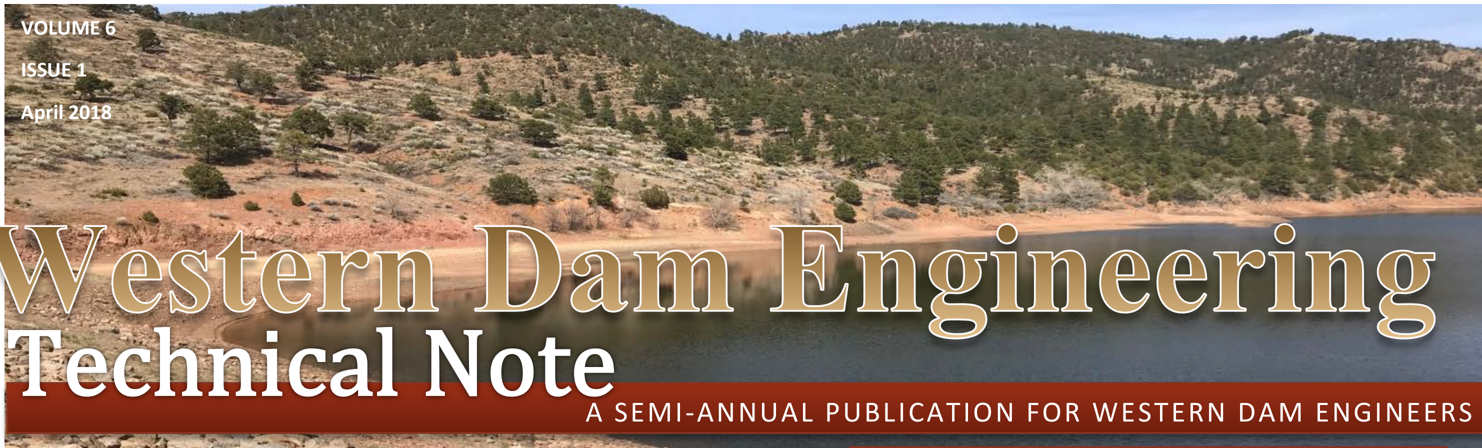

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April 2018

Western Dam Engineering Technical Note

A SEMI-ANNUAL PUBLICATION FOR WESTERN DAM ENGINEERS

In this issue of the ***Western Dam Engineering Technical Note***, we present articles on **risk analysis in dam safety**, **spillway assessments**, and considerations for **retrofitting dams for small hydropower**. This newsletter is meant as an educational resource for civil engineers who practice primarily in rural areas of the western United States. This publication focuses on technical articles specific to small and medium dams. It provides general information. The reader is encouraged to use the references cited and engage other technical experts as appropriate.

The Western Dam Engineering Technical Note is sponsored by the following agencies:

- Colorado Division of Water Resources
- Montana Department of Natural Resources
- Wyoming State Engineer's Office
- New Mexico Office of the State Engineer

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Good to Know

Comments/Feedback/Suggestions?

Email Colorado Dam Safety to submit feedback on Articles. Please use article title as the subject of the email.

Upcoming ASDSO Webinar Dam Safety Training:

- *Reexamination of the 2004 Failure of Big Bay Dam, 5/08/18*
- *Designing Spillways to Mitigate Failure Modes, 6/12/18*

Upcoming Classroom Technical Seminars:

- *Fundamentals of Reinforced Concrete Design of Hydraulic Structures, May 15-17, 2018; Phoenix, AZ*
- *Seepage Through Earthen Dams, June 12-14, 2018; Chicago, IL*

Upcoming Conferences:

ASDSO Northeast Regional Conference, Lancaster, PA; June 4-6, 2018

ASDSO Training Website Link

In this Issue

Risky Business Introduction to Dam Safety Risk Assessment

By: Elliott Drumright, PE, PhD and Jennifer Williams, PE

Introduction

Dams are a vital part of our Nation's infrastructure, providing tremendous economic, environmental, and social benefits. The benefits of dams, however, are countered by the risks they can present. The regulatory and legal responsibility for maintaining a safe dam rests with the owner. The cost of the proactive maintenance required to ensure the continued safety of dams can be difficult to manage. The cost-benefit of this responsibility may not always be readily apparent. However, when dam safety incidents occur, they can be financially devastating to the owner.

The application of risk assessments has fundamentally changed the practice of dam safety engineering in the United States and will continue to do so. Risk assessment is a rational method by which dam owners/operators and their engineers can develop a thorough understanding of the risk posed by their dams and the key factors that influence its performance. The limited financial and labor resources available to owners drive the need for strategic prioritization to address the most critical deficiencies first. Risk assessments have proven to be a valuable tool in risk management for dam owners as it helps to more appropriately prioritize financial resources in executing plans for observation, repairs or upgrades. This article discusses dam owner liability and the use of risk assessments as a risk management tool.

Table 1. Dam Failure Statistics [12]

Failure Mechanism	Erosion		Embankment Sliding	
Mode of Failure	External Erosion (Overtopping)	Internal Erosion	Static Instability	Seismic Instability
% World-wide failures	48%	46%	4%	2%

Typical Potential Failure Modes for Embankment Dams

Dam failures continue to occur. The International Commission on Large Dams (ICOLD) summarized world-wide dam failure statistics as shown in Table 1. A large percentage of dam failures occur during first filling or record pool events. However, even dams that have operated successfully for a long period of time can fail or suffer from a significant dam safety incident that has economic impact to the owner. From January 1, 2005 through June 2013, state dam safety programs reported 173 dam failures and 587 "incidents" - episodes that, without intervention, would likely have resulted in dam failure [4].

Based on the history of recorded failures and dam safety incidents, the most likely modes of failure for embankment dams have become better understood in recent decades. These "Potential Failure Modes" (PFMs) are generally described by the location or pathway of the failure mode and the mechanism of failure. The Colorado Division of Water Resources [CDSE References] provides a list of 24 of the most common failure modes for embankment dams, grouped among the following categories:

External Erosion
Overtopping of Embankment (insufficient spillway capacity or seiche wave)
Erosion of Spillway (failure of lined or unlined chute, overtopping walls)
Internal Erosion
Internal Erosion Through Embankment (concentrated leak, backward piping, contact erosion, suffusion/suffosion)
Internal Erosion Through Foundation (backward piping, concentrated leak, contact erosion, suffusion/suffusion)
Internal Erosion of Embankment Into Foundation (concentrated leak, backward piping)
Concentrated Leak Erosion of Embankment at

Contact (foundation, abutment or structure)
Concentrated Leak Erosion or Backward Piping Along Conduit
Internal Erosion Into/out of Conduit
Static Instability
Static Slope Stability (rise in phreatic surface or slump causing internal erosion)
Rapid Drawdown Against Upstream Slope
Seismic Instability
Seismic Deformation (deformation causing overtopping)
Seismic Cracking (transverse cracking or separation at contact leading to internal erosion)

This list is not intended to be all-inclusive and does not consider mechanical or operational malfunctions (e.g. gate failure). However, the list is a good starting point for small earthfill dams without gated spillways. Internal erosion dominates the list of Potential Failure Modes, as there are numerous mechanisms and pathways that can lead to an internal erosion failure or incident. The concept of internal erosion is discussed further in references [12] and [17], as well as in previous Western Dam Engineering articles [1] and [2].

Evolution and Hierarchy of Risk Assessments in Dam Safety

Much of the information presented in this section of the article is summarized from Reference [11]. Prior to the application of risk assessments, dam safety engineering practice in the United States focused on evaluating dams through visual inspections and comparison of analysis results with deterministic criteria. Some representative examples of such criteria are:

- Comparing spillway capacity with a specific inflow design flood (e.g. a probable maximum flood or a 100-year flood for high or low hazard dams, respectively).
- Comparing calculated stability factors of safety to recommended or required minimums.
- Comparing calculated stresses in structures to allowable or ultimate strengths of the corresponding materials.

However, these typical deterministic criteria did not address all of the common failure modes typical of dams. Most prominently, they did not address seepage and internal erosion concerns. In the past two decades Potential Failure Mode Analyses (PFMAs) and Risk Assessments have seen increasing application as a method to supplement (but not replace) regulatory criteria. Owners and engineers who have used these processes have almost universally noted the following benefits:

- A more thorough understanding of the dam and the features which influence its performance
- A better understanding of the most important PFMs for a dam, which in some cases had not previously been clearly identified or understood
- Improved surveillance and monitoring programs that are better targeted toward the dam's true vulnerabilities
- Better informed operators with regard to the dam's sensitivities to operational procedures
- In some cases, identification of serious safety concerns that had previously not been identified, particularly with regard to internal erosion PFMs.
- A better understanding of urgency of any identified dam safety deficiencies, and
- More appropriate allocation and prioritization of available resources to address those deficiencies that represent the highest risk.

Dam safety risk analysis in the United States has its roots in the Bureau of Reclamation's (Reclamation's) application of Failure Modes and Effects Analysis (FMEA) in the 1980s under the leadership of J. Lawrence Von Thun. The FMEA is an approach that evolved into what we know today as "Potential Failure Modes Analysis" (PFMA) or a more-rigorous "Quantitative Risk Analysis" (QRA). The initial FMEA/PFMA approach changed the basic thought process in dam safety engineering from one of evaluating dams based on criteria alone to one of critically assessing the ways a dam could fail. The steps in a modern PFMA process include:

- Assemble and critically review all available information about the dam, including design and construction records, performance records, instrumentation data, analyses, and photographs.
- Compile a complete list of possible ways the dam could fail, known as Potential Failure Modes (PFMs); compiled without consideration of the likelihood of failure for each failure mode.
- Screen the PFMs to identify which ones are credible or plausible and which are physically impossible or so remote in likelihood as to be judged not credible, documenting the reasons for that judgment.
- For the credible or plausible PFMs, (1) compile lists of adverse/unfavorable factors (factors making the PFM more likely) and positive/favorable factors (factors making the PFM less likely), (2) identify surveillance and instrumentation methods for detection of initiation or progression of the PFM, (3) identify measures for reducing the risk of the PFM and (4) identify missing data or analyses that would be required to evaluate the likelihood of the PFM.
- Compile a list of major findings and understandings that came to light during the process.

Quantitative Risk Analysis

Risk is a measure of both the likelihood of failure and severity of adverse consequences. Beginning in the 1990s, through collaboration with BC Hydro and Australian colleagues, Reclamation evolved its FMEA/PFMA methodology into Quantitative Risk Analysis (QRA), which considered both the relative likelihoods of the PFMs and their life-loss consequences. Reclamation, later joined by the U.S. Army Corps of Engineers (USACE), published a document called ***Best Practices in Dam and Levee Safety Risk Analysis*** [17], which contains guidance for detailed QRAs; the most sophisticated form of risk analysis currently used in dam safety practice. QRA consists of estimating (1) the annual probability of a certain load on the dam (normal pool, flood load, seismic load, etc), (2) the probability of failure given that load, and (3) failure consequences (e.g., expected life loss). "Risk" is measured in dam safety practice as an annualized life-loss probability as the product of those three estimates, as follows:

$$ALL = P_L \times P_F \times C$$

Where:
ALL = annualized life-loss risk ("Risk")
P_L = probability of a load (static, seismic, hydrologic)
P_F = probability of failure, given the load
C = consequences – life loss

The annual probabilities of failure are typically estimated by developing event trees for the failure modes of concern and then estimating occurrence probabilities for each event in the trees. An example event tree for an internal erosion PFM is shown on Figure 1. Consequences are typically defined as an estimated life-loss that would occur upon a dam failure. Reclamation has published guidelines for developing numeric estimates of life-loss consequences for QRA in Reference [18], which has been superseded by Reference [19] as an interim document until final implementation.

Detailed QRAs are typically used to support decisions to complete additional investigations or to implement risk reduction measures. Such analyses have also been used to evaluate risk reduction effectiveness for dam modification alternatives and to evaluate risk during construction of a dam safety modification.

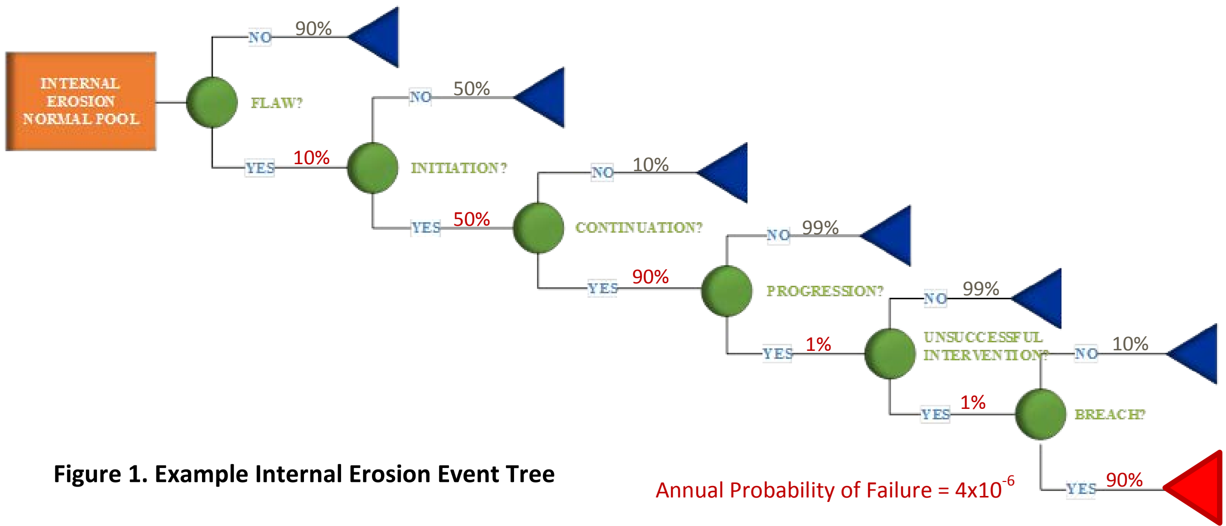

Figure 1. Example Internal Erosion Event Tree

As QRAs became more common in dam safety, it became apparent that guidelines were needed to help evaluate the results of the analyses. Reclamation published *Interim Dam Safety Public Protection Guidelines, A Risk Framework to Support Dam Safety Decision Making* [20] and a companion document, *Rationale Used to Develop Reclamation's Interim Dam Safety Public Protection Guidelines* [21]. Reclamation's guidelines primarily consist of two measures: annualized failure probability less than $1x10^{-4}$ and average annualized life loss less than $1x10^{-3}$. USACE and FERC have also published similar risk guidelines in Reference [16] and [10], respectively. The concept of using societal tolerability to life loss risk is not unique to dam safety. The practice of using life loss risk as a means of managing assets and procedures has been used by organizations and regulators in the nuclear, petroleum/natural gas, mining, aviation, health, and defense industries.

Semi-Quantitative Risk Analysis

QRAs are relatively labor intensive compared to the PFMA process. This is due to the depth of understanding, amount of analyses, and group discussion required to achieve credible consensus on a quantitative estimate of the probability of occurrence for each node in an event tree. It was recognized that a more simplistic approach to the process could be used as a screening tool to more efficiently evaluate several dams within an inventory or dams with a large number of PFMs. Depending on the level of effort involved, this is commonly referred to as a Screening Level Risk Analysis (SLRA) or Semi-Quantitative Risk Analyses (SQRA).

A screening level risk analysis is a relatively low effort, simplistic method to quickly assess risks. The method uses simple tools and approaches in a systematic manner to evaluate each dam within an inventory. The goal is to efficiently develop risk estimates for each dam in a way that enables the relative risk among the dams to be evaluated and priorities for further study or remediation to be established [10]. SLRAs are usually performed expeditiously with only one or two individuals. SQRAs follow a similar procedure, but with a goal of a more informed and credible result performed by a small multi-disciplinary team led by a trained facilitator.

Best Practices in Dam and Levee Safety Risk Analysis contains guidance for Semi-Quantitative Risk Analyses (SQRAs). In this approach, likelihood categories and consequence categories are used rather than detailed quantitative estimates of probabilities of failure and consequences. Examples of these categories are shown on Figures 2 and 3. The consequence categories can be tailored such that it encompasses the issues of most importance to the owner, while still achieving the intent of any relevant regulatory context. An example may be to employ economic or operational considerations in the consequence level descriptions if loss of life is not expected. However, in order to compare relative risks, a consistent description is required for all dams being evaluated under a selected framework. Any SQRA being performed for a dam under the jurisdiction of an agency with established guidelines (e.g. Reclamation, USACE, FERC) must meet the established category definitions for said agency.

SQRAs are sometimes used for portfolio risk analyses for a group of dams as a prioritization tool, to determine which dams and/or PFMs should be addressed first. SQRAs are typically more efficient both in time and cost than QRAs, but do not provide a quantitative risk value that is appropriate for comparison to published risk guidelines. Instead SQRAs provide a value that can be used as a relative comparison among the set of dams evaluated and a general indication of the level of risk a dam and/or PFM poses.

LIKELIHOOD CATEGORY	DESCRIPTION
Very High:	The annual failure likelihood is more frequent (greater) than 1/1,000. There is ***direct evidence or substantial indirect evidence*** to suggest it has initiated or is likely to occur in near future.
High:	The annual failure likelihood is between 1/1,000 and 1/10,000. The ***fundamental condition or defect is known to exist;*** indirect evidence suggests it is plausible; and key evidence is weighted more heavily toward "more likely than "less likely".
MODERATE	The annual failure likelihood is between 1/10,000 and 1/100,000. The ***fundamental condition or defect is known to exist;*** indirect evidence suggests it is plausible; and key evidence is weighted more heavily toward "less likely" than "more likely".
Low:	The annual failure likelihood is between 1/100,000 and 1/1,000,000. the possibility cannot be ruled out, but there is ***no compelling evidence to suggest it has occurred*** or that a condition or flaw exists that could lead to initiation.
Remote:	The annual failure likelihood is more remote than 1/1,000,000. ***Several events must occur concurrently or in series to cause failure***, and most, if not all, have negligible likelihood such that the failure likelihood is negligible.

Figure 2. Example Likelihood Categories [17].

CONSEQUENCE CATEGORY	DESCRIPTION
Level 5:	Downstream discharge results in extremely high property and/or environmental damage. Extremely high direct loss of life can be expected due to limited warning for very large population centers and/or limited evacuation routes (incremental life loss greater than 1,000).
Level 4:	Downstream discharge results in extensive property and/or environmental damage. Extensive direct loss of life can be expected due to limited warning for large population centers and/or limited evacuation routes (incremental life loss in the range of 100 to 1,000).
Level 3:	Downstream discharge results in significant property and/or environmental damage. Large direct loss of life is likely, related primarily to difficulties in warning and evacuating recreationists/travelers and smaller population centers, or difficulties evacuating large population centers with significant warning time (incremental life loss in the range of 10 to 100).
Level 2:	Downstream discharge results in moderate property and/or environmental damage. Some direct loss of life is likely, related primarily to difficulties in warning and evacuating recreationists/travelers and small population centers (incremental life loss in the range of 1 to 10).
Level 1:	Downstream discharge results in limited property and/or environmental damage. Although life-threatening releases occur, direct loss of life is unlikely due to severity or location of the flooding, or effective detection and evacuation.
Level 0:	No significant impacts to the downstream population other than temporary minor flooding of roads or land adjacent to the river.

Figure 3. Example Consequence Categories [17].

EFFORT

Quantitative Risk Analysis (QRA)
Quantitative estimate of annualized risk based on estimates of failure probability and consequences for each PFM. Appropriate for comparison to tolerable risk guidelines, prioritization and decision making based on urgency.

Semi-Quantitative Risk Analysis (SQRA)
Semi-Quantitative assessment of likelihood and consequences of each PFM. Appropriate for prioritization based on relative risk.

Potential Failure Mode Analysis (PFMA)
Qualitative assessment of likelihood of each PFM

Semi-Quantitative Risk Analysis Process

SQRAs are a valuable and cost-effective tool for dam owners to gain a comprehensive condition assessment of their dam(s) and develop a more thorough understanding of the risks they pose. SQRAs provide a more informative assessment than PFMAs for prioritization decision making. This section provides an overview of the SQRA process. Descriptions of the PFMA process can be found in References [5], [9] and [17] and descriptions of the QRA process can be found in References [10] and [17]. An overview of the steps to complete a SQRA is summarized below. More detailed description and guidance for the SQRA process can also be found in References [10] and [17].

Plan

Gather and organize available data for the dam including design and construction records, performance records, instrumentation data, analyses, and photographs. Pertinent data might include: Flood reservoir levels and frequency estimates; seismic loading; embankment geometry and internal zoning; construction materials (embankment, internal drainage features, etc); inlet/outlet works description and capacity; spillway description and capacity; geologic foundation conditions; operational records; analyses and field investigations; inspection reports; instrumentation data; inundation maps including flood wave travel times; and consequence estimates.

Prepare

Review the available information, complete a site inspection to create a mental picture of the data reviewed, and brainstorm in an organized manner a list of PFMs, without consideration of likelihood. Define what the team will consider as "failure", which most often consists of uncontrolled release of the reservoir. However, some owners may also want to consider "operational failures", in which a breach of the reservoir does not occur, but the functionality of the facility is impaired or put out of service. Develop any tailored descriptions of consequence levels appropriate for the owner and regulator. Select the SQRA team. Often the team will include engineers, owners, operators, and regulators such that the team gains the required technical expertise for credible judgements and gain buy-in from all interested parties. The team should be multi-disciplinary and the following expertise should be represented:

- **Operations/Owner** – Providing knowledge of how the dam operates, means of response, and history of site (construction, performance)
- **Dam Safety Engineering** – Providing knowledge of mechanisms by which failure can occur for various components of a dam and appurtenances. Knowledge of information and analysis that can be used to evaluate failure potential. May require various disciplines including geotechnical and geological, structural, hydrologic/hydraulic, etc.
- **Risk** - Experience in risk facilitation and the consistent application of a risk-based evaluation across various sites.

Execute

Define the loading on the dam (normal reservoir pool, flood-level pool, seismic [earthquake], and seasonal ice). Review the brainstorm list to screen out any physically impossible or non-credible failure modes. Fully "develop" the remaining failure modes. The development and evaluation of each plausible failure mode includes the following steps:

- Develop a description of the PFM, describing the step-by-step series of events from initiation to breach so all participants have a common understanding.
- Develop a listing of positive and adverse factors for each PFM. These factors help support the team judgment on the likelihood of the PFM progressing to failure. *Best Practices in Dam and Levee Safety Risk Analysis* [17] provides some guidance on factors to consider for various PFMs, in particular internal erosion PFMs.
- The facilitator assists the team in developing a consensus on the likelihood category and consequence category for the PFM through an elicitation process. The team's reasoning for the selected categories is documented.
- Uncertainty and confidence level in the judgement (strong, medium, or poor) is also discussed and documented. Additional studies needed to reduce uncertainty are noted.
- Actions that could reduce the risk and effective means of monitoring the PFM are also noted.

Document

Results of SQRA are commonly portrayed on a risk index or risk matrix chart, by PFM, an example of which is provided on Figure 4. The results of the SQRA can be used to develop recommended priorities for additional studies or initiating concepts for risk reduction measures such as changes to reservoir operations or rehabilitation. The risk matrix is also a good communication tool as it provides an easy-to-understand portrayal of the results for decision makers.

Advantages of Risk-Based Evaluations

The SQRA method is an organized approach to evaluating the risk of dams. The thought process involved in completing such an assessment can provide:

- A thorough understanding of the dam components and their associated risks to the owner/operator
- An understanding whether likelihood of occurrence or consequences are driving the risk
- Establishes an industry-current level of due diligence (standard of care) that is being recognized by state dam regulatory agencies.
- A tool for prioritizing additional studies and initiating modification studies
- A more informed surveillance/monitoring and operations/maintenance program

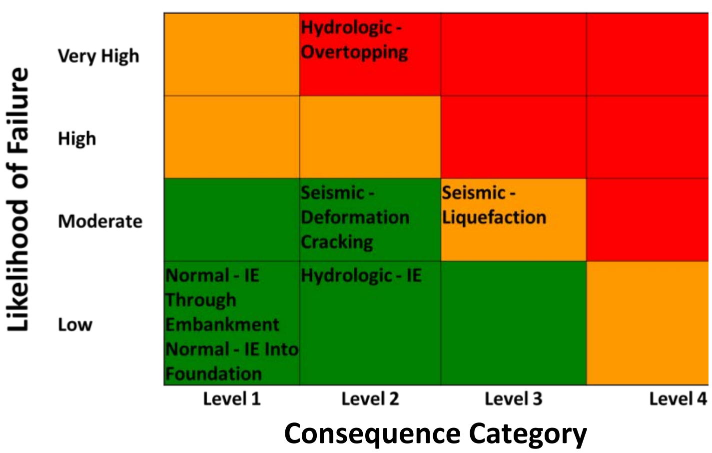

Figure 4. Example SQRA Risk Index

Owner Liability and Due Diligence

> **In a Minnesota court case from 1910, the ruling stated "The Owner is bound [required] to exercise in construction and maintenance of the dam a degree of care proportionate to the injuries likely to result to others if it proves insufficient." (Binder 2002).**

Over half of the dams in the U.S. are owned by private entities. These owners are ultimately liable for any dam safety incident that causes impacts to other parties due to improper operation, maintenance, or negligence. SQRA is a good tool to demonstrate an owner's due diligence in identifying and addressing highest risk problems first. According to ASDSO (2017), the extent of a dam owner's liability for a failure varies from state to state. Some states apply so-called **strict liability**, whereby the owner is liable for damages regardless of the cause of failure. Other states use the concept of **negligence**, which considers the degree of care used by the owner in constructing, operating and maintaining their dam. As noted in the inset, previous case law has established that the standard of care should be in proportion to the downstream hazards involved, but cannot be presumed to be absent, even in the case of an irrigation dam far from a town or county road. According to Binder [6], regardless of whether the theory is strict liability or negligence, tort law is moving in the direction of victim compensation. In most courts, the odds are substantial that the result will be a finding of liability in the case of a dam failure, particularly when personal injury or death is involved.

To establish reasonable due diligence (standard of care) ASDSO recommends that dam owners provide, at a minimum, the following for their facilities:

1) **A dam safety permit** in the state of origin (where applicable). This usually begins with an assessment of whether the dam is "jurisdictional"; i.e. subject to the dam safety rules of the state. Assuming so, although this places the dam and its ownership on the ledger of the state dam safety regulator, it also avails the owner with access to the knowledge base and inspection capabilities of their state's dam and water resources engineers.
2) **Emergency Action Plan** is a document that outlines the plan of action to be taken to reduce the potential for property damage and loss of life in an area affected by a dam failure or large flood. *EAPs are an extremely valuable tool for protecting the public*. Most dam regulatory agencies have EAP guidelines regarding content and updates.
3) **An operations and maintenance plan**. The operations section should describe procedures for normal operating conditions as well as flood passage conditions, including operation triggers, sequence, and procedures for all inlet and outlet conveyances. The maintenance section can be a simple ledger with date and type of action completed (mowing, brush and debris removal). Of note, some activities such as regrading the crest or replacement of a toe drain or outlet pipe may require advance notification and separate permit with the state agency.
4) **Documented periodic inspections**. The owner/operator should document regular

inspections, with the frequency of inspections indicated by the state rules, or more importantly, by the hazards present downstream. Additional but less frequent inspections are usually provided by state officials when the dam is included on the state register.

5) **Warning signs and controlled access**. Methods of limiting liability for ingress by persons (signs and fencing), and for undesirable access by animals; for example, fencing to prevent grazing on the downstream slope of a dam.

State dam safety programs have minimum regulations that must be reviewed and followed, and they often follow these minimum due diligence practices. Owners are encouraged to read references such as [3], [6] and [15] to gain a better understanding of dam owner liability.

Summary

The increasing application of risk analysis in the U.S. over the past 30 years has resulted in the dam safety community 1) openly recognizing in a formal manner the many ways a dam can fail and the consequences of those failures, 2) using risk as a tool for prioritizing risk reduction actions, and 3) focusing monitoring programs and remediation efforts on the failure modes with the highest risk dams. Dam owners need to recognize that dam failures can occur and the impacts such a failure would have on them and downstream population and infrastructure. A risk-based evaluation is a method to understand the likely failure modes for a particular dam, help owners detect changes in their dam, and provide a basis of understanding of why comments from dam safety inspectors regarding, for example, seepage spots, dense woody vegetation, and deteriorated outlet pipes or structures are in an effort to reduce the owner's risk.

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When Spills Go Their Own Way -
Evaluations of Concrete-Lined Spillways

By: Paulo Virreira, PE

Introduction

On February 12, 2017, the California Department of Water Resources (DWR) and local emergency managers decided to order the evacuation of approximately 188,000 residents downstream of the nation's largest dam, Oroville Dam. The decision to order the evacuation stemmed from a February 7th incident in the gated concrete service spillway, in which a partial failure of the concrete chute slab exposed the unprotected foundation to flows of approximately 52,000 cubic feet per second (cfs), resulting in significant damage to the service spillway. Limitation of flows through the damaged service spillway, combined with heavy inflows to the reservoir, ultimately led to flow over the fixed-crest emergency spillway for the first time in the project's history. Flow over the unlined hillside downstream of the emergency spillway structure resulted in the initiation of erosion gullies, which deepened and began to progress rapidly toward the spillway crest structures. The erosion was judged to potentially endanger the stability of the concrete crest structure, and the decision to evacuate was made.

Figure 1. Final Damage at the Oroville Dam Service Spillway [1].

The issues that led to the Oroville Dam spillway incident are not unique to large dams or spillways with large discharge capacities. They are common conditions that can initiate failures of concrete-lined spillways with capacities much less than that at Oroville Dam. Subsequent investigations by an independent team of dam safety experts and geologists attributed the cause of the initial damage in the service spillway to a series of inadequate design details and construction flaws that are not unusual among spillways designed and constructed in the same era [1].

Lessons learned from concrete spillway failures and advances in the understanding of potential failure modes (PFMs) associated with them have led to improvements in the design and analyses of these structures. Had DWR conducted a more comprehensive evaluation of the spillway at Oroville Dam prior to the incident, many of the vulnerabilities as those cited by the Independent Forensic Team [1] may have been identified and the incident potentially avoided. While no lives were lost, the incident at Oroville Dam serves as a reminder to dam owners and the dam safety community at large of the importance of conducting comprehensive evaluations of dams and their appurtenant structures.

While comprehensive evaluations should be conducted for all major features of a dam facility, this article presents a summary of practices for assessing concrete-lined spillways for small to medium sized dams. The steps for conducting comprehensive spillway inspections, including design reviews, on-site visual inspections and methods for assessing the potential for initiation and development of common PFMs associated with concrete spillways are reviewed. At the end of the article, two case histories of concrete chute spillway failures for small dams are presented along with a brief synopsis of the Oroville Dam Spillway Incident.

Comprehensive Spillway Evaluations

Routine inspections to identify the adequacy and changes in the condition or performance of a dam facility are a critical component of any dam safety program. The recommended frequency of routine dam safety inspections varies and is a function of hazard classification, which is typically assigned as a function of reservoir size and potential downstream impacts related to failure. Typically, dams classified as large or posing a high and significant hazard require annual physical inspections and dams classified as small or low hazard are inspected on a less frequent basis.

While routine inspections to identify changes in the condition or performance of the facility are a critical component of any dam safety program, a comprehensive spillway evaluation differs from a routine inspection in that it considers visual observations of the spillway as well as evaluations of the site geology, design features, construction history, and performance history of the structure(s) under a range of loading conditions. A consideration of the performance of the dam facility under a range of loading conditions can help to establish confidence in decisions regarding the likelihood of a PFM initiating and progressing to dam failure.

Like comprehensive evaluations for other components of dam facilities (i.e., embankments, outlet works, reservoir rim, etc.), evaluations of spillways should be sufficiently detailed to identify specific areas of concern and recommend remedial repairs, operational restrictions, modifications, or additional analyses and studies necessary to determine a spillway's suitability for safe and continued operation.

Reclamation's *Safety Evaluation of Existing Dams* (SEED) manual defines the primary phases of a comprehensive dam safety evaluation as consisting of "reviewing the dam design and design data; reviewing the construction methods and materials and operational history by means of available records; examining the behavior and condition of the existing structure; performing necessary analyses; developing final conclusions and recommendations; and preparing a final report."

Once assembled, the Comprehensive Evaluation report becomes a basis for positive actions at the dam as well as future inspections. The report is also useful in "making the case" and providing justification for recommended actions, or inaction. As a result of the comprehensive inspection process, future routine inspections and reports become more efficient and focused based on components or area(s) of the dam which are identified to pose the highest likelihood for PFM initiation and/or progression.

The components of a comprehensive spillway evaluation discussed in this article are:

- Data Review;
- On-site Visual Inspections;
- Analyses; and
- Potential Failure Mode review

Data Review

An important first step toward conducting a comprehensive evaluation of a spillway, or any dam component, is a thorough desktop study. This should include a review of the available original design documents, construction documentation and performance history (monitoring) reports. Consideration should be given to determine if the appropriate loading conditions were evaluated during the original design and, whenever possible, the original design criteria should be reviewed to determine if changed conditions at the site have created a need for changes to the criteria. If new engineering studies have been developed (e.g., flood studies, regional seismicity studies, etc.), it should be confirmed that all the relevant design documents have been updated and that the spillway is expected to perform as originally intended both hydraulically and structurally.

Design Details

Many of the concrete spillways in operation today were designed and constructed more than 50 years ago. The knowledge of the loads and vulnerabilities associated with the operation of concrete spillways has increased significantly within that period. As a result, many of the common design features and details previously used have been revised to better resist the loads and reduce the likelihood that a PFM can fully develop.

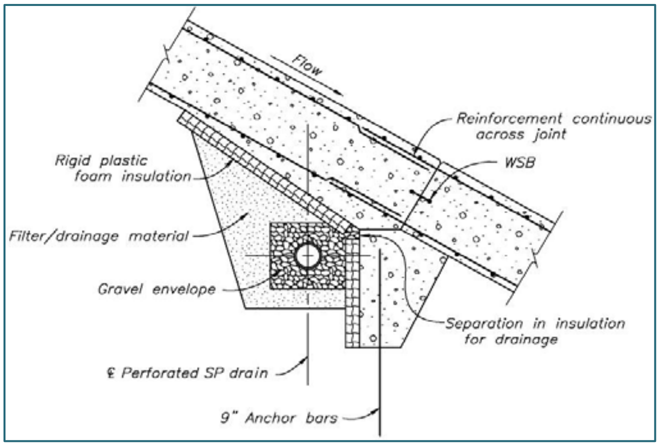

Figure 2. Common Defensive Design Details Used in Modern Spillway Designs [2].

Common features in today's designs that were often omitted in legacy concrete spillways and may affect the overall safety of the design include flexible waterstops, transverse cutoffs, filtered foundation drains, shear keys and double-mat reinforcement. An evaluation of the design details used for a particular spillway during the data review portion of a comprehensive evaluation can help to identify potential vulnerabilities, which may increase the likelihood that a PFM could initiate.

Adequate Drainage – Based upon a review of the design documents, if an unfiltered drainage system is suspected, regular inspection of the drain outfalls both during and after spill events may be necessary to indicate whether erosion of the foundation has initiated and if the drains are still active and sufficiently effective. The review should also evaluate if the under-drain system reduces the effective thickness of the chute slabs along the drain pipe alignments. If the spillway at an existing dam was designed and built without any drainage features, observations of seepage through slab and wall joints could indicate a vulnerability of the structure to uplift pressures and a review of the performance and inspection history should be conducted to establish the overall stability of the spillway and likelihood of PFM initiation under various loading scenarios.

Waterstops - The primary concern with the use of metallic waterstops in legacy designs is that they are rigid and do not accommodate differential movement across joints well. The presence of metallic waterstops in a spillway should be considered a vulnerability and movement at those joint locations should be regularly monitored. The lack of a waterstop at joint locations should also be considered in combination with joint preparation requirements and under-drainage design to evaluate the likelihood of adverse seepage across the joint.

Joint Detailing – Proper joint detailing can significantly decrease the likelihood of initiating a PFM. Effective joint details include cutoff walls along transverse joint locations to reduce the ability of flow entering gaps to reach the foundation and the use of shear keys and dowels to reduce the potential for slabs to offset into the flow. The lack of either of these details or through-reinforcement crossing at joints indicates the slab is vulnerable to differential movement.

Slab Thickness/Reinforcement – In the past, misunderstandings and underestimation of uplift pressures resulted in the construction of thin, lightly reinforced concrete slabs with insufficient capacity to resist the actual uplift loads that may develop or adequately control cracking. Modern designs call for concrete slabs of sufficient thickness to accommodate two mats of reinforcement to control cracking, resist uplift, and increase ductility.

Figure 3. Brittle Collapse of Unreinforced Slab System due to Foundation Erosion [10].

Foundation Anchorage – Proper sizing, spacing, and embedment of anchor bars both into competent rock foundations and adequately sized slabs can provide significant resistance to uplift pressures that can lift slabs off their foundations. As part of the data review, an evaluation should be made to confirm that any anchorage provided is properly developed into a competent rock foundation and capable of achieving the necessary design bond strength. Similarly, any anchors provided should be sufficiently embedded into the concrete slab to adequately develop their full anchorage strength. Slabs with anchors unable to be fully developed should be re-evaluated for stability with an appropriately reduced anchorage capacity.

Construction Methods and Materials

The desk study should include a review of engineering data and records obtained during the original construction period to determine if the structures were constructed as designed or if any unusual or unanticipated conditions were encountered during construction that may have necessitated a revision to the original design. Unforeseen conditions encountered during construction can have major effects on the safety of a dam facility and its ability to operate and behave as originally intended. Unexpected foundation conditions that required over-excavation and treatment or relocation of features are common concerns for concrete-lined spillways.

Poor construction methods can also have an effect on a spillway's overall safety and performance. Inadequate quality control or material testing during construction can result in the use of inferior materials or the creation of vulnerabilities within the structure. A review of available as-built drawings, construction photographs and field reports/memos can aid in the evaluation of the construction in comparison with both the original design and current best practices. Construction photos of the foundation surface conditions during slab placement are particularly valuable.

Site Geology

Characterization of site geology is an important aspect of a comprehensive evaluation for spillways. Foundation conditions of the spillway chute slabs and crest structure influences the performance of the spillway under flood flows. Understanding the bedrock lithology of the underlying foundation can be gained from geologic maps of the region, site geology maps developed during construction, and mapping of rock exposures. Geologic investigations including test holes and rock cores at the spillway or embankment site should also be reviewed for an understanding of rock characterization including the erodibility potential.

Review of Performance History (Unusual Observations)

Previous studies and past performance documentation can be used when evaluating the performance of the spillway under various flow conditions. For example, flow patterns under various discharges and gate openings.

Projects with a long operating history often develop conditions or responses that have been consistently observed and documented, eventually turning into expected behavior. For example, if the past ten inspections showed the same damp area on the face of an embankment with the reservoir at normal pool, it can be easy to assume these conditions are benign and do not imply an unsafe condition. In reality, dams behave dynamically, constantly responding to changes in their loading or operation. Spillways are no different. The presence and extent of unfavorable conditions can develop over time. "The normalization of unusual historic observations (normalization of deviance) whereby departures from desirable or preferred conditions become expected and accepted"[14] should be guarded against. Otherwise, a dam owner may fail to recognize the significance of flaws that could indicate a developing PFM.

On-Site Visual Inspections

With the perspective provided by the previous steps, the final step in a comprehensive evaluation is an evaluation of the visible features by on-site inspection. The inspection should include all accessible areas of the spillway with an emphasis on conditions that might impact the development of identified credible PFMs. Whenever possible, a team of diverse subject matter experts should be assembled to inspect different aspects of the structure and confirm or revise any conclusions or assumptions that were made as a result of the desk study. Regions of distress, unexpected movements, unusual seepage or leakage, and all other observations related to the safety of the spillway should be identified and recorded.

Some conditions are difficult to establish visually. Delamination is not always apparent during visual inspections. Tapping/rapping the concrete surface with a hammer, chains, or other object can produce a hollow sound if delamination is present. If drains are present, outfalls can be inspected for evidence of foundation materials migrating into the drainage system. In addition to inspections of drain outfalls, remote operated vehicle (ROV) cameras can be used to inspect the condition of underdrains as well.

Unfavorable concrete conditions such as cracks, offset joints, gaps in the concrete, surface irregularities, pitting/evidence of cavitation, settlement and heaving can develop and change over time. As such, their presence and extent should be carefully documented during the on-site inspection to establish a reference for comparison during future inspections. The condition of any known/existing unfavorable conditions should be inspected and documented as a part of this effort.

Performance Analysis

Any numeric or physical models of the spillway should be reviewed during the comprehensive evaluation. The following section presents typical spillway PFMs and analyses that may inform their evaluation.

Assessing Typical Potential Failure Modes Associated with Concrete-Lined Spillways

The proper assessment of latent structural deficiencies and adverse performance trends that may indicate the initiation of a Potential Failure Mode (PFM) is an important part of the evaluation of concrete-lined spillways. The initiation or partial progression of any of these PFMs could have detrimental consequences including economic, social, or environmental impacts, even if they do not fully progress to breach of the reservoir. While each dam site poses unique challenges and concerns, concrete-lined spillways have some common PFMs that should always be considered and monitored. Familiarity with the specific chain of events that could lead to the initiation of one of these typical PFMs and the factors that make a particular failure mode more or less likely to develop, is important for successfully identifying a developing PFM and achieving a successful intervention.

Three PFMs are described here, each with unique conditions that may initiate failure of a concrete-lined spillway chute. Some common visual ques and dated engineering details prone to weakness are presented below, along with engineering methods for assessing the likelihood that the PFMs may initiate and develop. Event trees and progressions to failure of spillway concrete and breach of the reservoir are described for each PFM and summarized following the discussion on assessment.

Failure of Concrete-Lined Spillways due to Foundation Erosion

Foundation erosion spillway failures occur as a result of inadequately filtered drainage paths beneath the concrete-lined chute. The migration of foundation material into and along available drainage paths (e.g., sub-drains, filter material, or other joints/cracks in the liner), leads to undermining of the foundation and can result in a structural collapse [2]. This PFM is most likely to initiate in spillways without a modern drainage system beneath the spillway concrete liner and inadequate filtering between drainage and foundation materials. Refer to Figure 4 for an example event tree for this PFM.

Example Potential Failure Mode Event Tree (Foundation Erosion)

- Presence of Erodible Foundation
  - Reservoir at or above threshold level
    - Spillway Flows Initiate Foundation Erosion
      - Inadequate Defensive Design Measures lead to Development of Voids Beneath Slab
        - Slab Collapses Exposing Foundation
          - Headcut Initiates
            - Unsuccessful Intervention
              - Headcut Propagates Upstream
                - Control Structure is Destabilized
                  - Breach

Figure 4. Example Event Tree for Development of Foundation Erosion Potential Failure Mode [2].

Visual Indications that Foundation Erosion May Initiate

Similar to the initiation of stagnation pressures, the presence of unfavorable concrete conditions, which may allow spillway flows to enter and access the unprotected foundation, should be investigated. See the previous discussion on initiation of stagnation pressures for examples of unfavorable concrete conditions that may divert flows into and along the spillway slab/foundation interface. Signs that foundation erosion may be occurring include:

- Discolored discharge from spillway drains
- Discolored discharge through joints/cracks in the spillway slabs or walls
- Settlement or voids adjacent to structures
- Sections of cracked and/or deformed spillway chute slabs
- Sediment deposits near spillway under drain and/or seepage exit points

Figure 5. Foundation Erosion under Spillway Chute Slab due to Migration of Material through Unfiltered Drains [9].

Engineering Analyses to Support Initiation and Development of PFM

If the visual assessment concludes that conditions may exist for foundation erosion to initiate, qualified geotechnical engineers and geologists should be consulted to evaluate the erodibility of the foundation and determine whether an unfiltered exit exists. These conditions could permit the migration of enough supporting foundation material to shift or collapse the spillway slab.

Studies including the previous hydraulic analyses discussed (e.g., flood studies, frequency flood hydrographs, flood routing studies, etc.) should be conducted to estimate depths of flow and velocities at key locations where erosion is considered possible. Knowledge of the velocity for varying discharge events can help to inform the potential for particle migration to initiate due to surface discharge. As previously mentioned, flood routings can also provide information on the duration of discharge events and inform the likelihood of the PFM to progress and fully develop. It should be noted that groundwater infiltration or seepage can also initiate erosion without the activation of the spillway. In these cases an estimate of the seepage or infiltration rate would be necessary to evaluate the potential for particle migration.

A good understanding of the site geology can also be helpful. Features such as shear zones, areas of weathered material, or transverse fractures in the foundation should be identified and their impact on the erodibility of the foundation evaluated. In addition to the hydraulic analyses, geotechnical studies that should be considered include:

- Filter Compatibility Evaluation
- Stream Power Erodibility Index
- Site Spillway Erosion Analysis
- The REMR Erosion Prediction Method
- Soil Erosion Rate

Results from these studies can help to inform the likelihood for the progression and full development of this PFM. See References [4], [9] and [10] for more information regarding procedures for estimating the potential for foundation erosion in concrete spillways.

Stagnation Pressure Failure of Spillway Chutes

Stagnation pressure related spillway failures occur as a result of water flowing into cracks and joints during spillway releases. If no drainage exists, or if the drainage is inadequate, the trapped water can cause an increase in the uplift pressures under the slab. If these uplift pressures exceed the resisting forces of the chute structure (concrete, reinforcement, anchors, etc.) the chute lining is potentially subject to failure or “jacking.” See Figure 6 below for a depiction of the development of stagnation pressures beneath a concrete chute slab.

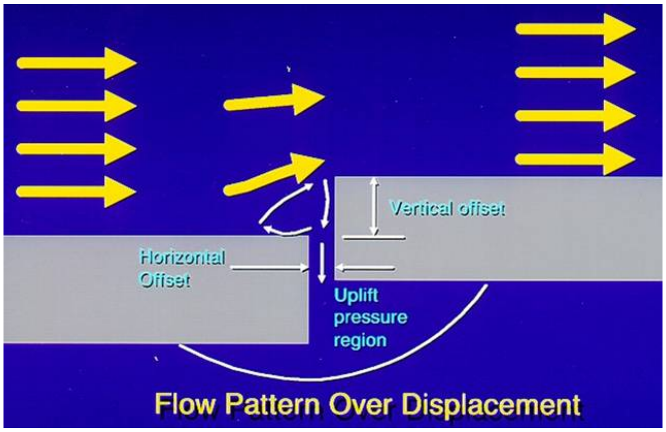

Figure 6. Typical Development of Stagnation Pressures under Spillway Chute Slab [2].

A number of conditions or events must exist or occur to lead from initiation, through progression, to full development of this failure mode. Basic knowledge of these conditions or events is helpful in evaluating the vulnerability of a particular spillway to this PFM. Refer to Figure 7 for an example event tree for this PFM.

Example Potential Failure Mode Event Tree (Stagnation Pressures)

- Unfavorable Concrete Conditions Exist
  - Reservoir at or above Threshold Level
    - Spillway Activates
      - Flows are Sufficient to Initiate Stagnation Pressures
        - Inadequate Defensive Design Measures result in Slab Displacement
          - Foundation Exposed to Spillway Flows
            - Headcut Initiates
              - Unsuccessful Intervention
                - Headcut Propagates Upstream
                  - Control Structure is Destabilized
                    - Breach

Figure 7. Example Event Tree for Development of Stagnation Pressure Potential Failure Mode.

Visual Indications that Stagnation Pressures May Initiate

Unfavorable concrete conditions can develop and change over time in a way that may increase the likelihood of stagnation pressures initiating. Therefore, it is recommended that a visual assessment of their presence and extent be conducted as part of the routine physical inspections of the spillway.

Examples of unfavorable conditions that might contribute to the initiation of this PFM include:

- Cracks/Open Joints Offset into the Flow Path
- Concrete Delamination from the Foundation
- Alkali-Silica Reactivity
- Freeze-Thaw Damage
- Sulfate Attack

In addition to those listed, any condition(s) that might increase the potential for initiating cracks, opening existing cracks and joints, creating offsets into the flow, and causing separation of the chute from the supporting foundation should be carefully evaluated. Visual ques that this PFM may be a concern include seepage through spillway joints and/or wall/slab interfaces after spill events. See Reference [2] for more information on identifying unfavorable concrete conditions in concrete spillways, including discussions on the minimum size of gaps/openings that could initiate stagnation pressures.

Engineering Analyses to Support Initiation and Development of the PFM

The presence of unfavorable concrete conditions is an indication that this failure mode may be able to initiate and progress. If this is the case, qualified structural and hydraulic engineers should be consulted to determine if hydraulic jacking of the slab may be possible or if the drainage system will be sufficient to dissipate the increase in uplift at these locations.

Typical analyses required to evaluate the potential for initiation of this PFM include:

- Flood Studies
- Frequency Flood Hydrographs
- Flood Routing Studies
- Development of Water Surface Profiles
- Structural analysis of spillway slabs and walls

In general, pressures and flows into offset joints and cracks increase with flow velocity [2]. Water surface profiles can be developed from flood routings, which estimate depths of flow and velocities at key locations along the spillway for varying flood levels. Knowledge of the flow velocity at joint and crack locations in the spillway aids in estimating the pressures that can be generated beneath the concrete lining. These local pressures can then be compared to the capacity of the concrete lining to resist uplift at these locations. Flood routings can also provide information on the duration of discharge events. This information can help to inform the likelihood for the progression and full development of this PFM. (See the subsequent discussions on erosion and headcutting.)

See Reference [2] for more information regarding engineering analyses necessary to estimate stagnation pressures and their impacts on concrete spillways.

Cavitation Damage Induced Failure of Concrete Spillway

Cavitation related spillway failures are another PFM that should be considered when evaluating concrete spillways. Cavitation is the formation of vapor cavities in a liquid. When the vapor cavities collapse near a flow boundary, damage typically occurs to the material located at the flow boundary. Cavitation related spillway failures occur as a result of high velocity flow, where water pressure is reduced locally due to an irregularity in the flow surface, causing vapor cavities to form in the flow and collapse, sending out shock waves that can cause major damage to the concrete lining.

Similar to the stagnation pressure PFM discussed previously, a number of conditions or events must exist or occur to lead from initiation, through progression, to full development of a cavitation induced failure. Refer to Figure 8 for an example event tree.

Example Potential Failure Mode Event Tree (Cavitation)

- Unfavorable Concrete Conditions Exist
  - Flood Event Occurs Raising Reservoir Elevation
    - Spillway Activates
      - Flows are Sufficient to Initiate Cavitation
        - Concrete Slab Fails/Exposes Foundation to Flows
          - Headcut of Foundation Initiates
            - Unsuccessful Intervention
              - Headcut Propagates Upstream
                - Control Structure is Destabilized
                  - Breach

Figure 8. Example Event Tree for Development of Cavitation Potential Failure Mode.

Visual Indications that Cavitation May Initiate

Cavitation is typically initiated by isolated irregularities or roughness along a flow surface. The presence and extent of irregularities in the concrete lining, particularly abrupt changes in the flow surface, should be evaluated as part of routine physical inspections of the spillway. Examples of irregularities in concrete spillway surfaces that may initiate cavitation include:

- Joints/Cracks Offset Into or Away from the Flow
- Holes (e.g., Weep Holes) along the Flow Surface
- Grooves in the Concrete Lining
- Protrusions
- Calcite Buildup

The presence and extent of previously sustained cavitation damage should also be assessed. It should be noted that cavitation damage is not constant with time and may initially appear as pitting of concrete surfaces. Following the initial pitting, a phase occurs where the damage rate rapidly increases. During this period, an elliptical shaped section of material loss may be observed. This is because cavitation damage occurs at the downstream extent of the cloud of collapsing bubbles (see Figure 9 for an example) and increases in length and width as the impinging flows continue.

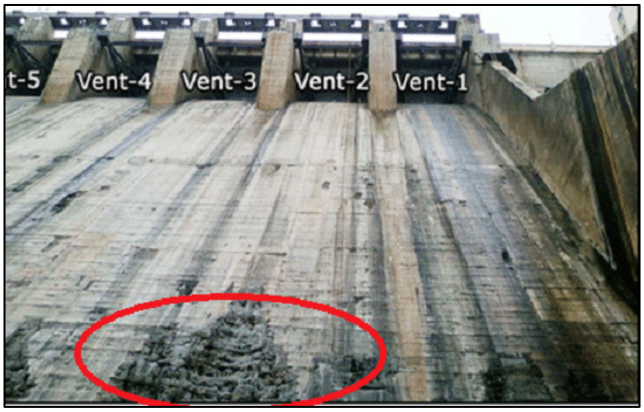

Figure 9. Cavitation Damage of Concrete Spillway Liner.

As cavitation progresses, reinforcing bars can lose their concrete cover, become exposed, and vibrate, causing mechanical damage of the concrete surface and fatigue failure of the reinforcing bars themselves. Therefore, evidence that may indicate more advanced cavitation damage includes exposed or damaged concrete reinforcement. In extreme cases, when flow velocities are sustained, a portion of the concrete chute lining can be completely removed, exposing the underlying foundation.

In most cases, this failure mode is unlikely to progress to the point where dam failure occurs, due to the long flow duration required to cause damage to the concrete lining [3] sufficient to initiate a headcut that progresses and destabilizes the control structure. However, unfavorable concrete conditions can develop and change over time, which can have a direct impact on a spillway's susceptibility to cavitation and their presence should be continually assessed.

Engineering Analyses to Support Initiation and Development of the PFM

If unfavorable conditions indicating the potential for initiation of cavitation are identified, the potential for damage due to cavitation should be evaluated by qualified hydraulic and structural engineers. Similar to stagnation pressures, typical engineering analyses required to properly evaluate this PFM include:

- Flood Studies
- Frequency Flood Hydrographs
- Flood Routing Studies
- Development of Water Surface Profiles
- Structural analysis of spillway slabs and walls

Similar to the evaluation of stagnation pressures, estimates of the depths of flow and velocities at locations where irregularities in the lining or abrupt changes in the flow have been identified help to develop cavitation indices that can be used to estimate the potential for cavitation damage to initiate in a given spillway chute. The procedure for calculating the cavitation index is presented on Figure 10.

$$\sigma = \frac{P - P_v}{\frac{\rho V^2}{2}}$$

Where,

P = Pressure at flow surface (atmospheric pressure + pressure related to flow depth)

P_v = Vapor pressure of water

ρ = density of water

V – Average flow velocity

Figure 10. Procedure for Calculating Cavitation Index [3].

Lower cavitation indices indicate a higher potential for cavitation damage. It should be noted that cavitation indices decrease with an increase in flow velocity and a decrease in the pressure at the flow surface. Therefore, cavitation indices usually vary along the spillway for a given discharge event resulting in portions of the spillway being vulnerable to the initiation of cavitation, while other portions are not [3]. For this reason, a range of discharge events should be considered, so the specific flow for different sections of a spillway may be evaluated for an initiating failure condition.

For typical concrete, USACE notes that the "initiation of cavitation damage is likely when the cavitation index, σ falls between 0.2 and 0.5. For large protrusions that are introduced into the flow abruptly (such as baffle blocks or splitter walls), cavitation damage can occur when σ is as high as 1.0 or higher." See Reference [3] for more information regarding procedures for estimating cavitation potential in concrete spillways.

Progression to Failure (Inadequate Defensive Design Measures, Unsuccessful Detection and/or Intervention, Progressive Erosion and Headcutting of the Spillway Foundation, Breach)

The previous sections discussed three of the typical PFMs associated with failure of spillway concrete and how to assess a given spillway for the potential of the failure mode to initiate. This section presents considerations that may contribute to the likelihood of the PFMs to progress through the remaining nodes in the event tree to failure.

Inadequate Defensive Design Measures

When the presence of unfavorable conditions has been confirmed and engineering studies indicate stagnation pressures, cavitation, or erosion of the foundation can initiate, the presence and adequacy of any defensive design measures should be evaluated. Adequately detailed defensive design measures may be able to prevent the PFM from initiating or fully developing. An absence of defensive design measures in spillways with erodible foundations, may exacerbate the potential to develop stagnation pressures and/or cavitation and is an indication that these failure modes may be able to initiate and fully develop.

The following is a brief list of typical defensive design measures that can mitigate PFM initiation or development in and around concrete spillways [2]:

- Waterstops (can block path for water flow through joints in slabs);
- Transverse cutoffs (prevent vertical offsets at transverse joints and limit path for water from inside of chute to foundation);
- Longitudinal reinforcement/dowels across chute floor joints (minimize width of cracks and openings at joints and may prevent offsets);
- Anchor bars (provide resistance to uplift pressures lifting slabs off foundation);
- Filtered underdrains (relieve uplift pressures that can be generated under slabs – filtering prevents movement of foundation materials into drainage system and initiation of foundation erosion); and
- Insulation (insulates the drainage system and prevents it from freezing, and also prevents frost heave locally).

See the discussion above on spillway design details under Comprehensive Spillway evaluations for a brief discussion on some of the defensive design measures listed.

Unsuccessful Detection and/or Intervention

After a PFM has initiated and a section of concrete spillway is in danger of failing, successful detection followed by an effective intervention is an opportunity to prevent a failure mode from progressing and fully developing. The most obvious form of intervention for gated spillways is to close the gates and cease flows over the spillway. While discontinuing use of the spillway allows detection and may prevent progression of a PFM in the spillway, it can lead to other problems, such as a high reservoir loading on the dam or even dam overtopping. Therefore, closing spillway gates may not be a practical solution for all flood events.

Other forms of intervention may include utilizing all outlet release capacity to reduce flows through the spillway, armoring failed/distressed spillway sections, diverting flows away from impacted spillway sections, or constructing a temporary spillway cut in a benign saddle or other area.

Any form of intervention that changes the operation or management of the reservoir or dam facility in response to a developing PFM should be carefully considered as it may unintentionally raise the risks or consequences associated with other portions of the dam facility. As often is the case, “there can be a tendency to oversimplify complex failure modes involving multiple interactions of system components. Knowledge of the full range of dam safety risks related to all operational aspects is required for an organization’s managers to decide on appropriate actions to manage those risks.” [1]

Erosion

As part of a comprehensive evaluation of a spillway, a good understanding of the soil and rock properties beneath the spillway footprint is important for predicting the potential for initiation and progression of erosion. If a first section of spillway fails, it exposes the foundation to spillway flow. If an intervention is unsuccessful, foundation erosion at the failed chute section can lead to the development of a headcut. Whether headcutting initiates is primarily dependent on the erodibility of the foundation, the velocity and duration of flow. Whether any initiation points, such as slope changes from flat to steep or changes in geology, exist in the profile also impacts the potential for progression of the PFM. In general, rock foundations may take longer and require higher energy flows to initiate erosion and progress to headcutting than soil foundations. Cohesionless (e.g. sandy) foundation materials being the most erodible.

Headcutting/Breach

Given an exposed erodible foundation with a flow path and velocity capable of initiating a headcut, it is likely that headcutting could develop and progress upstream toward the control structure. Typically, once a section of spillway chute fails and headcutting initiates, erosion progresses upstream under the adjacent chute section until a change in geology or design configuration occurs. The adjacent upstream chute section may then cantilever over the erosion hole until it is undermined, becomes unstable, and collapses. The erosion would continue under the next upstream section and the process repeats until the spillway crest structure is reached, destabilizes, and fails.

Features of the spillway crest structure that will influence the likelihood of breach include erodibility of the spillway crest structure foundation, anchorage of the structure, cutoffs, inclination of the bedrock surface, etc. The existence of defensive design details like these can delay or ultimately prevent failure of the crest structure, even with the formation and propagation of an upstream headcut.

If the spillway foundation is somewhat erosion resistant, the duration of the spillway flow may be critical to the development of a full reservoir breach. In the event of a shorter duration flood, headcutting may not reach the reservoir before the flood is over. However, in highly erodible foundations, the reservoir may be breached a short time after the headcutting has initiated.

Consequences Redefined

Historically, a potential failure mode analysis (PFMA), identified and developed PFMs associated with an uncontrolled release of the reservoir. However, recent events at Oroville Dam have demonstrated that serious incidents can arise from more frequent events that do not necessarily lead to a breach of the reservoir, but still have significant impacts to the owner and the public. [1]

In light of recent events at Oroville Dam, dam owners may need to consider the impacts of significant consequences that are less than a complete breach of the reservoir, when evaluating dam facilities and their associated component structures [1]. In addition to consequences related to an uncontrolled release, it is recommended that PFMAs also consider the following: “a) limitations of an owner’s ability to control the reservoir, b) costs of emergency management and repairs, c) damage to or loss of resources and project benefits, d) environmental damage, e) impacts on society, f) damage to reputation, and g) third-party liability” [1]. See Appendix F-3 of Reference [1] for more information on recommendations for revisions to the PFMA process when evaluating dam safety risks.

Case Studies

Havana Street Dam – Concrete Spillway Failure Case Study

Havana Street Dam is a flood control structure comprised of a homogeneous rolled earth embankment, a 30-inch-diameter service spillway, and a trapezoidal-shaped emergency spillway that is approximately 56 feet wide with an ungated concrete control section and riprap-lined chute. Prior to the incident in the spillway, the dam had the capacity to impound a maximum of approximately 400 acre-feet of storage at a depth of approximately 13 to 16 feet.

On September 12, 2013, a significant precipitation event that affected much of the Rocky Mountain Region of Colorado caused the emergency spillway at Havana Street Dam to activate. Eventually, spillway flows initiated erosion beneath a section of the riprap-lined chute, which continued until a headcut formed in the chute. The headcut propagated upstream until it reached the spillway control section. Once at the spillway control section, the headcut began to erode the supporting foundation for the structure, eventually leading to a collapse of the concrete control section and breach of the reservoir. The spillway was only active for approximately 5 hours before the breach occurred. Witnesses indicate that the failure in the spillway lasted approximately 45 minutes, from initiation of erosion in the riprap-lined channel to propagation of the headcut and collapse of the control section.

Figure 11. Headcut Eroding Spillway at Havana Street Dam.

To determine the cause of the failure, a comprehensive evaluation of the dam and spillway was conducted by engineers from Colorado Dam Safety (14). The evaluation concluded that the flood event did not exceed the design capacity of the spillway at Havana Street Dam, but the erosion protection in the spillway channel and defensive design measures provided were insufficient to safely convey the flow experienced during the event. The spillway structure was founded on an erodible foundation without a robust filter between the riprap lining and the underlying soils to prevent particle migration. No cut-off structures were provided in the channel to arrest or retard headcut migration and the concrete control section cutoff wall did not extend below the erodible material.
Had a comprehensive evaluation been conducted prior to the flooding event of September 12, 2013, the lack of these defensive design measures would have been apparent and the high likelihood for the development of this PFM may have been identified.

Figure 12. Breached Spillway at Havana Street Dam.

Goose Pasture Tarn Dam – Concrete-Lined Spillway Semi-Quantitative Risk Analysis

Originally constructed in 1964 for recreational purposes, Goose Pasture Tarn serves as the primary water source for the town of Breckenridge, CO. It is comprised of a 50-foot-tall zoned embankment with an uncontrolled concrete service spillway structure and adjacent RCC emergency spillway. The main spillway chute is approximately 152 feet long, averages approximately 40 feet in width and is approximately 12 -inches thick.

In 2004 seeps were observed emanating from joints within the slab, leading to a coring investigation which discovered several areas of voids beneath the slab. Concerns that seepage beneath the slab may be heaving the slab and eroding the supporting foundation led to repairs in 2006, which included the installation of anchors to resist uplift pressures, a grouting program to fill the voids discovered beneath the slab, and construction of a thin concrete overlay to accommodate and develop the new anchors into the slab.

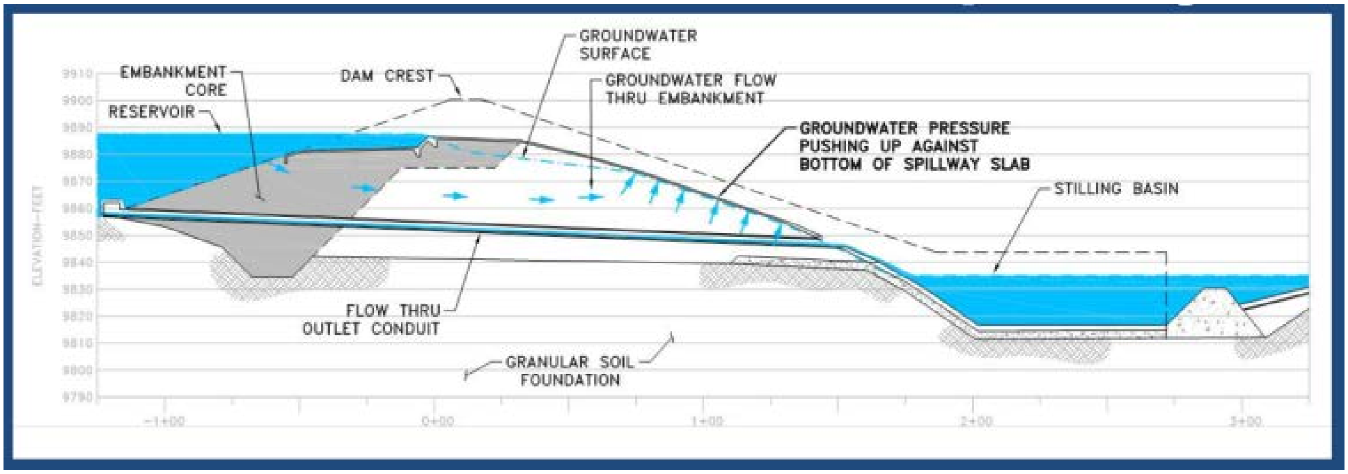

Figure 13. Development of uplift pressures beneath Goose Pasture Tarn Dam Spillway.

Figure 14. Configuration of Goose Pasture Tarn Dam.

In 2015, monitoring wells in the dam recorded increasing phreatic levels in an area beneath the lower spillway slab, which could lead to hydraulic jacking of the slab. As a result of these new observations, a comprehensive evaluation of the spillway was conducted in 2016, which determined that many of the repairs made in 2006 had failed due to continued seepage and frost heave beneath the spillway slab. The damage to the repairs included several failed anchors, de-bonding of the new concrete overlay and the development of new voids beneath the recently grouted foundation.

The dam's owner and their engineer contacted the Colorado State Division of Water Resources – Dam Safety Branch to discuss the new findings and further investigate the cause. Engineers from the Colorado Dam Safety Branch facilitated a semi-quantitative risk analysis (SQRA) in April 2016, which evaluated the condition of the Goose Pasture Tarn Dam and the impacts of interim repair options, and identified a new safe reservoir operating elevation until permanent repairs to the spillway could be made.

During the SQRA it was estimated that a significant snow-melt runoff flood could result in a spillway discharge duration of approximately 2 to 5 weeks. The long duration of flows, coupled with the cracks/offsets in the flow surface, insufficient drainage, and the unfiltered foundation would likely result in the initiation of stagnation pressures, erosion, and development of a headcut. The inability to control flows would reduce the likelihood for a successful intervention and failure of the spillway and breach of the dam was found to be likely. The SQRA concluded that lowering the normal storage level of the reservoir to approximately 4.0 feet below the crest of the service spillway, to accommodate the full range of historic inflow conditions and prevent activation of the service spillway was necessary. The lowered storage pool permits the owners to continue supplying water to their constituents and reduces the likelihood that a PFM will initiate to an acceptable level.

It is recommended that owners of small dams engage their state dam safety officials any time concerns arise indicating the development of a PFM. Note that the State of Colorado DWR Dam Safety Branch has developed Comprehensive Dam Safety Evaluation Tools to help owners assess their structures and determine if a PFM may be developing on their project. See Reference [13] for more information and tools that aid dam owners, engineers and regulators in conducting comprehensive dam safety evaluations.

Oroville Dam – February 2017 Dam Safety Incident

On February 7, 2017, the discharge through the service spillway at Oroville Dam in California was being increased from approximately 42,500 cfs to 52,500 cfs when a disturbance in the chute flow condition was observed by California Department of Water Resources (DWR) personnel. About two hours after the initial disturbance, the spillway gates were fully closed and initial observations of the spillway chute were made. Initial observations noted significant missing portions of the chute slab and a large erosion hole propagating upward, beneath the remaining portion of the chute. A climb inspection of the erosion hole was completed on February 8.

Figure 15. Initial Damage Sustained at Oroville Dam Service Spillway (February 7, 2017) [1].

DWR knew that it would need to operate the damaged service spillway because of expected inflow to Lake Oroville from a significant storm; hence, it was decided to begin opening the spillway gates to test the service spillway's capabilities in the damaged condition. The gates were reopened at about 4:00 pm on February 8, 2017, and several different discharge levels, up to as much as 65,000 cfs, were trialed through February 10, while the service spillway chute was observed for additional damage. DWR's intent was to release just enough discharge through the service spillway to prevent flow over the emergency spillway. However, inflow from the storm was greater than predicted, and flow over the emergency spillway occurred for the first time in the project's history on the morning of February 11.

The reservoir level increased to a maximum level of about Elevation 902.6 ft, about 1.6 ft above the emergency spillway's crest, at about 3:00 pm on February 12, about 31 hours after the flow over the emergency spillway began. The flow over the emergency spillway at the peak reservoir level was estimated to be about 2,500 cfs, less than 4 percent of the capacity required to pass the probable maximum flood.

The flow discharging from the emergency spillway channelized across the natural terrain, causing extensive erosion, including headcutting, which was observed to be aggressively approaching the emergency spillway control structure on the afternoon of February 12. A concern developed that the headcut could propagate beneath the emergency spillway control structure and result in a partial release of the reservoir.

In response to these concerns, DWR and local emergency managers made the difficult decision to order the evacuation of approximately 188,000 residents downstream of the dam. Service spillway releases were increased to 100,000 cfs and flow over the emergency spillway ceased about 8:00 in the evening of February 12.

Between February 12, 2017 and May 19, 2017, the damaged service spillway was operated to manage the reservoir and prevent any additional discharges over the emergency spillway. Continued operation of the service spillway ultimately resulted in significantly increased erosion and headcutting of the service spillway foundation and loss of additional sections of the spillway chute slab and sidewalls. To date, estimates for repair of the Oroville Dam exceed $870 million dollars [12].

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Retrofitting Dams for Small Hydro

By: Rose Sorenson and Chad Vensel, PE

Introduction

Hydropower (hydro) is one of America's oldest, most affordable, and reliable renewable energy sources. It is currently the nation's largest source of renewable energy, accounting for about half of the total renewable energy generation. This article focuses on the concept of hydropower and the engineering design process as it applies to retrofitting existing dams with a small hydropower facility. Because regulations on hydropower systems vary by state, this article will only briefly discuss regulatory considerations.

There is currently no widely-accepted definition of the term "small hydro." However, the Federal Energy Regulatory Commission (FERC) classifies hydropower facilities with the potential to produce 10 megawatts (MW) or less to be small hydro. This article utilizes this definition of small hydro.

The potential electrical generation at currently non-powered dams is extensive, and could be leveraged to help meet the nation's rising energy demands. The top non-powered dams with potential hydropower capacities greater than 1 MW are presented on Figure 1 [1]. Tapping into this currently unused energy source could add up to 12 gigawatts (GW) of new, renewable energy generation to the grid.

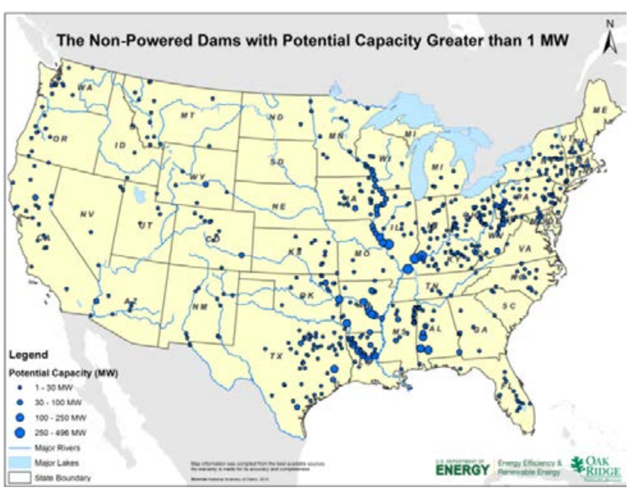

Figure 1. Locations of the Top Non-Powered Dams with Potential Hydropower Capacities Greater than 1 MW [1].

Hydropower has many benefits in addition to being profitable for an owner/developer. Hydropower is generally a clean renewable energy source, which can offset carbon produced by coal or natural gas power plants. Hydropower facilities located on dams have the potential for consistent/flexible power, which can stabilize the electrical grid. A hydropower turbine can also act as a pressure reducer for dam outlets and other pipelines. Furthermore, development of hydropower facilities leads to local job creation during construction and afterwards during operation.

Hydropower 101

Water and electricity are usually a bad combination, so how exactly can water be converted into electrical energy? The general premise is actually fairly simple and largely based on potential energy (dust off those physics textbooks!).

Water stored at an elevation higher than a streambed elevation contains gravitational potential energy. When this water is released, it is converted to kinetic energy and can be used to generate electrical power. A typical dam hydropower facility is shown on Figure 2. At sites with significant topographic relief, the net available head relative to the turbine location can be increased by extending the penstock downstream of the dam and locate the turbine and powerhouse at a lower elevation

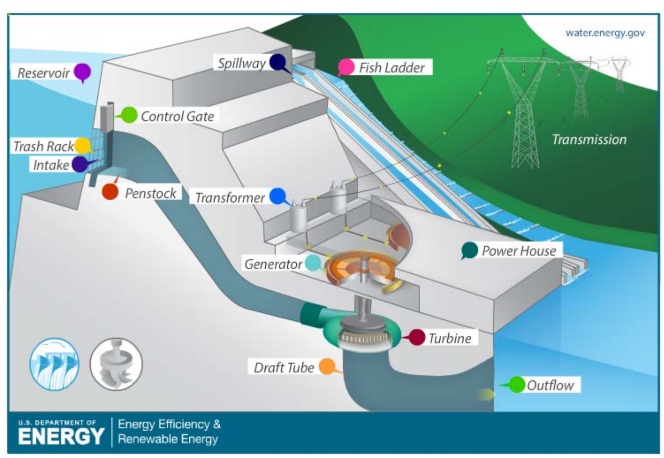

Figure 2. Typical Hydropower Facility Located on a Dam [2].

Penstocks (i.e., conduits) are used to convey discharge from a higher elevation to a turbine, which is typically located near a streambed invert. This discharge is then conveyed through a turbine, which is rotated by the kinetic energy of the flow. The turbine is connected by a shaft to a generator, which in turn creates electrical energy.

Hydropower generation is a function of water head, discharge, and turbine/generator efficiency:

$$P = 0.084 * H * Q * E$$

Where:

P, Power = electrical power in kilowatts (KW)

0.084 = converts units of feet and seconds into KW

H, Net Head = difference between the water intake and outfall water elevation (after accounting for energy losses) in feet

Q, Flow Rate = Volume of water discharged from dam in cubic feet per second

E, Efficiency = A measure of how well the turbine and generator convert the power of falling water into electrical power (decimal form) and is commonly assumed to be 0.89 for preliminary estimates.

A relationship between net head, flow rate, and power generation is shown on Figure 3.

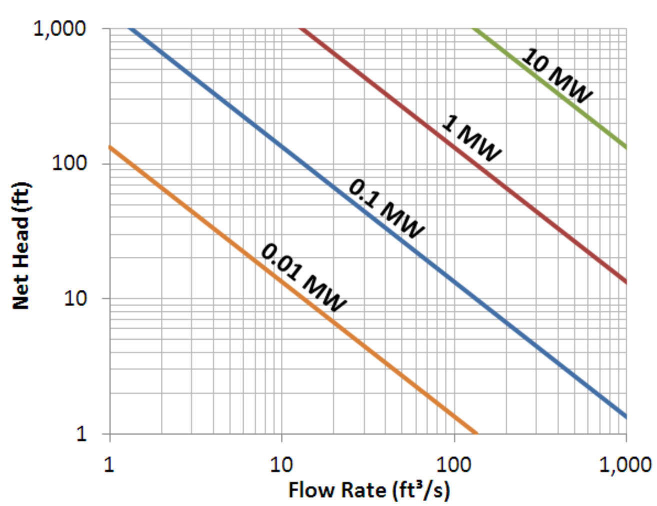

Figure 3. Relationship between Net Head, Flow Rate, and Power

Typical Steps Required for Small Hydro Development

One of the first things to consider when planning a hydropower project is the cost-benefit ratio. The first question to be asked is whether or not the electricity will be put "on the grid" or used onsite.

The steps required to modify a non-powered dam from a potential hydropower site to a functioning hydropower facility are similar to most civil infrastructure projects and typically include:

I. Design Process
    i. First Look
    ii. Screening Study
    iii. Feasibility Study
    iv. Preliminary Engineering
    v. Detailed Design and Procurement
II. Construction and Equipment Installation
III. Testing, Commissioning, and Operation

Design Process

Designing a small hydro facility is an iterative process where detail and scope increases with each iteration. A project may prove to be unfeasible during any iteration, halting the design process. However, if a site proves to be unfeasible, it could become feasible in the future if various factors change. These factors could include energy prices, renewable energy demand, government incentives and environmental regulation.

First Look

The first iteration in the design process includes a brief overview of a potential hydropower site. An owner/ developer will need to identify key characteristics of the site including:

- Net head available;
- Reservoir storage availability;
- Known operating limitations like downstream user demands, environmental requirements, and seasonal variability of inflows and head water levels.
- Existing features that could be used in hydropower development (e.g., outlet structures or conduits that could be pressurized for purposes of power generation);
- Geological aspects;

- Gaged flow data;
- Proximity and accessibility to existing transmission line connections; and
- Potential fatal flaws (to the extent possible).

It is also prudent to evaluate non-technical considerations such as environmental impacts, potential disturbance to existing infrastructure, land ownership issues, water use constraints (e.g., minimum discharge requirements), and ownership of water rights. These factors could significantly increase the cost and schedule of a proposed project.

Screening Study

The second iteration of the small hydro facility design process includes refinement of the site's key characteristics and other considerations identified during the "first look." Additionally, the owner/developer should evaluate electrical generation potential as well as a cost-benefit ratio and overall project economics.

Historically, potential operating costs and revenue were estimated by performing a site visit to evaluate key requirements for the project site. Potential power generation studies were evaluated using gaged flow data and reservoir operations to provide an estimate of the total installed capacity and average annual generation. Potential revenue estimates were evaluated based on power purchase rates available from utilities.

Contemporary methods utilize a computer screening program and assessment reports. An example of a computer based assessment tool is the U.S. Bureau of Reclamation (Reclamation) *Hydropower Energy and Economic Analysis Tool* [2]. This tool was developed for the purpose of screening 530 existing non-powered Reclamation projects throughout their portfolio. Key input data of this tool are daily flow data, and headwater and tailwater levels. From this input data the tool:

- Develops a daily flow duration curve;
- Estimates an installed capacity for the site;
- Estimates the average annual energy generation; and
- Provides an estimated cost for the hydro facility based on historical costs and adjustment to the current timeframe.

On these bases, the assessment tool provides an overall economic analysis with expected costs and benefits for an extended period.

Feasibility Study

The third iteration of the small hydro facility design process involves further development of evaluations completed during the "first look" and "screening study." A key aspect of the feasibility study is determining the turbine generator type and size. The most common turbine types are Pelton, Francis, and Kaplan. More specialized types include Turgo, Pumps as Turbines (PAT), Cross Flow, and Low Head turbines. Each turbine has different recommended head (height of standing water) and flow (volume of water) ranges as illustrated on Figure 4.

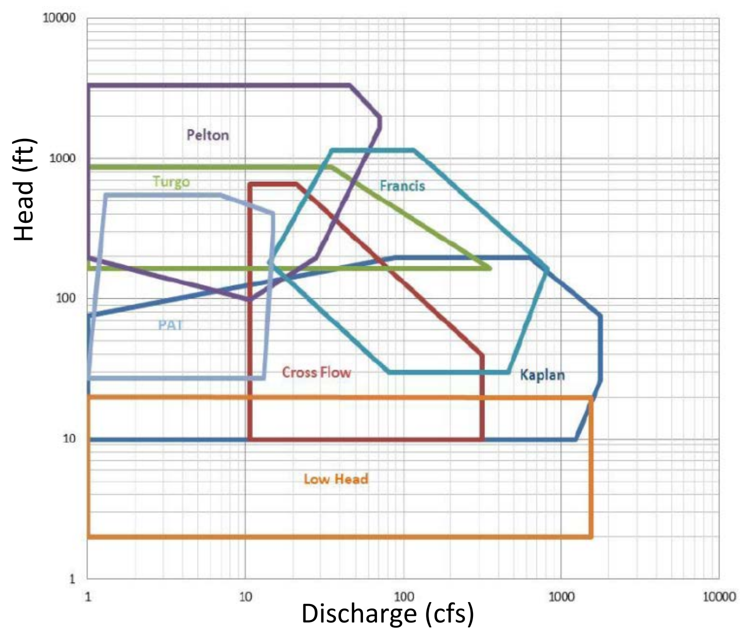

Figure 4. Turbine Selection Chart [4].

Cost details, not considered as part of the "screening study," should be evaluated during this design phase and include:

- Quantity and cost estimates of civil infrastructure;
- Potential costs associated with upgrading existing infrastructure for the purposes of power generation (e.g., pressurizing conduits that

previously operated under open channel flow conditions);
- Quantity and cost estimates of significant mechanical/electrical equipment (e.g., turbine generator); and
- Assessment of state/federal financial incentives (e.g., tax credits).

FERC licensing requirements should also be assessed during the “feasibility study.” There could be a potential reduction or waiver of some FERC licensing requirements depending on installed capacity and/or environmental impacts.

Preliminary Engineering

The fourth iteration of the small hydro facility design process, “preliminary engineering,” includes further refinement of the previous design phases, as well as completion of any applicable permits.

The most common permit required for small hydro on an existing dam (not owned by Reclamation) is a FERC Preliminary Permit. This permit provides an owner or developer the exclusive right for two years to study a project and submit a FERC license application or waiver. If the owner/developer is not already a power producer, a Power Purchase Agreement (PPA) will need to be negotiated for a project to move forward. The most important part of a PPA is the power pricing rates. Further information regarding small hydro FERC permitting and licensing can be found from Reference [5].

Additional permits include but are not limited to:

- The United States Army Corps of Engineers (USACE), Clean Water Act, Section 404 Permit;
- USACE Nationwide Permits;
- Individual Permits; and
- State/Local Permits.

Permitting is a lengthy, expensive process that can delay a project or even prevent a site from being developed. Owners/Developers should plan for the time and expenses involved in obtaining permits and do research on the required permits in advance of this phase.

Detailed Design and Procurement

The final iteration of the small hydro facility design process includes full refinement and completion of all previous evaluations as well as obtaining a FERC license or exception, securing funding and developing complete project drawings, specifications, construction cost and schedule estimates.

Depending on the installed capacity of a proposed project, either a full licensing process is required or an exemption (if the capacity is under 10 MW). Another option is to apply for a Conduit Exemption, which can typically be obtained for hydroelectric units installed in existing flow lines.

Figure 5 presents typical features and their relative percentages for small hydro project construction cost estimates. Indirect costs, like engineering design, construction management, and administration, can be a significant project cost burden for small hydro projects.

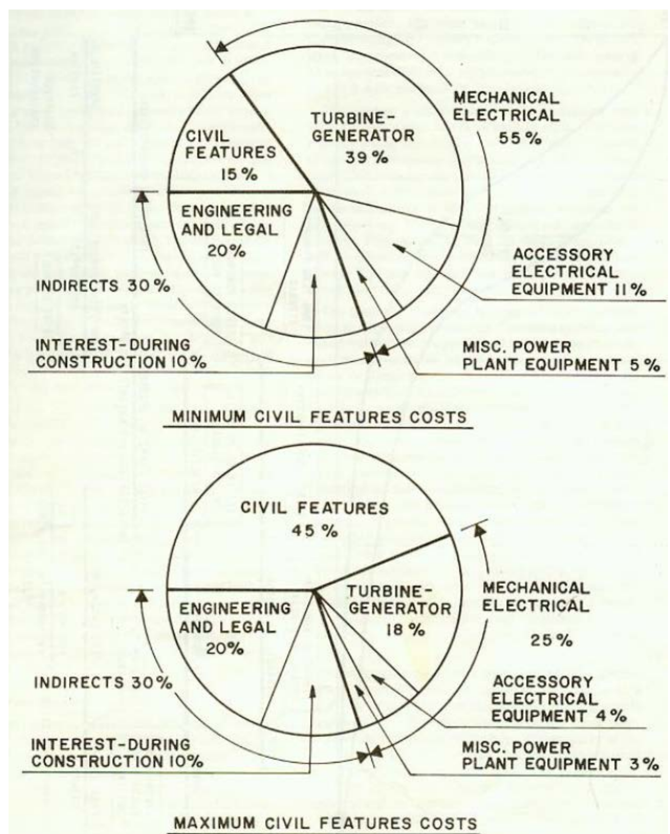

Figure 5. Typical Cost Elements of Small Hydro Projects [6].

An advantage to adding small hydro to an existing non-powered dam is that the monetary cost of dam construction has already been incurred, so adding power to the existing dam structure can often be achieved at a lower cost. However, the owner/developer may need to secure grants, loans, credits and other incentives to fully fund the project. Some grant, loan, credit and incentive sources include, but are not limited to:

- Reclamation's WaterSMART Grant Program;
- USDA's REAP Program (grant money and/or loan guarantees);
- Federal investment tax credits; and
- State/local incentives (grant money, loans, and/or loan guarantees).

Construction and Equipment Installation

As with any civil infrastructure project, it is important to choose a qualified contractor or design-build team that has experience on similar projects. Some critical areas of the project that require precise construction from an experienced contractor include penstock alignment, existing dam protection during construction, and turbine installation.

Testing, Commissioning, and Operation

After construction is complete the efficiency of the turbines, generators, transformer, and transmission lines should be tested to check that actual energy production is similar to the anticipated production estimated during design. The controls and various components should also be tested to ensure failsafe mechanisms (e.g., turbine shut off valve(s), wicket gates, etc.) work properly, especially during emergency shutdown. The turbine(s) can also be tested to ensure smooth operation (e.g., no cavitation) over a range of flow rates and heads.

Upon completion of successful testing, the hydropower facility can be officially commissioned, at which point, the hydropower facility will officially go on the grid and start receiving revenue for energy production.

After commissioning, a hydropower facility requires maintenance to run properly. Most modern hydropower facilities have automatic controls; however, trained plant operators can be beneficial, particularly in identifying small issues and minimizing interruptions in production.

Potential Pitfalls

Despite the best efforts of an owner/developer, the design iterations detailed above are not a guarantee of an issue-free small hydro project development. The following common pitfalls should also be considered:

- Often, specific requirements for obtaining tax credits or other government incentives involve achieving specified targets like start of construction (date) or commissioning of generation. Missing these targets can jeopardize receiving incentives.
- Private or non-utility developments typically require a PPA to obtain financing and guarantee an owner/developer the price for generating electricity. It can be difficult to obtain a favorable PPA if the peak hydropower generation occurs when other generation is readily available and/or energy demand is low.
- Private or non-utility owners/developers who do not plan to use the electricity on site will also need to negotiate the type and associated cost of the hydropower facility's interconnection with a utility's transmission line. If a utility requires an expensive interconnect, this component can represent a significant portion of the budget for a small hydro project.
- Private or non-utility owners/developers that do plan to use the electricity on site will need to use the electricity immediately because it cannot be stored.
- Obtaining a full FERC license can be a lengthy, extensive, and expensive process. The difficulty in licensing varies widely from site to site. The addition of hydropower to an existing dam generally has a less intensive licensing process than that required for a new full site development. However, in any case, the licensing process can become more difficult when there are environmental impacts or local concerns from project opponents. Based on public participation and agency concerns during the licensing process, FERC license requirements may include certain local improvements not directly associated with the project (e.g., fish ladders) or even changes to

the overall operation of the existing project, when hydropower is installed. Another consideration is that additional inspections are required for a FERC licensed facility.

- Overestimating the flow rates and droughts or climate change decreasing the expected amount of water could all result in less power generation than expected.
- Under-sizing or over-sizing the turbine generator unit can lead to lower turbine and generator efficiencies.

Project Examples

Lakewood Reservoir Dam Pipeline and Hydroelectric

The project featured the design of a new 10.9-mile-long gravity flow pipeline from the dam with a total elevation drop of about 1,760 feet. The pipeline and penstocks supply a new 3.5 MW hydroelectric impulse turbine and generator (Figure 6). The project is a major component of the City's domestic water supply and delivers water from the City's primary water treatment plant. Preliminary work consisted of evaluation of alignment alternatives for permitting, hydraulic and surge protection analyses, structural integrity evaluation of the City's existing pipeline, hydropower plant sizing and feasibility analyses, preparation of construction cost estimates and economic analyses for replacement of the existing pipeline.

The final design consisted of the bid drawings, specifications and cost estimates and also designs for replacement of the lower 1.5 miles of the pipeline, installation of the turbine bypass valve, replacement of the intake works and the installation of the upper 1.5 miles of pipeline. The final design also included completion of all documents necessary for the permitted pipeline alignment.

Figure 6. Lakewood Reservoir Dam Pipeline Hydroelectric Powerhouse

Logan First Dam and Hydroelectric Project

Logan First Dam is a small concrete dam and powerhouse originally constructed in 1914. Due to aging infrastructure, rehabilitation designs were completed for the existing buttress dam, spillway and hydroelectric facilities.

The non-overflow dam and powerhouse segments were raised 4.0 feet to increase electrical generation. The existing power plant was also removed and replaced, which included installation of a new 300 kW axial flow-turbine/generator with a fully integrated computerized control system. Additional modifications included the installation of a valved construction diversion pipe, which could later be converted to accept a second turbine/generator unit.

Conclusion

Retrofitting an existing dam with a small hydropower facility is a beneficial option for an owner/developer. This unique type of hydropower development is favorable because the financial burden and environmental challenges of building a new dam have already generally been incurred. Also, when a project is considered a small hydro facility (10 MW or less), it has the added benefit of having a relatively low impact on the environment and lower cost.

The steps to develop a small hydro project on an existing dam consist of going through the design and permitting process (first look, screening study, feasibility study, preliminary engineering, and detailed design and procurement), construction/equipment installation, and testing, commissioning, and operation.

There are potential pitfalls that will need to be navigated to ensure a successful project. Some possible issues include missing targets required for tax credits, being unable to negotiate a favorable PPA, being required to install an overly expensive interconnect, and having a difficult FERC licensing process. In spite of the potential drawbacks, retrofitting an existing dam with a small hydropower facility can provide owner/developers with benefits that outweigh the risks.

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