NSW Department of Commerce | NSW Water Solutions

Hunter Water Corporation

TILLEGRA DAM DESIGN - CONSULTANCY 361802

Storage Rim Stability and Seepage Potential
Engineering Geotechnical Report

VOLUME V

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FINAL REPORT

Tillegra Dam - Storage Rim Landslide Risk Assessment

Prepared for

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1.1 Introduction

This report describes the methodology, results and conclusions of a landslide risk assessment that has been carried out by URS Australia Pty Ltd (URS) as part of the storage rim geotechnical investigations for the proposed new Tillegra Dam, on the Williams River. The report has been prepared for the NSW Department of Commerce on behalf of Hunter Water Corporation.

The risk assessment was carried out in accordance with the ANCOLD Guidelines on Risk Assessment (ANCOLD 2003) and using the principles of the Australian Geomechanics Society Risk Management Guidelines (AGS 2007). Estimates of the probabilities of failure were developed using event tree methods and estimated in a risk workshop attended by a panel of experts and Hunter Water.

1.2 Background

Hunter Water plans to augment its current water supply with the construction of an on river storage, known as Tillegra Dam, on the Williams River, approximately 3½kms upstream of the confluence with the Chichester River. A concrete faced rockfill design has been adopted with a maximum height of 80m.

Geotechnical investigations of the Tillegra Dam storage area have been carried out by NSW Department of Commerce (Commerce 2009). The area of investigation extends along the Chichester Range up to 3.5 km north of the dam site. North of this area, the mountain range broadens out providing very lengthy flow paths and reduced hydraulic gradients that can be expected to limit seepage to negligible proportions. Beyond the study area the storage pools on the valley floor and surcharge loading on the storage rim is not an issue.

To the south and west of the dam site, a broad, complex ridge system occurs. The area of investigation extends approximately 2kms west in the Native Dog Creek section of the storage to include two (2) saddles (designated Saddles A and B) which represent the lowest points in the storage.

As part of the storage rim investigations, Commerce (2009) has divided the project area into nine (9) geological domains. A domain in this context represents an area with uniform lithology and structure with boundaries which may be defined by a significant change in structure or lithology, often by a fault.

Figures showing the location and extent of the geological domains are provided in Volume I of Commerce (2009). The relevant geotechnical investigation data is presented at Volumes II and III of Commerce (2009).

1.3 Purpose of the Risk Assessment

The purpose of this risk assessment was to assess the dam safety risks associated with potential landslides around the reservoir rim of the proposed Tillegra Dam.

The key considerations for the risk assessment were as follows;

- Potential loss of the storage caused by a large scale failure of the eastern ridge system resulting from reservoir loading and/or earthquake shaking;
- Identification of pre-existing landslides which could affect the integrity of the reservoir and/ or dam safety;
- Potential for re-mobilisation of pre-existing landslides and the impact on storage operation if this were to occur; and
- Consideration of viable mechanisms of large first time slides taking account of bedding, faulting and jointing in each domain.

Section 1 Introduction

This risk assessment study has been carried out in conjunction with geotechnical investigations and assessments by the Department of Commerce and Pells Sullivan and Meynink (PSM), which are reported in the following two documents:

"Tillegra Dam Design - Storage Rim Stability and Seepage Potential Engineering Geotechnical Report (Volumes I, II and III)", by the NSW Department of Commerce, Report No. 08-GN31A-R*2,* January 2009 (Commerce 2009); and

"Tillegra Dam - Storage Rim Landslide Risk Assessment", by Pells Sullivan Meynink, Report PSM1271.R1, January 2009 (PSM 2009).

2.1 Risk Analysis

Risk is defined as the probability of a loss occurring in a given time period (annually). The equation for risk is;

Risk = [Probability of the loading] × [Probability of adverse response given the loading] × [Adverse consequence given the failure].

The first two components of this equation, when multiplied, produce the annual probability of failure.

2.2 Risk Workshop

The risk analysis was conducted by holding a risk workshop which was attended by a panel including risk facilitator, representatives of Department of Commerce who have been performing the investigations and assessments related to the stability and watertightness of the storage rim, and experts in landslide and dam safety. The workshop attendees are given in Table 2-1.

Table 2-1 Risk Workshop Participants

Name	Organisation	Role
Bob Broadfoot	Hunter Water Corporation	HWC Project Engineer
Dene Jamieson	Department of Commerce	Commerce Project Design Manager
John Young	Department of Commerce	Project Engineering Geologist
Brian Cooper	Department of Commerce	Dam Safety Expert
Tim Sullivan	PSM	Landslide Expert
Don Macfarlane	URS	Project Reviewer, Engineering Geology
Mark Foster	URS	Risk Facilitator
Tom Wanner	URS	URS Project Manager, Risk Analyst

The risk workshop involved the following steps:

- Identification of potential modes of failure associated with storage rim instability;
- Identification of loading events which could impact on storage rim stability;
- Estimating probabilities of failure using event tree methods; and
- Comparison of the risks against tolerable risk criteria.

2.3 Identification of Failure Modes

At the start of the risk workshop, the participants identified the potential mechanisms by which instability of the reservoir rim could lead to an uncontrolled release of the Tillegra Dam storage. This was done systematically for each of the geotechnical domains identified by the geotechnical investigations. Each potential failure mode was listed and discussed in the risk workshop.

The failure modes that were considered to have negligible contribution to risk were excluded from the event tree analysis. The criteria by which failure modes were excluded were as follows:

- Areas where there were no viable mechanisms for instability or where the depth of stored water is too small for a viable mechanism for the storage to be released or for a landslide induced wave to be generated.
- Where the event was considered inconceivable (ie. the likelihood of the event occurring was considered to be negligible).
- Where the consequence of the event was assessed to not impact on dam safety.

2.4 Loading Events

The workshop participants identified a number of different loading events which could impact on the stability of the reservoir rim. These included:

- Normal operation of the reservoir.
- Large rainfall event.
- Extreme flood event.
- Extreme earthquake event.

2.4.1 Normal operation of the reservoir

The normal operation will involve cycles of filling and drawing down of the reservoir. The annual probability of this loading event is 1.0, as this will happen each year.

2.4.2 Large rainfall event

Large rainfall events have the potential to re-initiate movements of pre-existing landslides or may initiate first time slides. The workshop participants adopted the 1 in 100 annual exceedance probability (AEP) rainfall event as the initiating event for the event trees for a rainfall induced landslide.

2.4.3 Extreme flood event

An extreme flood event condition represents a very rare rainfall event that falls within the dam catchment area. This will cause a significant rise in the reservoir level and hence inundate a greater area around the storage rim. The Probable Maximum Flood (PMF) event was used for the initiating event for this loading condition. The dam spillway will be designed to safely pass the Probable Maximum Flood event with a freeboard of 1.3 metres. The Probable Maximum Flood has an estimated AEP in the order of 1 in 10,000,000 (Commerce Nov 2008).

2.4.4 Extreme earthquake event

An extreme earthquake event condition represents a very rare earthquake occurring in the vicinity of the dam site. This event would cause substantial ground shaking and hence may initiate movements of existing landslides or may initiate first time slides. The Maximum Design Earthquake (MDE) event was used for the initiating event for this loading condition. The dam will be designed to survive the MDE without causing an uncontrolled loss of storage. The MDE has an assumed AEP of 1 in 10,000. For this site, the MDE has a peak ground acceleration of 0.24 g for earthquakes above magnitude 5.0 (ES&S 2008).

For Domain 5, the Maximum Credible Earthquake (MCE) was also modelled, and this event has an AEP of 1 in 100,000 and a peak ground acceleration of 0.5g.

2.5 Estimation of Failure Probabilities

The annual probabilities of landsliding leading to the release of the storage were assessed using event tree methods. Event trees are used to represent sequences or progressions of events that could result in adverse consequences when a dam or associated structure responds to various loading conditions. By providing a graphical representation of the logic structure for the progression of each failure mode, an event tree becomes the template for subsequent assessment of event probabilities and calculation of probability of failure. The total probability is calculated by multiplying each of the event probabilities that lead to failure.

Estimates of the event probabilities were based on the consensus of the expert panel in the risk workshop and using the mapping scheme in Table 2-2 (ANCOLD 2003, after Barneich et al 1996). This scheme is widely used and an acceptable method for relating the probability of failure to objective information on the occurrence elsewhere of that type of failure. The scheme has been extensively validated by dam engineers and probabilistic analysis specialists (ANCOLD 2003) and is used widely in Australia for dam safety risk assessments.

Table 2-2 Mapping scheme linking description of likelihood to quantitative probability (ANCOLD 2003, after Barneich et al, 1996)

Description of Condition or Event	Order of Magnitude of Probability Assigned
Occurrence is virtually certain	1
Occurrence of the condition or event are observed in the available database	10^{-1}
The occurrence of the condition or event is not observed, or is observed in one isolated instance, in the available database; several potential failure scenarios can be identified.	10^{-2}
The occurrence of the condition or event is not observed in the available database. It is difficult to think about any plausible failure scenario; however, a single scenario could be identified after considerable effort.	10^{-3}
The condition or event has not been observed, and no plausible scenario could be identified, even after considerable effort.	10^{-4}

Section 3 Risk Assessment Results

3.1 Risk Assessment Context

This risk assessment was carried out to evaluate the risks associated with potential instability (i.e. landsliding) of the storage rim to lead to an uncontrolled release of the Tillegra Dam storage.

3.2 Identification and Screening of Failure Modes

Two potential scenarios were identified for instability of the storage rim to lead to an uncontrolled release of the storage. These were;

- A large scale slide of the outer side of the storage rim where it is formed by a mountain ridge leading to an uncontrolled release of the storage through the ridge, or
- A large scale, extremely rapid landslide on the inner side of the storage rim which generates waves in the stored water which overtop the dam structure and cause it to fail.

Potential mechanisms of slope instability of the reservoir rim are the mobilisation of pre-existing landslides and first time slides.

The following sections describe the assessment of potential failure modes for each of the geotechnical domains based on the discussions in the workshop, and records the reasons for excluding those failure modes that were assessed to be not viable. The location of the geotechnical domains are shown in Figures 2A and 2B of the main geotechnical investigation report (Commerce 2009). A description of the geotechnical domains is also given in the main report (Commerce 2009).

In the context if this risk assessment, the following terminology was used to describe the scale or size of existing or potential slide masses;

- Small scale slide – a feature having a volume less than about 100,000 cubic metres.
- Medium scale slide – a feature having a volume between about 100,000 to 1,000,000 cubic metres.
- Large scale slide – a feature having a volume greater than about 1,000,000 cubic metres.

3.2.1 Geotechnical Domain 0

Domain “0” refers to the remainder of the Chichester range north (upstream) of Domain 1.

The key characteristics of this Domain are summarised as follows;

- Bedding dips at a low angle (<10 degrees) and dips to the east.
- The ridge has a very long seepage path and reduced hydraulic gradients that can be expected to limit seepage to negligible proportions.
- There will only be a low storage level at this location, and site evidence indicates the groundwater is typically high along the Chichester Range. Therefore it can reasonably be inferred that the natural groundwater level will be higher than the storage level.
- The storage pools on the valley floor and surcharge loading on the storage rim is not an issue
- Slope stability analysis for large scale outer ridge stability through Domain 1 indicates an acceptable factor of safety and the stability of the slope is not significantly affected by storage filling.

Table 3-1 presents the results of the failure mode screening for Geotechnical Domain 0.

Table 3-1 Failure Mode Screening for Geotechnical Domain 0

Failure Mode	Contributing Factors	Include or Exclude
Small scale slides - pre-existing and first time slide features	• Small scale surficial slides are likely to be present on the inner and outer rim slopes • The runout from small scale slides may not reach the reservoir and the slide mass is too small to generate a wave	**EXCLUDE**: • Small scale surficial slides do not pose a risk to dam safety
Medium scale slides - pre-existing and first time slide features	• No evidence of pre-existing medium scale slides from aerial photos or field investigation. • Absence of such features is supported by the geotechnical conditions of this domain (i.e., low angle bedding and inferred high shear strength rock mass).	**EXCLUDE**: • Pre-existing or first time medium scale slides assessed to be not feasible in this domain.
Large scale slides - pre-existing and first time slide features	• No evidence of pre-existing large scale slides from aerial photos or field investigations. • Absence of such features is supported by the geotechnical conditions of this domain (i.e., low angle bedding and inferred high shear strength rock mass.) • The geotechnical environment is not conducive to large scale instability. • 2D stability analysis for Domain 1 indicates acceptable Factor of Safety despite conservative assumptions (e.g., long continuous weak slip plane, and no 3D side shear strength included).	**EXCLUDE**: • Pre-existing or first time large scale slides assessed to be not feasible in this domain.

3.2.2 Geotechnical Domain 1

The key characteristics of this domain are summarised as follows;

- Bedding dips at a low angle (<10 degrees) and dips to the east.
- The ridge has a very long seepage path (although less than Domain 0).
- There will only be a low storage level at this location, and site evidence indicates the groundwater is typically high along the Chichester Range. Therefore it can reasonably be inferred that the natural groundwater will be higher than the storage level.

- 2D slope stability analysis for large scale outer ridge stability (with conservative assumptions) indicates an acceptable factor of safety and the stability of the slope is not significantly affected by storage filling.
- There is a thrust fault located along the western toe of the domain which daylights beyond the toe of the slope.

Table 3-2 presents the results of the failure mode screening for Geotechnical Domain 1.

Table 3-2 Failure Mode Screening for Geotechnical Domain 1

Failure Mode	Contributing Factors	Include or Exclude
Small scale slides - pre-existing and first time slide features	• Small scale slides do exist on the inner rim slope (slide 1A – 4,000 m^3) and are likely to exist on the outer rim slopes. • The runout from small scale slides may not reach the reservoir and the slide mass is too small to generate a wave	**EXCLUDE**: • Small scale slides do not pose a risk to dam safety
Medium scale slides - pre-existing and first time slide features	• No evidence of pre-existing medium scale slides from aerial photos or field mapping. • Absence of such features is supported by the geotechnical conditions of this domain (i.e., low angle bedding and inferred high shear strength rock mass).	**EXCLUDE**: • Pre-existing or first time medium scale slides assessed to be not feasible in this domain.
Large scale slides - pre-existing and first time slide features	• No evidence of pre-existing large scale slides from aerial photos or field mapping. • Absence of such features is supported by the geotechnical conditions of this domain (i.e., low angle bedding and inferred high shear strength rock mass.) • The geotechnical environment is not conducive to large scale instability. (Refer to PSM 2009) • 2D stability analysis indicates an acceptable factor of safety (> 2) despite conservative assumptions (e.g., long continuous weak slip plane, and no 3D side shear strength included).	**INCLUDE**: • Pre-existing or first time large scale slides assessed to be not feasible in this domain. • However, for the purposes of the risk assessment, it was included to allow quantification of the risk associated with outer rim sliding.

3.2.3 Geotechnical Domain 2

The key characteristics of this domain are summarised as follows;

- Bedding dips at a low to intermediate angle (5-14 degrees) and dips to the west. Strike direction changes to parallel to the ridge in the South East of the Domain.
- The ridge has a very long seepage path (although less than Domain 0).
- There will only be a low storage level at this location, and site evidence indicates the groundwater is typically high along the Chichester Range. Therefore it can reasonably be inferred that the natural groundwater will be higher than the storage level.
- There is a thrust fault located along the western toe of the domain but it does not provide a conceivable mechanism for medium / large scale sliding as the bedding is dipping to the west at 14 degrees and is not daylighting.

Table 3-3 presents the results of the failure mode screening for Geotechnical Domain 2.

Table 3-3 Failure Mode Screening for Geotechnical Domain 2

Failure Mode	Contributing Factors	Include or Exclude
Small scale slides - pre-existing and first time slide features	• Small scale slides do exist on the eastern side of the range (outer rim slope). There are no pre-existing small-scale slides on the inner rime slope • The runout from small scale slides may not reach the reservoir and the slide mass is too small to generate a wave	**EXCLUDE**: • Small scale slides do not pose a risk to dam safety
Medium scale slides - pre-existing and first time slide features	• There is a pre-existing medium scale slide (slide feature 2A – 370,000 m^3) within domain 2. • The presence of the pre-existing slide 2A is consistent with the geological and geomorphological setting (dip of the bedding and creek undercutting the toe of the slope).	**INCLUDE**: • Pre-existing medium scale slide (slide 2A feature including upslope extension) is known to exist in this domain.
Large scale slides - pre-existing and first time slide features	• No evidence of pre-existing large scale slides from aerial photos or field mapping. • Large scale outer rim slide is not feasible due to the bedding dipping to the west. • Large scale inner rim slide is not feasible – drilling indicates good quality rock at shallow depth, low permeability rock mass, no evidence of disturbance which could be indicative of deeper seated sliding • No kinematically feasible mechanism is present.	**EXCLUDE**: • Pre-existing or first time large scale slides assessed to be not feasible in this domain.

3.2.4 Geotechnical Domains 4, 5 and 7

These domains have similar characteristics in terms of storage rim stability and the key characteristics are summarised as follows;

- Bedding dips at a moderate angle to the south-west, and dips much steeper than the ground surface.
- The ridge has a very long seepage path.
- At the southern end of Domain 5, the groundwater levels are inferred to be below the proposed storage level at the dam site.
- The folded beds in Domain 4 and the dip direction of the bedding is such that both medium and large scale sliding is not feasible.
- There are no low angle joint features present.
- The Tillegra Fault is confirmed as remaining on the east side of the Chichester Range.
- The Tillegra Fault dips away from the dam site and projects above the ridge, and hence it does not represent a viable failure mechanism for rim instability.

Table 3-4 presents the results of the failure mode screening for Geotechnical Domains 4, 5 and 7.

Table 3-4 Failure Mode Screening for Geotechnical Domains 4, 5 and 7

Failure Mode	Contributing Factors	Include or Exclude
Small scale slides - pre-existing and first time slide features	• Small scale slides do exist on the eastern side of the range (outer rim slope), but not on the inner rim slope. • The runout from small scale slides may not reach the reservoir and the slide mass is too small to generate a wave	**EXCLUDE**: • Small scale slides do not pose a risk to dam safety
Medium scale slides - pre-existing and first time slide features	• There is no evidence for a pre-existing medium scale slide in this domain. • A viable but unlikely failure mechanism exists for a first time slide in a small area within Domain 5 (slide 5A - 290,000 m^3) where bedding is parallel to the slope and the joint set normal to the slope could provide a breakout mechanism.	**INCLUDE**: • Geotechnical conditions indicate a possible but unlikely mechanism for a first time medium scale slide on the inner slope of Domain 5. • The risk of dam failure via this mechanism is very low. However, the loading case has been included to confirm this assessment.
Large scale slides - pre-existing and first time slide features	• No evidence of pre-existing large scale slides from aerial photos or field mapping. • Large scale outer rim slide is not feasible due to the bedding dipping to the west. • Large scale inner rim slide is not feasible as the dip angle of the bedding limits the scale of the potential slide.	**EXCLUDE**: • Pre-existing or first time large scale slides assessed to be not feasible in this domain.

3.2.5 Geotechnical Domain 8 (Elwari Mountain)

The key characteristics of this domain are summarised as follows;

- The bedding dips into the mountain on both sides of the mountain due to a synclinal fold.
- The faults at the toe on each side of the mountain are inferred to be steeply inclined.
- The folded beds due to the syncline and the dip direction of the bedding is such that medium and large scale sliding is not feasible.
- There are no low angle joint features present.
- There is a pre-existing small scale feature (8A) which is joint controlled but it is inferred to be an area of minor surficial creep.

Table 3-5 presents the results of the failure mode screening for Geotechnical Domain 8 (Elwari Mountain).

Table 3-5 Failure Mode Screening for Geotechnical Domain 8

Failure Mode	Contributing Factors	Include or Exclude
Small scale slides - pre-existing and first time slide features	• A small scale area of surficial creep does exist on the inner rim slope (feature 8A), and there is the potential for first time small scale slides to occur similar to feature 8A. • The runout from small scale slides may not reach the reservoir and the slide mass is too small to generate a significant wave	**EXCLUDE**: • Small scale slides do not pose a risk to dam safety
Medium scale slides - pre-existing and first time slide features	• No evidence of pre-existing medium scale slides from aerial photos or field mapping. • Absence of such features is supported by the geotechnical conditions of this domain (i.e., low angle bedding and inferred high shear strength rock mass).	**EXCLUDE**: • Pre-existing or first time medium scale slides assessed to be not feasible in this domain.
Large scale slides - pre-existing and first time slide features	• No evidence of pre-existing large scale slides from aerial photos or field mapping. • Absence of such features is supported by the geotechnical conditions of this domain (i.e., bedding dipping into the slope.) • The geotechnical environment is not conducive to large scale instability. • No kinematically feasible mechanism is present.	**EXCLUDE**: • Pre-existing or first time large scale slides assessed to be not feasible in this domain.

3.2.6 Geotechnical Domain 9

The key characteristics of this domain are summarised as follows;

- There is no evidence of pre-existing slides.
- Domain 9 includes the extension of the Elwari Mountain ridge system, which is a continuation of the synclinal structure indentified in Elwari Mountain.
- The bedding dips into the eastern and western slopes.
- The bedding flattens in the valley floor associated with Native Dog Creek.

Table 3-6 presents the results of the failure mode screening for geotechnical domain 9.

Table 3-6 Failure Mode Screening for Geotechnical Domain 9

Failure Mode	Contributing Factors	Include or Exclude
Small scale slides - pre-existing and first time slide features	• No evidence of pre-existing small scale slides from aerial photos or field mapping. • The runout from small scale slides may not reach the reservoir and the slide mass is too small to generate a significant wave	**EXCLUDE**: • Small scale slides do not pose a risk to dam safety
Medium scale slides - pre-existing and first time slide features	• No evidence of pre-existing medium scale slides from aerial photos or field mapping. • Absence of such features is supported by the geotechnical conditions of this domain (i.e., bedding dips into the slopes and inferred high shear strength rock mass).	**EXCLUDE**: • Pre-existing or first time medium scale slides assessed to be not feasible in this domain.
Large scale slides - pre-existing and first time slide features	• No evidence of pre-existing large scale slides from aerial photos or field mapping. • The geotechnical environment is not conducive to large scale instability. • No kinematically feasible mechanism is present.	**EXCLUDE**: • Pre-existing or first time large scale slides assessed to be not feasible in this domain.

3.2.7 Geotechnical Domains 3 and 6

In Domain 3, the bedding dips into the slope and there are no feasible mechanisms for first time slides. Therefore, Domain 3 was excluded from the event tree analysis.

Domain 6 is the area east of the Tillegra Fault and is not affected by the storage and has no stability issues, and therefore it was excluded from the event tree analysis.

3.2.8 Saddle A

The key characteristics of Saddle A are summarised as follows;

- There is no evidence of pre-existing slides.
- The bedding strikes northwest-southeast through the axis of the saddle. The bedding does not daylight.
- There are two major joint sets and neither of these daylight.

Table 3-7 presents the results of the failure mode screening for Saddle A.

Table 3-7 Failure Mode Screening for Saddle A

Failure Mode	Contributing Factors	Include or Exclude
Small scale slides - pre-existing and first time slide features	• No evidence of pre-existing small scale slides from aerial photos or field mapping. • The runout from small scale slides may not reach the reservoir and the slide mass is too small to generate a significant wave	**EXCLUDE**: • Small scale slides do not pose a risk to dam safety
Medium scale slides - pre-existing and first time slide features	• No evidence of pre-existing medium scale slides from aerial photos or field mapping. • Absence of such features is supported by the geotechnical conditions of this domain (i.e. bedding normal to the axis of the saddle and inferred high shear strength rock mass).	**EXCLUDE**: • Pre-existing or first time medium scale slides assessed to be not feasible in this domain.
Large scale slides - pre-existing and first time slide features	• No evidence of pre-existing large scale slides from aerial photos or field mapping. • The geotechnical environment is not conducive to large scale instability. • No kinematically feasible mechanism is present.	**EXCLUDE**: • Pre-existing or first time large scale slides assessed to be not feasible in this domain.

3.2.9 Saddle B

The key characteristics of Saddle B are summarised as follows;

- There is no evidence of pre-existing slides.
- The bedding dips shallowly to the northeast and does not daylight.
- There is a major joint set dipping very steeply to the west (striking through the axis of the saddle).
- The Brownmore fault is associated the major joint set. The fault lineament is normal to the axis of the saddle and does not present a potential stability problem.

Table 3-8 presents the results of the failure mode screening for Saddle B.

Table 3-8 Failure Mode Screening for Saddle B

Failure Mode	Contributing Factors	Include or Exclude
Small scale slides - pre-existing and first time slide features	• No evidence of pre-existing small scale slides from aerial photos or field mapping. • The runout from small scale slides may not reach the reservoir and the slide mass is too small to generate a significant wave	**EXCLUDE**: • Small scale slides do not pose a risk to dam safety
Medium scale slides - pre-existing and first time slide features	• No evidence of pre-existing medium scale slides from aerial photos or field mapping. • Absence of such features is supported by the geotechnical conditions of this domain (i.e., low angle bedding and inferred high shear strength rock mass).	**EXCLUDE**: • Pre-existing or first time medium scale slides assessed to be not feasible in this domain.
Large scale slides - pre-existing and first time slide features	• No evidence of pre-existing large scale slides from aerial photos or field mapping. • The geotechnical environment is not conducive to large scale instability. • No kinematically feasible mechanism is present.	**EXCLUDE**: • Pre-existing or first time large scale slides assessed to be not feasible in this domain.

3.2.10 Remaining Storage Rim Areas

The area outside the main study area (shown as light green on Figure 1 in Volume 1 of the Commerce report) has been screened and excluded from further risk analysis. For this area, it is assessed as inconceivable that the integrity of the reservoir and/or the dam could be threatened by land sliding because:

- The storage pools on the lower, flatter slopes of the ridge system;
- The mountain ranges broaden out providing for very lengthy seepage paths and reduced hydraulic gradients;
- There are no pre-existing large scale landslides capable of affecting the integrity of the reservoir and/ or dam safety.

3.3 Risk Analysis Results

3.3.1 Failure Modes

The failure modes screening described in the preceding section identified the following potential failure modes for evaluating the risks:

- Domain 1 – Potential large scale, first time slide of the ridge leading to uncontrolled release of the storage.
- Domain 2 – Mobilisation of the pre-existing medium scale slide 2A feature, leading to the formation of a wave in the storage and overtopping failure of the dam structure.
- Domain 5 – Potential medium scale, first time slide of the inner slope leading to the formation of a wave in the storage and overtopping failure of the dam structure.

3.3.2 Event Tree Structure

Figures 3-1, 3-2 and 3-3 depicts the sequence of events that would be required for each of the three storage rim slide mechanisms to cause an uncontrolled release of the storage. These sequence of events were then used as a basis for developing the event trees for estimating the probability of failure for each of the loading conditions (i.e. normal operating, 1 in 100 year rainfall event, extreme flood event and extreme earthquake event).

The detailed event trees for each of the failure modes are provided in Appendix A to this report.

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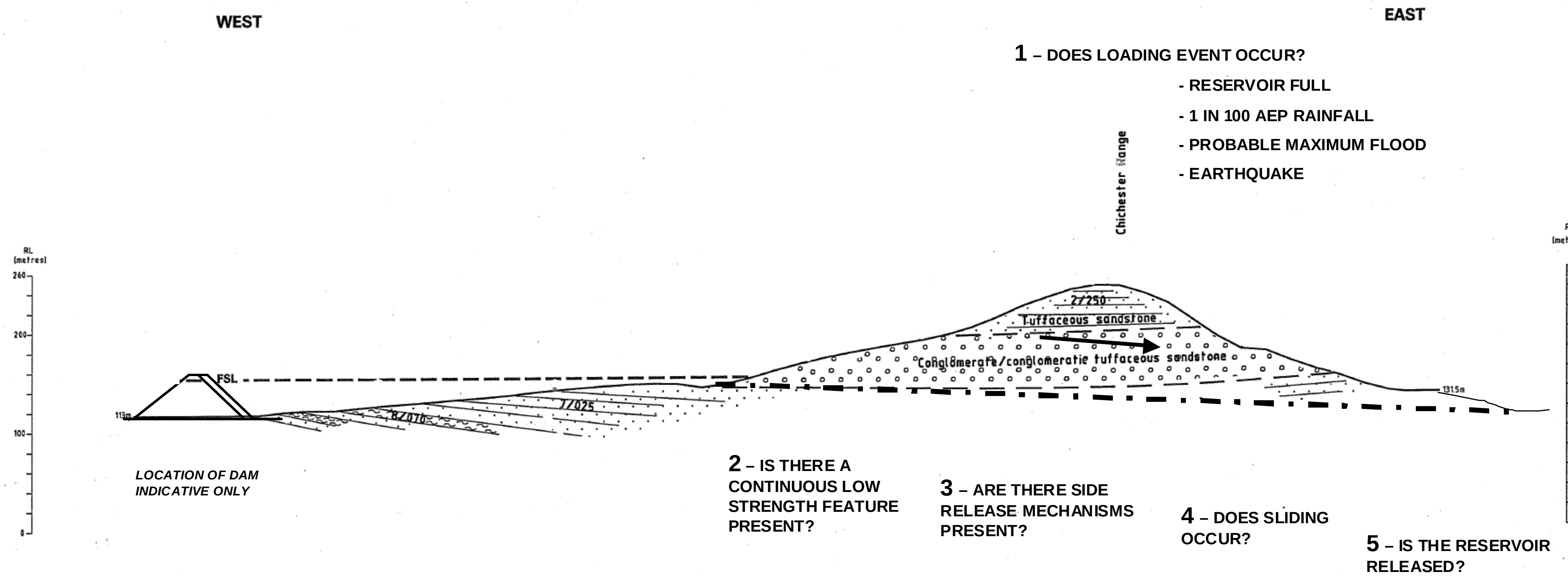

Figure 3-1 Schematic cross section showing the sequence of events for Domain 1 storage rim instability

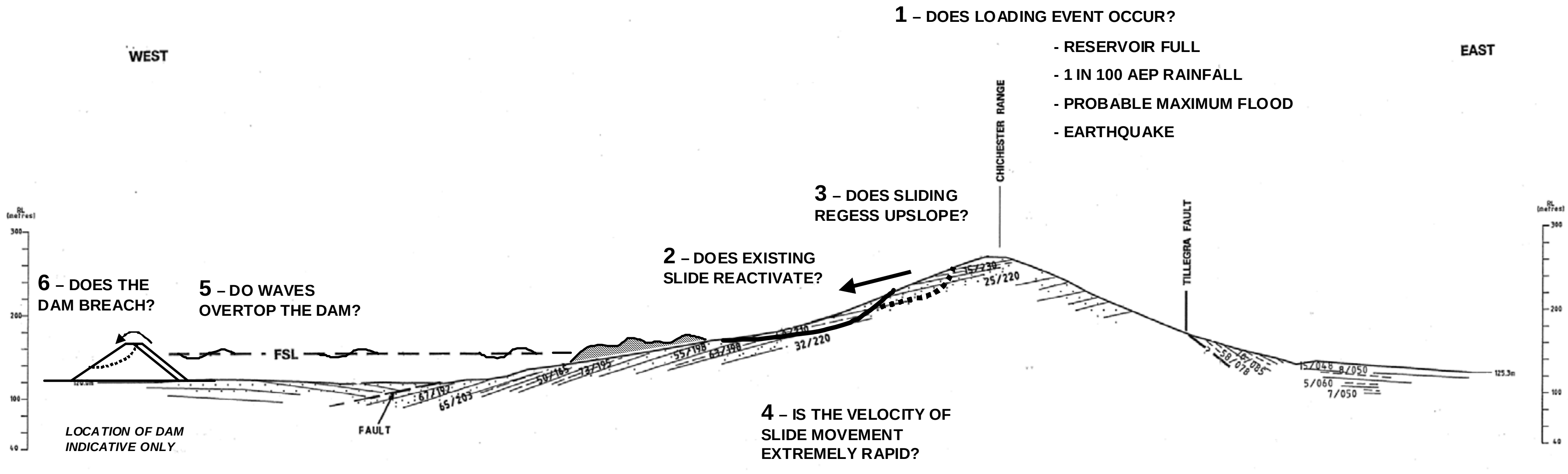

Figure 3-2 Schematic cross section showing the sequence of events for Domain 2 storage rim instability

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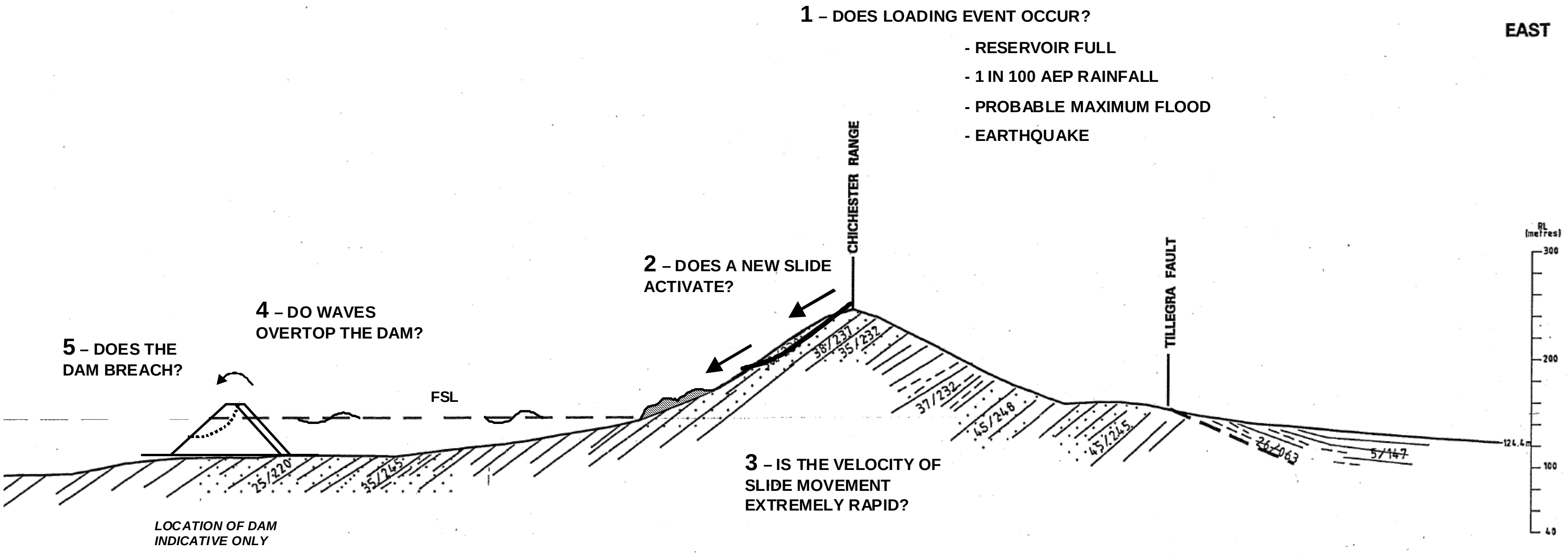

Figure 3-3 Schematic cross section showing the sequence of events for Domain 5 storage rim instability

3.3.3 Annual Probabilities of Failure

The probabilities of failure for each of the three failure modes were assessed by the workshop participants by assigning probabilities to each of the events (or nodes) on the event trees. The annual probability of the failure mode is then calculated by multiplying the annual probability of the loading event to each of the succeeding probabilities on the event tree branches that lead to an uncontrolled release of the storage.

Appendix A provides the detailed event trees for each of the failure modes showing the assessed probabilities. **Appendix B** provides tables which list the factors that were considered by the workshop participants in assessing each of the event probabilities on the event trees. There are tables for each individual loading case (PMF, earthquake, rainfall event, normal operations) as appropriate to the particular slope failure mode assessed.

The estimated annual probabilities of failure for each failure mechanism for each potential failure mode assessed are presented in Table 3-9.

Table 3-9 Estimated Annual Probabilities of Failure

Potential Failure Mode	Reservoir Full Event	1 in 100 Year Rainfall Event	Probable Maximum Flood Event	Maximum Design Earthquake Event	All Loading Events
Domain 1 - Potential large scale, first time slide of the ridge leading to uncontrolled release of the storage.	5.0E-13	5.0E-15	5.0E-20	5.0E-17	5.1E-13
Domain 2 - Mobilisation of the pre-existing medium scale slide 2A feature, leading to the formation of a wave in the storage and overtopping failure of the dam structure.	5.0E-12	2.7E-11	9.0E-13	2.5E-15	3.3E-11
Domain 5 - Potential medium scale, first time slide of the inner slope leading to the formation of a wave in the storage and overtopping failure of the dam structure.	5.1E-10	1.4E-11	1.4E-13	1.1E-12	5.2E-10
Totals	**5.2E-10**	**4.1E-11**	**1.0E-12**	**1.1E-12**	**5.6E-10**

It can be seen from Table 3-9 that the estimated probabilities of failure for each mechanism of storage rim instability are extremely low. Events having probabilities of 1 in 10,000,000 (1E-7) or less are usually considered to be negligible or barely conceivable, and the probabilities assessed for the storage rim failure mechanisms are many times less than this. These extremely low probabilities are due to the very low likelihood for each of the sequence of events that are required for sliding to cause an uncontrolled release of the storage. The analysis demonstrates that even if sliding occurs, the likelihood of it impacting on the safe operation of the storage is negligible.

The total annual probability of storage rim instability by all the potential failure modes is calculated by adding the annual probabilities of each mode. This gives a total annual probability of storage rim instability of 5.6×10^{-10} (1 in 1,800,000,000).

3.4 Discussion of Risk Assessment Results

The risk workshop evaluation yielded extremely low probabilities for an uncontrolled loss of storage due to reservoir rim instability for the three potential failure modes judged most likely to occur. The loading cases considered were normal operations (full reservoir), PMF, earthquake, and a 100 year rainfall event. The highest probabilities in each case related to normal operations or the 100 year rainfall event because the probabilities of the Maximum Design Earthquake and Probable Maximum Flood events are so low. It is acknowledged that there are flood loading events between the 1 in 100 year event and PMF event that have not been analysed in this risk assessment, however the exclusion of these intermediate events does not change the outcomes of the risk assessment as the probabilities of failure given the flood loading event occurs would also be extremely low.

3.4.1 Contributing Factors

The main factors contributing to the extremely low assessed probabilities are summarised for each domain as follows;

Domain 1

- Large scale sliding of the Chichester Range would require a continuous sub-horizontal low strength feature to be present and vertical side release mechanisms to exist for this to be a viable mechanism. There is no evidence from the geological mapping that such features are present and the potential for such features to be present were assessed to be very low based on the geotechnical conditions of this domain. The two known mapped faults are dipping in directions such that failure along these features is not kinematically feasible.
- Even if it is assumed that a kinematically feasible mechanism is present, then the factors of safety for sliding are greater than 2 for a conservative 2-D analysis of slide planes that could potentially take out the entire rim and release the storage (Commerce 2009). An independent 3-D slope stability analysis by PSM (PSM 2009) assumed a vertical tension crack at the ridge of the crest with full hydrostatic head applied to the head scarp and failure through rock mass along a bedding plane dipping at 10 degrees out of the reservoir. The results of the analysis indicate a factor of safety of around 3.1. In this case however, the dam storage could not be released by the assumed slope failure block.
- The use of conservative parameters across a theoretical continuous bedding plane, the presence of topographic restraints limiting the potential size of the slide and the lack of lower strength planes at depth in all test locations, indicate that the above analyses are very conservative. The stability of the ridge system in Domain 1 is estimated to be considerably greater than indicated above. The likelihood for large scale instability is assessed to be negligible.

Domain 2

- The stability analysis by PSM (2009) indicates that with a fully saturated slope, the factor of safety for the existing slide 2A approaches or falls below 1.0. This indicates that the slide is likely to be re-activated when it becomes saturated. With the dam present and storage at full supply level and a fully saturated slope, the factor of safety approaches 1.0, indicating likely re-activation.
- If the existing slide 2A remobilises, then the slide is expected to be very slow moving. Extremely rapid movement of the slide mass was judged to be very unlikely based on the assessment that the surface of rupture is already at residual strength and the average dip of the slide planes are only 14 degrees.

- Even if the slide mass was assumed to remobilise and move extremely rapidly, then the estimated wave heights induced in the reservoir are too small to impact on the safety of the dam.

Domain 5

- A first time slide at location 5A in Domain 5 would require a bedding plane failure within the rock mass and a breakout across bedding at the toe. Geological mapping did not find any evidence for adversely orientated joint sets or other geological features which could provide a breakout at the toe. The outcrops at location 5A show massive sandstone in the toe region.
- The stability analysis (by PSM 2009) of Slide 5A indicates a calculated Factor of Safety in excess of 1.5 for an extreme earthquake event having an AEP of 1 in 100,000 and a peak ground acceleration of 0.5g. This indicates sliding at location 5A is very unlikely even for very large earthquake loading events.
- Location 5A is well above the proposed storage level, and would not be affected by storage operations.
- If a first time slide were to initiate from Location 5A and assumed to travel extremely rapidly into the storage, then the waves induced in the reservoir are estimated to be in the order of 5 m, but likely to be much smaller allowing for 3D effects (PSM 2009). These waves would be too small to impact on the safety of the dam.

3.4.2 Comparison to Risk Criteria

The very low probabilities of failure yield risks that are significantly lower than the acceptable levels of the NSW Dams Safety Committee and ANCOLD risk guidelines for new dams for both individual and societal risk. The very low probabilities of dam failure and loss of storage are consistent with the normal design objective of new large dams to safely handle extremely rare loading events such as extreme floods and earthquakes.

A key finding of the risk assessment is that a sequence of events is required for failure to occur and since each of these loading events has a very low likelihood of occurring, the outcomes of the assessment are not sensitive to major changes to any one or two of the event probabilities.

Section 4 Conclusions

The main conclusions of this risk assessment study are as follows:

- A large number of potential failure modes for the Tillegra dam storage rim were considered and evaluated. Factors considered included geological and groundwater conditions, the results of numerical stability analyses and a range of loading conditions, including extreme loads caused by earthquake or PMF events.
- Based on the failure mode screening, three potential failure modes for large scale storage rim instability were identified for analysis in the risk workshop. These were:
  - Domain 1 – Potential large scale, first time slide of the ridge leading to uncontrolled release of the storage.
  - Domain 2 – Mobilisation of the pre-existing medium scale slide 2A feature, leading to the formation of a wave in the storage and overtopping failure of the dam structure.
  - Domain 5 – Potential medium scale, first time slide of the inner slope leading to the formation of a wave in the storage and overtopping failure of the dam structure.
- The estimated probabilities of failure for each mechanism of storage rim instability are extremely low (i.e. many times less than a probability of 1 in 10,000,000 which is usually considered to be negligible or barely conceivable). These extremely low probabilities are due to the very low likelihood of occurrence for each of the events that would be required to initiate sliding on a scale sufficient to cause an uncontrolled release of the storage.
- The total annual probability of storage rim instability by all the potential failure modes was estimated to be 5.6×10^{-10} or 1 in 1,800,000,000.
- The risks resulting from the landslide hazard are significantly lower than the acceptable levels under the NSW Dams Safety Committee and ANCOLD risk guidelines for new dams for both individual and societal risk.
- These extremely low probabilities are also consistent with the design objective of new large dams to safely handle extremely rare loading events such as extreme flood and earthquake events.

References

Australian National Committee on Large Dams (ANCOLD 2003), *Guidelines on Risk Assessment*, October 2003.

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Department of Commerce (Commerce 2009), *Tillegra Dam Design - Storage Rim Stability and Seepage Potential Engineering Geotechnical Report (Volumes I, II and III), Report No. 08-GN31A-R2, Final Report V4.1,* February 2009.

ES&S (2008), *Tillegra Dam Earthquake Hazard Assessment*, Environmental Systems and Services (ES&S) Seismic Research Centre, July 2008.

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Event Trees

Appendix A

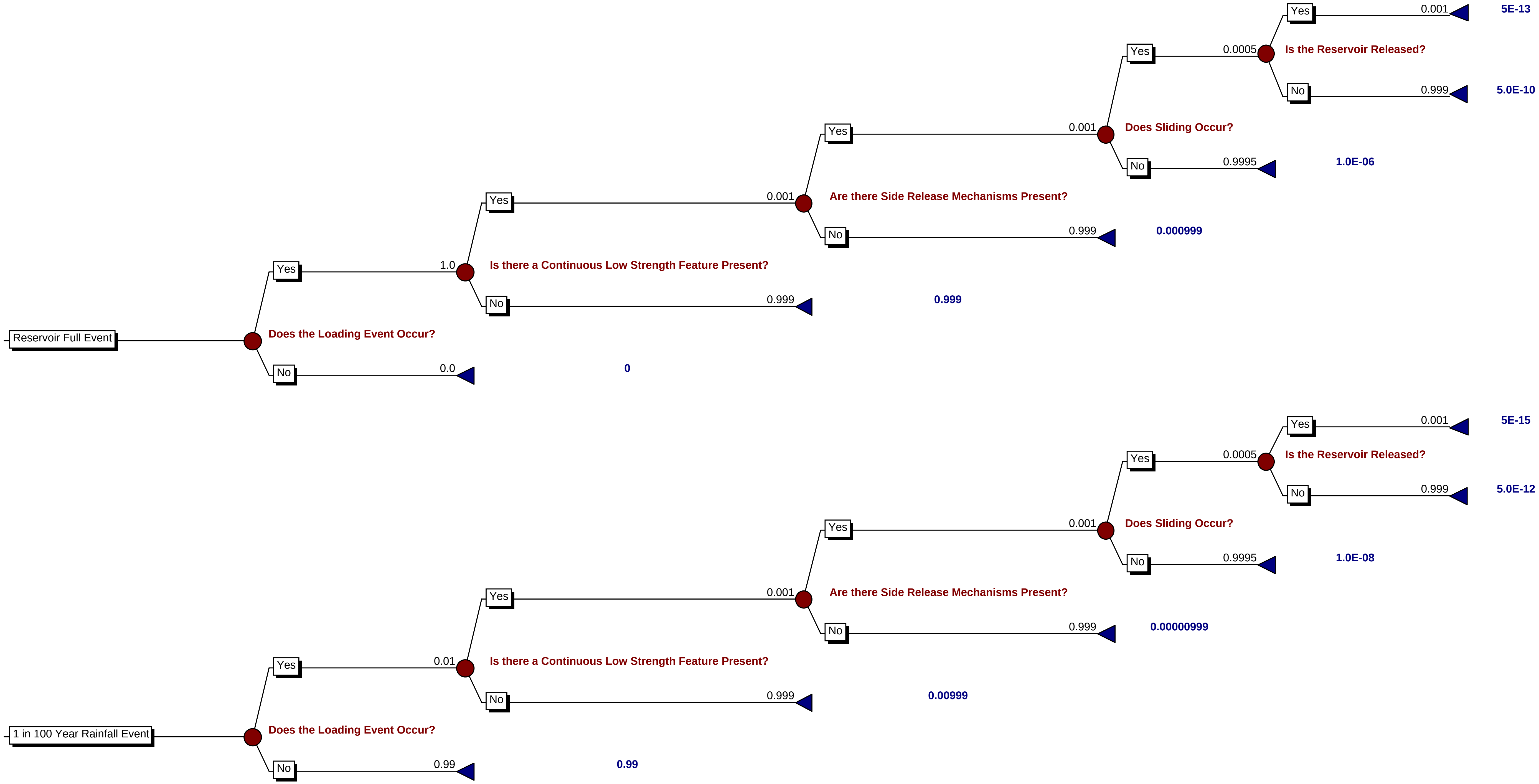
TILLEGRA DAM STORAGE RIM LANDSLIDE RISK ASSESSMENT

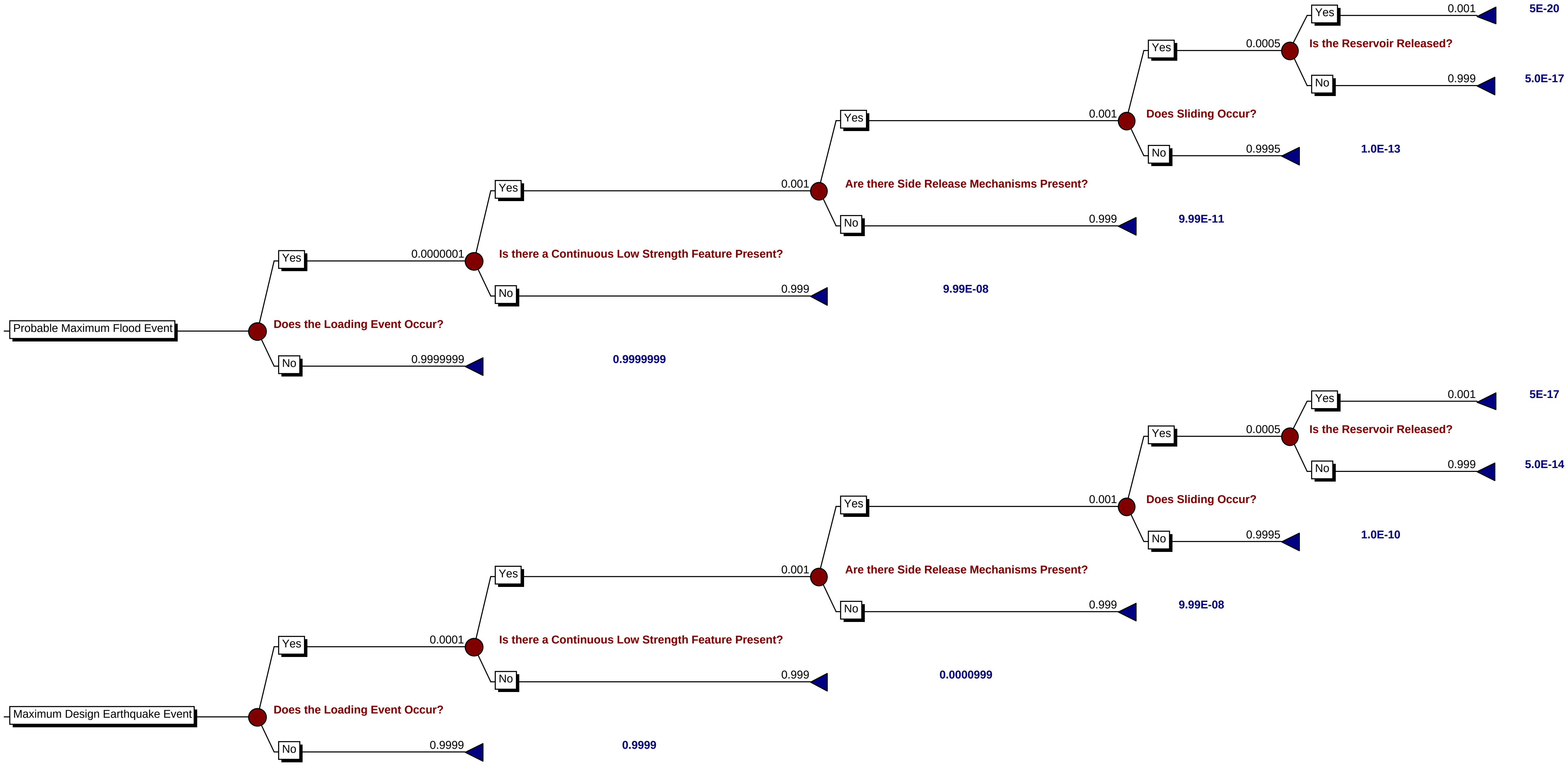
Summary Results

Geotechnical Domain	Potential Failure Mode	Annual Probability of Uncontrolled Storage Release				
		Reservoir Full Event	1 in 100 Year Rainfall Event	Probable Maximum Flood Event	Maximum Design Earthquake Event	All Loading Events
Domain 1	Potential large scale, first time slide of the ridge leading to uncontrolled release of the storage.	5.0E-13	5.0E-15	5.0E-20	5.0E-17	5.1E-13
Domain 2	Mobilisation of the pre-existing medium scale slide 2A feature, leading to the formation of a wave in the storage and overtopping failure of the dam structure.	5.0E-12	2.7E-11	9.0E-13	2.5E-15	3.3E-11
Domain 5	Potential medium scale, first time slide of the inner slope leading to the formation of a wave in the storage and overtopping failure of the dam structure.	5.1E-10	1.4E-11	1.4E-13	1.1E-12	5.3E-10
	Totals	**5.2E-10**	**4.1E-11**	**1.0E-12**	**1.1E-12**	**5.6E-10**

TILLEGRA DAM STORAGE RIM LANDSLIDE RISK ASSESSMENT

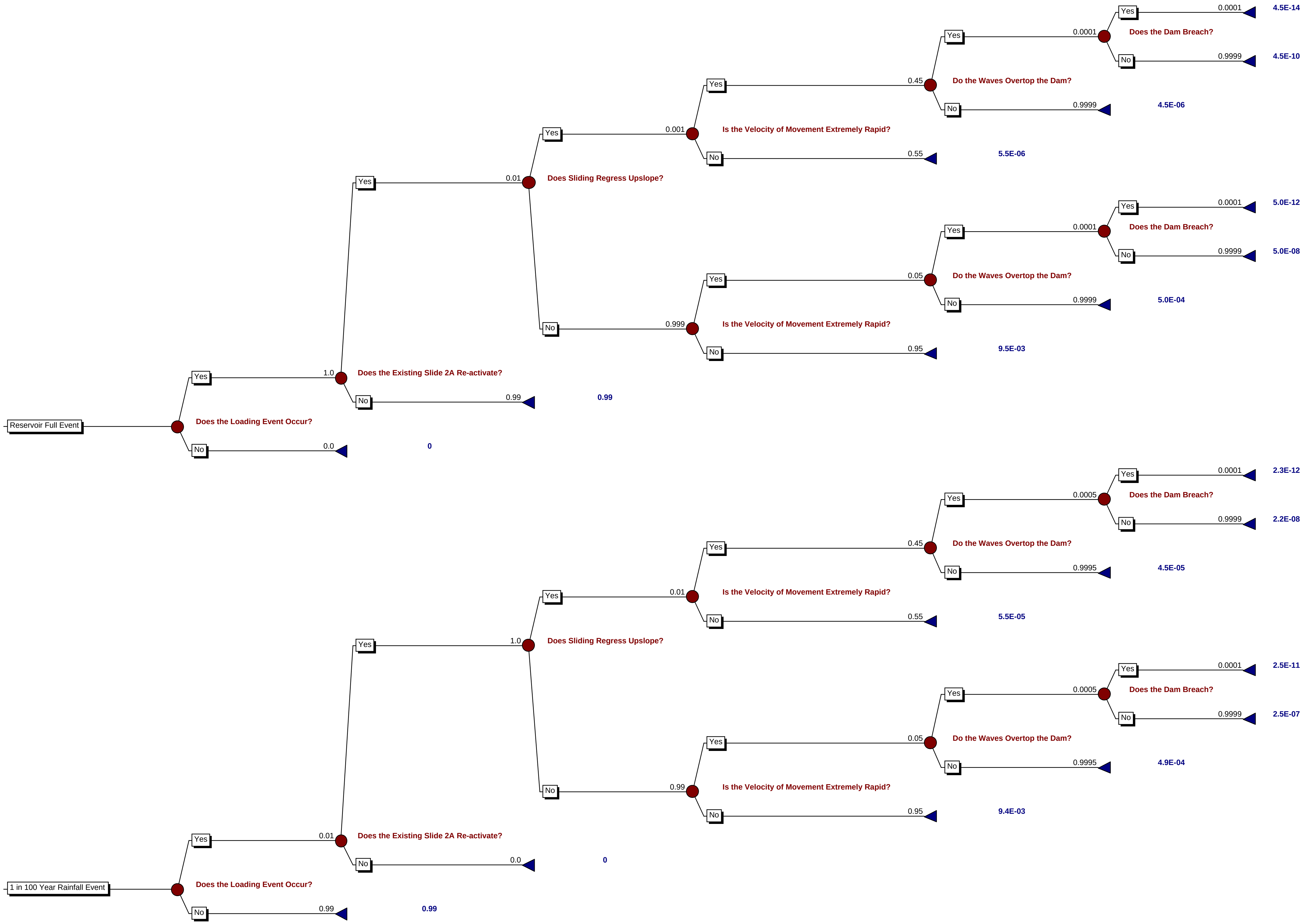
Domain 1




Probable Maximum Flood Event
Does the Loading Event Occur?
Yes
0.0000001
No
0.9999999
0.9999999
Is there a Continuous Low Strength Feature Present?
Yes
0.001
No
0.999
9.99E-08
Are there Side Release Mechanisms Present?
Yes
0.001
No
0.999
9.99E-11
Does Sliding Occur?
Yes
0.0005
No
0.9995
1.0E-13
Is the Reservoir Released?
Yes
0.001
5E-20
No
0.999
5.0E-17
Maximum Design Earthquake Event
Does the Loading Event Occur?
Yes
0.0001
No
0.9999
0.9999
Is there a Continuous Low Strength Feature Present?
Yes
0.001
No
0.999
0.0000999
Are there Side Release Mechanisms Present?
Yes
0.001
No
0.999
9.99E-08
Does Sliding Occur?
Yes
0.0005
No
0.9995
1.0E-10
Is the Reservoir Released?
Yes
0.001
5E-17
No
0.999
5.0E-14

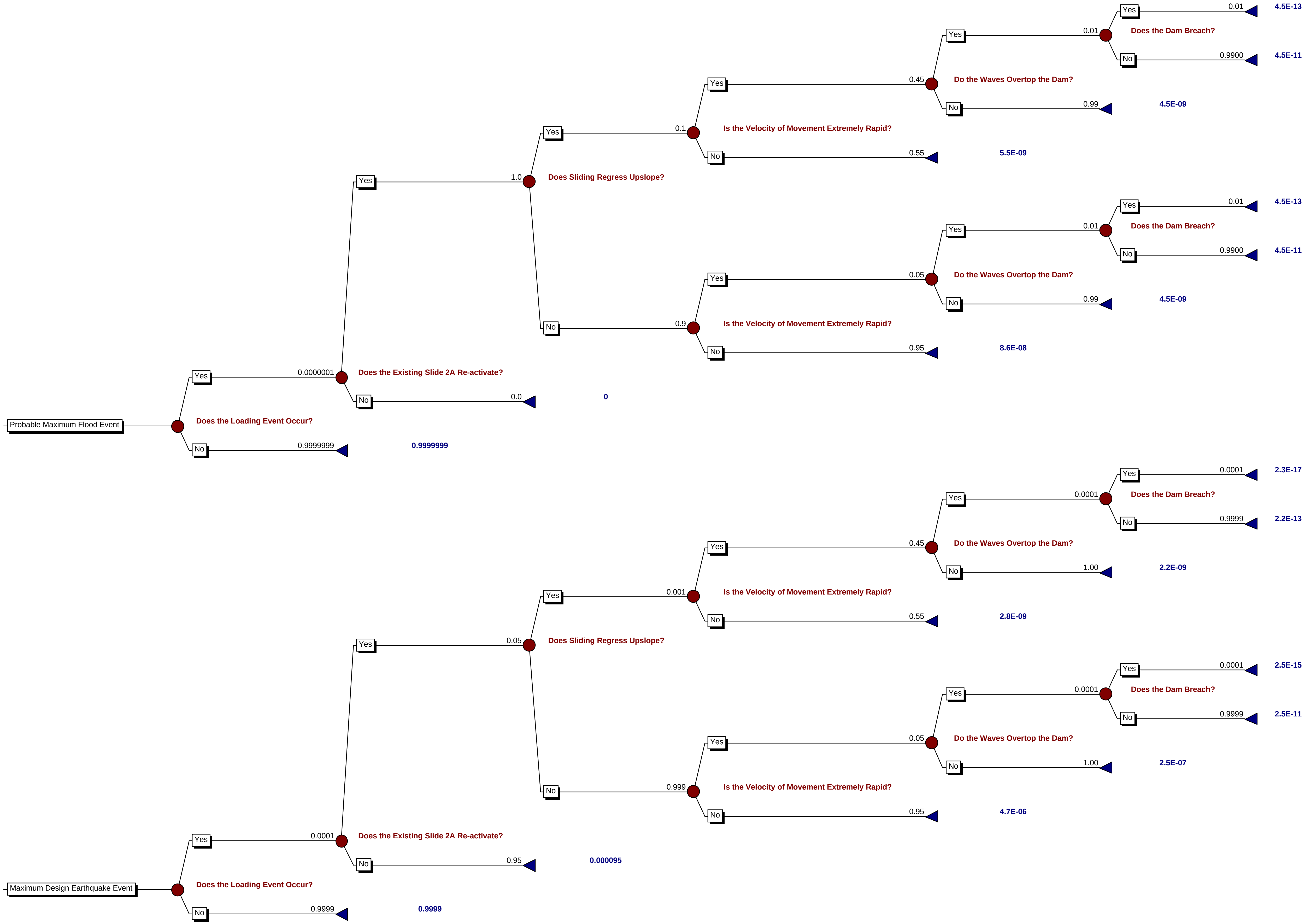
TILLEGRA DAM STORAGE RIM LANDSLIDE RISK ASSESSMENT

Domain 2



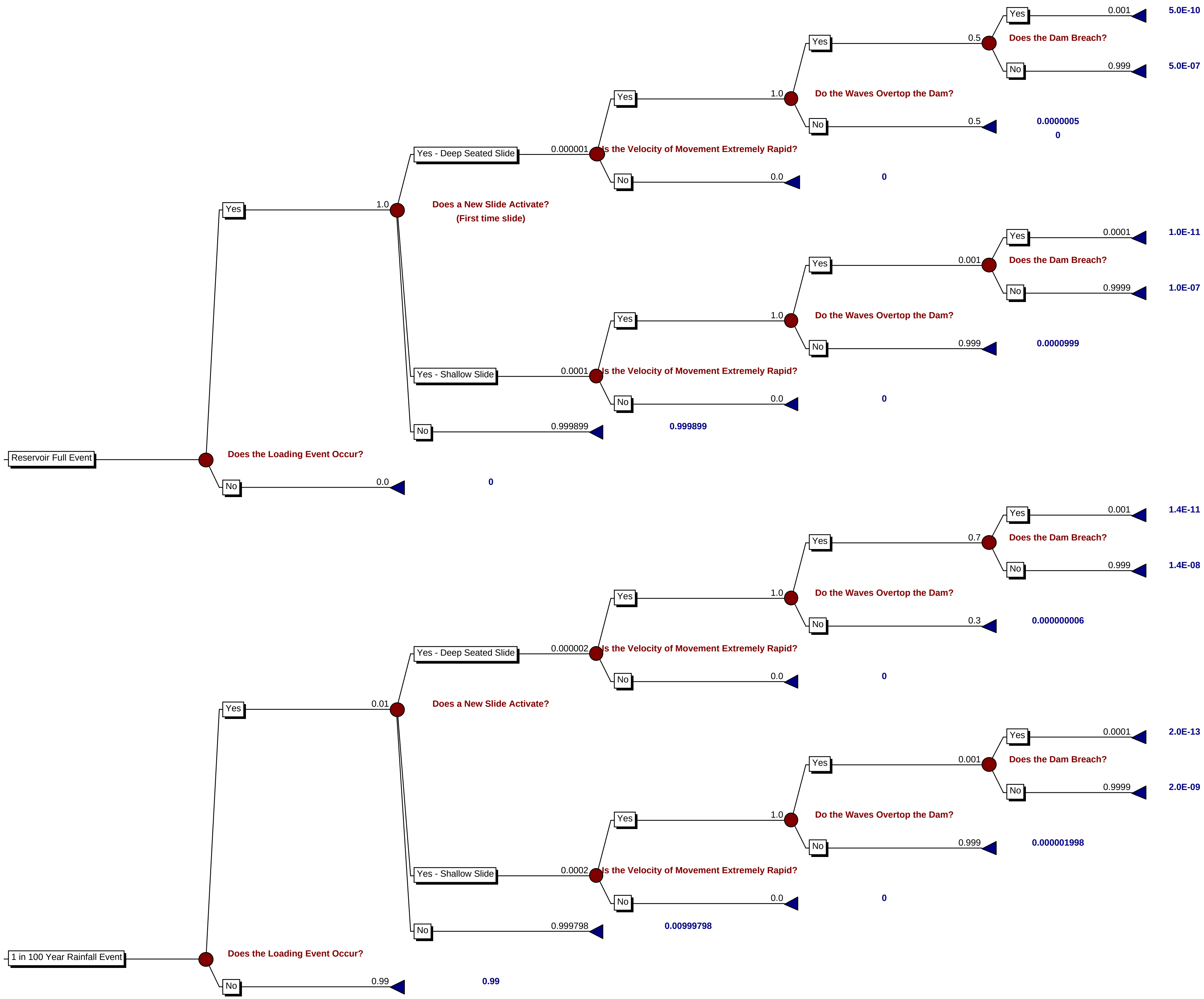
TILLEGRA DAM STORAGE RIM LANDSLIDE RISK ASSESSMENT

Domain 2



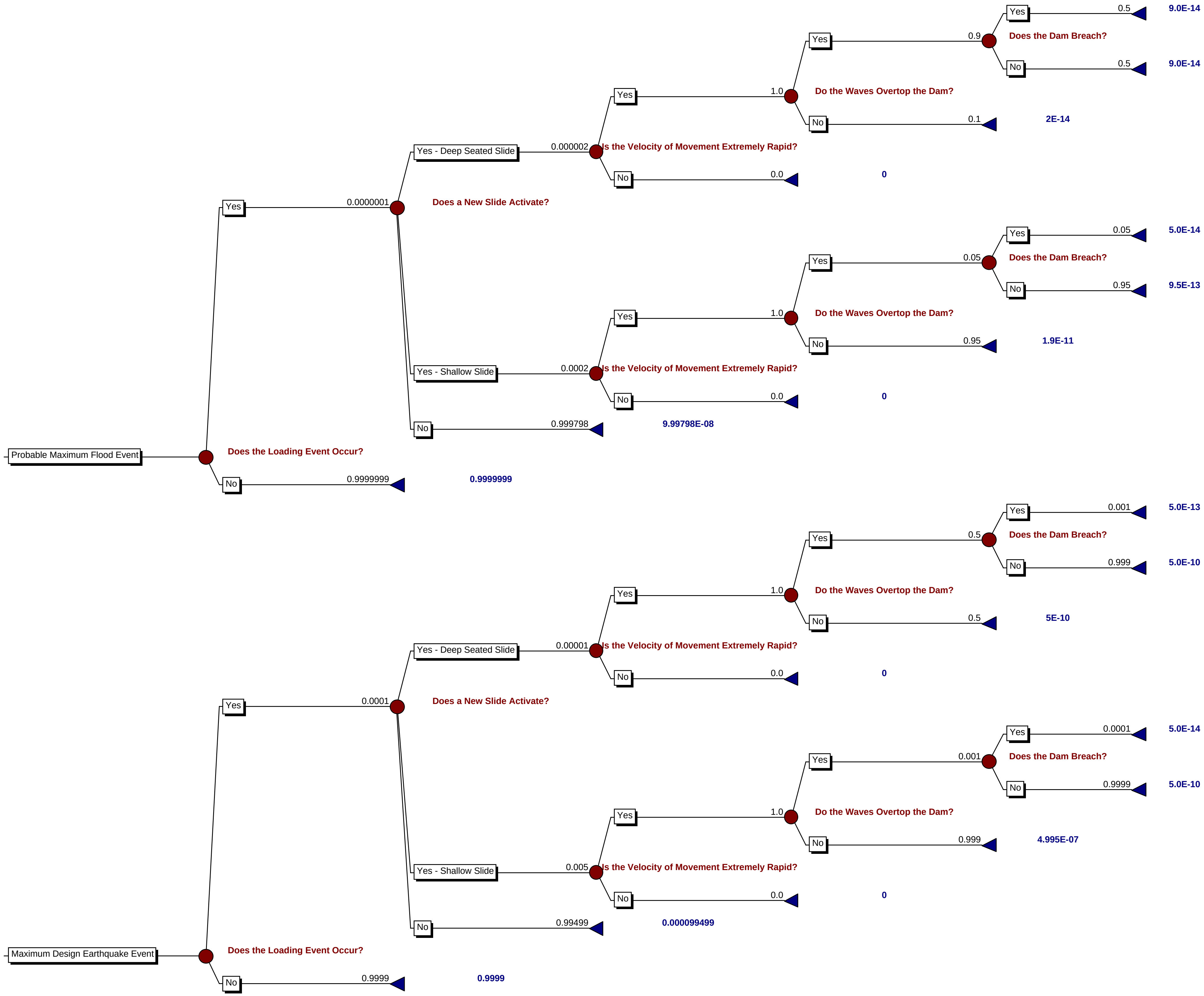
TILLEGRA DAM STORAGE RIM LANDSLIDE RISK ASSESSMENT

Domain 5



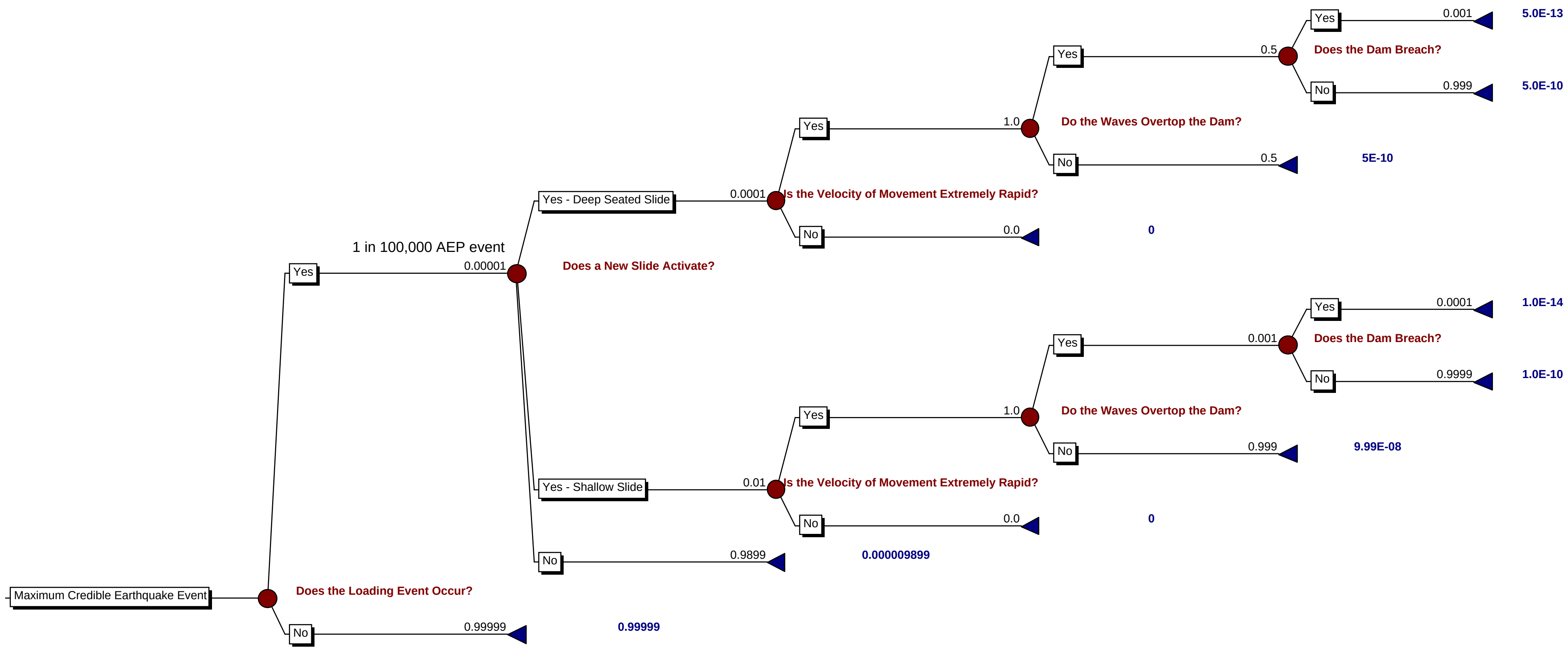
TILLEGRA DAM STORAGE RIM LANDSLIDE RISK ASSESSMENT

Domain 5



TILLEGRA DAM STORAGE RIM LANDSLIDE RISK ASSESSMENT

Domain 5



Probability Factor Tables

Appendix B

TILLEGRA DAM STORAGE RIM LANDSLIDE RISK ASSESSMENT

Domain: ***1***

Loading Case: ***Reservoir Full Event***

Loading Condition	Reasoning	Assigned Probability
Does the Loading Event Occur?	Reservoir filling assumed to occur each year	1
Is there a Continuous Low Strength Feature Present?	● No evidence of bedding surface shears along bedding or across bedding - have seen no evidence for this. ● Feature would need to be very long - 600m long ● Two known mapped faults are geometrically not related to the domain and are dipping in directions such that failure is not kinematically feasbile	0.001
Are there Side Release Mechanisms Present?	● Large three dimensional effects from side shear ● Requires geological features to provide side release mechanisms - assessed to be not conceivable	0.001
Does Sliding Occur?	● 2D stability analyses (i.e. ignoring side resistance) indicate factor of safety for a deep outer slide without the dam is 2.2, and 2.1 with the dam (cohesion 0 kPa, phi=12°). ● The 2D analyses used conservative strength and piezometer surfaces and ignoring 3D effects, so actual factor of safety will be greater ● Requires friction angle phi=6° to get FOS=1 (in 2D analysis), and can't envisage shear strength this low.	0.0005
Is the Reservoir Released?	● The slide mass would need to travel a long distance for a catastrophic release of the storage to occur - can't envisage a mechanism for the slide mass to travel on a low angle shear surface ● If sliding were to occur, can't envisage uncontrolled release of the storage, could lead to leakage	0.001

TILLEGRA DAM STORAGE RIM LANDSLIDE RISK ASSESSMENT
Domain: ***1***
Loading Case: ***1 in 100 Year Rainfall Event***

Loading Condition	Reasoning	Assigned Probability
Does the Loading Event Occur?	1 in 100 Annual Exceedance Probability (AEP) rainfall event	0.01
Is there a Continuous Low Strength Feature Present?	● Assessment same as for Reservoir Full condition. ● No evidence of bedding surface shears along bedding or across bedding - have seen no evidence for this. ● Feature would need to be very long - 600m long ● Two known mapped faults are geometrically not related to the domain and are dipping in directions such that failure is not kinematically feasible	0.001
Are there Side Release Mechanisms Present?	● Large three dimensional effects from side shear ● Requires geological features to provide side release mechanisms - assessed to be not conceivable	0.001
Does Sliding Occur?	● 2D stability analyses (i.e. ignoring side resistance) indicate factor of safety for a deep outer slide without the dam is 2.2, and 2.1 with the dam (cohesion 0 kPa, phi=12°). ● The 2D analyses used conservative strength and piezometer surfaces and ignoring 3D effects, so actual factor of safety will be greater ● Requires friction angle phi=6° to get FOS=1 (in 2D analysis), and can't envisage shear strength this low. ● Rainfall event judged to make only a small incremental increase in piezometric conditions, this would make little difference to the global stability of the ridge ● Assessed probability same as for the Reservoir Full condition	0.0005
Is the Reservoir Released?	● The slide mass would need to travel a long distance for a catastrophic release of the storage to occur - can't envisage a mechanism for the slide mass to travel on a low angle shear surface	0.001

TILLEGRA DAM STORAGE RIM LANDSLIDE RISK ASSESSMENT

Domain: ***1***

Loading Case: ***Probable Maximum Flood Event***

Loading Condition	Reasoning	Assigned Probability
Does the Loading Event Occur?	Probable Maximum Flood (PMF) event has an estimated AEP of 1 in 10,000,000	0.0000001
Is there a Continuous Low Strength Feature Present?	● Assessment same as for Reservoir Full condition. ● No evidence of bedding surface shears along bedding or across bedding - have seen no evidence for this. ● Feature would need to be very long - 600m long ● Two known mapped faults are geometrically not related to the domain and are dipping in directions such that failure is not kinematically feasible	0.001
Are there Side Release Mechanisms Present?	● Large three dimensional effects from side shear ● Requires geological features to provide side release mechanisms - assessed to be not conceivable	0.001
Does Sliding Occur?	● 2D stability analyses (i.e. ignoring side resistance) indicate factor of safety for a deep outer slide without the dam is 2.2, and 2.1 with the dam (cohesion 0 kPa, phi=12°). ● The 2D analyses used conservative strength and piezometer surfaces and ignoring 3D effects, so actual factor of safety will be greater ● Requires friction angle phi=6° to get FOS=1 (in 2D analysis), and can't envisage shear strength this low. ● PMF event judged to make only a small incremental increase in piezometric conditions, this would make little difference to the global stability of the ridge ● Assessed probability same as for the Reservoir Full condition	0.0005
Is the Reservoir Released?	● The slide mass would need to travel a long distance for a catastrophic release of the storage to occur - can't envisage a mechanism for the slide mass to travel on a low angle shear surface ● If sliding were to occur, can't envisage uncontrolled release of the storage, could lead to leakage	0.001

TILLEGRA DAM STORAGE RIM LANDSLIDE RISK ASSESSMENT

Domain: ***1***

Loading Case: ***Maximum Design Earthquake Event***

Loading Condition	Reasoning	Assigned Probability
Does the Loading Event Occur?	Maximum Design Earthquake (MDE) event has an AEP of 1 in 10,000	0.0001
Is there a Continuous Low Strength Feature Present?	● Assessment same as for Reservoir Full condition. ● No evidence of bedding surface shears along bedding or across bedding - have seen no evidence for this. ● Feature would need to be very long - 600m long ● Two known mapped faults are geometrically not related to the domain and are dipping in directions such that failure is not kinematically feasible	0.001
Are there Side Release Mechanisms Present?	● Large three dimensional effects from side shear ● Requires geological features to provide side release mechanisms - assessed to be not conceivable	0.001
Does Sliding Occur?	● 2D static stability analyses (i.e. ignoring side resistance) indicate factor of safety for a deep outer slide without the dam is 2.2, and 2.1 with the dam (cohesion 0 kPa, phi=12°). ● The 2D analyses used conservative strength and piezometer surfaces and ignoring 3D effects, so actual factor of safety will be greater ● Requires friction angle phi=6° to get FOS=1 (in 2D analysis), and can't envisage shear strength this low. ● Maximum Design Earthquake event has a peak ground acceleration of 0.24g, this was judged to make little difference to the global stability of the ridge ● Assessed probability same as for the Reservoir Full condition	0.0005
Is the Reservoir Released?	● The slide mass would need to travel a long distance for a catastrophic release of the storage to occur - can't envisage a mechanism for the slide mass to travel on a low angle shear surface ● If sliding were to occur, can't envisage uncontrolled release of the storage, could lead to leakage	0.001

TILLEGRA DAM STORAGE RIM LANDSLIDE RISK ASSESSMENT

Domain: *2*

Loading Case: *Reservoir Full Event*

Loading Condition	Reasoning	Assigned Probability
Does the Loading Event Occur?	Reservoir filling assumed to occur each year	1
Does the Exisiting Slide Re-activate?	● Existing slide is approximately 370,000 m^3 in size ● The toe of the existing slide 2A would be inundated by about 15m by the storage filling ● Test pits indicated no evidence of groundwater ● No evidence of springs, but Melaleuca Trees above scarp indicate likely wet conditions ● Filling of the storage to FSL would inundate the toe of the slide. Stability analysis by PSM 2008 indicates factor of safety reduces from 1.79 for dry case to 1.49 for FSL case (i.e reduces FOS by about 17%, but FOS still greater than 1.0) ● A possible scenario is erosion to undermine the toe (not likely under first fill) ● Mechanism of movement for Slide 2A is rainfall induced saturation of the slide mass	0.01
Does Sliding Regress Upslope?	● There is an upper creep zone surrounding Slide 2A to the north, northeast and east, about 1.5m to 2.0m deep, periodic creep movement (about 200,000 m^3 in size). ● Lower slide has moved, but no evidence of regression of the creep zone into a landslide ● Creep zone unaffected by storage filling (well above FSL storage level) ● Assigned probability of 0.001- difficult to think of a scenario	0.001
Is the Velocity of Movement Extremely Rapid?	● Surface of rupture is already at residual strength ● The toe area is a thick "shove zone" of breacciated rock - this is not expected to give a brittle release mechanism. ● Past performance shows long history of slow movements despite high rainfall events over a long period ● Assigned probability of 0.05 for case where sliding does not regress upslope based on Glastonbury and Fell method (refer to PSM 2009). ● Probability assessed using the Glastonbury and Fell method is 0.45 if upslope regression occurs (refer to PSM 2009).	0.45 (if sliding regresses upslope) 0.05 (if upslope sliding does not occur)
Do the Waves Overtop the Dam?	● Slide is not in direct path to dam (dam face oblique to wave direction) and would require waves to reflect off Elwari Mountain ● Analysis by PSM indicates only relatively small wave heights if the slide moves extremely rapidly (7.6m waves for 2D analysis, and <0.1m allowing for 3D effects of waves reaching the dam). ● The freeboard at FSL (i.e. height between FSL and crest level of the dam) is 7.9m - this is larger than the predicted wave runup on the face of the dam ● Assigned event probability of 0.0001 - no plausible scenario could be identified.	0.0001 (if sliding regresses upslope) 0.0001 (if sliding does not regress upslope)
Does the Dam Breach?	● If waves were to overtop the dam, then these would be for only short duration and small volume ● The crest will be sealed and the parapet wall heel buried, so the crest is unlikely to be affected by small waves overtopping the crest ● Waves would need to erode out about the upper 8m of the embankment, can't envisage this for small short duration wave overtopping. ● Assigned event probability of 0.0001 for breach given overtopping - no plausible scenario could be identified.	0.0001 (if sliding regresses upslope) 0.0001 (if sliding does not regress upslope)

TILLEGRA DAM STORAGE RIM LANDSLIDE RISK ASSESSMENT

Domain: *2*

Loading Case: *1 in 100 Year Rainfall Event*

Loading Condition	Reasoning	Assigned Probability
Does the Loading Event Occur?	1 in 100 Annual Exceedance Probability (AEP) rainfall event	0.01
Does the Exisiting Slide Re-activate?	● Mechanism of movement for Slide 2A is rainfall induced saturation of the slide mass ● Evidence of rainfall induced movement of Slide 2A in the June 2007 rainfall event - many rainfall events in the historic record of similar or larger magnitude ● A 1 in 100 AEP rainfall event is likely to saturate the slope - stability analysis indicates FOS <1.0 for saturated condition	1.0
Does Sliding Regress Upslope?	● Geomorphology indicates lower slide 2A has moved in the past, but no evidence of regression of the upper creep zone into a slide ● A 1 in 100 AEP rainfall event is likely to saturate the slope	0.01
Is the Velocity of Movement Extremely Rapid?	● Surface of rupture is already at residual strength ● The toe area is a thick "shove zone" of breacciated rock - this is not expected to give a brittle release mechanism. ● Past performance shows long history of slow movements despite high rainfall events over a long period ● Assigned probability of 0.05 for case where sliding does not regress upslope based on Glastonbury and Fell method (refer to PSM 2009). ● Probability assessed using the Glastonbury and Fell method is 0.45 if upslope regression occurs (refer to PSM 2009).	0.45 (if sliding regresses upslope) 0.05 (if upslope sliding does not occur)
Do the Waves Overtop the Dam?	● Slide is not in direct path to dam (dam face oblique to wave direction) and would require waves to reflect off Elwari Mountain ● Analysis by PSM indicates only relatively small wave heights if the slide moves extremely rapidly (7.6m waves for 2D analysis, and <0.1m allowing for 3D effects of waves reaching the dam). ● The amount of freeboard for the 1 in 100 flood event (i.e. height between maximum reservoir level and crest level of the dam) is 5.5m - this is less than the FSL condition but still larger than the predicted wave runup on the face of the dam ● Assigned event probability of 0.0005 - 5 times higher then the reservoir full condition.	0.0005 (if sliding regresses upslope) 0.0005 (if sliding does not regress upslope)
Does the Dam Breach?	● If waves were to overtop the dam, then these would be for only short duration and small volume ● The crest will be sealed and the parapet wall heel buried, so the crest is unlikely to be affected by small waves overtopping the crest ● Waves would need to erode out about the upper 5m of the embankment, can't envisage this for small short duration wave overtopping. ● Assigned event probability of 0.0001 for breach given overtopping - no plausible scenario could be identified (same as for reservoir full condition).	0.0001 (if sliding regresses upslope) 0.0001 (if sliding does not regress upslope)

TILLEGRA DAM STORAGE RIM LANDSLIDE RISK ASSESSMENT

Domain: ***2***

Loading Case: ***Probable Maximum Flood Event***

Loading Condition	Reasoning	Assigned Probability
Does the Loading Event Occur?	Probable Maximum Flood (PMF) event has an estimated AEP of 1 in 10,000,000	0.0000001
Does the Exisiting Slide Re-activate?	● Mechanism of movement for Slide 2A is rainfall induced saturation of the slide mass ● Evidence of rainfall induced movement of Slide 2A in the June 2007 rainfall event - many rainfall events in the historic record of similar or larger magnitude ● A PMP rainfall event is likely to saturate the slope - stability analysis indicates FOS <1.0 for saturated condition	1.0
Does Sliding Regress Upslope?	● Geomorphology indicates lower slide 2A has moved in the past, but no evidence of regression of the upper creep zone into a slide ● A PMP rainfall event is likely to saturate the slope	0.01
Is the Velocity of Movement Extremely Rapid?	● Surface of rupture is already at residual strength ● The toe area is a thick "shove zone" of breacciated rock - this is not expected to give a brittle release mechanism. ● Past performance shows long history of slow movements despite high rainfall events over a long period ● Assigned probability of 0.05 for case where sliding does not regress upslope based on Glastonbury and Fell method (refer to PSM 2009). ● Probability assessed using the Glastonbury and Fell method is 0.45 if upslope regression occurs (refer to PSM 2009).	0.45 (if sliding regresses upslope) 0.05 (if upslope sliding does not occur)
Do the Waves Overtop the Dam?	● Slide is not in direct path to dam (dam face oblique to wave direction) and would require waves to reflect off Elwari Mountain ● Analysis by PSM indicates only relatively small wave heights if the slide moves extremely rapidly (7.6m waves for 2D analysis, and <0.1m allowing for 3D effects of waves reaching the dam). ● The minimum amount of freeboard for the PMF flood event (i.e. height between maximum reservoir level reached and the crest level of the dam) is 1.2m - this is still larger than the predicted wave runup on the face of the dam allowing for 3D effects and need for waves to reflect off Elwari Mountain ● Assigned event probability of 0.01 - can think of several scenarios.	0.01 (if sliding regresses upslope) 0.01 (if sliding does not regress upslope)
Does the Dam Breach?	● If waves were to overtop the dam, then these would be for only short duration and small volume ● The crest will be sealed and the parapet wall heel buried, so the crest is unlikely to be affected by small waves overtopping the crest ● Waves would need to erode out about the upper 1.2m of the embankment, difficult to envisage this for short duration wave overtopping. ● Assigned event probability of 0.01 for breach given overtopping - not observed in the database, but can think of several scenarios	0.01 (if sliding regresses upslope) 0.01 (if sliding does not regress upslope)

TILLEGRA DAM STORAGE RIM LANDSLIDE RISK ASSESSMENT

Domain: ***2***

Loading Case: ***Maximum Design Earthquake Event***

Loading Condition	Reasoning	Assigned Probability
Does the Loading Event Occur?	Maximum Design Earthquake (MDE) event has an AEP of 1 in 10,000	0.0001
Does the Exisiting Slide Re-activate?	● Earthquake loading is unlikely to coincide with a very wet period - unlikely coincidence of with an extreme loading event ● Earthquake would tend to temporarily reduce the FOS during the earthquake - may re-activate sliding - ● Assign a probability 5 times greater than for th ereservoir full condition.	0.05
Does Sliding Regress Upslope?	● There is an upper creep zone surrounding Slide 2A to the north, northeast and east, about 1.5m to 2.0m deep, periodic creep movement (about 200,000 m^3 in size). ● Lower slide has moved, but no evidence of regression of the creep zone into a landslide ● Creep zone unaffected by storage filling (well above FSL storage level) ● Assigned probability of 0.001- difficult to think of a scenario	0.001
Is the Velocity of Movement Extremely Rapid?	● Surface of rupture is already at residual strength ● The toe area is a thick "shove zone" of breacciated rock - this is not expected to give a brittle release mechanism. ● Past performance shows long history of slow movements despite high rainfall events over a long period ● Assigned probability of 0.05 for case where sliding does not regress upslope based on Glastonbury and Fell method (refer to PSM 2009). ● Probability assessed using the Glastonbury and Fell method is 0.45 if upslope regression occurs (refer to PSM 2009).	0.45 (if sliding regresses upslope) 0.05 (if upslope sliding does not occur)
Do the Waves Overtop the Dam?	● Slide is not in direct path to dam (dam face oblique to wave direction) and would require waves to reflect off Elwari Mountain ● Analysis by PSM indicates only relatively small wave heights if the slide moves extremely rapidly (7.6m waves for 2D analysis, and <0.1m allowing for 3D effects of waves reaching the dam). ● The freeboard at FSL (i.e. height between FSL and crest level of the dam) is 7.9m - this is larger than the predicted wave runup on the face of the dam ● Assigned event probability of 0.0001 - no plausible scenario could be identified.	0.0001 (if sliding regresses upslope) 0.0001 (if sliding does not regress upslope)
Does the Dam Breach?	● If waves were to overtop the dam, then these would be for only short duration and small volume ● The crest will be sealed and the parapet wall heel buried, so the crest is unlikely to be affected by small waves overtopping the crest ● Waves would need to erode out about the upper 8m of the embankment, can't envisage this for small short duration wave overtopping. ● Assigned event probability of 0.0001 for breach given overtopping - no plausible scenario could be identified.	0.0001 (if sliding regresses upslope) 0.0001 (if sliding does not regress upslope)

TILLEGRA DAM STORAGE RIM LANDSLIDE RISK ASSESSMENT

Domain: ***5***

Loading Case: ***Reservoir Full Event***

Loading Condition	Reasoning	Assigned Probability
Does the Loading Event Occur?	Reservoir filling assumed to occur each year	1
Does a New Slide Activate? (First time slide)	● At Location 5A, there is thickly bedded sandstone, bedding parallel to ground surface ● Would require a breakout at the toe, but outcrops show massive sandstone in the toe region with exposures 20m by 15m showing no defects. ● The potential slide mass is 50m above storage level - hence it would not be affected by storage operations ● Slightly weathered or better quality rock, widely spaced joints in rock mass ● Extent/size of slide limited by need to break through rock mass ● Assigned a probability for activating a new deep seated slide of 10^{-6} based on; Probabilty of release mechanism of 0.01 (potential unknown scenario/feature for toe break out), and Probability of activiating given a release mechanism of 0.0001 (no evidence of any creep, incipent sliding or previous sliding, rock outcrops have probably been present for thousands of years). ● Assigned a probability for activating a new shallow slide (i.e single bed thickness) of 10^{-4}	0.000001 (for deep seated slide) 0.0001 (for shallow slide)
Is the Velocity of Movement Extremely Rapid?	● If fist time slide were to activate, then it would be extremely rapid movement due to the brittle nature of the rock mass, and relatively steep slide surface (32 - 36 degrees towards the reservoir)	1.0 (for deep seated slide) 1.0 (for shallow slide)
Do the Waves Overtop the Dam?	● Estimated slide volume is in the order of 1 million m^3 for deep slide and 300,000 m^3 slide ● The estimated wave heights for an extremely rapid slide of this size is in the order of 10.6m for 2D analysis and ≤ 0.1m allowing for 3D effects. ● No direct path from slide to dam, dam face oblique to wave direction and would require waves to reflect off Elwari Mountain (the wave height analysis conservatively assumed no attenuation of the wave height after reflecting off Elwari Mountain). ● The freeboard at FSL (i.e. height between FSL and crest level of the dam) is 7.9m - this is much larger than the predicted wave runup on the face of the dam ● Assigned event probability of 0.5 for deep slide and 0.001 for shallow slide	0.5 (deep seated slide) 0.001 (shallow slide)
Does the Dam Breach?	● If waves were to overtop the dam, then these would be for only short duration and small volume ● The crest will be sealed and the parapet wall heel buried, so the crest is unlikely to be affected by small waves overtopping the crest ● Waves would need to erode out about the upper 8m of the embankment, can't envisage this for small short duration wave overtopping. ● Assigned event probability of 0.0001 for breach given overtopping - no plausible scenario could be identified.	0.001 (deep seated slide) 0.0001 (shallow slide)

TILLEGRA DAM STORAGE RIM LANDSLIDE RISK ASSESSMENT

Domain: ***5***

Loading Case: ***1 in 100 Year Rainfall Event***

Loading Condition	Reasoning	Assigned Probability
Does the Loading Event Occur?	1 in 100 Annual Exceedance Probability (AEP) rainfall event	0.01
Does a New Slide Activate? (First time slide)	● At Location 5A, there is thickly bedded sandstone, bedding parallel to ground surface ● Would require a breakout at the toe, but outcrops show massive sandstone in th etoe region with exposures 20m by 15m showing no defects. ● The potential slide mass is 50m above storage level - hence it would not be affected by storage operations ● Slightly weathered or better quality rock, widely spaced joints in rock mass ● Extent/size of slide limited by need to break through rock mass ● Assigned a probability for activating a new deep seated slide two times greater than the reservoir full condition - slight increase in likelihood due to likely saturation of the slope during the rainfall event.	0.000002 (for deep seated slide) 0.0002 (for shallow slide)
Is the Velocity of Movement Extremely Rapid?	● If fist time slide were to activate, then it would be extremely rapid movement due to the brittle nature of the rock mass, and relatively steep slide surface (32 - 36 degrees towards the reservoir)	1.0 (for deep seated slide) 1.0 (for shallow slide)
Do the Waves Overtop the Dam?	● Estimated slide volume is in the order of 1 million m^3 for deep slide and 300,000 m^3 slide ● The estimated wave heights for an extremely rapid slide of this size is in the order of 10.6m for 2D analysis and ≤ 0.1m allowing for 3D effects. ● No direct path from slide to dam, dam face oblique to wave direction and would require waves to reflect off Elwari Mountain (the wave height analysis conservatively assumed no attenuation of the wave height after reflecting off Elwari Mountain). ● The freeboard for 1 in 100 flood event (i.e. height between max reservoir level and crest level of the dam) is 5.5m - this is larger than the predicted wave runup on the face of the dam ● Assigned event probability of 0.7 for deep slide and 0.001 for shallow slide	0.7 (deep seated slide) 0.001 (shallow slide)
Does the Dam Breach?	● If waves were to overtop the dam, then these would be for only short duration and small volume ● The crest will be sealed and the parapet wall heel buried, so the crest is unlikely to be affected by small waves overtopping the crest ● Waves would need to erode out about the upper 5m of the embankment, can't envisage this for small short duration wave overtopping. ● Assigned event probability of 0.0001 for breach given overtopping - no plausible scenario could be identified.	0.001 (deep seated slide) 0.0001 (shallow slide)

TILLEGRA DAM STORAGE RIM LANDSLIDE RISK ASSESSMENT
Domain: ***5***
Loading Case: ***Probable Maximum Flood Event***

Loading Condition	Reasoning	Assigned Probability
Does the Loading Event Occur?	Probable Maximum Flood (PMF) event has an estimated AEP of 1 in 10,000,000	0.0000001
Does a New Slide Activate? (First time slide)	● At Location 5A, there is thickly bedded sandstone, bedding parallel to ground surface ● Would require a breakout at the toe, but outcrops show massive sandstone in th etoe region with exposures 20m by 15m showing no defects. ● The potential slide mass is 50m above storage level - hence it would not be affected by storage operations ● Slightly weathered or better quality rock, widely spaced joints in rock mass ● Extent/size of slide limited by need to break through rock mass ● Assigned a probability for activating a new deep seated slide two times greater than the reservoir full condition - slight increase in likelihood due to likely saturation of the slope during the rainfall event.	0.000002 (for deep seated slide) 0.0002 (for shallow slide)
Is the Velocity of Movement Extremely Rapid?	● If first time slide were to activate, then it would be extremely rapid movement due to the brittle nature of the rock mass, and relatively steep slide surface (32 - 36 degrees towards the reservoir)	1.0 (for deep seated slide) 1.0 (for shallow slide)
Do the Waves Overtop the Dam?	● Estimated slide volume is in the order of 1 million m^3 for deep slide and 300,000 m^3 slide ● The estimated wave heights for an extremely rapid slide of this size is in the order of 10.6m for 2D analysis and ≤ 0.1m allowing for 3D effects. ● No direct path from slide to dam, dam face oblique to wave direction and would require waves to reflect off Elwari Mountain (the wave height analysis conservatively assumed no attenuation of the wave height after reflecting off Elwari Mountain). ● The freeboard at PMF (i.e. height between PMF reservoir level and crest level of the dam) is 1.2m - waves from large slide is likely to overtop the dam in this scenario ● Assigned event probability of 0.9 for deep slide and 0.01 for shallow slide	0.9 (deep seated slide) 0.05 (shallow slide)
Does the Dam Breach?	● Breach is likely if large slide occurs when there is only 1.2 m freeboard - waves unravel downstream rockfill face. ● For shallow slide, breach is less likely. Can think of several scenarios, assigned probability of 0.05.	0.5 (deep seated slide) 0.05 (shallow slide)

TILLEGRA DAM STORAGE RIM LANDSLIDE RISK ASSESSMENT
Domain: ***5***
Loading Case: ***Maximum Design Earthquake Event***

Loading Condition	Reasoning	Assigned Probability
Does the Loading Event Occur?	Maximum Design Earthquake (MDE) event has an AEP of 1 in 10,000	0.0001
Does a New Slide Activate? (First time slide)	● At Location 5A, there is thickly bedded sandstone, bedding parallel to ground surface ● Would require a breakout at the toe, but outcrops show massive sandstone in the toe region with exposures 20m by 15m showing no defects. ● Earthquake increases likelihood of slide activating - potential for breakout through rock mass at the toe ● For deep seated slide, assigned a probability 10 times greater than the reservoir full condition. ● For shallow slide, assigned a probability 15 times greater than the reservoir full condition.	0.00001 (for deep seated slide) 0.005 (for shallow slide)
Is the Velocity of Movement Extremely Rapid?	● If fist time slide were to activate, then it would be extremely rapid movement due to the brittle nature of the rock mass, and relatively steep slide surface (32 - 36 degrees towards the reservoir)	1.0 (for deep seated slide) 1.0 (for shallow slide)
Do the Waves Overtop the Dam?	● Estimated slide volume is in the order of 1 million m^3 for deep slide and 300,000 m^3 slide ● The estimated wave heights for an extremely rapid slide of this size is in the order of 10.6m for 2D analysis and ≤ 0.1m allowing for 3D effects. ● No direct path from slide to dam, dam face oblique to wave direction and would require waves to reflect off Elwari Mountain (the wave height analysis conservatively assumed no attenuation of the wave height after reflecting off Elwari Mountain). ● The freeboard at FSL (i.e. height between FSL and crest level of the dam) is 7.9m - this is much larger than the predicted wave runup on the face of the dam allowing for 3D effects reaching the dam ● Assigned event probability of 0.5 for deep slide and 0.001 for shallow slide	0.5 (deep seated slide) 0.001 (shallow slide)
Does the Dam Breach?	● If waves were to overtop the dam, then these would be for only short duration and small volume ● The crest will be sealed and the parapet wall heel buried, so the crest is unlikely to be affected by small waves overtopping the crest ● Waves would need to erode out about the upper 8m of the embankment, can't envisage this for small short duration wave overtopping. ● Assigned event probability of 0.0001 for breach given overtopping - no plausible scenario could be identified.	0.001 (deep seated slide) 0.0001 (shallow slide)

TILLEGRA DAM STORAGE RIM LANDSLIDE RISK ASSESSMENT
Domain: ***5***
Loading Case: ***Maximum Design Earthquake Event***

Loading Condition	Reasoning	Assigned Probability
Does the Loading Event Occur?	Maximum Design Earthquake (MCE) event has an AEP of 1 in 100,000	0.00001
Does a New Slide Activate? (First time slide)	● At Location 5A, there is thickly bedded sandstone, bedding parallel to ground surface ● Would require a breakout at the toe, but outcrops show massive sandstone in the toe region with exposures 20m by 15m showing no defects. ● Earthquake increases likelihood of slide activating - potential for breakout through rock mass at the toe ● For deep and shallow seated slides, assigned a probability 100 times greater than the reservoir full condition.	0.0001 (for deep seated slide) 0.01 (for shallow slide)
Is the Velocity of Movement Extremely Rapid?	● If fist time slide were to activate, then it would be extremely rapid movement due to the brittle nature of the rock mass, and relatively steep slide surface (32 - 36 degrees towards the reservoir)	1.0 (for deep seated slide) 1.0 (for shallow slide)
Do the Waves Overtop the Dam?	● Estimated slide volume is in the order of 1 million m^3 for deep slide and 300,000 m^3 slide ● The estimated wave heights for an extremely rapid slide of this size is in the order of 10.6m for 2D analysis and ≤ 0.1m allowing for 3D effects. ● No direct path from slide to dam, dam face oblique to wave direction and would require waves to reflect off Elwari Mountain (the wave height analysis conservatively assumed no attenuation of the wave height after reflecting off Elwari Mountain). ● The freeboard at FSL (i.e. height between FSL and crest level of the dam) is 7.9m - this is much larger than the predicted wave runup on the face of the dam allowing for 3D effects reaching the dam ● Assigned event probability of 0.5 for deep slide and 0.001 for shallow slide	0.5 (deep seated slide) 0.001 (shallow slide)
Does the Dam Breach?	● If waves were to overtop the dam, then these would be for only short duration and small volume ● The crest will be sealed and the parapet wall heel buried, so the crest is unlikely to be affected by small waves overtopping the crest ● Waves would need to erode out about the upper 8m of the embankment, can't envisage this for small short duration wave overtopping. ● Assigned event probability of 0.0001 for breach given overtopping - no plausible scenario could be identified.	0.001 (deep seated slide) 0.0001 (shallow slide)