
CHALLENGES IN CLASSIFYING AND DESIGNING SPILLWAY UPGRADES FOR A SMALL EMBANKMENT DAM UPSTREAM OF AN URBAN POPULATION

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ABSTRACT

A 10 m high embankment dam located 4 km upstream of a populated area was assessed during its Dam Safety Review as requiring an upgrade to the spillway capacity to comply the current CDA Dam Safety Guidelines and BC Dam Safety Regulations. At normal operating levels, the Dam stores approximately 31,000 m³ of water. The Dam was completed in 1966 and has been successfully operated by the Dam Owner without incident for over 50 years as a critical part of the water distribution system, specifically the diversion and intake location for the irrigation system serving the area's rural community. Various studies were completed on the Dam to assess its compliance and classification under the new criteria.

Due to the confined valley and orientation of the spillway weir, the only feasible solution to continue the existing operation without decommissioning and replacement, was to raise the crest of the Dam in order to pass the new design flood through the existing spillway. Given the downstream permanent population, the inundation study showed areas of residential and commercial properties affected. A detailed study translating inundated areas into an estimated loss of life and economic losses followed. A discussion of the risk mitigation efforts and emergency planning that is possible with a forecasted flood induced event led to a solution that satisfied both the consequence criteria of the CDA Dam Safety Guidelines, the BC Dam Safety Regulations and the engineering design limitations for this small dam and reservoir volume.

RÉSUMÉ

Lors de l'étude d'évaluation de sa sécurité, il a été déterminé qu'un barrage en remblai de 10 m de hauteur situé à 4 km en amont d'une zone peuplée nécessitait une augmentation de sa capacité d'évacuation pour se conformer aux lignes directrices actuelles de l'ACB et aux *Dam Safety Regulations* de la Colombie-Britannique. Au niveau d'exploitation normale, le barrage emmagasine environ 31 000 m³ d'eau. Il a été achevé en 1966. Il a été exploité sans incident par la Ville, depuis plus de 50 ans, en tant que composante essentielle du système de distribution d'eau, en particulier pour le détournement et l'approvisionnement d'un système d'irrigation desservant la communauté rurale. Diverses études ont été réalisées sur le barrage pour évaluer sa conformité et sa classification selon les nouveaux critères.

En raison du confinement de la vallée et de l'orientation du déversoir de l'évacuateur, la seule solution possible pour poursuivre l'exploitation actuelle sans déclassement et remplacement consistait à relever la crête afin de passer la nouvelle crue de conception. Compte tenu des populations permanentes à proximité, l'étude d'inondation a démontré qu'une portion importante des propriétés résidentielles et commerciales était touchée. Une étude détaillée corrélant les zones inondées avec les pertes de vie potentielles et les dégâts sur le plan économique a été réalisée. Une discussion portant sur l'effort d'atténuation des risques et sur la planification des mesures d'urgence avec l'inondation anticipée a permis de trouver une solution qui satisfasse à la fois aux critères de conséquences des lignes directrices de l'ACB, aux *Dam Safety Regulations* de la Colombie-Britannique ainsi qu'aux limites de conception d'ingénierie d'un petit barrage avec son volume de réservoir restreint.

1 INTRODUCTION

Facility Description and Purpose

A 10 m high zoned earthfill embankment dam, located 4 km upstream of a populated area, was assessed during its Dam Safety Review as requiring an upgraded spillway capacity to comply with the current Canadian Dam Association's Dam Safety Guidelines (CDA DSG), as revised in 2007, and BC Dam Safety Regulations. A plan overview and section of the Diversion Dam are shown in Figures 1 and Figure 2 respectively. A relatively small reservoir, at normal operating levels, the dam stores approximately 31,000 m³ (25 acre feet) of water. The Diversion Dam form part of a series of dams that the Dam Owner uses to manage, divert and store water for residential, agricultural and commercial use.

The spillway consists of a free over flow concrete chute with a 15 m long side weir running perpendicular to the dam crest. There are no spillway sluice gates, or other mechanical equipment required to operate the dam or pass flows. The Diversion Dam was completed in 1966 and has been successfully operated by the Dam Owner without incident for over 50 years.

While the dam (referred to as "Diversion Dam" herein) is not intended to offer any storage for the water supply system employed by the region, it is a critical part of the water distribution system for the Dam Owner, specifically used for the diversion of flow to feed an irrigation system serving the area's rural community. The main water storage facility is well upstream and feeds both this facility and a second drinking water diversion dam further downstream.

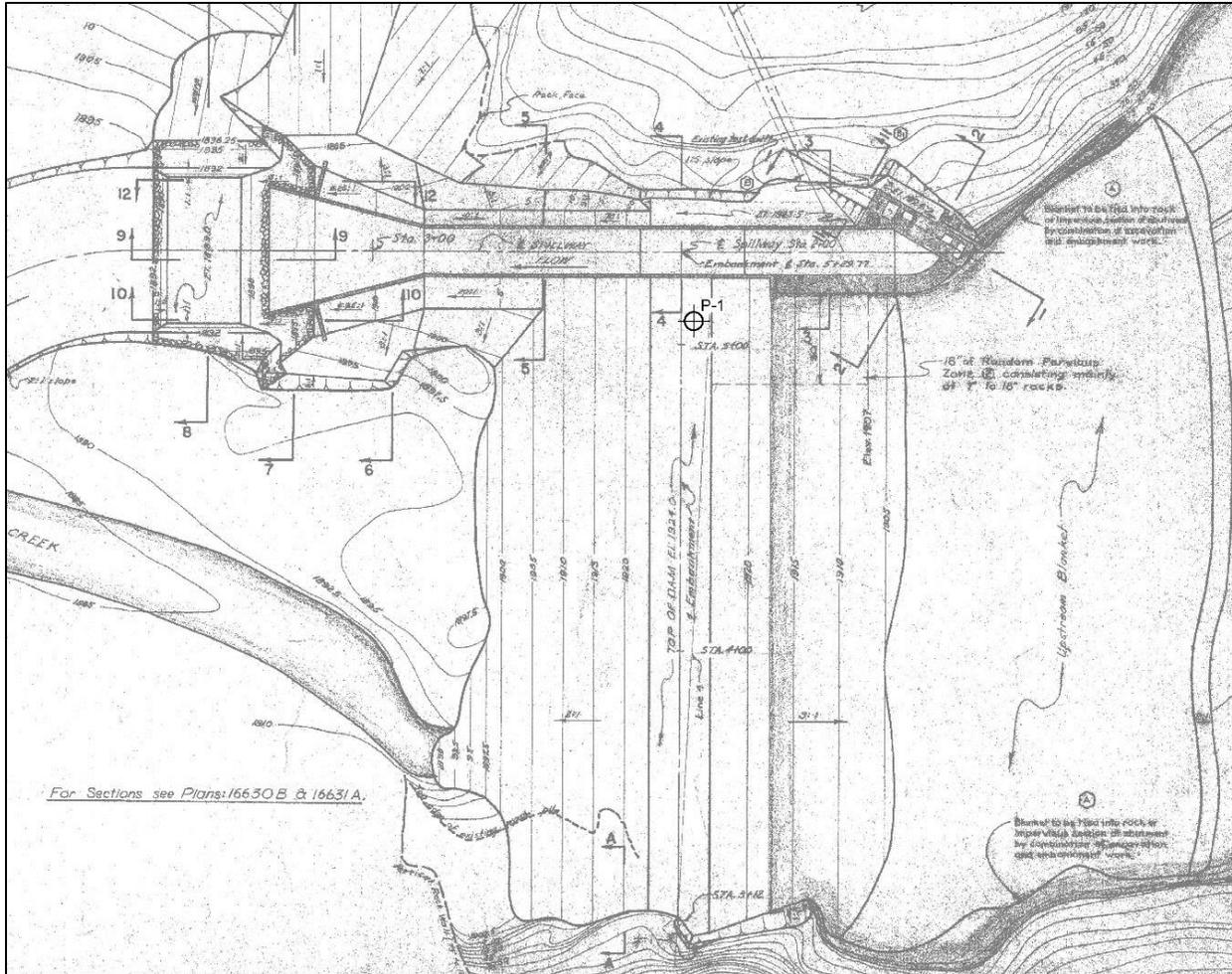


Figure 1: Dam General Arrangement Plan

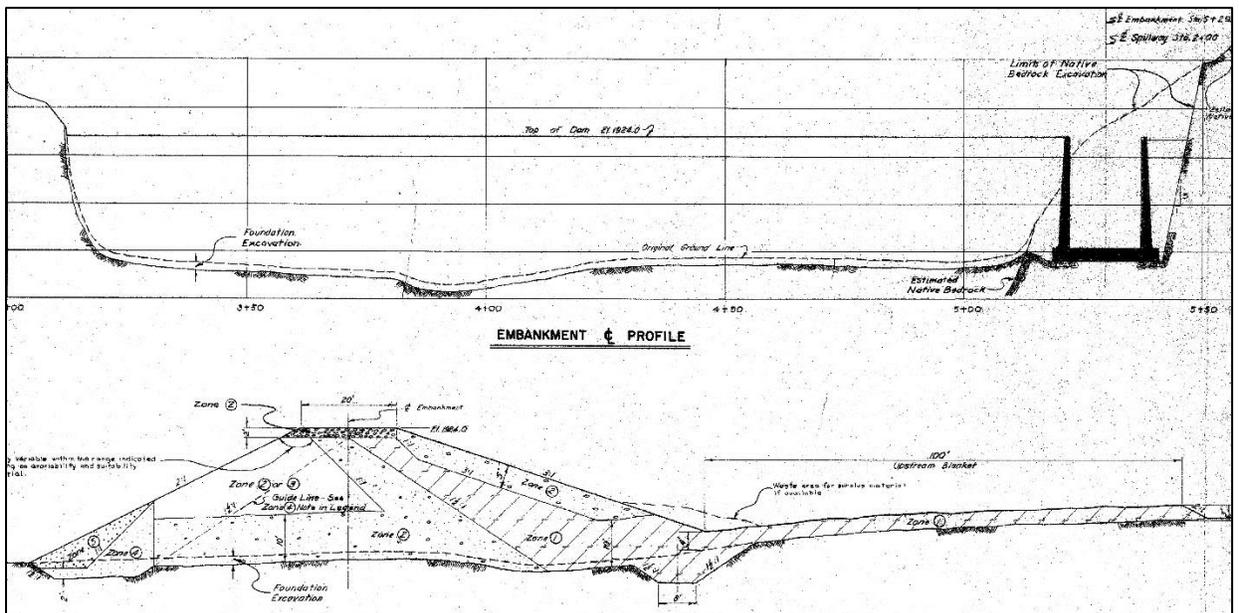


Figure 2: Dam Elevation and Section

Project Intent

The Dam Owner had an appreciation for the importance of Dam Safety, especially considering the location of the Diversion Dam upstream of the population it was serving. The intent of the project was to bring the facility into compliance with the BC Dam Safety Regulations, utilizing the CDA DSG as well as the expertise of industry professionals.

2 HISTORY OF CLASSIFICATION

2.1 2003 Dam Safety Review

A review of the consequence category for the Diversion Dam was carried out in September, 2002. The findings of the review indicated that due to the small storage volume there is likely to be little or no incremental risk to life safety resulting from dam failure and that the consequence category is more dependent on the economic and socio-economic consequences of failure. No change to the existing Low consequence category was recommended at that time. At the time, prior to the revision of the CDA DSG, a “Low” consequence dam was described as follows:

- Life Safety: No fatalities anticipated
- Socioeconomic, Financial & Environmental: Moderate Damages.

Based on the qualitative approach that was common at the time, it was determined that with such a small impounded volume of water and an additional reservoir downstream to provide some minor additional attenuation, a “Low” consequence was appropriate.

The following key recommendations regarding potential deficiencies were identified in the conclusions of the 2003 DSR:

- The concrete spillway should be checked for flow capacity and its ability to safely pass the IDF, defined as the 1/1000 year event. The reservoir catchment area and upstream watershed characteristics need to be defined for this study in order to determine the IDF peak inflow and flood hydrograph.
- A more detailed flood analysis may be conducted to determine if the dam downstream is able to safely pass flood waters following a failure at this facility. If so, the consequence category can be taken as “Low”. If the downstream dam cannot pass the flows from an upstream failure, a “High” consequence should be assigned to the Diversion Dam.
- It was recommended that a plan be developed showing the potential inundation area downstream of the dam, including all infrastructure and inhabited areas. Together with an economic analysis to determine the incremental cost of failure, this will allow a more definitive assessment of the incremental consequences of failure to be determined. It will also provide a basis for periodic review of conditions downstream of the dam.

2.2 2006 Flood Routing and Inundation Study

Following the recommendations of the 2003 DSR, a Flood Routing and Inundation Study was completed. Both seismic and flood induced failure scenarios (i.e. sunny day and rainy day failures) were completed as part of the study. Given there remained some uncertainty as to the appropriate consequence and IDF, flood scenarios were investigated for the 50 year, 100 year, 200 year and 1000 year return periods (corresponding with a “High” consequence classification).

2.2.1 Flood Scenario

The results of a failure resulting from the flood induced scenario resulting from a failure, indicated that the creek and the downstream dam provide some attenuation of peak flows produced by the dam failure. Predicted outflows at the breach were 40% reduced by the time they travelled through the populated area from immediately downstream of the breach. There was considerable uncertainty in the inundation scenario without a breach in the populated area. The results indicated, however, that the flood without a breach may just barely be contained within the natural banks of the downstream channel. Even with the small reservoir,

a rise in water level above the natural banks of the channel was therefore predicted to occur in the event of a failure and likely causing flooding of the populated area in the vicinity of the creek. Inundation maps of the lower portion of the creek were produced indicating the approximate inundation limits of the peak flows generated by the dam breach.

2.2.2 Earthquake Scenario

For the earthquake scenario, predicted peak flows following a “sunny-day breach” indicated that the banks of the creek in the populated area downstream will not be overtopped and there was no incremental risk to loss of life for the conditions specified in this analysis.

2.3 Impact of Nearby Dams

A lower dam, located further downstream, is much closer to the populated area. It was determined that deficiencies at the downstream dam should be addressed first to eliminate the risk of a cascading failure, prior to finalizing any required upgrades to the spillway at the Diversion Dam. This would allow the Diversion Dam to be assessed independently and with a consequence category that was more appropriate to the size of this facility.

Significant structural rehabilitation, abutment and spillway work was undertaken and completed at the downstream dam in 2012. Given its proximity to the populated area, it was upgraded for an “Extreme” consequence classification, now able to pass flows approximately 4 or 5 times greater than the incremental flows from a potential failure of the small upper Diversion Dam.

2.4 2010 Dam Failure Consequence Review and 2014 Dam Safety Review

The consequence category was revisited again in 2010, subsequent to inundation studies conducted in 2005/2006 and the Diversion Dam was reclassified in the “Extreme” category, based on the assumption that failure of the dam might cause failure of the dam downstream. At the time it did not take into consideration the inundation results of only a single failure and was based entirely on the inundation results of the downstream dam.

The subsequent 2014 Dam Safety Review, however, correctly took into account the significant upgrades at the downstream dam in 2012. It was recommended that the Diversion Dam revert to a “High” consequence classification based on the Population at Risk (PAR) shown during a flood induced scenario in the 2006 dam breach study, and given that the downstream dam was now in compliance with an “Extreme” classification and was able to pass the associated IDF (PMF).

It is important to note, however, that the inundation studies in 2006 were conducted using a one-dimensional model and did not provide detailed depth/velocity mapping. The “High” dam failure consequence classification, while related to real inundation mapping was still relatively qualitative as it related to Loss of Life and considered that a sudden sunny day failure (e.g., due to an earthquake) did not result in additional PAR due to the small reservoir volume.

In addition to assessing a dam’s technical compliance, an important part of a DSR process was assessing the Dam Owner’s and operator’s knowledge and responsibility in their role. It was assessed that the Owner of this Dam operates multiple dams in the region and consistently draws comments including that they are “taking [their] responsibility for the safety of [the Dam]”. The DSR further noted that “those responsible have intimate knowledge of the dam and are undertaking routine surveillance” and have commissioned various studies, working towards following up on recommendations of the dam safety engineers.

3 ENGINEERING STUDIES AND STABILITY ASSESSMENTS

As mentioned above, a number of engineering studies were commissioned by the Dam Owner in addition to the Dam Safety Reviews that demonstrated the safety of the dam in all aspects other than the uncertain consequence rating. These studies are summarized here.

3.1 *Embankment Stability*

Embankment stability analyses have been carried out to investigate the stability of the Diversion Dam under both static and seismic loading conditions. These have included checking the stability of the earthfill embankment for each of the following cases:

- Static stability of the downstream slope for normal operating reservoir at full pool;
- Static stability of the upstream slope;
- Seismic loading of the Dam from the Earthquake Design Ground Motion (EDGM), including consideration of the liquefaction potential of embankment fill and foundation materials; and
- Post-earthquake stability.

For static stability of the downstream slope under maximum operating reservoir conditions, the minimum factor of safety is 1.6 for a shallow potential slip surface within the downstream slope of the Dam. The factor of safety is higher (approximately 2.2) for a deeper slip surface that passes through the core and crest of the dam (potential to cause a loss of freeboard). For static stability of the upstream slope the calculated minimum factor of safety is 1.8 for the full reservoir, increasing to 1.9 for a drained (empty) reservoir. These factors of safety exceed the minimum required static factor of safety of 1.5.

For seismic stability some deformation of the embankment is predicted to result from settlement of the fill materials during dynamic earthquake movement. Potential settlement of the embankment crest has been estimated using the empirical relationship provided by Swaisgood (2003). This relationship was developed from an extensive review of case histories of embankment dam behaviour due to earthquake loading. Required inputs to the relationship are the earthquake magnitude, the peak ground acceleration on rock at the site, the depth to rock (overburden thickness) and the embankment height. The predicted maximum crest settlement for the maximum dam section is negligible (approximately 0.02 m) for the EDGM.

The maximum embankment deformations and crest settlements of less than 0.1 m calculated for the EDGM would not have a significant impact on the available embankment freeboard (minimum of 2 metres for normal operating conditions) or result in any loss of embankment integrity.

The post-earthquake factor of safety is likely to be similar to the static factor of safety as the embankment fill and foundation soils are not considered to be potentially liquefiable under seismic loading from the EDGM, and are unlikely to experience any significant loss of strength, if any. This indicates that the dam is not susceptible to a flow slide or large deformations during or after the EDGM event.

3.2 *Seepage Analysis and Piping Failure Assessment*

In addition to the detailed stability analysis of the embankment, an assessment of the internal erosion and piping potential was completed. This was requested by the Regulator following the 2014 DSR as due diligence and was commissioned by the owner shortly thereafter.

There are three general failure modes for internal erosion of embankment dams. These include:

- Internal erosion through the embankment, including internal erosion associated with through penetrating structures such as conduits or outlet pipes
- Internal erosion through the foundation soil, and
- Internal erosion of the embankment into or at the foundation.

The assessment of the internal erosion and piping potential of the Dam was carried out by reviewing the conformance of the fill zone gradations with recognized filter design criteria. The review was carried out based on the ‘no-erosion’ filter guidelines provided by the US Department of Agriculture (1994). These guidelines are based on the recommendations of Sherard and Dunnigan (1985) which are currently adopted internationally as suitable criteria for ‘large dams’ where there is the potential for high seepage force. The dam is not considered ‘large’ and these criteria are therefore inherently conservative. The USDA (1994) design criteria include filtering criteria, and prevention of gap graded filters and segregation. Filter design criteria have been applied to the embankment and foundation materials.

Whilst there remained some uncertainty regarding the in-situ gradations of the embankment fill materials, no immediate remedial work or further investigation was recommended. Any subsurface investigation to assess the fill zone gradations (such as test pits) could well disturb the continuity of the existing embankment zonation and do more harm than good. No significant risk of erosion was identified. Some maintenance and surveillance activities were recommended, namely:

- Qualitative assessment of the discharge (if any) from an existing downstream drain pipe should be completed as part of the routine inspection. Cloudy or silty discharge may indicate some internal erosion of the impervious zone and this should be promptly reported to the dam safety engineer.
- The vegetation growth in the downstream left abutment contact area should be cleared to allow better monitoring (as recommended in the 2014 Dam Safety Review).
- Seepage monitoring should continue in accordance with existing maintenance and surveillance procedures. In the event that seepage is shown to increase (particularly if the seepage water is cloudy or discoloured), this may indicate the initiation of internal erosion and the dam safety engineer should be contacted immediately for direction.

3.3 *Hydraulic Capacity of Spillway*

Following the successful stability and seepage assessment analyses that were completed on the Dam, it was becoming clear that the main point of compliance would be related to the spillway capacity. The spillway, pictured below in Figures 3 and Figure 4, is a 15 m long side overflow weir with an oversized outlet channel.



Figure 3: Spillway Overflow Weir



Figure 4: Spillway Outlet Channel

An empirical estimation of the spillway capacity was completed in 2005, suggesting that once the 0.5 m recommended freeboard to the dam crest was considered, the overflow weir had a capacity of approximately $76 \text{ m}^3/\text{s}$. The Inflow Design Flood (IDF) associated with the “High” consequence was $104 \text{ m}^3/\text{s}$. The reservoir is too small to offer any attenuation to the IDF so the spillway discharge capacity was required to pass the full IDF.

It can be seen from the pictures that there is some curvature to the weir at the upstream end which would affect that calculation. In addition, if a small dam crest raise is considered to increase the freeboard and therefore the spillway capacity, it is likely that the upstream end of the spillway would be drowned/backwatered, further affecting the ability to assess the spillway capacity empirically. For this reason a 3D CFD model (ANSYS) of the spillway was used to assess its capacity moving forward, providing confidence in the recommended height of the dam crest raise. The image below shows the spillway when it is drowned/choked at the upstream end during an IDF event.

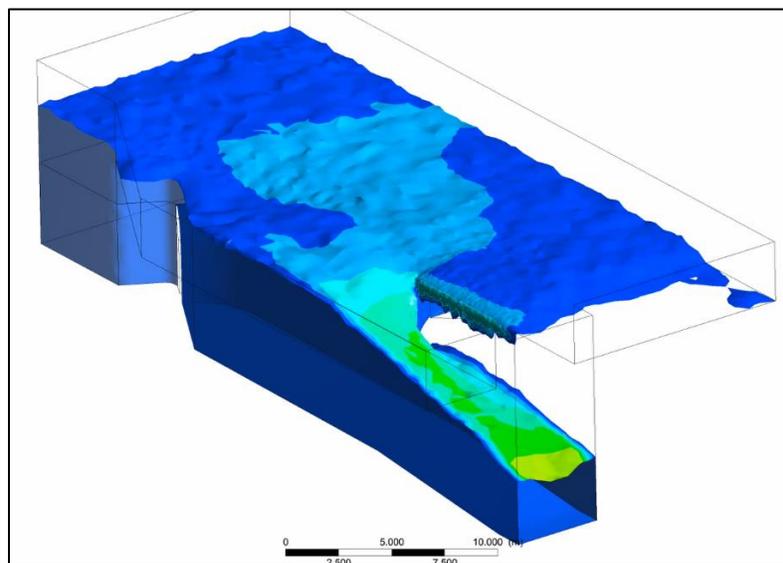


Figure 5: ANSYS Model showing IDF in the Spillway

3.4 *Conclusions as Discussion following the completion of various Engineering Studies*

It was determined that the Diversion Dam as a whole was well built and well managed with:

- The Dam employed adequate safety factors in its embankment stability.
- It was not considered at any major risk of a piping failure, especially with consistent surveillance and monitoring of the minor seepage water, which the Dam Owner had already demonstrated.
- The spillway's free overflow weir was undersized, but only by approximately the amount of freeboard required.
- The spillway's outlet channel was oversized and offered plenty of additional capacity.
- There was no mechanical equipment such as critical spillway gates, sluice gates etc... that affected the reliability of the spillway.
- The small impounded volume of water was shown in the original inundation study to remain inside the natural channel downstream as it travelled through the populated area downstream of the Dam in the event of a sunny day or seismically induced failure without any warning.

And yet, there remained some uncertainty around the appropriate dam failure consequence category to assign. A consequence classification of "High" was considered the minimum consequence for a dam upstream of a permanent PAR. Furthermore some of that PAR was within the inundation zone identified in the original inundation mapping. The inundation mapping was much coarser 10 years prior and had been with a smaller IDF as the consequence had not yet been raised to "High" at the time. Therefore, the number of the PAR that was considered incremental to a dam failure event, was unclear and given that there was no depth/velocity mapping in the older study translating the inundated PAR to an estimated loss of life was relatively meaningless.

It was also apparent that any dam crest raise that would provide the required spillway capacity with sufficient freeboard to safely pass the "High" IDF would increase the impounded volume during rainy day overtopping failure of the dam. This could in turn increase the PAR, and therefore, also potentially increase the consequence category recommended by the CDA DSG. In addition, given the narrow, confined rock valley in which the Dam was constructed, it was not considered feasible to increase the length of the concrete overflow spillway.

A minor earthfill embankment crest raise was considered feasible, however any significant raise that would precipitate from a further increase in the consequence would:

- Reduce the safety factors on the embankment stability, and
- Increase the inundated area, PAR and Loss of Life due to a flood induced overtopping failure.

Both of these effects are not considered consistent with the goals of the CDA DSG and the BC Dam Safety Regulations.

The unfortunate consequence of all of the above was, that although the Dam was well built and well managed, a small footprint earthfill embankment and represented a crucial piece of infrastructure for the Dam Owner's water management system, the Dam may need to be decommissioned. This was also not considered consistent with the intent of the CDA DSG or the BC Dam Safety Regulation.

4 SEEKING OUT A MEANINGFUL SOLUTION

4.1 *Refined Inundation Study*

Meetings and communications were initiated between the Regulator, the Dam Owner and the various engineers who had contributed thus far. It was determined that a refined inundation study would be appropriate and should be completed to better define the PAR and the potential loss of life and economic loss during a dam failure event. This would allow more advanced computer modelling techniques to be used in order to provide a clearer picture of:

- Water depths and velocities in the inundated areas
- Incremental inundation with the current IDF
- Detailed house counts, commercial vs. residential, as well as information on multi-unit buildings incorporated into the PAR estimates.

The refined dam breach inundation study was completed by evaluating the incremental inundation downstream of the Diversion Dam for conditions without and with a dam breach. The dam breach outflow hydrographs were generated in HEC-HMS and then routed through the downstream channel network using a two-dimensional hydrodynamic model HEC-RAS 2D (version 5.0.3) to simulate the inundation extents. The flood routing model accounts for the attenuation of the flood wave as it propagates downstream.

The computational mesh used for the 2D modelling was set as a 10 m grid throughout the populated area with a larger spacing of 20 m in the canyon-like reaches between the dam and the populated area. Major inputs were also updated for this inundation modelling such as:

- Topography, incorporating a digital elevation model (DEM) from LiDAR data including detailed 1 m contour interval topography in the populated area and 5 m contours in the upper reaches that was provided by the owner.
- Channel roughness was updated to be spatially distributed based on land cover
- Hydrology was reviewed to include the last ten years of available data and updated accordingly.

The dam breach parameters (e.g., breach width, side slopes, and time to fail) were determined as a function of dam and reservoir properties for the flood induced and sunny day failure scenarios. The range of possible breach parameters was determined through empirical equations commonly used in dam breach studies (Bureau of Reclamation 1988, Froehlich 2008, MacDonald and Langridge-Monopolis 1984, Xu and Zhang 2009). The various combinations of possible breach parameters were then modelled in HEC-HMS using the Monte Carlo method to determine the 95th percentile peak discharge, or the peak discharge that has a probability of exceedance of 5% in a dam breach. The outflow hydrographs were then routed downstream for scenarios with and without dam breach to establish the incremental inundation due to the breach. Outputs included inundation maps and detailed depth-velocity maps.

The effort was thorough and offered both the Regulator and the Dam Owner some confidence moving forward as further decisions were to be made regarding the Dam consequence classification. It was noted that in addition to informing the Dam's consequence, the Dam Owner would be able to put the flood inundation maps to use in Emergency Response Plans as well as long term maintenance of the creek itself. Areas of the creek where banks were expected to breach could be remediated and shored up, adding opportunities to improve the safety of the area for smaller natural floods such as the 50 and 100 year floods. The Dam's Owner was investing in the Dam's performance and as an added bonus was getting useful information on the water management of the region as a whole.

4.1.1 Sunny Day Failure

The results confirmed the finding from the earlier dam breach assessment that the sunny day failure, in which case the population downstream would have no warning of a failure, would result in very negligible breaching of the downstream channel banks as the flood wave travelled through populated areas.

4.1.2 Flood Induced Failure

The flood induced scenario indicated that inundation of populated areas would occur due to the natural flood without a dam breach; however, there was also a noted incremental increase not only in the inundation zone, but also in depths and velocities in the areas adjacent to the downstream channel.

4.2 Loss of Life Analysis

There are many different methods to estimate loss of life for dam failure scenarios. The approach developed by the U.S. Department of the Interior Bureau of Reclamation presented in the publication “RCEM – Reclamation Consequence Estimating Methodology: Guidelines for Estimating Life Loss for Dam Safety Risk Analysis” (RCEM 2014) was selected for this study, as recommended by the B.C. Ministry of Forests, Lands and Natural Resource Operations (FLNRO 2017). The RCEM approach relies on world-wide case history data to guide the selection of fatality rates and on a graphical representation of fatality rates as a function of flood severity and warning time. The flood severity is quantitatively defined in terms of the Depth-Velocity (DV) product, and is considered a transparent and defensible method of portraying loss of life estimates (RCEM 2014).

The flooded areas downstream from the Dam were divided into three general reaches based on the occupancy type. Reach 1 was assumed to have no PAR as there is limited access to this reach and no residential development. Reach 2 has residential development along the downstream creek, while Reach 3 is generally characterized as commercial with some residential development. Furthermore, there could be more road traffic through Reach 3. The DV values for each reach were calculated directly in the 2D hydrodynamic model. The results indicated that the highest DV values develop within the channel banks, and that the DV values decrease quickly when the channel banks are breached.

The PAR downstream of the Dam was assumed to be permanent and present for the Loss of Life analysis. Various aspects of the PAR estimation such as building occupation could overestimate the PAR, while other aspects such as vehicle and pedestrian traffic would be difficult to account for and could underestimate the PAR, but overall the strategies were well researched and agreed upon by all parties.

The PAR for the scenarios without and with dam failure are summarized in the following Table 1.

Table 1: Flood Induced Population at Risk

Scenario	PAR
Without Dam Failure	1269
With Dam Failure	2388
Incremental	1119

RCEM 2014 identifies that the flood severity has a significant influence on fatality rates. The case history data indicates that, in general, the highest estimated fatality rates are associated with the highest estimated DV values. The fatality rates presented in the following table were used in the loss of life estimation. They were based on little to no warning time as it was determined that the flood wave caused by a breach would

arrive to the populated area within 25 to 40 minutes. There was further consideration of whether the presence of a natural flood event could be considered as part of the warning system.

Table 2: Fatality Rates for Loss of Life Estimates – Flood Induced Failure Scenario

DV Range (m ² /s)	PAR Fatality Rate Range	
	Low	High
< 1.4	0	0.01
1.4 to 2.8	0.01	0.05
2.8 to 4.6	0.05	0.11
> 4.6	0.11	1.0

The above fatality rates resulted in the following Loss of Life estimates that were used to inform the consequence classification discussion.

Table 3: Estimated Loss of Life – Flood Induced Failure Scenario

Scenario	Loss of Life
Without Dam Failure	0 to 13
With Dam Failure	3 to 34
Incremental	3 to 21

The results indicated a Loss of Life estimate that straddled the < 10 persons requirement to be compliant with the “High” Consequence. At the low end of RCEM estimating strategy, there was an incremental increase of 3 persons, but at the high end, there was an incremental increase of 21 persons.

4.2 Conclusions and Collaborative Approach between Dam Owner, Engineer and Regulator

The results indicated a Loss of Life estimate that straddled the < 10 persons requirement to be compliant with the “High” dam failure consequence classification. At the low end of RCEM estimating strategy there was an incremental increase of 3 persons, but at the high end the incremental increase was 21 persons. It was clear that this Dam would remain without a black and white solution.

Again discussions between the three relevant parties (Dam Owner, Dam Safety Engineer and Dam Safety Regulator) were initiated. The following is a summary of the critical points that were acknowledged by all parties:

- A small dam raise in form of a parapet wall would provide the necessary freeboard to safely pass the current IDF without compromising the embankment safety factors.
- It was confirmed that an increase in the Dam’s consequence classification to “Very High” consistent with the high end estimate of Los of Life of 21 persons would result in a larger IDF for which there were no feasible enhancements to the current Dam. The narrow rock canyon limited the spillway capacity upgrade to embankment raises. The larger IDF would result in a raise that would sacrifice the embankment safety factor while coincidentally increasing the potential inundation zone and the PAR in the event of a breach.
- The low end estimate in Los of Life (3 persons), on the other hand, confirms the Dam’s classification as “High”, and the Dam could be brought into compliance in relatively short order.

The discussion moved to discuss the question, “On what basis would one prudently and responsibly suggest that the lower loss of life estimate was applicable to this particular case?”

- The Dam is located in an area with developed emergency services and health services.
- The breach would occur only in the event of an extreme flood that would provide some additional measure of warning (forewarning) to the PAR.

- The Dam is located in an area with enforced building codes and other applicable standards where one can expect reasonable performance of surrounding infrastructure.

Additionally, as summarized in Section 2.5, the Dam was considered a low risk facility, in good condition, well maintained and not relying critically on mechanical equipment to manage its safety. The extensive amount of work that had been commissioned by the Dam Owner, both independently and at the request of the Regulator, demonstrated a desire to manage the region's water infrastructure safely. Most importantly the updated inundation studies provided the Dam Owner with the tools to meaningfully revise and improve their Emergency Response Plans.

It was determined and agreed upon that the Dam would retain its current IDF and "High" consequence classification. The Dam Owner would proceed with the construction of a small parapet wall that would increase the freeboard sufficiently to pass the IDF related to a "High" consequence classification. This was agreed to by the Dam Safety Regulator on the following conditions that would ensure the incremental Loss of Life in the event of a flood induced breach would be kept as low as possible, or near zero, and within the CDA DSG recommendations for a "High" classification:

- The Emergency Response Plans for the region be updated.
- Those updates would include a requirement for real time flow monitoring on the creek downstream of the Dam.
- Implementation of an alarm system that would be triggered in the event flood flows increased to a level that would allow warning time and evacuation procedures to be implemented, thus removing the PAR near the creek where fatality rates due to high DV products could most likely occur.
- Specific procedures for those responding to the alarm on how to assess the flows and when to progress the Emergency Response.

The discussions throughout this work were constructive and collaborative, and most importantly found a solution that was committed to dam safety and believed by all parties to be consistent with the goals and intent of the CDA Dam Safety Guidelines and BC Dam Safety Regulations.

4 REFERENCES

- British Columbia Dam Safety Regulation (B.C., Reg. 40/2016 – O.C. 114/2016 of the Water Sustainability Act), February 29, 2016.
- Ministry of Forests, Lands and Natural Resource Operations, Dam Safety Program. 2017. "Downstream Consequence of Failure Classification Interpretation Guideline", Revised March 2017.
- Association of Professional Engineers and Geoscientists of BC (APEGBC), 2017. Flood Mapping in BC. APEGBC Professional Guidelines V1.0.
- Bureau of Reclamation, U.S. Department of the Interior. 1988. Downstream Hazard Classification Guidelines. December 1988.
- Canadian Dam Association (CDA). 2007, Revised 2013. Dam Safety Guidelines.
- Cathcart, J. "The Effects of Storm Severity and Scale on the Linearity of Watershed Response Revealed Through the Regional L-Moment Analysis of Annual Peak Flows." Ph.D. Thesis, University of British Columbia, 2001.
- Froehlich, D.C., 2008. Embankment dam breach parameters and their uncertainties. *Journal of Hydraulic Engineering*, Vol. 134, no. 12, p. 1708-1721.
- Ancil, F., C. Perrin and V. Andréassian. 2003. "ANN output updating of lumped conceptual rainfall-runoff forecasting models." *J. American Water Resources Association*, Vol.39: pp 1269-1279.
- Bennett, Tony, and Tali Serota. 2014. "Emergency Action Planning – In Action: Practices and Lessons Learned at OPG." Canadian Dam Association Annual Conference. Banff, Alberta. October 4-9, 2014.
- Braess, D. 1986. *Non Linear Approximation Theory*. Springer-Verlag, Berlin.
- MacDonald, T.C., and Langridge-Monopolis, J., 1984. "Breaching Characteristics of Dam Failures," *Journal of Hydraulic Engineering*, ASCE, vol. 110, no. 5, p. 567-586.

- MGS Engineering Consultants, Inc (MGS). Dam Safety Guidelines – Technical Note 1 – Dam Break Inundation Analysis and Downstream Hazard Classification. Prepared for Washington State Department of Ecology, Water Resources Program, Dam Safety Office. October 2007.
- Ministry of Forests, Lands and Natural Resources Operations (FLNRO), 2017a. “Downstream Consequence of Failure Classification Interpretation Guideline”. Revised March 2017.
- Ministry of Forests, Lands and Natural Resources Operations (FLNRO), 2017b. Acceptance of Redetermination of Dam Failure Consequence Classification. Dam file: 76915-20/220/CAMPDEN. November 14, 2017.
- RCEM, 2015. “RCEM – Reclamation Consequence Estimating Methodology – Interim Guidelines for Estimating Life Loss for Dam Safety Risk Analysis”. Bureau of Reclamation, Denver, Colorado, July 2015.
- Singh, Krishan P., and Snorrason, Arni (1982). Sensitivity of Outflow Peaks and Flood Stages to the Selection of Dam Breach Parameters and Simulation Models, SWS Contract Report 288, Illinois Department of Energy and Natural Resources, State Water Survey Division, Surface Water Section at the University of Illinois, 179 p.
- Xu, Y. and Zhang, L.M., 2009. Breach parameters for earth and rockfill dams. *Journal of Geotechnical and Geo environmental Engineering*. Vol. 135, no. 12, p. 1957-1970.