Protections 2016 Ft. Collins, Colorado, USA, 7-9 September 2016
2nd International Seminar on
Dam Protection Against Overtopping
ISBN: 978-1-1889143-27-9 DOI:

Using Risk to Inform Overtopping Protection Decisions

W.R. Fiedler[1]
[1]Civil Engineer, (86-68300), Technical Service Center
Bureau of Reclamation
Denver, CO 80225
USA
E-mail: wfiedler@usbr.gov

ABSTRACT

The decision to implement overtopping protection as a dam safety modification alternative can be difficult. The decision involves a conscious decision to allow a dam to overtop for floods above a threshold flood. If a large flood occurs that initiates dam overtopping, there is no turning back, and the dam and the overtopping protection must be able to resist the overtopping flows. The chance of intervention being successful for a dam that is already overtopping, should erosion initiate, would be very unlikely. There is more of a comfort level among many dam engineers in providing conventional solutions to a dam overtopping issue. These traditional measures include raising the dam crest to provide additional surcharge space to store a portion of the flood inflows or providing additional spillway capacity to more closely match the peak flood inflows. There is often the perception among experienced dam engineers that these traditional measures provide a safer solution and pose less risk than an overtopping solution. This paper will present scenarios that demonstrate that in some cases, overtopping protection may be just as safe or the safer alternative, by exposing the downstream population to equal or less risk of dam failure during a large flood event. These scenarios will consist of an embankment dam where a replacement gated spillway alternative will be compared to overtopping protection and a concrete dam where raising of the dam will be compared to providing overtopping protection for the dam foundation.

Keywords: *Overtopping Protection, Risk, Dam Safety, Modifications.*

1. INTRODUCTION

The Bureau of Reclamation (Reclamation) relies on information from risk analyses and risk assessments to guide all aspects of its dam safety program. Results of a potential failure modes analysis (PFMA) and risk analysis estimates along with the supporting dam safety case are used to assess risk at each dam and make decisions on whether additional actions are required to better understand or reduce dam safety risk. One of the key inputs into the dam safety decisions at the end of a dam safety study is the risk estimates related to the key Potential Failure Modes (PFMs) for a given dam. Risk estimates for individual PFMs as well as the total risk are plotted on Reclamation's f-N chart shown on Figure 1. Two measures of risk are portrayed. The Annualized Failure Probability is the product of the probability of the loading (normal operations, flood, or earthquake) and the probability of dam failure given the loading. The Annualized Life Loss is the product of the Annualized Failure Probability and the life loss estimated to result from dam failure. The f-N chart portrays threshold values for increasing justification to take action to reduce risk related to the two measures of risk, which are a threshold value of 1E-4 for the Annualized Failure Probability, and a threshold value of 1E-3 for the Annualized Life Loss (Reclamation, 2011). These threshold values are intended to reflect society's tolerance for risk (annualized life loss) and to be consistent with the background risk that individuals face (annualized failure probability). The threshold values are consistent with a number of dam safety guidelines worldwide. In addition to the risk estimates, Reclamation considers the supporting arguments for the numerical estimates (the dam safety case) as well as the uncertainty and confidence in the risk estimates when making dam safety decisions.

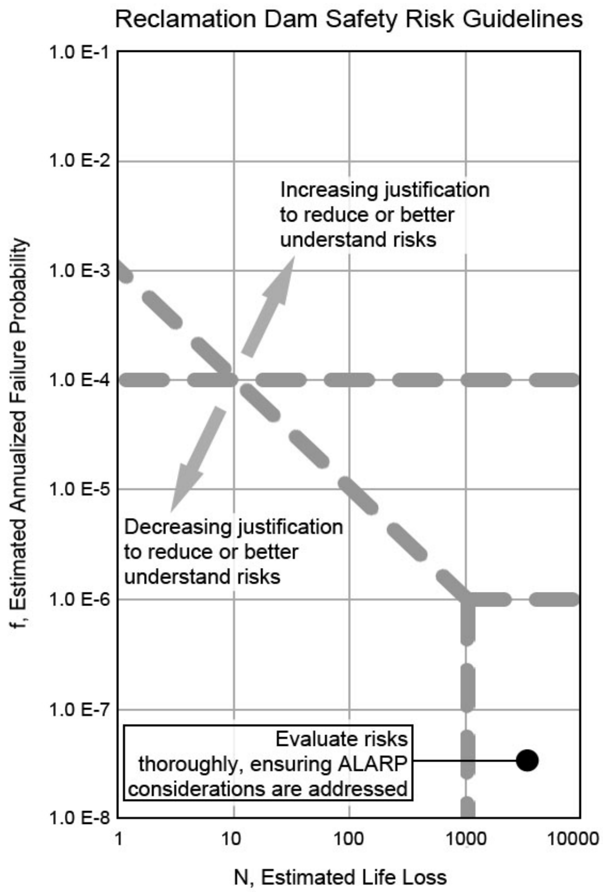

Figure 1 – Reclamation's f-N Chart

This paper will focus on the potential failure mode due to dam overtopping during a large flood, considering both the depth and duration of overtopping. Two examples are presented – one for an embankment dam and one for a concrete arch dam. Both dams have baseline risks which indicate increasing justification to take action to reduce risk. Corrective action studies were initiated at both dams and traditional alternatives as well as overtopping alternatives were considered. The examples will demonstrate how traditional alternatives and overtopping protection alternatives might compare in terms of risk reduction.

1.1. Embankment Dam Example

Cody Dam is a zoned earthfill embankment dam with a crest that is 790 feet long and 35 feet wide at crest elevation 3264.0, and that is paved with asphalt-concrete. The structural height of the embankment is 245 feet and the spillway crest is at elevation 3250.0. The upstream face of the dam slopes at 3H:1V between the embankment crest and the reservoir floor. The downstream face slopes at 3H:1V between the crest and elevation 3125, then at 4H:1V from elevation 3125 to the downstream toe. Both the upstream and downstream faces are protected by a layer of riprap.

The existing concrete spillway is 300-feet wide with an uncontrolled ogee crest and a chute and hydraulic jump stilling basin. The existing spillway has a design capacity of 36,000 ft^3/sec at reservoir water surface elevation 3261.0.

A hydrologic hazard study was conducted for Cody Dam and frequency flood hydrographs were then developed and routed through Cody Dam. Some of the key results from the hydrologic hazard study and the flood routing study are presented in Table 1. The studies indicate that Cody Dam will be overtopped for a flood with a return period between 1000 and 10,000 years. The dam is by projected to overtop by 10 feet (average depth of flow over dam crest) for the PMF, which is very close in peak and volume to the 200,000-year flood event.

Table 1. Frequency Peak discharges and volumes for Cody Dam.

Return Period (yr)	AEP Estimate (ft^3/s)	7-day Volume (ac-ft)	Freeboard (ft)	Max Overtopping Discharge (ft^3/s)	Duration of Overtopping (hours)
100	30,100	36,440	5.0	0	0
500	45,600	69,818	2.4	0	0
1,000	67,000	89,723	0.5	0	0
10,000	105,000	184,957	-1.4	3,400	3
50,000	140,000	277,130	-4.6	20,400	8
100,000	175,000	327,962	-7.2	40,000	12
200,000	240,000	567,427	-10.0	65,500	16

AEP – Annual Exceedance Probability

1.1.1. Potential Failure Mode

Based on the flood routing results, it was apparent that a potential failure mode related to overtopping of Cody Dam during a flood that exceeds the magnitude of a 1000-year event should be investigated further. The following potential failure mode description was developed:

> The dam overtops during a large flood and erosion initiates at the change in slope along the downstream slope of the dam, at elevation 3125. The erosion rapidly results in a large scour hole. Headcutting ensues and erosion progresses upstream through repeated headcutting and localized slope failure. The headcutting progresses through the dam crest and the dam is breached.

A team risk analysis was conducted to evaluate this potential failure mode as well as other potential failure modes for Cody Dam.

1.1.2. Risk Estimates

Annualized failure probabilities for the flood overtopping potential failure mode were estimated for the baseline case and a summary of the event tree estimates is provided in Table 2. The event tree used is simple. It includes the assumption that if the dam overtops, failure will be imminent and only three conditional events are considered – Dam Overtops, Erosion Occurs and Headcutting Initiates, and Headcut Proceeds to Dam Breach. For the 1000- to 10,000-year flood load range under baseline conditions, it was estimated the probability of dam overtopping was approaching likely (0.8; based on the fact that for smaller floods in this load range the dam would not be expected to overtop). For all other flood load ranges, it was estimated that the dam would be very likely (0.99) to overtop. Given that the dam overtops, it was judged that erosion occurring and headcutting initiating was very likely (0.99) for all flood load ranges. Given that erosion has occurred and headcutting has initiated it was generally estimated that breach of the dam was very likely (0.99), except for the 1000- to 10,000-year flood load range, where it was judged to be likely (0.9). This was due to the consideration that for floods in the range of a 1000- to 10,000-year event, the flood duration may not be sufficient to progress all the way to dam breach. Based on the estimates made for each flood load range, the total annualized failure probability was determined by summing the estimates for the four branches. This resulted in a total annualized failure probability of 7.2E-4 (the flood overtopping potential failure mode was the dominant potential estimated with 90 percent of the risk being contributed by this potential failure mode), which exceeds Reclamations Public Protection Guideline value of 1E-4 and provides increasing justification to take action to reduce risk. For the purpose of the examples in this paper, only annualized failure probability estimates are considered and they are portrayed as single value estimates. Life loss consequences and the annualized life loss estimates, as well as ranges in the estimates that reflect the inherent uncertainty in the risk estimates, are also not portrayed.

Table 2. Annualized Failure Probability – Baseline Condition for Cody Dam.

Flood Load Range	Load Probability	Dam Overtops	Erosion Occurs and Headcutting Initiates	Headcut Proceeds to Dam Breach	Annualized Failure Probability
1k to 10k	0.0009	0.8	0.99	0.9	6.4E-4
10k to 50k	0.00008	0.99	0.99	0.99	7.7E-5
50k to 100k	0.00001	0.99	0.99	0.99	9.7E-6
100k to 200k	0.00001	0.99	0.99	0.99	9.7E-6
					7.2E-4

Since the baseline estimate indicated justification to take action to reduce risk, modification alternatives that reduced the probability of the dam overtopping and the dam breaching during a large flood event were considered. The two alternatives were a more traditional option of providing a new replacement gated spillway and a second alternative involving overtopping protection consisting of precast concrete blocks on the downstream face of the dam.

The replacement spillway alternative consisted of a spillway regulated by three 25-foot wide by 22-foot high radial gates that has a capacity of 45,500 ft^3/s at elevation 3261.0. The spillway was designed to pass the PMF with 3 feet of freeboard. A gated spillway was chosen because there was not a site for a wider uncontrolled spillway and the gated spillway allowed for significant additional spillway capacity within the constraint of the existing dam crest elevation. The gated spillway did create a vulnerability in terms of spillway operation reliability.

The initial flood routings assumed that all three spillway gates were fully functional during a flood and that the full spillway capacity was realized for a given gate opening. The routings evaluated the change in spillway discharge for more frequent floods under the modified gated operation, as compared to the baseline condition. Operations will limit releases to no more than the inflow at a given point during the flood, and it was concluded that gated spillway operations would not significantly increase downstream releases. Flood routings were also performed in which one of the spillway gates was assumed to be inoperable during the entire flood routing. This simulated an issue with a single gate for the entire flood or an issue that would affect multiple gates for a portion of the flood. Issues could consist of debris plugging of the spillway, inability of power supplies and backup power supplies to perform, operator error or an operator intentionally holding back on spillway releases to minimize downstream flooding or electrical/mechanical issues with the gate operating system. The reduced risk with the replacement gated spillway in place was estimated. After considering the potential issues described above, the risk analysis team concluded that there was a 5 percent chance that the full spillway capacity would not be realized during a flood. The relatively low probability was based on the lack of large trees in the drainage basin, the fact that redundant power supplies are provided and the fact that the gates are well maintained and the gates and power supply are exercised regularly. This probability was assigned to all flood load ranges as it was generally thought to be independent of the flood magnitude. For the 95 percent chance that the spillway capacity was not restricted, all floods can be passed, including the PMF. The only probability of dam overtopping and potential dam failure is associated with reduced spillway capacity. Based on the flood routing results, the risk estimates made by the risk analysis team are summarized in Table 3. For the Dam Overtops event, the probability was estimated as 0.5 for the 1000 to 10,000 year event. This estimate was based on the flood routing results, which indicated that the dam would not overtop for floods in the lower half of this range but would be expected to overtop for floods in the upper half of the range. The estimates for the Erosion Occurs and Headcutting Initiates and Headcut Proceeds to Breach events were the same as those for the baseline condition. The total annualized failure probability was estimated to be 2.5 E-5. This indicates that when gate reliability is considered, the replacement gated spillway alternative reduced risk to almost an order of magnitude below the threshold guideline value of 1 E-4.

Table 3. Annualized Failure Probability – Replacement Gated Spillway Condition for Cody Dam.

Flood Load Range	Load Probability	Gate Inoperable	Dam Overtops	Erosion Occurs and Headcutting Initiates	Headcut Proceeds to Dam Breach	Annualized Failure Probability
1k to 10k	0.0009	0.05	0.5	0.99	0.9	2.0E-5
10k to 50k	0.00008	0.05	0.99	0.99	0.99	3.9E-6
50k to 100k	0.00001	0.05	0.99	0.99	0.99	4.9E-7
100k to 200k	0.00001	0.05	0.99	0.99	0.99	4.9E-7
						2.5 E-5

A second alternative consisting of placing precast blocks on the downstream face of the dam was also considered as a modification alternative. The blocks had no effect on the probability of the dam overtopping, but they did significantly improve the dam's ability to resist the overtopping flows without experiencing erosion. If the blocks remained in place, the team judged that there would be almost no chance of erosion initiating and the dam eventually breaching. The team did conclude that there was a chance that an individual block or blocks could fail and that this could lead to erosion, failure of more blocks and eventually headcutting and a breach of the dam. The team altered the event tree to consider the following events after the dam overtopped: Block Fails; Erosion Initiates at Failed Block; Additional Blocks are Undermined and Fail; and, Headcut Proceeds to Breach (see Table 4 for estimates for each of these events by flood load range; the estimates for the Dam Overtopping event were not changed from the baseline condition, as the overtopping protection did not alter this). The team judged that the probability of a block failing would vary from 5 percent to 10 percent for the flood load ranges considered. Failure of a block was judged to most likely occur due to debris within overtopping flows impacting on blocks. The risk analysis team believed that debris loading would increase with the magnitude of the flood. There was some uncertainty in this estimate, given the difficulty in analyzing blocks for this type of failure. The team ultimately relied on the successful operation of this type of overtopping protection at other dams and the fact that there was a limited source of debris in the drainage basin. The team also thought the erosion would be very likely (0.99) to initiate if a block failed and that the chance of additional blocks failing would be slightly less than likely (0.8) to very likely (0.99) for the floods considered. Given the previous events occur, the team thought that the headcutting leading to dam breach would vary from likely (0.9) to very likely (0.99). The risk estimates for the overtopping protection alternative are summarized in Table 4. The total annualized failure probability was estimated to be 3.6 E-5, which was below the threshold value of 1 E-4 but by less than an order of magnitude.

Table 4. Annualized Failure Probability – Overtopping Protection Condition for Cody Dam.

Flood Load Range	Load Probability	Dam Overtops	Block Fails	Erosion Initiates at Failed Block	Additional Blocks Undermined and Fail	Headcut Proceeds to Dam Breach	Annualized Failure Probability
1k to 10k	0.0009	0.8	0.05	0.99	0.8	0.9	2.6E-5
10k to 50k	0.00008	0.99	0.05	0.99	0.9	0.99	3.5E-6
50k to 100k	0.00001	0.99	0.07	0.99	0.95	0.99	6.5E-7
100k to 200k	0.00001	0.99	0.10	0.99	0.99	0.99	9.6E-7
							3.1E-5

1.1.3. Alternative Evaluation

This example addresses the high baseline risk for an embankment dam from flood overtopping. The baseline risk exceeds the threshold value for annualized failure probability by a considerable amount (7.2 E-4 compared to the threshold value of 1 E-4), indicating that there is increasing justification to take action to reduce risk. Two alternatives were evaluating for reducing the risk of flood overtopping – constructing a replacement spillway with greater capacity and providing overtopping protection consisting of precast concrete blocks on the downstream face of the dam. Both alternatives were designed for the PMF, which is close in magnitude to a 200,000-year event. The replacement spillway option was designed to prevent all conceivable floods from overtopping the dam, but is dependent on the full capacity of the spillway being realized during a flood. The overtopping protection option was designed to allow dam overtopping but to armor the downstream face to prevent erosion that could lead to headcutting and breach of the dam, but is dependent on the integrity of the precast blocks. If both alternatives performed perfectly, the risk of flood overtopping dam failure would be negligible, but the vulnerabilities inherent in both designs create some risk of dam failure. The risk estimates indicate that the risk reduction achieved by both alternatives are comparable – an annualized life loss estimate of 2.5 E-5 for the spillway replacement alternative and 3.1 E-5 for the overtopping protection alternative. Both alternatives provide risks that are close to an order of magnitude below the threshold value of 1 E-4.

1.2. Concrete Dam Example

Bison Dam is a concrete arch dam containing approximately 147,300 yd^3 of concrete. The dam has a structural height of 199 feet and a hydraulic height of 195 feet, and the 15-foot-wide crest is about 960 feet long at elevation 4725.5. The dam has a maximum base width of 117 feet. Parapets are located on the upstream and downstream edges of the crest, with the top of the parapets at elevation 4729.0. The upstream face of the dam is vertical from abutment to abutment and is curved on a radius of 405 feet. The downstream face has a variable slope from crest to base and from crown to abutment, and gradually increasing curvature toward the base of the dam. The dam foundation is generally competent except for a 30-foot wide fractured zone between two inactive faults on the left abutment of the dam.

The spillway is a morning-glory-type spillway located in the left abutment. From the drop inlet, discharges pass through a 29.5-foot-diameter concrete-lined tunnel which then discharges into the Moon River. Maximum capacity of the spillway, with a reservoir water surface elevation of 4729.0, is approximately 50,000 ft^3/s.

A hydrologic hazard study was conducted for Bison Dam and frequency flood hydrographs were then developed and routed through Bison Dam. Some of the key results from the hydrologic hazard study and the flood routing study are presented in Table 5. The studies indicate that Bison Dam will be overtopped for a flood with a return period between 100 and 500 years. The dam is projected to overtop by about 15 feet for the PMF. The PMF hydrograph is slightly smaller than the hydrograph for the 1,000,000-year flood event.

Table 5. Frequency Peak discharges and volumes for Bison Dam.

Return Period (yr)	AEP Estimate (ft^3/s)	7-day Volume (ac-ft)	Freeboard (ft)	Max Overtopping Discharge (ft^3/s)	Stream Power Range (kW/m^2)
100	23,817	36,440	2.5	0	n/a
500	40,486	69,818	-2.1	9100	25 to 100
1,000	49,644	89,723	-3.4	19,600	50 to 250
10,000	90,874	184,957	-6.9	57,900	100 to 400
50,000	132,029	277,130	-9.3	90,300	200 to 700
100,000	153,606	327,962	-10.4	107,400	250 to 800
1,000,000	243,500	567,427	-14.9	182,600	350 to 1200

1.2.1. Potential Failure Mode

Based on the routing results, a potential failure mode related to overtopping of Bison Dam during a flood that exceeds the magnitude of a 100-year event was identified. The following potential failure mode description was developed:

> During a large flood event, the dam overtops and the overtopping flow forms a high velocity jet that impinges on the dam foundation. The impinging jet initiates erosion of the foundation on the left abutment of the dam where the rock is highly fractured, creating a scour hole. As the overtopping continues, the scour hole deepens and is extended upstream by headcutting. The headcutting results in a portion of the dam to be undermined. The loss of foundation support causes overstressing in the dam which cannot be re-distributed. The dam cracks and fails due to a removable section being created.

A team risk analysis was to evaluate this and also consider other potential failure modes for Bison Dam.

1.2.2. Risk Estimates

The potential failure mode required an evaluation of the potential for the foundation rock to erode when exposed to overtopping flows. The concept of using a rock mass index to correlate with the power it would take to remove the rock was original developed by Kirsten (1983) to characterize the rip-ability of earth materials using mechanical equipment and its associated horsepower. This was extended to examine the removal of rock from flowing water, and at that time the term “erodibility index” was coined. This index was correlated empirically to the erosive power of flowing water, or the energy rate of change, termed “stream power”. Data from the performance of unlined spillways in both soil and rock were used to calibrate the method for erosion potential.

The stream power – erodibility index method can be used to estimate the likelihood of rock erosion initiating. The current use of this method is well documented (Annandale, 2006). The erodibility index (and its possible variability) represents how erodible the foundation material is. It is relatively simple to calculate. The erodibility index, K_h, is calculated from:

$$K_h = M_s K_b K_d J_s \quad (1)$$

M_s is the mass strength, usually defined as the uniaxial compressive strength (UCS) for rock (expressed in MPa) when the strength is greater than 10 MPa, and $(0.78)(UCS)^{1.05}$ when the strength is less than 10 MPa. K_b defines the particle or fragment size of rock blocks that form the mass, which can be determined from joint spacing or rock mass classification parameters. The simplest and most straight forward relationship is $K_b = RQD/J_n$, where J_n is a modified joint set number. K_d describes the interblock strength, and is usually taken as J_r/J_a, where J_r and J_a are based on joint surface characteristics defined by Barton's Q-system. The relative shape and orientation of the blocks is accounted for by the J_s parameter. This represents the ease with which the water can penetrate the discontinuities and dislodge the blocks.

The stream power represents the erosive power of the overtopping flows, and is much more complicated to rigorously compute. In the case of a plunging jet falling onto geologic materials, the jet will break up to some extent while falling through the air, reducing its energy and potential for producing erosion. However, as a conservative simplification, it can be assumed that all of the kinetic energy from an intact falling intact jet is dissipated on direct impact to the rock surface without any break-up of the jet, and the stream power can be estimated (in KW/m^2) from:

$$P = \gamma q H / d \tag{2}$$

where γ is the unit weight of water (9.82 KN/m^3), q is the unit discharge at the location being examined (m^3/s/m), H is the head or height through which the jet falls (m), and d is the thickness of the jet as it impacts the rock (m). This method will provide an indication as to the likelihood that erosion will initiate, but if so, additional judgment is needed as to whether the erosion will progress to the point of undermining and failing the dam.

The stream power-erodibility index method was used to evaluate the potential for erosion at Bison Dam. Ranges of erodibility index values were calculated for two different foundation rock types and are shown in Table 6. Ranges of stream power values for different return period floods were also calculated and are provided in Table 5. With these two sets of information, an evaluation was made on the potential for foundation erosion for different flow conditions. This evaluation was aided by using logistic regression results obtained by Wibowo et al. (2005) using data originally collected by Annandale (1995) from field observations from spillway channels and plunge pools. Figure 2 provides the results of the Wibowo et al. (2005) study along with data from Bison Dam. The leftmost plotted rectangle represents the conditions for a jet impinging on the fractured portion of the dam foundation, for the full range of spillway flows.

Table 6. Erodibility Index Values for Different Materials.

Material	Erodibility Index	Threshold Stream Power Density (kW/m^2)
Concrete - low	6400	715
Concrete - high	8500	885
Fractured rock - low	200	53
Fractured rock - high	400	89
Hard foundation rock - low	7100	603
Hard foundation rock - high	12000	1146

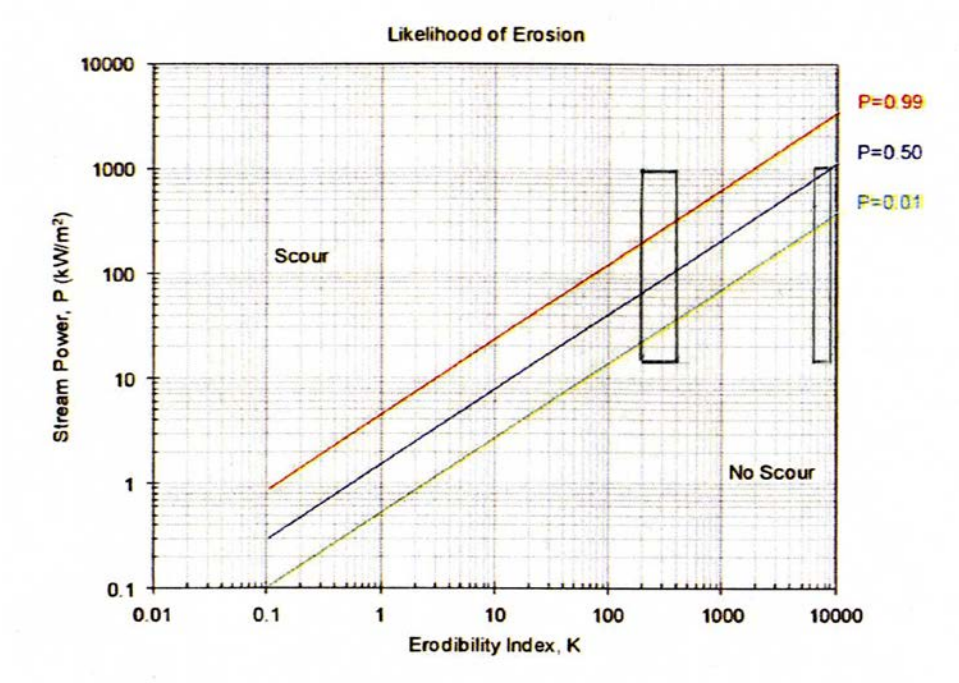

Figure 2. Graph for estimating likelihood of erosion (after Wibowo, 2005)

Based on the results described above, annualized failure probabilities for the flood overtopping potential failure mode were estimated for the baseline case and a summary of the event tree estimates is provided in Table 7. The event tree used considers three conditional events for a given range of flood loading – Dam Overtops, Erosion Initiates and the Dam Undermined and Loads Don’t Redistribute and the Dam Fails. For the 100- to 500-year flood load range under baseline conditions, it was estimated the probability of dam overtopping was approaching likely (0.8). For all other flood load ranges, it was estimated that the dam would be very likely (0.99) to overtop. Given that the dam overtops, it was judged that erosion occurring and the dam being undermined ranged from 0.1 (unlikely) to 0.99 (very likely) for the full range of floods considered. These estimates were based on the stream power values for a given flood loading range and where these values plotted on Figure 2 along with the range of erodibility index values for the weaker foundation rock. Given that erosion has occurred and the dam is undermined it was estimated that the probability of the dam not being able to redistribute the loads would range from 0.01 for the 100- to 500-year flood load range to 0.9 for the 100,000- to 1,000,000-year flood load range. The justification by the risk analysis team was that for smaller flows the extent of dam undermining would be small due to the duration of overtopping flows but for the largest floods undermining would be more extensive with longer durations of overtopping. Based on the estimates made for each flood load range, the total annualized failure probability was determined by summing the estimates for the four branches. This resulted in a total annualized failure probability of 1.7E-4 (the flood overtopping potential failure mode was the dominant potential estimated with 95 percent of the risk being contributed by this potential failure mode), which exceeds Reclamations Public Protection Guideline value of 1E-4 and provides increasing justification to take action to reduce risk.

Table 7. Annualized Failure Probability – Baseline Condition for Bison Dam.

Flood Load Range	Load Probability	Dam Overtops	Erosion Initiates and Dam Undermined	Loads Don't Redistribute and Dam Fails	Annualized Failure Probability
100 to 500	0.008	0.8	0.1	0.01	6.4E-6
500 to 1k	0.001	0.99	0.5	0.02	9.9E-6
1k to 10k	0.0009	0.99	0.99	0.05	4.4E-5
10k to 50k	0.00008	0.99	0.99	0.5	4.0E-5
50k to 100k	0.00001	0.99	0.99	0.7	6.9E-6
100k to 1000 k	0.00001	0.99	0.99	0.9	8.0E-6
					1.7E-4

Since the baseline estimate indicated justification to take action to reduce risk, modification alternatives that reduced the probability of the dam overtopping and the dam breaching during a large flood event were considered. The two alternatives were a more traditional option of raising the dam and a second alternative involving overtopping protection consisting of reinforced concrete overlays over the fractured portion of the dam foundation.

The dam raise consisted of raising the dam crest by 10 feet, which allowed the 10,000-year flood to be passed with 1 foot of freeboard. Flood routings were performed for the raised dam and it was concluded that Bison Dam would overtop for a flood with a return period of between 10,000 and 50,000 years. Stream power calculations from the baseline condition for various overtopping flows were used (all parameters are held constant except the return period of the flood assigned to discharges) and the flood overtopping annualized failure probability was re-estimated. The results are shown in Table 8 and indicate that the annualized failure probability would be reduced to 1.6 E-5, about an order of magnitude below the threshold value for increasing justification to take action to reduce risk of 1 E-4.

Table 8. Annualized Failure Probability – Dam Raise Condition for Bison Dam.

Flood Load Range	Load Probability	Dam Overtops	Erosion Initiates and Dam Undermined	Loads Don't Redistribute and Dam Fails	Annualized Failure Probability
100 to 500	0.008	0	n/a	n/a	0
500 to 1k	0.001	0	n/a	n/a	0
1k to 10k	0.0009	0	n/a	n/a	0
10k to 50k	0.00008	0.5	0.1	0.9	3.6E-6
50k to 100k	0.00001	0.99	0.5	0.9	4.4E-6
100k to 1000 k	0.00001	0.99	0.9	0.9	8.0E-6
					1.6E-5

The overtopping protection alternative consisted of 10-foot (minimum thickness) reinforced concrete overlays placed over the fractured portion of the left abutment foundation downstream of the dam. The overlays extended 30 feet on either side of the fractured zone and 100 feet downstream of the toe of the dam. The stream power-erodibility index evaluation considered the same stream power estimates from the baseline condition but used erodibility index values for concrete, as shown in Table 6. The combination of stream power values and erodibility index values for the full range of spillway overtopping flows are depicted as the plotted rectangle on the right side of Figure 2. This information was used to estimate the annualized failure probability from flood overtopping for the overtopping protection alternative. The results of this estimate are shown in Table 9, which indicates that the risk would be reduced more than an order of magnitude below the annualized failure probability threshold value of 1 E-4.

Table 9. Annualized Failure Probability – Overtopping Protection Condition for Bison Dam.

Flood Load Range	Load Probability	Dam Overtops	Erosion Initiates and Dam Undermined	Loads Don't Redistribute and Dam Fails	Annualized Failure Probability
100 to 500	0.008	0.8	0.01	0.01	6.4E-8
500 to 1k	0.001	0.99	0.01	0.02	2.0E-7
1k to 10k	0.0009	0.99	0.01	0.05	4.5E-7
10k to 50k	0.00008	0.99	0.02	0.5	7.9E-7
50k to 100k	0.00001	0.99	0.20	0.7	1.4E-6
100k to 1000 k	0.00001	0.99	0.40	0.9	3.6E-6
					6.5E-6

1.2.3. Alternative Evaluations

This example addresses the baseline risk for a concrete arch dam from flood overtopping, that is just above Reclamation's threshold value for increasing justification to take action to reduce risk. The baseline risk exceeds the threshold value for annualized failure probability (1.7 E-4 compared to the threshold value of 1 E-4). Two alternatives were evaluating for reducing the risk of flood overtopping – raising the dam by 10 feet and providing overtopping protection consisting of reinforced concrete overlays over an erodible portion of the dam foundation downstream of the dam. The dam raise was designed for the 10,000-year flood and the overtopping protection alternative was designed for the PMF, which is close in magnitude to a 1,000,000-year event. The dam raise was designed to prevent overtopping for floods up to and slightly greater than a 10,000-year event. The overtopping protection option was designed to allow dam overtopping but to armor the vulnerable portion of the dam foundation. The risk estimates indicate that the risk reduction achieved by both alternatives is significant and well below the threshold value of 1 E-4. The annualized failure probability estimate for the dam raise is 1.6 E-5, and is reduced even further to 6.5 E-6 for the overtopping protection alternative.

1.3. Conclusions

Traditional modification alternatives for addressing a flood overtopping potential failure mode focus on preventing overtopping of the dam. This can be accomplished by increasing the spillway discharge capacity, raising the dam which allows more of the flood to be stored or a combination of these two approaches. Overtopping protection alternatives allow the dam to overtop but are designed to prevent the overtopping flows from initiating erosion of the dam or dam foundation that could lead to dam breach. When comparing the two categories of approaches, traditional approaches are often perceived as posing less risk of dam failure. The examples presented in this paper demonstrate that this is not always the case. Depending on the circumstances, overtopping protection alternatives may reduce risk to comparable levels as traditional alternatives, especially when the vulnerabilities and limitations of traditional alternatives are considered. There may be cases when traditional alternatives pose less risk than overtopping protection alternatives, but a careful consideration of all the potential vulnerabilities and risks should be included in the selection process for modification alternatives. All designs have some vulnerabilities and a thorough identification and evaluation of these vulnerabilities must be performed. The design should include provisions to minimize these vulnerabilities.

2. REFERENCES

Annandale, G.W. (2006), Scour Technology – Mechanics and Engineering Practice, McGraw-Hill Civil Engineering Series, First Edition, New York.

Bureau of Reclamation, (2011), *Interim Dam Safety Public Protection Guidelines*, Dam Safety Office, Denver, Colorado.

Federal Emergency Management Agency (2014), *Technical Manual: Overtopping Protection for Dams, Best Practices for Design, Construction, Problem Identification and Evaluation, Inspection, Maintenance, Renovation, and Repair*, FEMA P-1015, U.S. Department of Homeland Security, Washington D.C.

Kirsten, H.A.D., (1983), “A Classification System for Excavation in Natural Materials,” the Civil Engineer in South Africa, pp. 292-308, July (Discussion in Vol. 25, No. 5, May 1983).

Wibowo, J.L., Yule, D.E., and Villanueva, E. (2005), “Earth and Rock Surface Spillway Erosion Risk Assessment,” Proceedings, 40th U.S. Symposium on Rock Mechanics, Anchorage Alaska.