Failure

Spillway slab failure is very unlikely as the slabs will be constructed on rock and anchored in place.

Dissipator Failure

The dissipater structure will be designed for the PMF flow and will only fail as a result of unforseen cavitation or turbulence.

C1.3 Construction Flood Event

Temporary flood diversion / storage provisions during construction will include a cofferdam (4 to 5m high) and a low level conduit, and will be designed to accommodate a 1 in 1000 year flood event without overtopping. It has been assumed that there will be a six month period during construction while the temporary flood provisions will be relied upon and after six months the embankment will be high enough that the reservoir volume and conduit capacity will be sufficient to accommodate the inflow from the PMF event.

Overtopping

The likelihood of overtopping of the coffer dam during construction in very small as it would require greater that a 1/1000 year AEP event.

Breach and Intervention

Overtopping of the coffer dam may not result in failure, particularly as construction equipment will be on site at the time and forecasting will have given some warning of such a large event.

C1.4 Moderate Earthquake (OBE) Events (Sunny Day)

The Operating Basis Earthquake (OBE) is a moderate sized earthquake with an annual exceedence probability of 1/150. In accordance with dam safety guidelines, the dam should accommodate this earthquake without significant loss of function.

A Probabilistic Seismic Hazard Assessment for New Zealand (Stirling et al. 2000)[2] indicates that the dam site has a 1/150 AEP peak ground acceleration of 0.28 g.

C1.4.1 Earthquake Induced Piping

Initiation

This scenario involves cracking of the core as a result of earthquake shaking. The dam site has subdued topography without abrupt "steps" where transverse cracking would be expected. The abutments and the end of the gravel ridge are areas where transverse cracking could conceivably occur.

Continuation

The fully intercepting filter will be designed to prevent excessive migration of material in the core arresting crack growth.

Progression

A Zone 2B ("crack filler") will be included upstream of the core to "clog" any crack that should develop in the core, preventing a crack from propagating back to the reservoir.

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[2] Stirling, M., McVerry, G. H., Berryman, K.R., McGinty, P. Villamoor, P., Van Dissen, R. J., Dowrick, D., Cousins, J. and Sutherland, R. (2000) *Probabilistic seismic hazard assessment of New Zealand: new active fault data, seismicity data, attenuation relationships and methods.* Institute of Geological and Nuclear Sciences Limited. Client Report 2000/53.

Intervention and Breach

Increased awareness and "emergency" monitoring will occur following the earthquake making it likely that increased or dirty seepage will be detected.

C1.4.2 Earthquake Induced Slope Instability

Earthquake Induced Failure

In this scenario OBE shaking causes slope failure in the embankment, which leads to a breach. Due to the inherently strong embankment configuration, large freeboard allowance and large crest width, the likelihood of a large enough deformation to occur during the OBE to cause loss of freeboard, is very small. A major slope failure would require a foundation shear plane which is considered very unlikely in the dam foundation materials.

The likelihood of a small amount of deformation occurring is much greater. Should such deformation occur as a result of the OBE reservoir drawdown would be initiated, with an associated risk of failure of the upstream shoulder. The strong and relatively free-draining gravel shoulder is unlikely to fail during such an event.

Breach and Intervention

Heightened awareness and emergency monitoring following the earthquake will result in a high probability of intervention preventing breach should this mechanism occur.

C1.4.3 Foundation Liquefaction

Liquefaction

Beneath the proposed dam footprint, foundation materials include Tertiary sediments (very dense or slightly cemented silty fine sand), sandy gravels and dense silts, none of which are liquefiable under the OBE. Liquefiable valley fill sediments have been avoided by moving the dam as far downstream as possible. Liquefiable materials found within the footprint will need removal or treatment and to get liquefaction-induced dam failure would require the presence of extensive liquefiable materials, undetected during the investigation and design.

Post Earthquake Instability

Should liquefaction occur beneath the dam footprint the strength of that part of the foundation would reduce greatly and this may result in deformation of the embankment. However the deformation is unlikely to result in a breach due to total loss of freeboard, owing to the wide crest and large design freeboard.

C1.4.4 Earthquake Induced Reservoir Landslide

Reservoir Landslide

Some natural shallow slope failures have been observed within the proposed reservoir, but the likelihood of a large OBE-earthquake induced landslide, (sufficiently large to cause a dam overtopping wave) is considered to be very low.

Should an OBE earthquake induced landslide generate a wave that reaches the dam the large freeboard and the wide crest should prevent breaching of the dam as a result of overtopping.

Seiche

Seiche waves are generated by earthquake shaking or direct fault rupture of the reservoir floor. In the case of the OBE, reservoir floor rupture is very unlikely and the intensity of shaking is not considered capable of overtopping the dam, given its large freeboard.

C1.5 Large Earthquake (MDE) Events (Sunny Day)

The Maximum Design Earthquake is the largest earthquake that could affect the dam based on the known geology. The adopted MDE is a rupture of the Hororata Fault, which is judged capable of generating a M7 earthquake and passes within 2 to 4 km of the dam. The expected peak ground acceleration at the dam site resulting from this earthquake is 0.65 g and the duration of severe shaking is expected to be 10 to 20 seconds.

Dam safety guidelines require that the dam must not allow uncontrolled release of the reservoir during the MDE, though damage can be sustained.

C1.5.1 Earthquake Induced Piping

Initiation

As in the case of the OBE, transverse cracking could conceivably occur at the abutments and the end of the gravel ridge are areas where transverse cracking. The likelihood of this occurring is higher in the case of the MDE because of the greater peak ground acceleration.

Continuation

The fully intercepting filter will be designed to prevent excessive migration of material in the core arresting crack growth.

Progression

A Zone 2B ("crack filler") will be included upstream of the core to "clog" any crack that should develop in the core, preventing a crack from propagating back to the reservoir.

Intervention and Breach

Increased awareness and "emergency" monitoring will occur following the earthquake making it likely that increased or dirty seepage will be detected.

C1.5.2 Earthquake Induced Slope Instability

Earthquake Induced Failure

MDE shaking is more likely to cause a slope failure in the embankment, leading to a breach than in the case of the OBE. However the likelihood of a large enough deformation to occur during the MDE to cause loss of freeboard, is still small.

The likelihood of a small amount of deformation occurring is much greater. Should such deformation occur as a result of the MDE reservoir drawdown would be initiated, with an associated risk of failure of the upstream shoulder. The strong and relatively free-draining gravel shoulder is unlikely to fail during such an event.

Breach and Intervention

Heightened awareness and emergency monitoring following the earthquake will result in a high probability of intervention preventing breach should this mechanism occur.

C1.5.3 Foundation Liquefaction

Liquefaction

Beneath the proposed dam footprint, foundation materials include Tertiary sediments (very dense or slightly cemented silty fine sand), sandy gravels and dense silts, none of which are liquefiable under the MDE. Liquefiable materials found within the footprint will need removal or treatment and to get liquefaction-induced dam failure would require the presence of extensive liquefiable materials, undetected during the investigation and design.

Post Earthquake Instability

Should liquefaction occur beneath the dam footprint the strength of that part of the foundation would reduce greatly and this may result in deformation of the embankment. However the deformation is unlikely to result in a breach due to total loss of freeboard, owing to the wide crest and large design freeboard.

C1.5.4 Earthquake Induced Reservoir Landslide

Reservoir Landslide

Should an MDE earthquake induced landslide generate a wave that reaches the dam the large freeboard and the wide crest should prevent breaching of the dam as a result of overtopping.

Seiche

In the case of the MDE, reservoir floor rupture is very unlikely and the intensity of shaking is not considered capable of overtopping the dam, given its large freeboard.

C1.5.5 Fault Rupture Within Dam or Reservoir Footprint - Causing Overtopping

During initial site investigations no evidence of active faulting has been found within the dam footprint. However, there is still some chance of encountering an active fault during detailed investigation and design. There is also a smaller chance of there being an active fault within the dam footprint that remains undetected.

Design features to mitigate the risk of breaching by overtopping the embankment as a result of movement on a foundation fault include the large freeboard and wide crest.

C1.5.6 Fault Rupture Within Dam or Reservoir Footprint - Causing Piping

Design features to mitigate the risk of breaching the embankment as a result of piping following movement on a foundation fault include the provision for a fully intercepting filter, a robust core and an upstream “crack-filler” zone.

Should a foundation fault be detected during design, a widened filter adjacent to the fault will be adopted to prevent dislocation of the filter during fault movement.

C1.5.7 Fault Rupture Within Dam or Reservoir Footprint - Causing Seiche

The western gully fault was shown to be an active fault during investigations for the regional landfill (Mark Yetton pers. Comm.). During movement of the Western Gully Fault, some seiche development would be expected. The magnitude of the seiche could be estimated by estimating the fault throw and modelling the effect. Given the large freeboard of the dam, overtopping as a result of this mechanism is considered to be very unlikely.

C1.6 Normal Operating Condition Events (Sunny Day)

Risk of dam failure as a result of piping or slope failure during normal operating conditions has been considered and is discussed below.

C1.6.1 Piping through the Dam

Initiation

A normal operating condition piping scenario involves initiation of piping under the normal operating range of the storage. This scenario is expected to involve internal erosion within the core due to normal piezometric pressures. The core will be constructed from either weathered greywacke gravels or Tertiary sediments and both of these materials are expected to be moderately erodible. Cracking of the core due to differential settlement of foundation soils or embankment settlement at steps in the foundation could also occur.

Continuation

The dam will incorporate a fully intercepting filter designed to prevent excessive migration of material in the core arresting crack growth.

Progression

A Zone 2B ("crack filler") will be included upstream of the core to "clog" any crack that should develop in the core, preventing a crack from propagating back to the reservoir.

Breach and Intervention

As a high hazard dam, a suitable monitoring system will be incorporated in the dam design and implemented during construction and operation of the dam. The monitoring system will conform with internationally accepted modern dam safety guidelines and will alert the operator to unexpected behaviour such as embankment deformation, elevated pore pressures or excessive seepage. This applies in particular early in the life of the structure where settlement and seepage flows need to be closely monitored to detect any potential failure mechanism. If piping occurs (the likelihood of which is very low due to the modern, fully intercepting filter), the monitoring system will provide a means of detecting excessive settlement or seepage, to provide an opportunity for intervention prior to dam breach.

C1.6.2 Slope Instability

Slope Failure

In this scenario slope failure in the embankment occurs during normal operating conditions, which leads to a breach. Due to the inherently strong embankment configuration, large freeboard allowance and large crest width, the likelihood of a large enough deformation to cause loss of freeboard, is considered very small. A major slope failure would require a foundation shear plane which is considered very unlikely in the dam foundation materials.

The strong and relatively free-draining gravel shoulders are unlikely to fail during first filling or normal embankment operation.

Breach and Intervention

Heightened awareness and monitoring at first filling when a failure is most likely will result in a high probability of intervention preventing breach should this mechanism occur. Any deformation of the embankment shoulders should be easily detectable by standard monitoring methods such as walkovers and levelling or surveying. The presence of a contractor on site during the first filling should also make effective intervention a high likelihood.

C1.6.3 Foundation Piping

Initiation

Features likely to initiate piping in the dam foundation include open work gravels, faults or fractures in the Tertiary sandstone. In addition the foundation gravels may be internally unstable.

Continuation

Design mechanisms to mitigate the risk include a soil-cement-bentonite (SCB) cutoff wall through gravels, grouting through sandstone as required (in areas of high permeability) and a blanket drain filter downstream of the core. These measures are considered to reduce the likelihood of foundation piping to be very low.

Progression

Should the SCB cut-off wall fail, it will still limit the flow beneath the dam as it is non-erodible. Should increased foundation seepage occur this may not affect the embankment stability.

Breach and Intervention

As this is a high hazard dam, it will need to be appropriately instrumented and seepage will be monitored. This type of scenario usually develops slowly. Springs and sand boils could occur giving lots of warning. There are limited intervention opportunities in this situation and slowly lowering the storage is probably the most effective hazard mitigation measure.

C1.6.4 Reservoir Rim Instability

Reservoir Landslide

Some natural shallow slope failures have been observed within the proposed reservoir, but the likelihood of a large landslide, (sufficiently large to cause a dam overtopping wave) is considered to be very low.

Should a landslide generate a wave that reaches the dam the large freeboard and the wide crest should prevent breaching of the dam as a result of overtopping.

C1.7 Summarised Probability Estimates of Dam Failure

Results from event tree analyses to assess the probability of dam failure (refer to Attachment C1) are summarised in Table C.2.

Table C.2: Estimated Annual Probabilities of Dam Breach or Partial Storage Loss

Event Category	Loading Event	Failure Mode	Mechanism	Estimated Annual Probability
Hydrological Events	Extreme Flood (ie Probable Maximum Flood, PMF)	Dam Breach	Flood Overtopping	2.0×10^{-8}, ie 1 in 50,000,000
			Flood Induced Piping	
			Flood Induced Instability	
			Spillway Failure	
		Partial Loss of Storage	Flood Overtopping	1.0×10^{-7}, ie 1 in 10,000,000
	Flood During Construction	Partial Dam Failure	Flood Overtopping	2.5×10^{-5}, ie 1 in 40,000
Sunny Day Events	Moderate Earthquake (Operating Basis Earthquake, OBE)	Dam Breach	Earthquake Induced Piping	4.7×10^{-9}, ie 1 in 210,000,000
			Earthquake Induced Slope Instability	
			Earthquake Induced Reservoir Landslide	
			Foundation Liquefaction (Immediate Failure)	
	Large Earthquake (Maximum Design Earthquake, MDE)	Dam Breach	Earthquake Induced Piping	1.3×10^{-9}, ie 1 in 750,000,000
			Earthquake Induced Slope Instability	
			Earthquake Induced Reservoir Landslide	
			Fault Rupture Causing Overtopping	
			Fault Rupture Causing Piping	
			Foundation Liquefaction (Immediate Failure)	
	Normal Operating Condition	Dam Breach	Piping Through Dam	9.9×10^{-8}, ie 1 in 10,000,000
			Slope Instability	
			Foundation Piping	
			Reservoir Rim Instability	

Appendix C - Attachment C1

Event Trees

PROPOSED WAIANIWANIWA WATER STORAGE DAM
RISK ASSESSMENT

LARGE EARTHQUAKE EVENT (MDE)
Sunny Day Failure

Earthquake event =	Magnitude 7, PGA = 0.7g	Hororata Fault, 2km from dam
Probability of earthquake event =	0.0001	1 in 10,000 years