Estling Lake Dam Potential Failure Mode Analysis

New Jersey Transit

October 2020

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1 Background

The New Jersey Transit (NJ Transit) Railroad Right-of-Way on the Morristown Line in the vicinity of Milepost 34.58 forms an embankment serving as the earth fill dam for the Estling Lake impoundment. It includes a spillway owned by the Estling Lake Corporation and the embankment owned by NJ Transit. See **Figures G-1** and **G-2**.

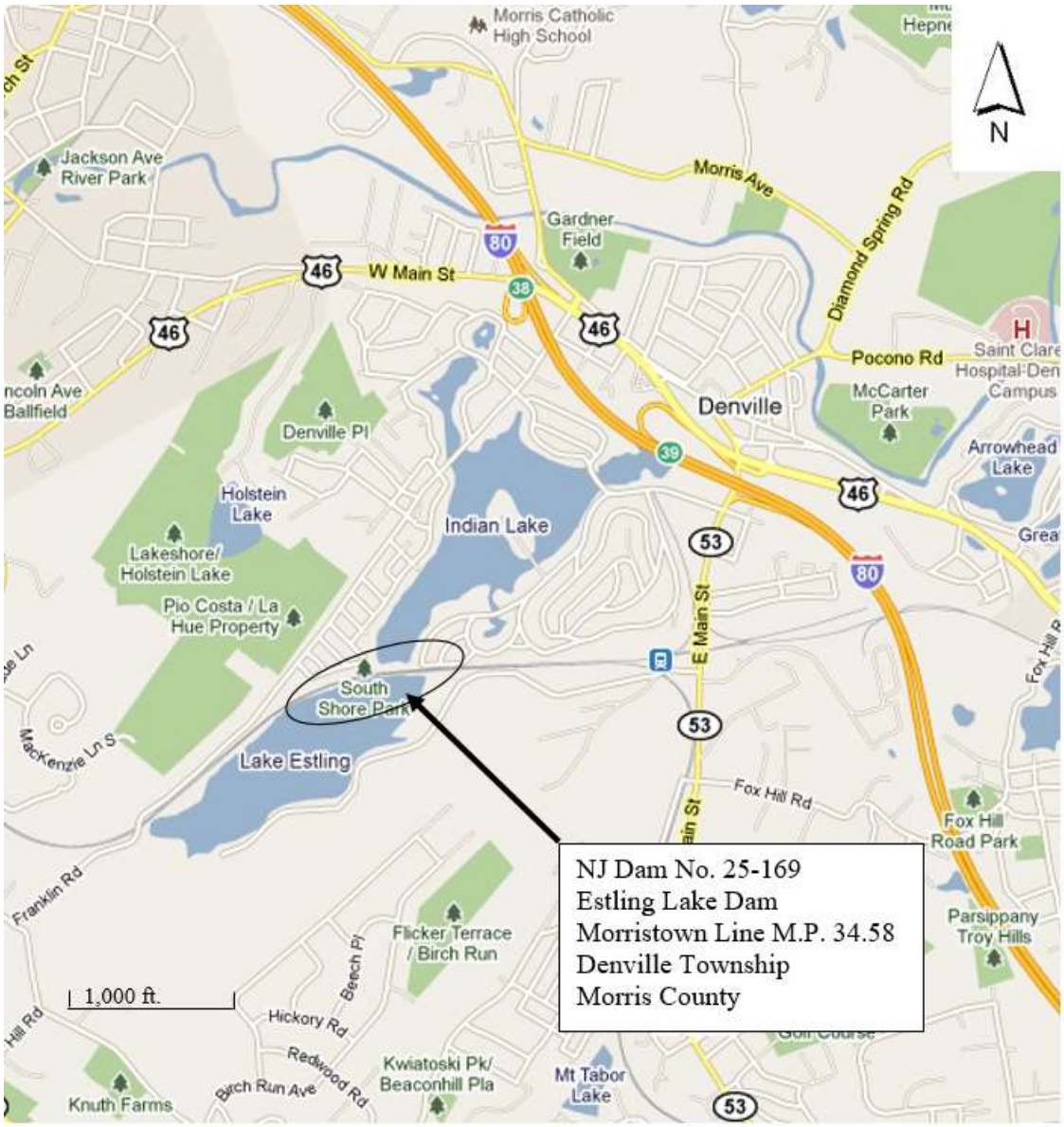

Figure G-1. Site Location

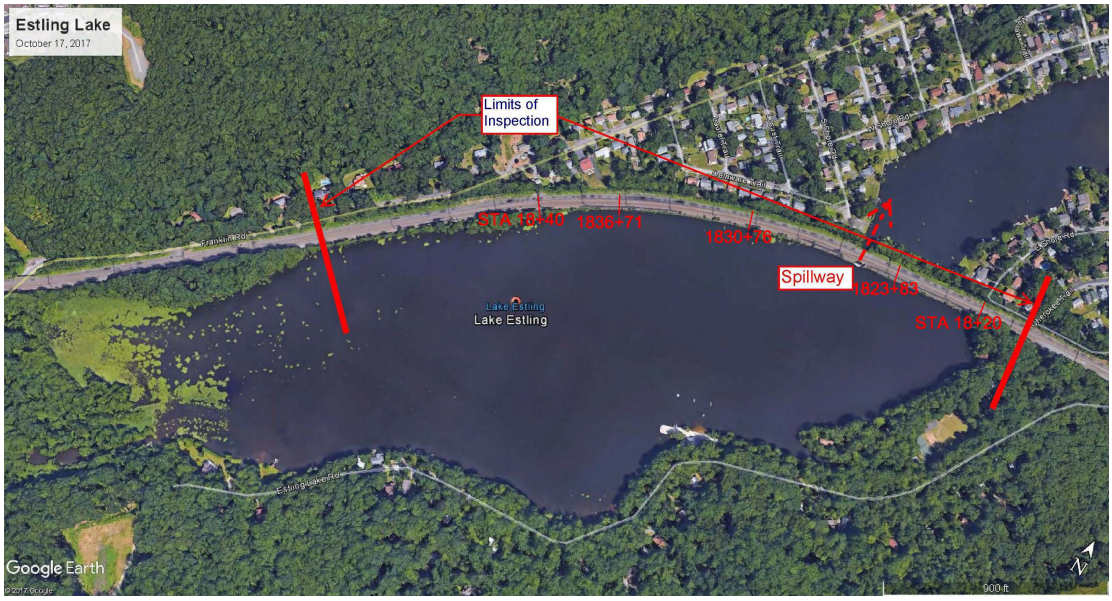

Figure G-2. Estling Lake Limits of Inspection from Formal Inspection Report

A Formal Inspection Report for Estling Lake Dam was submitted to NJDEP on September 5, 2018. The recommendations in this report require that NJ Transit submit the following additional documents to NJDEP:

1. Hydrologic & Hydraulic Evaluation
2. Potential Dam Failure Mode Analysis
3. Spillway and Embankment Stability Evaluation

The Hydrologic & Hydraulic Evaluation was completed in 2019. The Spillway and Embankment Stability Evaluation was submitted in February 2020.

The Potential Dam Failure Mode Analysis was held on August 6, 2020 and the results are described herein.

1.1 Site History

Estling Lake Dam is located in Denville, New Jersey, about 28 miles west of New York, New York. The earthen embankment dam was constructed in 1894, and includes two railroad tracks that are part of New Jersey Transit's Morristown Line. The location of Estling Lake is shown on the Site Location map in Figure G-1.

The dam consists of an approximately 2,000-foot long earthen embankment with a maximum height of 19.0 feet. The crest of the dam is approximately 50-feet wide, with slopes varying from 5:1 (horizontal to vertical) to less than 1:1 (horizontal to vertical) at the upstream slope and 1.5:1 (horizontal to vertical) to 2:1 (horizontal to vertical) at the downstream slope.

The spillway is centrally located on the embankment, and is comprised of an arched masonry design constructed of large granite blocks with a stepped box arrangement. The formal inspection report for the Estling Lake Dam indicated cracking was evident at the masonry spillway. Crack Mapping of the arched masonry spillway at Estling Lake Dam is included as Appendix B-1. A structural stability evaluation of the arched masonry spillway was performed as part of this report and expanded on in Section 5.0.

The lake drain structure is located east of the spillway entrance, and consists of a manually controlled 24-inch low-level outlet pipe valve.

Dam characteristics have been summarized in **Table G-1** below.

Table G-1. Dam Characteristics

General Information	
NJ File Number	25-169
Hazard Classification	Class I
County	Morris
Owner(s)	New Jersey Transit Corporation (Embankment) and Estling Lake Corporation (Spillway)
Structural Information	
Construction	1894
Drainage Area	6.44 square miles
Type of Impoundment	Earthen Embankment, Railroad Embankment
Embankment Length	2,000 feet
Embankment Height	19.0 feet
Top Width	50 feet
Upstream Slope	Varies 5H:1V to <1H:1V
Downstream Slope	Varies 1.5H:1V to 2H:1V
Lake Drain	24” low level outlet at east wingwall; Manually operated
Control Structure	Uncontrolled Stone Masonry Arched Spillway
Spillway	37-foot wide arched masonry design with stepped box arrangement
Key Elevations	
	Elevation (NGVD29 Datum)
Embankment Crest	Varies along length: 525.0 to 527.3 ft.
Principal Spillway	515.5 ft. (design elevation)

The Estling Lake Dam is classified as a Class I dam in accordance with Section N.J.A.C. 7:20-1.9 of the New Jersey Dam Safety Standards due to its ability to cause probable loss of life or extensive property damage should failure occur.

2 Evaluation Objectives

The objective of the Estling Lake Potential Failure Mode Analysis (PFMA) is to identify potential modes of failure for the dam in order to evaluate what measures may be taken to reduce either a) the likelihood that failure of the dam will occur and/or b) the consequences if the dam should fail. The results of the PFMA will be used to assist in focusing the future scope of work for the rehabilitation design.

This PFMA does not consider:

- The need to rehabilitate the dams to meet New Jersey dam safety regulations: While some deficiencies may not be considered a priority compared to other deficiencies, the regulations will likely still require modifications to address dam safety deficiencies, particularly where the dams do not meet specific regulatory criteria.
- Consequences other than loss of life: The PFMA did not include evaluation of consequences other than the estimated loss of life from flooding resulting from a dam breach. Other consequences could include, but are not limited to, lost benefits (recreation, flood protection), damage to property, economic impacts, owner liability and reputation, etc.
- Only dam failure risks were evaluated: Potential risks related to normal operations or improper operation of the dams, spillways, or outlet works were not considered. Potential risks related to malevolent acts were also not considered explicitly.

3 Risk Assessment Overview

3.1 Methods

Several agencies, including the US Bureau of Reclamation (Reclamation) and the US Army Corps of Engineers (USACE), have implemented the use of risk assessment to assist in evaluating and prioritizing dam modifications at both the portfolio and project level. Risks are typically portrayed graphically using charts that plot the likelihood of failure versus the consequences. One of these tools is called the f-N chart, which presents estimated number of lives that would be lost (N) on the x axis and the annualized probability of the failure (f) on the y axis.

This risk assessment was performed using methods generally consistent with Semi Quantitative Risk Assessment (SQRA) performed by Reclamation and USACE. For example, as part of their Periodic Assessments, USACE performs a PFMA and a SQRA. This typically consists of a review of the project history/issues and a week (or more)-long workshop with a team of engineers and geologists. For comparison, the PFMA performed for Estling Lake Dam included a review of the documents obtained from NJ Transit and consisted of a one-day risk workshop. Therefore, this PFMA is considered less comprehensive than those typically performed by USACE or Reclamation.

The identification of potential failure modes is the critical first step in a risk assessment. The team (facilitator and experts) reviewed available project data, reviewed previous site visit photographs, and then brainstormed potential failure modes (PFMs) to identify whether they were risk drivers and worthy of further evaluation as part of the PFMA. Detailed descriptions of each failure mode were developed to assist in quantifying probabilities of failure.

Once failure modes are identified and described, the probability and consequences of the failure are categorized, using the descriptions presented in Tables R-1 and R-2, which are based upon USACE ER-1110-2-1156, Safety of Dams – Policy and Procedures.

Table R-1. Failure Likelihood Categories

Category Name	Category Description
Remote	Several events must occur concurrently or in series to cause failure. Most, if not all, of the events are unlikely to very unlikely, and failure potential is negligible.
Low	The possibility cannot be ruled out, but there is no compelling evidence to suggest it has occurred or that a condition or flaw exists that could lead to its development (e.g., a flood or an earthquake with an annual exceedance probability more remote than 1 E-05/yr. would likely cause failure).
Moderate	The fundamental condition or defect is known to exist; indirect evidence suggests it is plausible; and key evidence is weighted more heavily toward unlikely than likely (e.g., a flood or an earthquake with an annual exceedance probability between 1 E-05/yr. and 1E-04/yr. would likely cause failure).
High	The fundamental condition or defect is known to exist; indirect evidence suggests it is plausible; and key evidence is weighted more heavily toward likely than unlikely (e.g., a flood or an earthquake with an annual exceedance probability between 1 E-04/yr. and 1 E-03/yr. would likely cause failure).
Very High	There is direct evidence or substantial indirect evidence to suggest it has occurred and/or is likely to occur (e.g., a flood or an earthquake with an annual exceedance High probability more frequent (greater) than 1 E-03/yr. would likely cause failure).

Table R-2. Consequence of Failure Categories

Category Name	Category Description
Level 0	No significant impacts to the downstream population other than temporary minor flooding of roads or land adjacent to the river.
Level 1	Although life threatening flows are released and people are at risk, loss of life is unlikely.
Level 2	Some life loss is expected (in the range of 1 to 10).
Level 3	Large life loss is expected (in the range of 10 to 100).
Level 4	Extensive life loss is expected (greater than 100).

Each of the failure modes evaluated was evaluated on a 5 x 5 risk matrix, shown as Figure R-1, where highest risks are represented in the upper right portion of the matrix. The matrix generally corresponds to a section of the f-N charts used by many dam safety agencies, as illustrated by the numbers in italics.

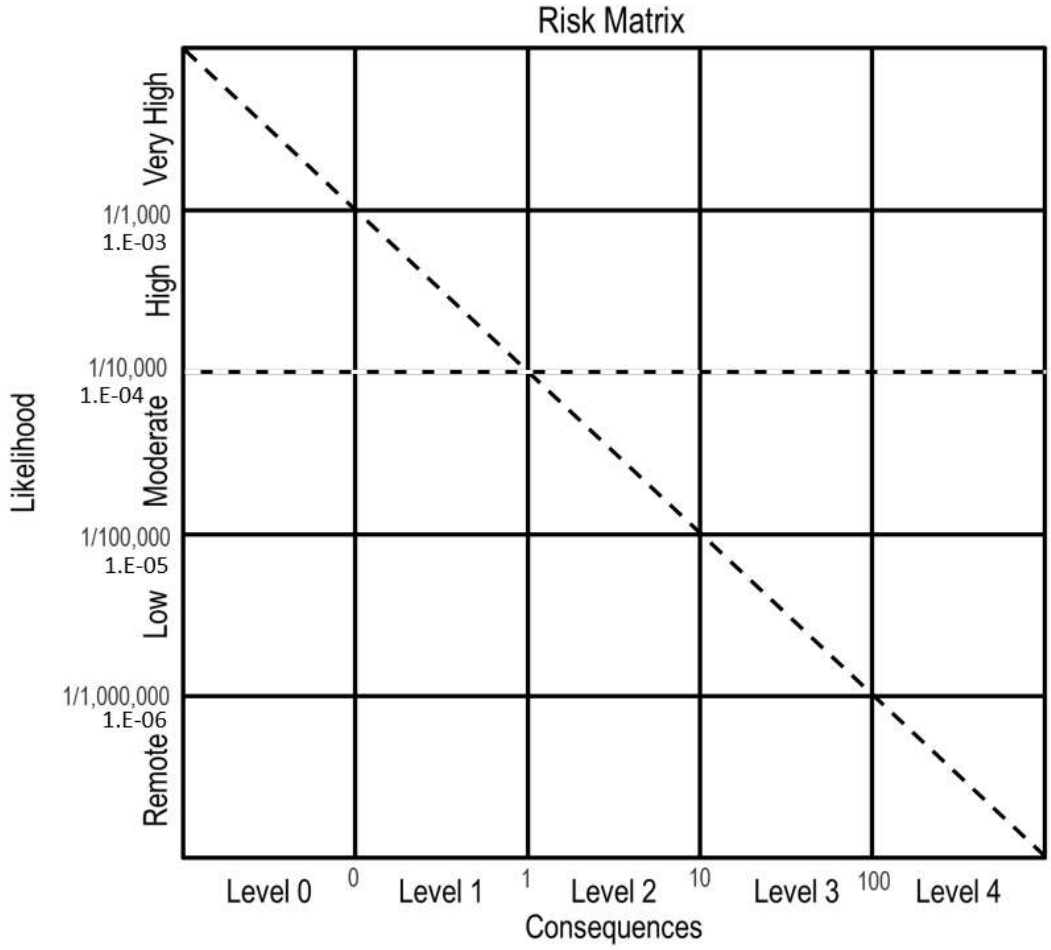

Figure R-1. Semi Quantitative Risk Matrix

After estimating the risks related to a given PFM, confidence in the risk estimates is discussed and a confidence category is assigned, in accordance with Table R-3 (based on USACE ER-1110-2-1156). The discussion of confidence also includes identification of data gaps and possible field investigations or analyses that could be used to fill these gaps.

Table R-3. Confidence Categories

Category Name	Category Description
Low	Confidence in the estimated category is low. Key additional information could very well change the assigned category.
Moderate	Confidence in the estimated category is in between High and Low. It is highly uncertain whether additional information would change the assigned category.
High	Confidence in the estimated category is high. It is unlikely that additional information would change the assigned category.

3.2 Approach

Prior to the risk workshop, previous analyses and available data were reviewed and compiled to inform the team to estimate probabilities for hydrologic and seismic loadings. For hydrologic loadings, a previous hydrologic and hydraulic study, Updated Hydrologic and Hydraulic Analysis Report dated January 2019 by SWM Consulting, was referenced. For geotechnical background, a previous geotechnical study, Estling Lake Dam Spillway and Embankment Stability Evaluation dated February 2020, was referenced.

Consequence estimates were developed from the dam breach analysis and inundation maps contained within the aforementioned report. No new breach analyses were performed to develop these estimates.

A day long workshop was facilitated on August 6th, 2020 to develop risk estimates for the identified risk driving failure modes.

3.3 Loadings and Probabilities

The loadings typically considered in a PFMA and risk analysis for a dam are hydrologic (flood) and seismic (earthquake). Detailed analyses were not performed to estimate the probabilities associated with these events.

The above-referenced H&H analyses formed the basis for updated estimates for inflow, outflow, and peak lake elevation for various flood events. To inform the team in estimating failure likelihoods, the team reviewed the spillway capacity and the resulting overtopping flows expected for the 0.4 and 0.5 Probable Maximum Precipitation (PMP) events. Inflow estimates for return period storms were plotted and extrapolated to extreme probabilities (i.e. 1E-06) and compared with the spillway capacity, as shown in Figure R-2.

This is considered to be a crude method for estimating extreme flood probabilities; however, there was no other credible data available. It is noted that for other dam safety studies, the PMP has been estimated to have a return period ranging from about 10,000 to over 1,000,000 years. Estimates performed for this study indicate that the spillway has capacity to pass a storm with a return period of approximately 1,000 years. The 0.5 PMP event is approximately a 5,000 - 9,000 year event. As noted above, this information was used to inform the PMFA team in developing likelihood of failure estimates; the team was given the latitude to consider the validity of these estimates.

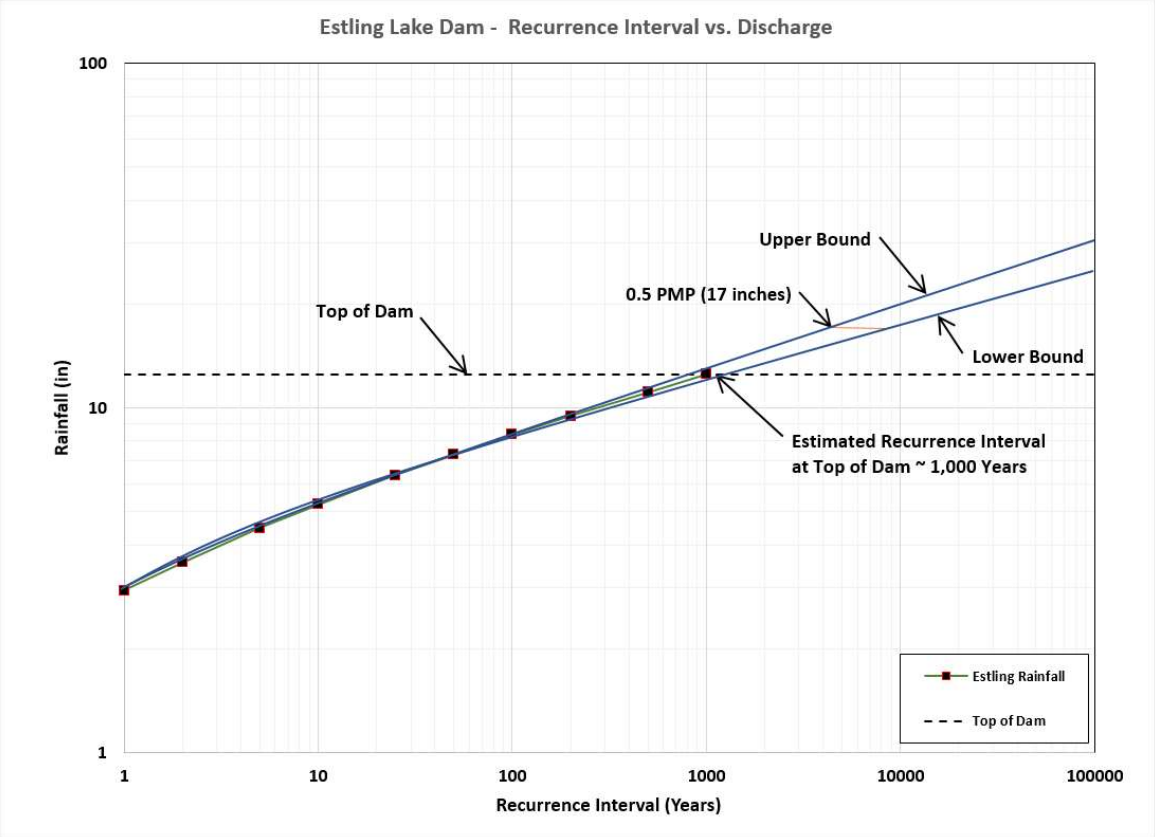

Figure R-2. Hydrologic Loading Estimates

PFMs from seismic loadings were informed based on available USGS seismic maps (https://www.usgs.gov/media/images/2014-seismic-hazard-map-new-jersey) which is also provided below.

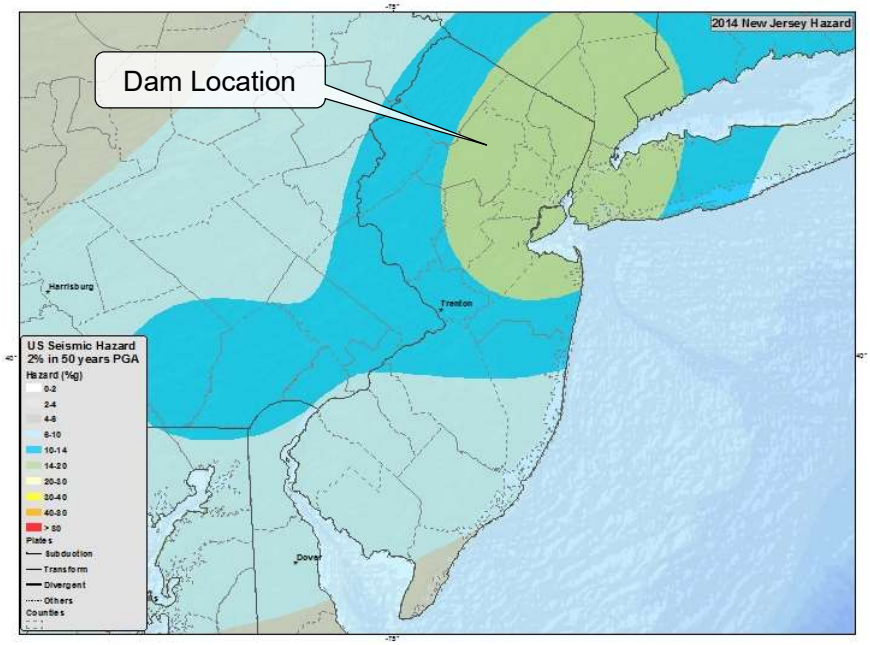

Figure R-3. 2014 Seismic Hazard Map of State of New Jersey

The PFMs were described as a series of events that contribute to the failure of the dam and to inform the team of their overall likelihood estimates (Table R-1); probabilities of each of these events were then developed and discussed. Verbal descriptors adopted by Reclamation (USACE/Reclamation, 2015), shown in Table R-4, were used for this process.

Table R-4. Verbal Descriptions Adopted by Reclamation

Descriptor	Assigned Probability
Virtually Certain	0.999
Very Likely	0.99
Likely	0.9
Neutral	0.5
Unlikely	0.1
Very Unlikely	0.01
Virtually Impossible	0.001

3.4 Consequences

To help inform the team in categorizing the potential consequences of each PFM, preliminary estimates of consequences were estimated from the inundation mapping within SWM Consulting's Updated Hydrologic and Hydraulic Analysis Report dated January, 2019. This report included inundation modeling and mapping for three conditions: (1) 0.5 PMP with dam failure; (2) 0.5 PMP without dam failure; and (3) Sunny day dam failure. The floodplain inundation mapping was used to estimate the number of structures impacted, along with the flooding depth at each structure. This data was then used to estimate population at risk (PAR) by assuming an average of 2.33 people per structure.

Consequence estimates should consider the "incremental" risk of a dam failure. In other words, impacts of the flood without a dam failure are not included in the estimated consequences of the dam failure. Inundation limits or PAR for the non-failure scenarios was not available; however, peak flows for the 100-year and PMF were available from the SWM Consulting's reports and were used to assist in informing team in estimating incremental consequences.

It is noted that PAR is not an estimate of life loss; it is an estimate of the number of people potentially located within the inundation zone for each dam and flooding category. Two references developed by Reclamation were used to convert the PAR estimates to life loss estimates. The method from Graham (1999), referred to as the DSO 99-06 Methodology, uses flood severity, warning time, and the public's understanding of flood severity to develop a "fatality rate," which is multiplied by PAR. The risk facilitator developed these estimates (presented in Tables R-5) and presented them to the team to help categorize the life loss consequences. It is noted that these estimates are total (not incremental) estimated PAR and life loss.

Table R-5. Consequence Estimates - DSO 99-06 Methods

Flow Scenario	Peak Flow (cfs)	Impacted Structures	PAR	Estimated Life Loss
PMF w/ Breach	19,862	393	916	9-27
PMF wo/ Breach	11,219	264	615	6-19
Sunny Day Breach	2,627	44	103	0-1

3.5 PFMA Workshop

The Potential Dam Failure Mode Analysis (PFMA) Workshop participants included a facilitator, dam safety technical experts, and representatives from the dam owner (NJ Transit and Estling Lake Corp.). The team is identified in Table R-6.

Table R-6. PFMA Workshop Team

Name	Organization	Role
David Althaver	NJ Transit	Dam Owner
Paul Falkowski	NJ Transit	Dam Owner
Alfred Edwards	Estling Lake Corp.	Dam Owner
Pete Davis	HDR	Project Principal
Chad Davis	HDR	Facilitator
Greg Yankey	HDR	Dams Expert - Geotechnical
Jason Abendroth	HDR	Dams Expert - Structural
Joseph Skupien	SWM Consulting	Dams Expert - Hydrology
Shivang Patel	AmerCom	Dams Expert - Geotechnical
Chris Bacchus	AmerCom	Dams Expert - Geotechnical

In preparation for the workshop, the team reviewed documentation for the dam, including past inspections, reports, various construction documentation, and available H&H and geotechnical models. The workshop was performed virtually on August 6th, 2020 utilizing video conferencing software. The workshop began with an overview of the risk process, presented by the facilitator, followed by presentations by the H&H, geotechnical, and structural experts, summarizing the components and construction of the dam, along with dam history and performance, and previous engineering analyses supporting identified issues or deficiencies.

The PFMA and SQRA portion of the process began with a presentation of the loading and consequence estimates, along with brainstorming to develop a list of PFMs to be considered. The team reviewed the list and identified the perceived highest risk PFMs. For each of these identified risk drivers, the team developed a detailed description of the PFM, from initiation through to a dam failure; each step of the event was listed in a table. The team then listed factors that suggest the PFM is more likely or less likely to occur.

The team then used available information to estimate the failure likelihood (Table R-1) and consequence category (Table R-2) for each PFM. A spreadsheet was used to document the various probabilities of each step of the event sequence, using verbal descriptors to assist the team in estimating likelihood.

The team then discussed confidence and uncertainty and developed a confidence category for the PFM, in accordance with Table R-3. Selected confidence categories were influenced by the degree of consensus of the team and availability (or lack of availability) of data or analyses to support the estimates. Data needs and potential analyses that would increase the level of confidence were identified for each failure mode.

4 PFMA Findings

Previous investigations and studies have shown the main issues at Estling Lake Dam to be:

- inadequate spillway capacity to safely convey the 0.5 PMP,
- vulnerability to embankment erosion,
- steep embankment slopes,
- concrete deterioration within culverts downstream of spillway weir,
- previous cracking of mortar within masonry spillway,
- one of the low level outlets is not functional, and
- insufficient drawdown capacity through low level outlet.

Several PFMs were discussed by the team and the following six PFMs were identified as possible risk drivers.

4.1 PFM H1: Overtopping of the Embankment (Inadequate Spillway Capacity)

Description: During an extreme flood event (0.5 PMP), the capacity of the spillway is exceeded and overtopping of the embankment occurs. Scouring of the embankment initiates and progresses to failure of the embankment and an uncontrolled release of the reservoir. Intervention is unsuccessful.

Failure Likelihood: The team identified the following factors related to the likelihood of this PFM.

Factors Making PFM "More Likely"	Factors Making PFM "Less Likely"
Prior studies have indicated that overtopping is possible. Overtopping initiates at the 0.4 PMP event. The overtopping depth of the most recent study for the 0.5 PMP is 1.7 ft. and has a duration of 2.8 hours.	The existing rails along the crest of the embankment provide an additional horizontal profile and reduce the concentration of flow, even within the low point of the embankment profile.
The downstream slope is very steep and near vertical in many locations. This slope results in reduced stability and concentrated flows that could increase erosion potential.	Gravel ballast composition includes a range of larger material which provides scour protection at lower flow rates.
At the top of the embankment is a railroad with rail and ties. Local scouring would be increased at the location of the rails and ties.	During a 0.5 PMP event, the Water Surface EL (WSEL) is approximately 513.5 ft., reducing the exposed embankment to about 12 feet. This tail water would dissipate energy of the overtopping flow traveling down the embankment and reduce the resulting scour at the toe of the dam.
There is a low point within the embankment which serves to concentrate flows and would increase velocities and scour potential.	

Likelihood: The likelihood estimate by the team was a Moderate.

Consequences: Based on the baseline estimates and discussions of the PFM, the consequence estimate by the team was a Level 2.

Confidence: Confidence for probability estimates is judged to be moderate for this failure mode. Confidence for consequence estimates is judged to be high because there is inundation mapping for both breach and non-breach PMP scenarios.

4.2 PFM G1: Internal Erosion - Railroad Bridge/Culvert - Perimeter Seepage

Description: During normal operations or a moderate flood (increased head), unfiltered seepage occurring along the Railroad Bridge/Culvert which initiates erosion (at downstream toe, into Bridge/Culvert etc.), erosion continues and progresses (along the Bridge/Culvert) until material loss is significant enough to cause a depression at the crest, resulting in loss of freeboard and an uncontrolled release of the reservoir.

Failure Likelihood: The team identified the following factors related to the likelihood of this PFM.

Factors Making PFM "More Likely"	Factors Making PFM "Less Likely"
This event can occur during moderate flood events and therefore does not require an extreme event to initiate the PFM.	
Available data do not indicate a drainage diaphragm is present around the bridge/culvert structures. Seepage along the structure is difficult to detect given the defect location and the composition of the ballast material.	The seepage path is long given the width of the embankment.
Uneven surfaces observed on both upstream and downstream slopes of embankment.	To date there have been no observed sinkholes within the embankment areas.
One of two low level outlets is operational and are relatively small diameter thus limiting capacity.	Train traffic is daily, which would provide opportunities for visual observation of sinkholes or other surface depressions.
The downstream slope is very steep and near vertical in many locations. This results in reduced stability and concentrated flows that could increase erosion potential.	
Ponding water has been noted on the downstream side of the embankment.	

Likelihood: The likelihood estimate by the team was a Low.

Consequences: Based on the baseline estimates and discussions of the PFM, the consequence estimate by the team was a Level 1.

Confidence: Confidence for probability estimates is judged to be moderate for this failure mode. The embankment is a variety of materials so additional investigation would be beneficial to further refine the subsurface profile, but given the inherent variability the confidence level would likely remain moderate. Confidence for consequence estimates is judged to be high because there is inundation mapping for the sunny day breach scenario.

4.3 PFM G2: Internal Seepage and Piping

Description: During normal operations or a moderate flood (increased head), unfiltered seepage occurring along a contact surface (at downstream toe, into foundation, etc.), erosion continues and progresses until material loss is significant enough to cause a depression at the crest (progressing from downstream to upstream), resulting in loss of freeboard and an uncontrolled release of the reservoir.

Failure Likelihood: The team identified the following factors related to the likelihood of this PFM.

Factors Making PFM "More Likely"	Factors Making PFM "Less Likely"
This event can occur during moderate flood events and therefore does not require an extreme event to initiate the PFM. Available data do not indicate a chimney drain or filtering layer is present within the embankment. Uneven surfaces have been observed on both the upstream and downstream slopes of the embankment. One of two low level outlets is operational and are relatively small diameter thus limiting capacity. The downstream slope is very steep and near vertical in many locations. This results in reduced stability and concentrated flows that could increase erosion potential. Ponding water has been noted on the downstream side of the embankment.	The seepage path is long given the width of the embankment. To date there have been no observed sinkholes within the embankment areas. Train traffic is daily, which would provide opportunities for visual observation of sinkholes or other surface depressions.

Likelihood: The likelihood estimate by the team was a Remote.

Consequences: Based on the baseline estimates and discussions of the PFM, the consequence estimate by the team was a Level 1.

Confidence: Confidence for probability estimates is judged to be moderate for this failure mode. The embankment is a variety of materials so additional investigation would be beneficial to further refine the subsurface profile, but given the inherent variability the confidence level would likely remain moderate. Confidence for consequence estimates is judged to be high because there is inundation mapping for the sunny day breach scenario.

4.4 PFM G3: Downstream Slope Stability

Description: During normal operations or a moderate flood (increased head/saturated soils), a slope failure occurs and progresses to loss of crest, which results in embankment overtopping and failure.

Failure Likelihood: The team identified the following factors related to the likelihood of this PFM.

Factors Making PFM "More Likely"	Factors Making PFM "Less Likely"
This event can occur during moderate flood events and therefore does not require an extreme event to initiate the PFM.	The seepage path is long given the width of the embankment.
Available data do not indicate a chimney drain or filtering layer is present within the embankment.	To date there have been no observed sinkholes within the embankment areas.
The soil profile beneath the embankment is inconsistent.	The ballast material provides an armoring effect for potential slips.
One of two low level outlets is operational and are relatively small diameter thus limiting capacity.	Train traffic is daily, which would provide opportunities for visual observation of sinkholes or other surface depressions.
The downstream slope is very steep and near vertical in many locations. This results in reduced stability and concentrated flows that could increase erosion potential.	
Ponding water has been noted on the downstream side of the embankment.	
Vegetation on the downstream slope inhibits visibility of the embankment slope.	

Likelihood: The likelihood estimate by the team was a Moderate.

Consequences: Based on the baseline estimates and discussions of the PFM, the consequence estimate by the team was a Level 1.

Confidence: Confidence for probability estimates is judged to be moderate for this failure mode. The embankment is a variety of materials so additional investigation would be beneficial to further refine the subsurface profile, but given the inherent variability the confidence level would likely remain moderate. Confidence for consequence estimates is judged to be high because there is inundation mapping for the sunny day breach scenario.

4.5 PFM S1: Progressive Failure of Downstream Bridges/Culverts

Description: Over time, scour of the downstream bridges/culverts results in loss of concrete inverts, resulting in instability of the structure's foundation, resulting in loss of embankment materials into failed bridges/culvert, progressing to loss of crest and uncontrolled release.

Failure Likelihood: The team identified the following factors related to the likelihood of this PFM.

Factors Making PFM "More Likely"	Factors Making PFM "Less Likely"
Most recent bridge inspection noted the presence of scour downstream of the structure. This was described as being 3.5ft deep and approximately 20ft downstream, just beyond the concrete apron slab.	The 1927 design documents indicate a concrete invert was placed within the structure.
Both structures are aged infrastructure given the original arch structure was constructed in 1870, followed by the upstream box structure which was constructed in 1927.	Structure is routinely inspected by NJ Transit according to NJDEP guidelines as well as Federal Railroad Administration guidelines. This Class I Dam is required to have a regular inspection (visual) every two years and a formal inspection (inspection and performance evaluation) every six years. The structures under the railroad require an annual inspection as per the Federal Railroad Administration, as well as an in-depth inspection every five years.
The foundation conditions of the original arch structure are unknown.	
The condition of the embankment material surrounding the structures is unknown.	

Likelihood: The likelihood estimate by the team was a Remote.

Consequences: Based on the baseline estimates and discussions of the PFM, the consequence estimate by the team was a Level 1.

Confidence: Confidence for probability estimates is judged to be moderate for this failure mode. Confidence for consequence estimates is judged to be high because there is inundation mapping for the sunny day breach scenario.

4.6 PFM S2: Seismic Failure of Spillway

Description: During a seismic event, the stone joints of the spillway fail resulting in the loss of structural integrity, leading to an uncontrolled release of the reservoir (through the culvert/bridge).

Failure Likelihood: The team identified the following factors related to the likelihood of this PFM.

Factors Making PFM "More Likely"	Factors Making PFM "Less Likely"
Rock elevation is around EL 400 with soils that may amplify motions created by the seismic event.	Near surface faulting is not documented within the area.
Previous mortar integrity issues have been noted in the past and may occur again in the future.	Previous seismic events have not resulted in noted damage to the structures.
Spillway is constructed of large stones, but these would still likely to be moved with flowing water if they were to be dislodged.	The noted cracks within the mortar have been repaired.
The timeframe for this failure mode would be nearly instantaneous negating the ability to intervene.	Spillway construction was with dry fit stones that are tightly fit together, limiting potential for movement or joint failure.

Likelihood: The likelihood estimate by the team was a Low.

Consequences: Based on the baseline estimates and discussions of the PFM, the consequence estimate by the team was a Level 1.

Confidence: Confidence for probability estimates is judged to be moderate for this failure mode. Confidence for consequence estimates is judged to be high because there is inundation mapping for the sunny day breach scenario.

5 Results and Recommendations

Based on the discussion by the team, the resulting risk estimates for the six PFMs considered to be risk drivers are summarized on Figure R-4 below.

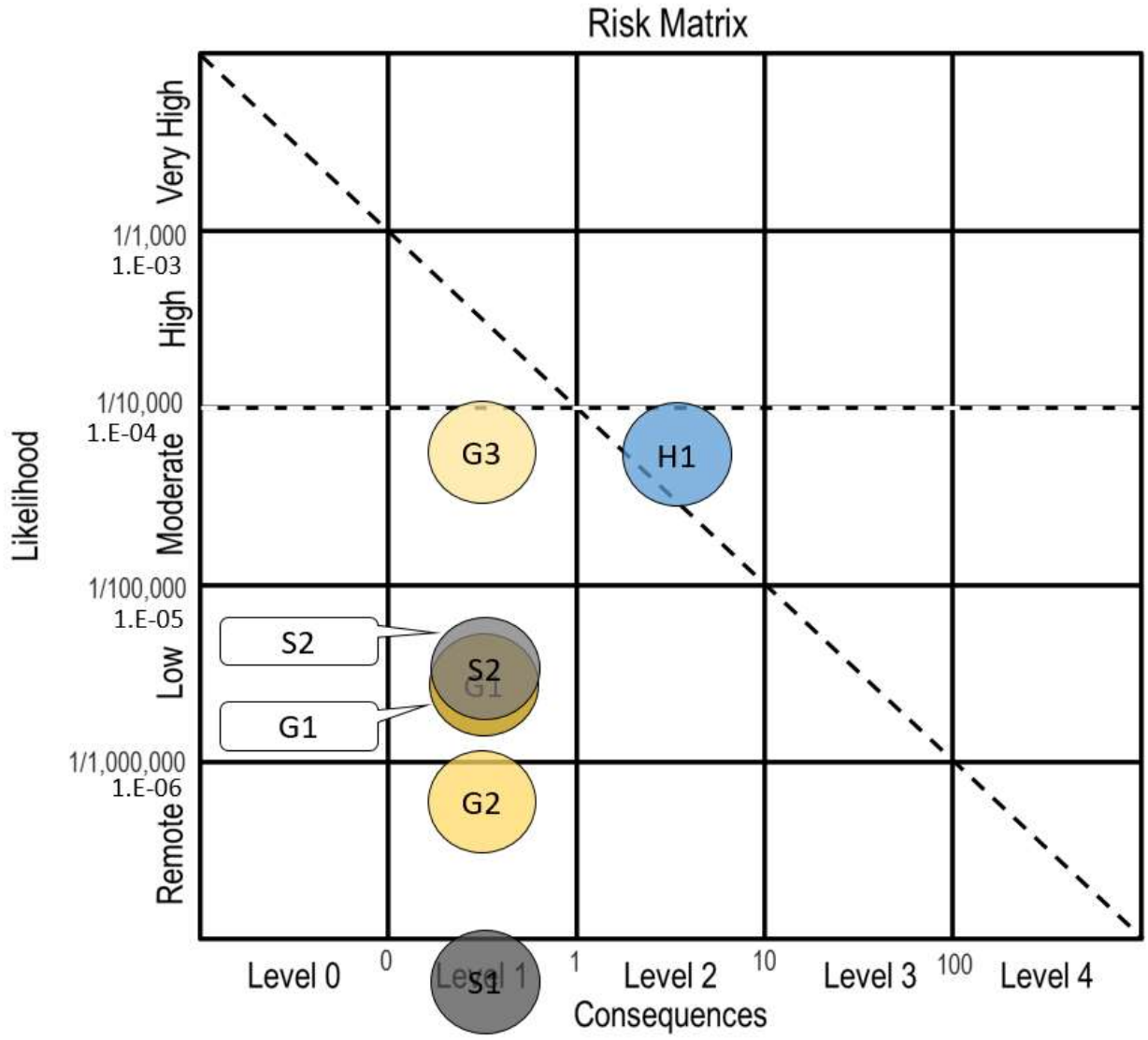

Figure R-4. Risk Estimates

6 Recommendations

HDR has performed this PFMA in an effort to evaluate the risks of Estling Dam. Given the dam does not currently meet dam safety regulations, these risks should be taken into consideration when determining future repair efforts at the dam in order to reduce the overall risk of the facility.

- Overtopping of the Embankment (Inadequate Spillway Capacity)
    - Previous studies indicate that the spillway can convey the 0.4 PMP. The Spillway Design Storm is 0.5 PMP resulting in overtopping of the dam. Given that enlargement of the current spillway would be difficult given the

restrictions downstream via the culverts, armoring the embankment should be considered to reduce the risk of this PFM.

- Internal Erosion - Railroad Bridge/Culvert - Perimeter Seepage
    - The railroad bridge/culvert currently provides a potential seepage path along the interface of the structure and the embankment material. A filter diaphragm around the structures could be considered to reduce the risk of this PFM.
- Internal Seepage and Piping
    - There is a potential for seepage paths along the contact surfaces (at downstream toe, into foundation) which that could result in erosion of the embankment material. A chimney and blanket drain could be considered to reduce the risk of this PFM.
- Downstream Slope Stability
    - Slope stability calculations indicate that the embankment does not achieve required factors of safety for several of the load cases. Enhanced drainage features noted above would increase safety factors and reduce the risk of this PFM.
- Progressive Failure of Downstream Bridges/Culverts
    - Given the age of the downstream bridge/culverts and the noted scour present downstream, there is a potential for a failure of these structures. Routine inspection along with required maintenance to control the scour and structural deterioration will help to mitigate the risk of this PFM.
- Seismic Failure of Spillway
    - Given the age of the spillway and the previous seismic events, there is a potential for a failure of the spillway during a seismic event. Routine inspection along with required maintenance of the spillway will help to mitigate the risk of this PFM.

While some deficiencies may not be considered a priority compared to other deficiencies, the regulations may still require modifications to address dam safety deficiencies, particularly where the dams do not meet specific regulatory criteria.

7 Limitations

This report represents the results of qualitative evaluations of the likelihood and estimated consequences associated with potential failure modes identified as part of the screening process described herein, applied to compare dam safety risks at this project. The screening level process informed the team's opinion as to whether failure modes were "credible" or "not credible."

These qualitative evaluations were based on data made available to the risk team at the time of the assessment and are intended to be used primarily to evaluate the relative risks of PFMs for ranking and initial screening. The estimated risks can then be used to prioritize dam safety actions, which could include additional explorations, engineering studies, analyses, O&M processes, surveillance and monitoring, as well as potential modifications. This report is not intended to be a comprehensive assessment of project-specific dam safety issues or deficiencies. Given the level of detail of this assessment, the uncertainty in likelihood and consequence estimates is considered high and therefore results are to be used only for comparison of risks within the context of this project.

We have endeavored to complete the services identified herein in a manner consistent with that level of care and skill ordinarily exercised by members of the profession currently practicing in the same locality and under similar conditions as this project. No other representation, express or implied, is included or intended, and no warranty or guarantee is included or intended in this report, or other instrument of service.

Appendices

Appendix R-1

Potential Failure Mode Worksheets

Potential Failure Mode Worksheet

Dam: Estling Lake Dam
PFM ID: H1
Name: Overtopping of the Embankment
Type: Hydrologic
Description: During an extreme flood event (0.5 PMP), the capacity of the spillway is exceeded and overtopping of the embankment occurs. Headcutting initiated and progresses to failure of the embankment and an uncontrolled release of the reservoir. Intervention is unsuccessful.

Probability Estimate (Event Sequence)

Node	Event Description	Estimated Probability	Comment
1	Loading - Extreme Flood	0.0001	0.5 PMP
2	Initiation/Progression - Embankment Overtops and Headcutting initiates	0.9	
3	Intervention unsuccessful	0.5	Would require significant advanced dewatering, which is not probable/feasible.
4	Progression/Failure - Headcutting erosion progresses to failure of the crest, uncontrolled release	0.9	
	Failure Mode Estimated Probability	**4.05E-05**	**MODERATE**

Node	Factors making failure "More Likely"	Node	Factors making failure "Less Likely"
1	Studies indicate that overtopping are possible	2	Rail provides additional protection given horizontal profile
1	Current analysis represents more realistic H&H results	2	Gravel/Ballast composition may reduce particle migration
2	Downstream slope is steep and nearly vertical	2	Higher tailwater (0.5 PMP without breach) causes tailwater of 513.5
2	Increased localized scour with railroad ties		
2	Variation in top of crest elevation with defined low point		
2	Erosion gullies/rutting of DS embankment face		
3	Duration of overtopping - over 2.8 hrs		

Confidence Statement (including opportunities to increase confidence)

Confidence for probability estimates is judged to be moderate for this failure mode. Confidence for consequence estimates is judged to be high because there is inundation mapping for both breach and non-breach PMP scenarios.

Potential Failure Mode Worksheet

Dam: Estling Lake Dam
PFM ID: G1
Name: Internal Erosion - Railroad Bridge/Culvert - Perimeter Seepage
Type: Geotechnical - Normal Conditions
Description: During normal operations or a moderate flood (increased head), unfiltered seepage occurring along the Railroad Bridge/Culvert which initiates erosion (at downstream toe, into Bridge/Culvert etc.), erosion continues and progresses (along the Bridge/Culvert) until material loss is significant enough to cause a depression at the crest, resulting in loss of freeboard and an uncontrolled release of the reservoir.

Probability Estimate (Event Sequence)

Node	Event Description	Estimated Probability	Comment
1	Loading	0.999	
2	Erosion initiates	0.05	
3	Erosion continues (unfiltered exit)	0.05	
4	Progression - pipe can form and hold a roof	0.1	
5	Progression - no constriction upstream to limit flows	0.9	
6	Progression - no self healing upstream zone	0.9	
7	Unsuccessful detection and intervention	0.5	
8	Loss of crest results in overtopping and dam breach	0.01	
	Failure Mode Estimated Probability	**1.01E-06**	**LOW**

Node	Factors making failure "More Likely"	Node	Factors making failure "Less Likely"
1	Normal pool/sunny day failure	2	Long seepage path
2	No drainage diaphragm around culvert	3	No observed sinkholes
2	Uneven surfaces upstream and downstream	7	Daily train traffic
2	Ponding water noted downstream		
2	Steep slopes near vertical		
7	Limited Lake Drain Capacity		
7	Difficult to detect issue given defect location and ballast material		

Confidence Statement (including opportunities to increase confidence)

Confidence for probability estimates is judged to be moderate for this failure mode. The embankment is a variety of materials so additional investigation would be beneficial to further refine the subsurface profile. Confidence for consequence estimates is judged to be high because there is inundation mapping for sunny day breach scenarios.

Potential Failure Mode Worksheet

Dam: Estling Lake Dam
PFM ID: G2
Name: Internal Seepage and Piping
Type: Geotechnical - Normal Conditions
Description: During normal operations or a moderate flood (increased head), unfiltered seepage occurring along a contact surface (at downstream toe, into foundation, etc.), erosion continues and progresses until material loss is significant enough to cause a depression at the crest (progressing from downstream to upstream), resulting in loss of freeboard and an uncontrolled release of the reservoir.

Probability Estimate (Event Sequence)

Node	Event Description	Estimated Probability	Comment
1	Loading	0.999	
2	Erosion initiates	0.02	
3	Erosion continues (unfiltered exit)	0.05	
4	Progression - pipe can form and hold a roof	0.1	
5	Progression - no constriction upstream to limit flows	0.9	
6	Progression - no self healing upstream zone	0.9	
7	Unsuccessful detection and intervention	0.5	
8	Loss of crest results in overtopping and dam breach	0.01	
	Failure Mode Estimated Probability	**4.05E-07**	**REMOTE**

Node	Factors making failure "More Likely"	Node	Factors making failure "Less Likely"
1	Normal pool/sunny day failure	2	Long seepage path
2	No toe drain or chimney drain/filter	3	No observed sinkholes
2	Uneven surfaces upstream and downstream	7	Daily train traffic
2	Ponding water noted downstream		
2	Steep slopes near vertical		
7	Limited Lake Drain Capacity		

Confidence Statement (including opportunities to increase confidence)

Confidence for probability estimates is judged to be moderate for this failure mode. The embankment is a variety of materials so additional investigation would be beneficial to further refine the subsurface profile. Confidence for consequence estimates is judged to be high because there is inundation mapping for sunny day breach scenarios.

Potential Failure Mode Worksheet

Dam: Estling Lake Dam
PFM ID: G3
Name: Downstream Slope Stability
Type: Geotechnical - Normal Conditions
Description: During normal operations or a moderate flood (increased head/saturated soils), a slope failure occurs and progresses to loss of crest, which results in embankment overtopping and failure.

Probability Estimate (Event Sequence)

Node	Event Description	Estimated Probability	Comment
1	Loading	0.999	
2	Slope failure occurs	0.9	
3	Slope failure progresses to crest	0.01	Crest width of 50ft
4	Unsuccessful detection and intervention	0.5	Vegetation and lack of visibility hinders detection
5	Loss of crest results in overtopping and dam breach	0.01	
	Failure Mode Estimated Probability	**4.50E-05**	**MODERATE**

Node	Factors making failure "More Likely"	Node	Factors making failure "Less Likely"
1	Normal pool/sunny day failure	2	Slope armoring of stone ballast
1	No toe drain or chimney drain/filter	3	Crest width of 50ft
1	Seepage noted downstream of embankment	3	No observed sinkholes
2	Previously noted slides on embankment	4	Daily train traffic
2	Inconsistent subsurface profile		
2	Steep slopes up to near vertical		
4	Vegetation on slope obscures inspection		
4	Limited Lake Drain Capacity		

Confidence Statement (including opportunities to increase confidence)

Confidence for probability estimates is judged to be moderate for this failure mode. The embankment is a variety of materials so additional investigation would be beneficial to further refine the subsurface profile. Confidence for consequence estimates is judged to be high because there is inundation mapping for sunny day breach scenarios.

Potential Failure Mode Worksheet

Dam: Estling Lake Dam
PFM ID: S1
Name: Progressive Failure of Downstream Bridges/Culverts
Type: Structural/Geotechnical
Description: Over time, scour of the downstream bridges/culverts results in loss of concrete inverts, resulting in instability of the structure's foundation, resulting in loss of embankment materials into failed bridges/culvert, progressing to loss of crest and uncontrolled release.

Probability Estimate (Event Sequence)

Node	Event Description	Estimated Probability	Comment
1	Scour of downstream channel	0.9	
2	Scour progresses and compromises concrete inverts	0.01	Structures are inspected routinely (annual on spillway) (5yrs indepth scour)
3	Scour continues and undermines foundation of structures	0.05	
4	Bridge/Culvert experiences structural failure	0.01	
5	Embankment material is lost into the structures	0.5	
6	Unsuccessful intervention	0.01	Structures are inspected routinely
7	Loss of crest results in overtopping and dam breach	0.01	
	Failure Mode Estimated Probability	**2.25E-10**	**REMOTE**

Node	Factors making failure "More Likely"	Node	Factors making failure "Less Likely"
1	Scour is present 3.5 ft deep approximately 20ft, just beyond concrete apron slab	2	Concrete invert
4	Age of structures	2	Routine Inspection of Structures
3	Unknown foundation conditions at the Arch Bridge		
5	Unknown condition of embankment material		

Confidence Statement (including opportunities to increase confidence)

Confidence for probability estimates is judged to be moderate for this failure mode. Confidence for consequence estimates is judged to be high because there is inundation mapping for sunny day breach scenarios.

Potential Failure Mode Worksheet

Dam: Estling Lake Dam
PFM ID: S2
Name: Seismic Failure of Spillway
Type: Seismic/Structural
Description: During a seismic event, the stone joints of the spillway fail resulting in the loss of structural integrity, leading to an uncontrolled release of the reservoir (through the culvert/bridge).

Probability Estimate (Event Sequence)

Node	Event Description	Estimated Probability	Comment
1	Seismic Loading	0.02	Previous activity 100 yrs ago (MMI 7).
2	Displacement of stone joints	0.1	
3	Loss of spillway stones	0.01	
4	Unsuccessful intervention	0.9	Short timeframe event
5	Failure of the spillway and uncontrolled release	0.1	
	Failure Mode Estimated Probability	**1.80E-06**	**LOW**

Node	Factors making failure "More Likely"	Node	Factors making failure "Less Likely"
1	Rock elevation is approximately EL 400 and the soil profile may amplify the motions.	1	No near surface faulting
2	Previous mortar integrity issues	2	Previous seismic events have not resulted in noted damage
3	Large stones but still able to be moved with flowing water	2	Recent repairs to joints
4	Short timeframe of failure mode	2	Spillway is construction of dry fit stones that is nearly water tight

Confidence Statement (including opportunities to increase confidence)

Confidence for probability estimates is judged to be moderate for this failure mode. Confidence for consequence estimates is judged to be high because there is inundation mapping for sunny day breach scenarios.