KLAMATH RIVER RENEWAL PROJECT - DAM BREACH ANALYSIS USED FOR DESIGNING THE FINAL BREACH OF THE IRON GATE DAM

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ABSTRACT

The Iron Gate Dam (IGD) is the most downstream dam of the four facilities of the Klamath River Renewal Project (Nistor et al. 2025). It was partially removed with conventional deconstruction techniques. Due to site and drawdown schedule constraints, the final remaining portion of the IGD had to be breached with a head difference of approximately 23 ft (7 m). The assessment of the planned breach and the final IGD reservoir release is presented in this paper. The range of peak outflows during the intentional breach phase was assessed for variable inflow conditions with the goal to establish the most sensitive and limiting breach parameters for safe final breaching and reservoir release. The design of the breach plug and breach channel through the remaining IGD dam incorporated the findings from the breach analysis and included a predefined cross sectional geometry and placed riprap, with the goal to have a peak breach outflow within the allowable flow limits. The final breach was initiated on August 28, 2024. The breach plug slowly eroded, requiring encouragement from long-arm excavators. The full river flow was discharging through the breach by the end of the day. The peak discharge recorded at the USGS gage downstream of Iron Gate Dam was well within the allowable flow limits. Overall, the planned breach was successful due to the breach analysis completed in the design phase.

RÉSUMÉ

Le barrage Iron Gate (BIG) est le barrage le plus en aval des quatre installations du projet de renouvellement de la rivière Klamath (Nistor et al., 2025). Il a été partiellement enlevé avec des techniques de déconstruction conventionnelles. En raison de contraintes liées au site et au calendrier de retrait, la dernière partie restante du BIG a dû être percée avec une différence de tête d'environ 23 pieds (7 m). L'évaluation de la rupture prévue et du rejet final du réservoir du BIG est présentée dans cet article. La variété des débits sortants de pointe pendant la rupture intentionnelle a été évaluée pour les afflux variables dans le but d'établir les paramètres de rupture les plus sensibles et les plus limitatifs qui seraient nécessaires pour la rupture finale. La conception du bouchon de rupture et du canal de rupture à travers le BIG restant incorporait ces constatations et comprenait l'enrochement placé et la géométrie de la section transversale, a suivi l'analyse de la rupture dans le but d'avoir une sortie de rupture de crête dans les limites d'écoulement autorisées. L'atteinte finale a été amorcée le 28 août 2024. Le bouchon de rupture s'est lentement érodé, ce qui a nécessité l'encouragement des excavatrices à long bras. La rivière complète coulait à travers la rupture à la fin de la journée. Le débit enregistré à l'instrumentation de l'USGS en aval du BIG se situait bien à l'intérieur des débits autorisés. Dans l'ensemble, l'atteinte planifiée a été couronnée de succès grâce à l'analyse de l'atteinte effectuée à l'étape de la conception.

1 INTRODUCTION

1.1 Background

The Iron Gate Dam (IGD) is the most downstream dam of the four facilities of the Klamath River Renewal Project (Nistor et al. 2025). It was partially removed after the reservoir had been substantially drawn down using conventional deconstruction techniques, along with the decommissioning of the other three facilities. The final breach of the IGD, and the draining of the residual water body in the former reservoir, was left for last. Due to drawdown schedule constraints, the final remaining portion of the IGD needed to be breached with a head difference of approximately 23 ft (7 m) for the remaining reservoir volume of approximately 22.5 million ft^3 (516 acre-ft, 0.64 million m^3).

A controlled breach was planned to limit peak outflow from the residual water body upstream of the dam. The target for peak outflow was aligned with the estimated bankfull discharge downstream of the dam to avoid overbank flooding.

Preliminary concepts that considered an uncontrolled breach of the final remaining portion of the IGD would result in a higher than allowable breach outflow. Proposals to manage the outflow included some form of grout curtain extending into the breach plug, or sectioned sheet pile if the native material was not too rocky. Both of these solutions were costly, impractical and schedule prohibitive. The engineering and construction required to install these solutions could have pushed the breach into the fall rainy season increasing the flood risk, and would require considerable time to remove while trying to manage the outflows. The breach analysis and subsequent design described in this paper successfully managed the uncertainty related to the attempt to controll the breach development considering erosive processes and was fundamental in avoiding heavy handed solutions that would have created challenging construction risks.

This paper presents the breach analysis conducted to establish:

- The range of peak outflows during the intentional controlled breach phase;
- The most sensitive and limiting breach parameters that would be required for safe final breaching and reservoir release; and
- The design of the breach plug and breach channel through the remaining IGD dam that incorporated the breach analysis.

1.2 Erosion Processes

The purpose of dam design is to avoid an uncontrolled breach of the dam. Most embankment dam breaches that have occurred in the past were uncontrolled erosional events. Erosion is a process that is strongly affected by feedback loops. Highly erosive flows, including dam breach outflows, can enlarge the breach channel, allowing for higher flows and consequently higher erosion. In this paper, this is referred to as a *positive feedback*. Conversely, flows can re-sort the bed (or dam) material leading to armoring and reduced erosion. Furthermore, if high enough flows cannot be sustained for a large breach channel (e.g., for a broad dam, or during the falling limb of the breach outflow hydrograph), the stream power of the outflow must decrease, leading to decreasing erosion. This is referred to as a *negative feedback* in this paper.

Design procedures for riprap and other erosion protection measures were developed with the intention of avoiding extensive erosion. Conceptually, these design procedures can build in negative feedback loops either explicitly (e.g., using higher factors of safety) or implicitly through the development and evolution of "standard practices" that incorporate subjective or qualitative measures. Usage of these procedures to allow moderate erosion is uncertain.

Breach analysis must account for positive feedbacks in the erosion process, either through assuming adverse conditions for the breach scenario (e.g., a weakness in the dam allows piping to initiate a breach), or intentionally skewing estimates towards conservatively negative outcomes for hazard classification or emergency preparedness. Some recent work has attempted to provide semi-quantitative methods for the rate of erosion and whether breach processes lead to positive or negative feedbacks (e.g., Adria et al. 2023; Annandale 2025), but there remains limited information on breach analysis for a design that would encourage a breach development in a controlled way.

2 SITE CONDITIONS AND SCENARIOS

2.1 Dam Geometry

During the final dam decommissioning phase, the IGD dam crest was to be left at an elevation of 2,228 ft (679.3 m), referred to as an Extended Cofferdam (KP 2022). This elevation would protect against the 1% probable flood from July 16 to September 15, including 3 ft (1 m) of freeboard (Nistor et al. 2025). The initial plan for the last phase in releasing the IGD reservoir would be installing a breach plug, lowering the dam crest to an elevation of 2,202 ft (671.3 m), and then initiating a breach through the plug after September 15. This breach elevation was selected based on the approximate lowest water surface level achievable when considering the hydraulic capacity of the historic diversion tunnel. IGD outflows from upstream inflows and reservoir drawdown were to be routed past the dam using the historic diversion tunnel prior to breaching the plug. The tunnel is further discussed in Capucao and Wechselberger (2025).

The breach plug was to be located at the right abutment at the deepest section of the dam. This approach would take advantage of the bedrock side slope as a physical limitation of the breach growing laterally towards the right (a "one-sided" breach). The bottom width of the plug would have been limited to approximately 40 ft (12.2 m) by the shape of the bedrock along the reservoir bottom. The cross-section used for breach modelling and the maximum bottom width of the breach based on terrain geometry at the dam are shown on Figure 1. The breach plug geometry was determined using the analysis discussed in the subsequent sections.

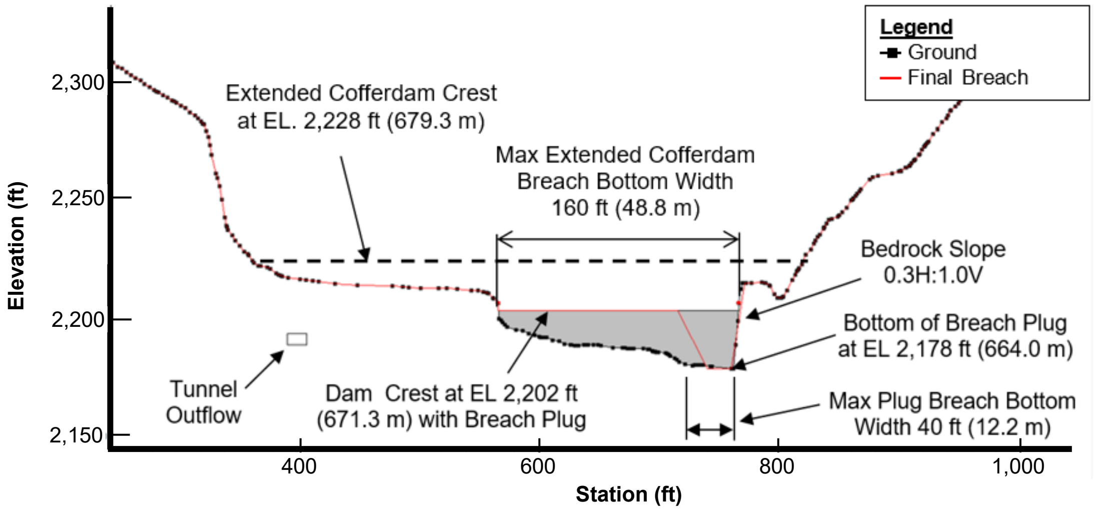

Figure 1: Iron Gate Dam and Breach Plug Cross-Section Relevant to Final Decommissioning Phase

2.2 Inflow Conditions and Criteria

The US Bureau of Reclamation (USBR) operates the Keno Dam upstream of the dam removal project. Outflows from the Keno Dam are controlled by the USBR, but releases follow natural hydrologic cycles and flows where possible. Flow rates in the Klamath River were anticipated to be low through the dam removal period, which would result in the lowest possible reservoir levels occurring around the time of the final dam breach, in line with the normal hydrologic cycle. Four different dam breach scenarios were investigated. The inflows and breach conditions were evaluated for the following four scenarios:

- **Scenario 1A** – peak outflows in which the final breach through the plug is undertaken during higher than the mean monthly flow conditions in September. The reservoir inflow and water surface level (WSL) for this scenario were represented by the condition that is equalled or exceeded 25% of the time in September.
- **Scenario 1B -** peak outflows in which the final breach through the plug is undertaken during lower than the mean monthly flow conditions in August. The reservoir inflow and WSL for this scenario were represented by the condition that is equalled or exceeded 75% of the time in August. This scenario represented the lower bound or best case of all evaluated scenarios.
- **Scenario 2** – peak outflows that would occur due to overtopping of the breach plug during higher than the mean monthly flow conditions in the second half of October. This hypothetical breach scenario may occur in case the final breach was not initiated earlier at lower reservoir WSLs and represents the worst-case scenario for breaching of the plug. The reservoir inflow and WSL for this scenario were represented by the condition that is equalled or exceeded 25% of the time in the second half of October.
- **Scenario 3** – peak outflows that would occur due to overtopping of the Extended Cofferdam prior to the completion of breach plug preparations, when the dam crest had not yet been lowered from elevation of 2,228 ft (679.3 m). This was considered to be the worst-case non-controlled breach scenario in terms of downstream consequences in the analysis.

Scenarios 1A and 1B evaluate the downstream impacts during a planned and intentional breach of the final breach plug, while Scenarios 2 and 3 evaluate the downstream impacts during an unintentional breach due to overtopping during the final stages of dam decommissioning. For brevity, this paper focuses on Scenario 1A. The 25% exceedance inflow used for this scenario was 1,170 cfs (33.1 m^3/s).

The primary goal of the final breach design was to release the remaining reservoir volume without causing overbank flooding or property damage in the downstream reaches. The target for maximum peak outflow discharge was 6,000 cfs, as measured at USGS Gaging Station No. 11516530, Klamath River below Iron Gate Dam, which was based on the estimated bankfull discharge downstream of the dam.

3 BREACH ANALYSIS AND DESIGN

3.1 Probabilistic Approach

An evaluation of which breach parameters could be used to achieve outflows less than the maximum target outflow was performed utilizing a probabilistic breach analysis in the HEC-RAS breach model with the McBreach add-on (Kleinschmidt Group 2019). The range of breach parameter values was based on both FERC (2015) recommended ranges and the physical limitations of the breach plug, as discussed in Section 2.1. The parameters used in the analysis are shown in Table 1.

Table 1: Input Parameters for Probabilistic Monte Carlo Simulations in McBreach

Breach Parameter (Unit)	Method	Distribution	Min.	Max.
Final Bottom Elevation (ft, m)	Deterministic	-		2,178,
Right Side Slope (xH: 1V)[3]	Deterministic	-		0.30
Left Side Slope (xH: 1V)	Probabilistic	Uniform	0.25	1.00
Formation Time (hr)	Probabilistic	Uniform	0.10	1.00
Weir Coefficient (imperial)	Probabilistic	Uniform	2.60	3.30
Progression	Deterministic	-		Sinusoidal
Final Bottom Width (ft)	Probabilistic	Uniform	1.00	40.0

The method in Table 1 is indicated as “deterministic” for the parameter values driven by the terrain geometry, or “probabilistic” for the conditions where a range of values was evaluated. The “uniform” distribution indicates that the selection of the parameter value within a given range was completely random. The right side breach slope is limited to the slope of the bedrock, as shown on Figure 1.

Figure 2 shows several plots for the resulting breach peak outflow (Y-axis) for each simulation against various probabilistic input parameters (X-axis, one parameter per row.). The left column plots show a subsample of 200 simulations near the 99th, 90th, 50th, 10th, and 1st percentile results for clarity, while the right column plots include the full Monte Carlo simulation population. The black line is a local polynomial regression smoothing function, as a general indication of the influence for each parameter. A flatter line indicates low influence.

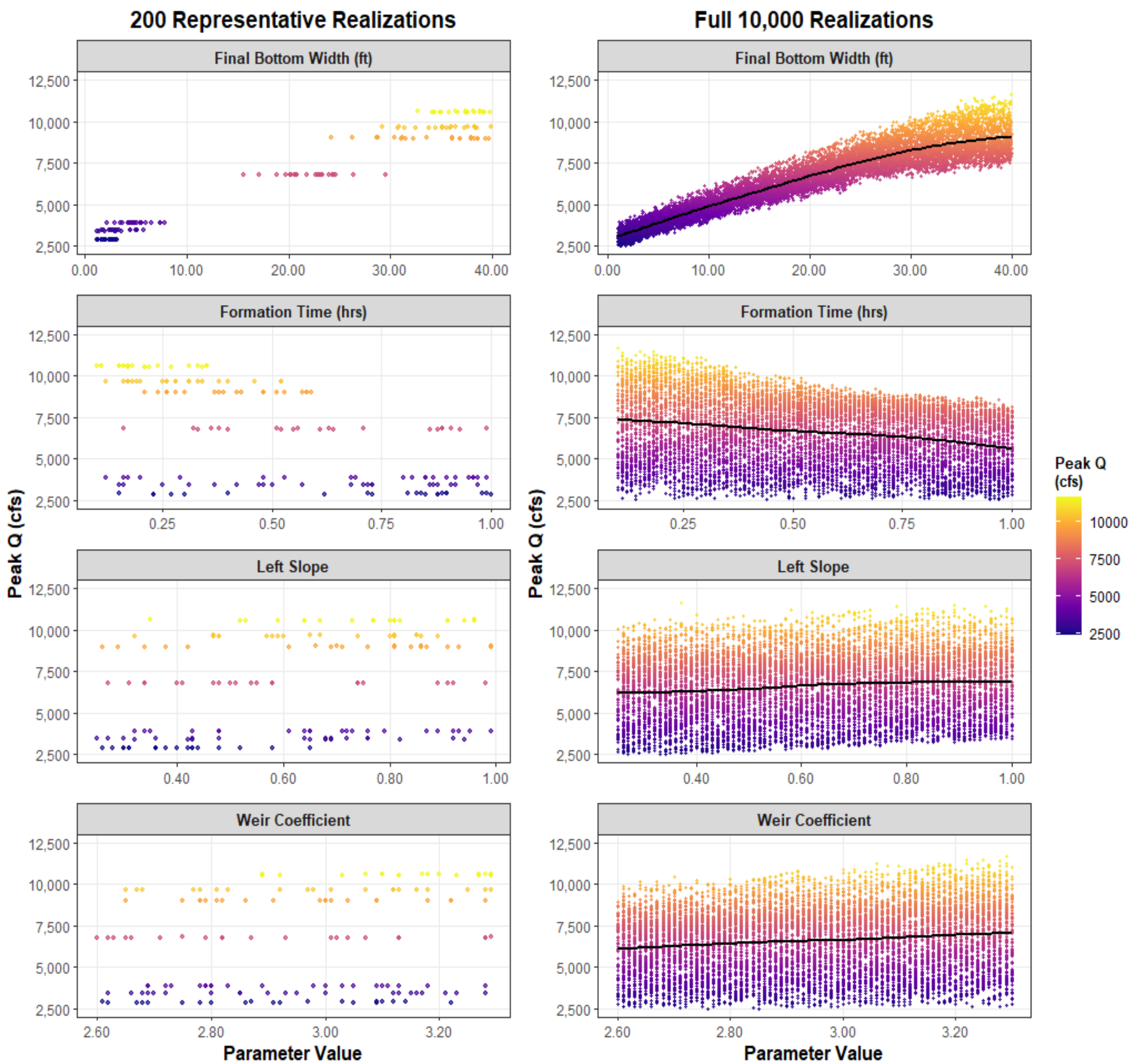

Figure 2: Monte Carlo Simulation Results

Based on 10,000 breach simulations with random parameter combinations, the 50th and the 99th percentile peak breach outflows were 6,800 cfs and 10,600 cfs (192.6 m^3/s and 300.2 m^3/s), respectively. The 99th percentile peak breach outflows typically resulted from a combination of breach parameters that had: breach bottom widths larger than 30 ft (9.1 m), breach formation times shorter than 0.2 hrs, left breach side slopes larger than 0.5H:1.0V, weir coefficients higher than 3.0 (imperial) or values higher than the recommended range in USACE (2019). The 50th percentile peak breach outflows typically resulted from a combination of breach parameters that had: breach bottom widths of approximately 20 ft (6.1 m), breach formation times longer than 0.5 hrs, left breach side slopes larger than 0.5H:1.0V, weir coefficient lower than 3.0 (imperial), or values within the recommended range.

In general and as expected, the peak breach outflow was more sensitive to the breach bottom width and the formation time, and less sensitive to the left breach side slope or the weir coefficient. These results indicate that many combinations of breach parameters may result in peak outflows with a magnitude greater than the acceptable discharge target.

Based on the probabilistic analysis, it was determined that it was necessary to implement measures for controlling the breach development prior to initiating the final breach through the plug (e.g. a pre-constructed narrow breach channel with adequate riprap sizing to slow down the breach formation). Further analysis was required to support specific plug geometries.

3.2 Empirical Breach Parameters Estimates

In addition to the probabilistic dam breach analysis, a selection of empirical equations recommended for breach analysis by FERC (2014) was also used to determine the critical breach parameters. The empirical equations are based on past failures of water retaining dams and include the investigations of: MacDonald and Langridge Monopolis (1984), US Bureau of Reclamation (1988), Von Thun and Gillette (1990), Froehlich (1995), Froehlich (2008), and the revised Froehlich (2016) equations for breach parameters (published subsequent to FERC 2014). These equations are summarized in Wahl (1998) and West et al. (2018).

The results of the analysis using empirical equations indicate that the breach bottom width would be larger than the possible width defined by the geometry of the bedrock at the toe of the dam, noting that the equations do not take geometric limitations into account. The breach formation time predicted using these equations is higher than 0.3 hours in most cases, indicating that the lower bound breach time of 0.1 hours recommended in FERC (2015) may be too conservative given the IGD plug height and reservoir volume during the final breach. Walder and O'Connor (1997) noted that the slowest breaches tend to have downcutting rates (breach height divided by formation time) around 33 ft/hr (10 m/hr). Overall, the IGD intentional breach would likely be comparatively slow with downcutting rates on the order of 33 ft/hr to 66 ft/hr (10 m/hr to 20 m/hr).

This analysis also confirmed that mitigation measures were required to further constrain the breach plug width, as a breach progressing wider than anticipated would not meet the acceptable discharge limits.

3.3 Breach Parameters for a Safe Breach

Following the probabilistic breach analysis, various breach conditions through the final plug were assessed to evaluate the effects of engineered measures on the peak breach outflow. The proposed measures to control the breach included riprapping through a dedicated breach channel, which was not considered during the probabilistic dam breach analysis or when using the empirical equations. The riprap and breach plug design is discussed later in Section 3.4. The breach analysis and the design of the riprap and breach plug was an iterative process, but it is presented linearly in this paper for clarity.

Figure 3 shows a sample of breach hydrographs developed for this part of the assessment.

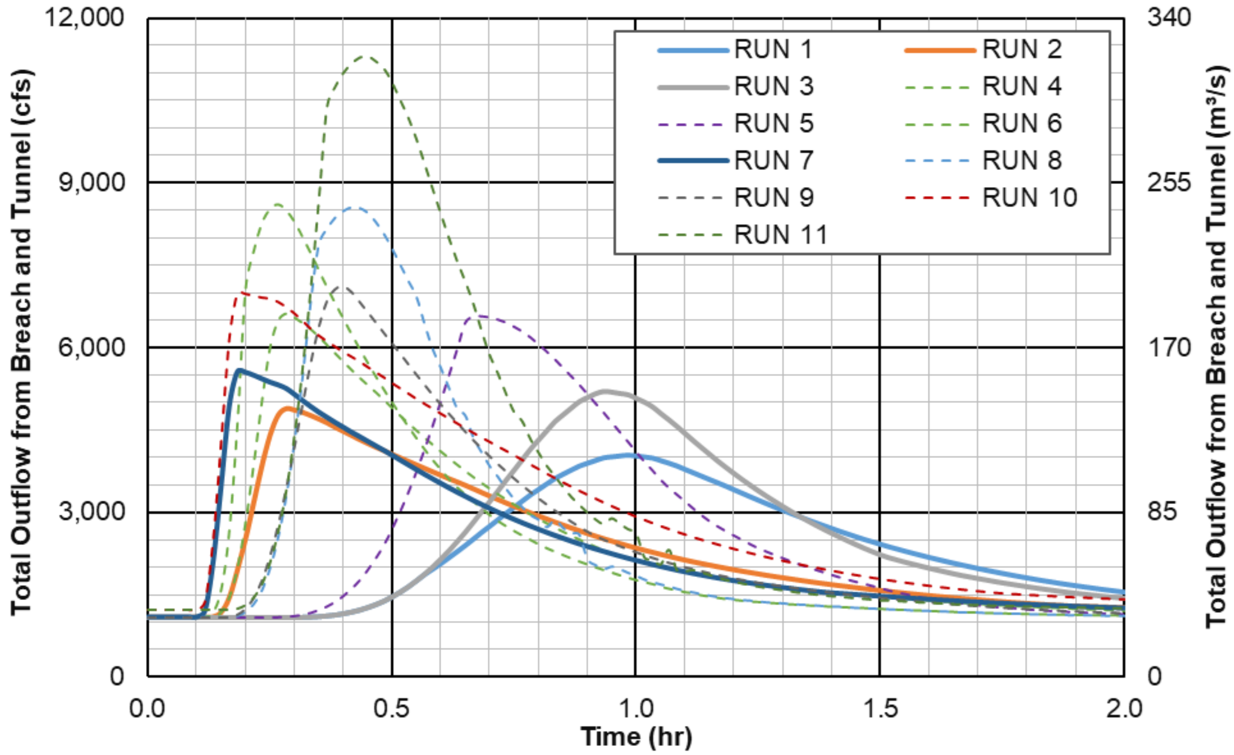

Figure 3: Example Breach Hydrographs from Safe Breach Parameter Assessment

The range of conditions for the hydrographs in Figure 3 included:

- Inflow and reservoir levels for the mean monthly September conditions for Runs 1 through 9 (intentional breaching of the plug) and for mean monthly October conditions for Runs 10 and 11 (delayed and unintentional breaching of the plug);
- Bottom breach widths ranging between 10 ft (3.0 m) and 40 ft (12.2 m);
- Formation times ranging between 0.1 hr and 1.0 hr;
- Breach side slope of 1.0H:1V for the left side and 0.3H:1V for the right bedrock side; and
- Weir coefficient of 2.8 that is approximately equal to the average value of the recommended range (USACE 2019) for Runs 1 through 7, and a weir coefficient of 3.3, or the maximum value of the recommended range (USACE 2019) for Runs 8 through 11.

The following observations are made based on these additional model runs:

- A narrow breach channel would sufficiently constrict the outflows even for a reservoir full to the breach plug crest, such that the total peak outflows from the reservoir including tunnel flows would not exceed 6,000 cfs despite using the most conservative fastest breach formation time of 0.1 hours, with the shallowest left side slope and the highest weir coefficient.

- Widening of the breach through the plug to the maximum bottom width of 40 ft., which is constrained by the terrain geometry, would result in total peak outflows that are higher than 8,000 cfs even when using moderate breach formation times of 0.5 hours. This result further confirmed that the width of the breach channel is one of the critical parameters during the final release of the IGD reservoir that would need to be controlled in order to limit the potential downstream impacts.
- A breach channel width of 20 ft in combination with a moderately fast breach formation time of 0.3 hours, and a moderately conservative side slope and weir coefficient, would result in a peak outflow of approximately 6,000 cfs. This result confirmed that a breach channel up to 20 ft wide would be acceptable for the final release of the IGD reservoir.

Breaching at reservoir WSLs that are lower than the breach plug crest would result in peak outflows that would likely be lower than the flows currently occurring annually or biannually, which are known not to cause overbank flooding.

3.4 Breach Plug Riprap Design

Riprap was used to limit the breach progression. The riprap design had to strike a delicate balance of allowing the outflow to erode the dam for the removal without eroding too quickly such that a positive feedback of erosion and outflows would lead to a larger than desired breach.

Due to site constraints and construction access and sequencing, the breach plug had to be realigned to the centre of the dam rather than adjacent to the bedrock. This had the downside that breach progression would be two-sided rather than one-sided, which could promote positive feedback erosion and higher outflows, but was addressed through the preconstructed breach channel and riprap design.

The riprap design is separated into three zones as follows:

- Zone 1: Downstream face of the dam outside of the breach plug
    - The goal is to mobilize the riprap material immediately downstream of the breach cut while protecting the rest of the breach plug's downstream face. This allows the breach to gradually progress while mitigating the risk of an abrupt breach expansion.
    - Riprap for Zone 1 is sized based on the Shield's parameter approach as presented in USBR PAP-0809 Riprap Design for Overtopped Embankments (1998) and in USBR PAP-0790 Simplified Design Guidelines for Riprap Subjected to Overtopping Flow (2010)
- Zone 2: 20 ft wide riprap-filled trench for the breach plug
    - If the breach cut widens and reaches the trench line, this feature is expected to unload riprap onto the side slope of the breach cut thereby protecting the slope from further erosion and widening beyond the trench line.
    - Riprap for Zone 2 is sized such that the mean flow velocity is less than the critical velocity for riprap mobilization based on FHWA Evaluating Scour at Bridges (2012).
- Zone 3: Downstream of the breach plug within the pre-constructed trapezoidal breach channel

- This feature is sized to protect the channel from erosion during peak breach outflows.
- Riprap for Zone 3 is assessed similarly to Zone 1 but with the goal of not mobilizing the riprap material in the trapezoidal channel.

The breach plug riprap arrangement and the three zones are shown in Figure 4 and Figure 5.

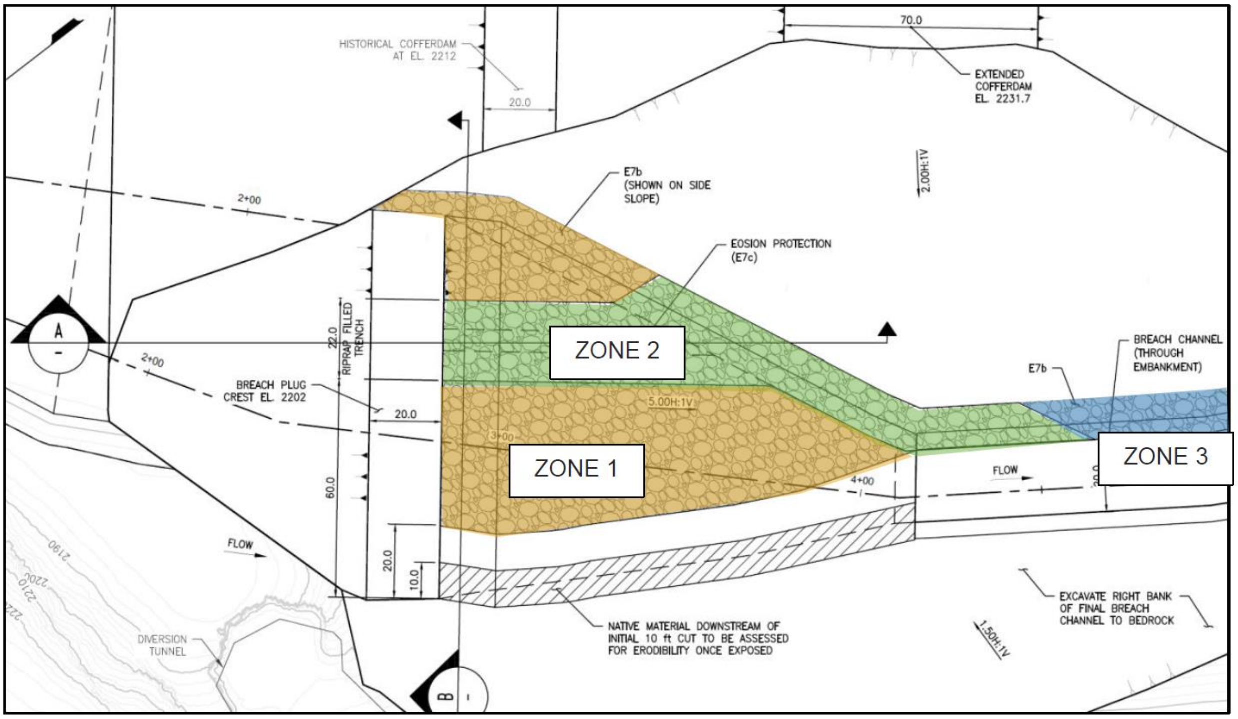

Figure 4: Breach Plug and Breach Channel Riprap Plan

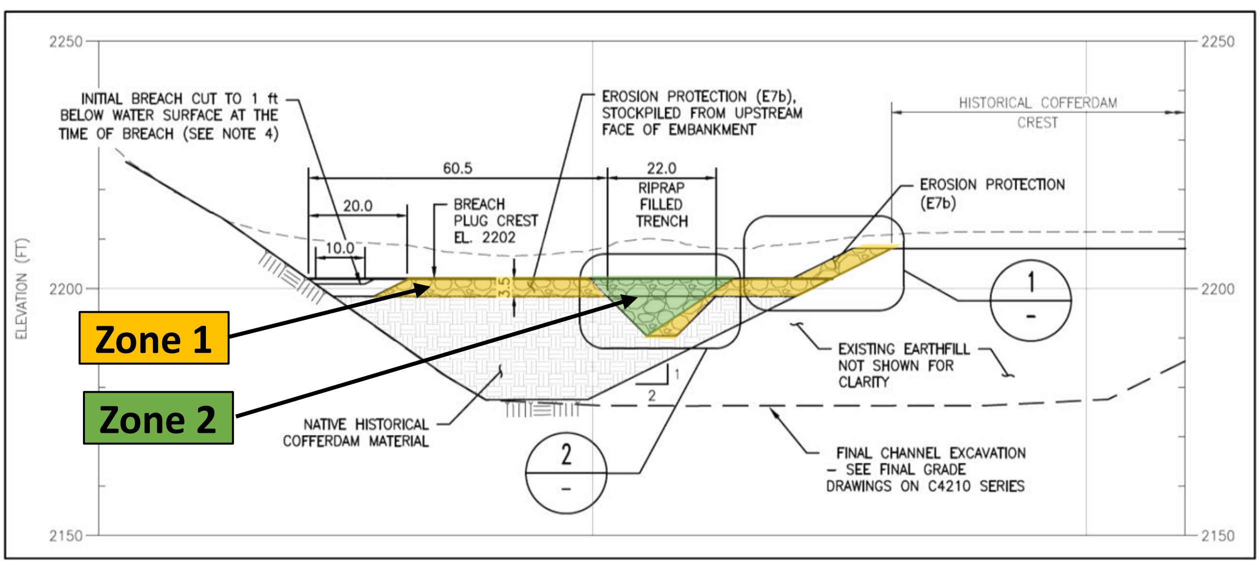

Figure 5: Breach Plug and Breach Channel Cross Section

4 BREACH OF THE IRON GATE DAM

4.1 Change in Conditions

Several changes occurred in the field between the time of breach analysis and the actual breach initiation due to site conditions, as follows:

- The breach plug had to be realigned from the right abutment, as noted in Section 3.4.
- The dam removal began earlier than initially planned and the breach was to be initiated at the end of August, two weeks ahead of schedule.
- The diversion tunnel had less capacity than anticipated based on surveys and CFD modelling, which resulted in higher reservoir levels for a given flow than assessed under the intentional breach scenarios. The details of the tunnel rating curve and change in capacity is further discussed in Capucao and Wechselberger (2025).

Subsequent breach analysis was completed four months before the intentional breach to address the various changes with a primary focus on lower tunnel capacity and increased reservoir levels. The results indicated that it would be difficult to mitigate peak breach discharges within the allowable targets when the height of water was more than 23 ft (7 m). Concurrent with the reanalysis by KP, KRRC and Kiewit approached the USBR to find a solution. USBR agreed to control the Keno Dam outflows within 900 cfs (25.5 m^3/s) , which would control the reservoir levels to 23 ft (7 m) or less. No further breach analysis or riprap redesign was deemed necessary with the reduced flows and reservoir levels.

4.2 Observations during Actual Breaching of the Breach Plug

The reservoir reached the desired level by August 28, 2024. The breach was initiated using a long arm excavator at 8:21 AM. The breach channel eroded relatively slowly throughout the day. A photo of the breach initiation is shown on Figure 6.


Figure 6: Breach Initiation with Long Arm Excavators

The Zone 1 riprap apron and coarse rockfill material in the dam provided resistance to downcutting, and the cohesive fines in the rockfill matrix allowed the side slopes of the incising channel to retain steep angles. The discharge and erosion did most of the dam material removal after the breach initiation; however, the long arm excavator occasionally needed to remove the plug material to encourage breach progression. This indicates that the Zone 2 riprap was slightly oversized for the breach outflow velocities, which was preferred to the alternative of being undersized.

The ambient flow prior to the breach was approx. 900 cfs (25.5 m^3/s). The peak discharge recorded at the USGS Station 11516530 downstream of Iron Gate Dam was 1,010 cfs (28.6 m^3/s), as shown on Figure 7. The observed pulses correspond to times when the excavators dug out the plug material, or when the positive feedback mechanisms of the breach eroded localized portions of the plug with smaller riprap material before encountering larger riprap resulting in a negative feedback and lower outflows.

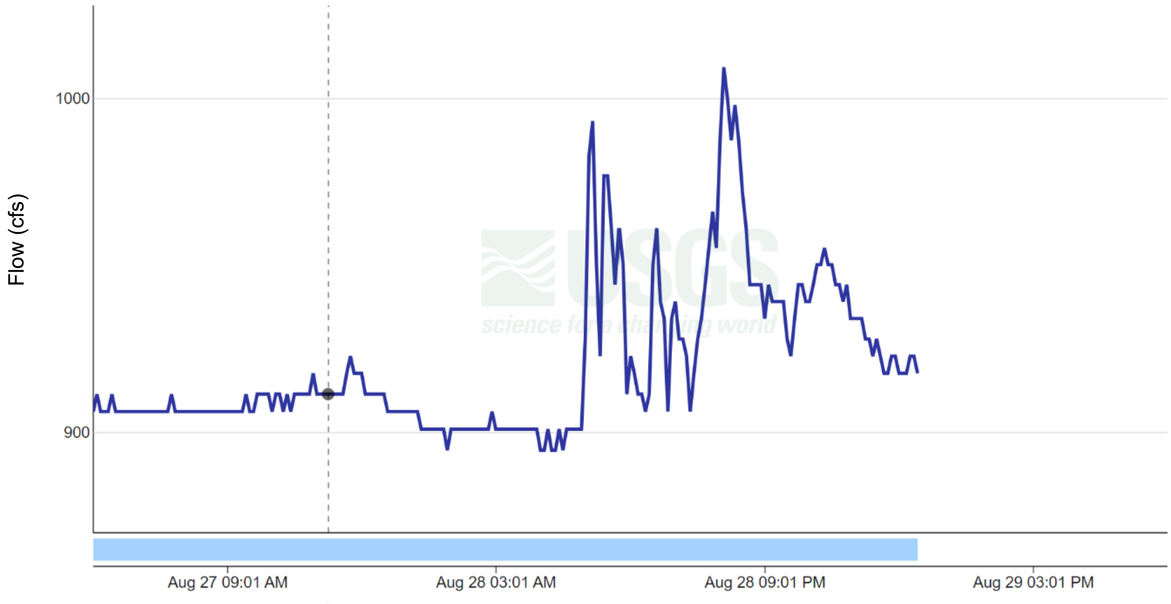

Figure 7: Measured Flow at USGS Station 11516530 Downstream of the Iron Gate Dam

The diversion tunnel inlet was progressively blocked with fill to direct the river flow through the breach channel later in the day. The full river was flowing through the breach by the following day. The cofferdam at Copco No. 1 was breached a few hours after Iron Gate, allowing the river to flow through the excavated dam site there as well. Water quality temporarily deteriorated with the mobilization of mud from the bottom of the Iron Gate reservoir, but it cleared up in approximately one month, in time before the fall salmon run.

5 CONCLUDING REMARKS

The intentional breach of the Iron Gate Dam was successfully completed to meet the construction constraints, maintain safe outflows for the downstream area, and meet other dam removal project requirements. With the aging dam infrastructure and the increasing number of dams being removed, intentional breaching may be a feasible approach to ensuring public safety and limiting the downstream consequences. The intent of this paper is to share some of the thought processes and encountered challenges from this project as a resource for future projects.

When faced with the uncertainty of the site conditions, multiple avenues of assessment were always considered. For example, the breach analysis for the intentional breach considered probabilistic methods, results from empirical equations, and deterministic analysis tailored to the specific conditions of the breach plug. The different stakeholders had different confidence in various data and methods; therefore, a conclusion based on all of them was key to building consensus and agreement in moving towards an acceptable intentional breach design.

The breach analysis ultimately “overestimated” the actual flow during the intentional breach; however, the analysis was useful from a risk management perspective. It was also necessary to achieve an acceptance from stakeholders that an intentional breach was a plausible and safe solution. It was anticipated from the outset of the breach analysis that a slow breach that required manual encouragement was a possible outcome, due to the successful negative feedback loop of the riprap on the breach processes. The goal of the breach analysis was to consider the potential outflows if the riprap was unsuccessful and the erosion feedback was positive. If the outflow from the positive erosional feedback was acceptable, then so must be the outflow from the negative erosional feedback.

This paper presents a brief summary of the discussions, analysis, design, and construction completed by KP, NHC, Kiewit, and others for the development of an intentional breach. This summary does not include all considerations. It should be apparent that despite the extensive effort, the reality of the field often differs from the best laid plans. A critical aspect of the success of the intentional breach was the coordination between KRRC, Kiewit, and USBR to temporarily reduce the Keno Dam outflows. The best solution to the changed conditions was not strictly within the control of the KRRC, like installing a larger riprap. This highlights the importance of working with regulatory agencies and other stakeholders to reach creative solutions for the challenges encountered in the field.

6 ACKNOWLEDGEMENTS

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