DAM SAFETY PALM SPRINGS
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A Reservoir Restriction Toolbox

An ASDSO Dam Design & Construction Committee Topic Paper

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ABSTRACT

A Dam Design and Construction Committee (DDCC) task group recently studied various methods that can be used to establish reservoir restrictions if unsafe conditions are observed at a dam. This paper will provide an overview of methods, including simple, intermediate, and advanced approaches, that can be employed to establish the safe storage level. The appropriate levels of analysis should be based on the conditions observed at the structure and information available to evaluate its performance. The paper also explores the life cycle of a reservoir restriction including setting a restriction level, revisions to the restriction level, lifting the restriction to allow full storage, and issuance of zero storage restrictions and breach orders. Several case studies are included to demonstrate the approach for the various risk and condition levels.

I. INTRODUCTION

The core function of dam safety regulators is to determine the amount of water that can be safely impounded by a dam or water retaining structure. The most effective means to protect the downstream public when a dam has deficiencies is to restrict the impounded storage. It is this authority of dam safety regulators to impose reservoir storage restrictions that have formed a foundation of trust that the public has placed in regulators.

The ability to store water is often considered a property right. That property ‘right’ is often critical to the solvency of the owner as it supports their means of production (e.g.: irrigation, power production, etc.) or allows them to provide services to their customers (e.g.: water utility, recreation, etc.). The ability to store water supports a healthy and functional society. Imposition of a storage restriction is tantamount to ‘taking’ that property right away, analogous to condemnation or eminent domain acquisition of real estate. In the case of water storage ‘rights’, the right is borne indirectly by the risk imposed on those living downstream of the dam. Given the critical nature of water storage on the owner’s means of production, the proper function of society, and the risk borne by the downstream public, it is incumbent on dam safety officials to provide reasonable and prudent justification for imposing storage restrictions when critical dam safety issues arise. The goal is to establish an effective reservoir restriction (i.e., restricted pool level) based on available evidence utilizing transparent and technically defensible analyses and best practices to reduce the risk to a tolerable level while, if possible, also allowing some level of storage for beneficial use. *It is important to note that the beneficial use of water must be held secondary to the safety of the downstream public*.

Once a dam safety deficiency is identified or observed, and after any immediate threat to the safety of the structure is mitigated, the dam safety regulator must determine what amount of storage the dam can safely impound. Imposing a reservoir storage restriction is the most common way to reduce the risk of dam failure because it reduces the pressure on all components of the dam and reservoir system. Reducing the impounded volume and hydraulic head also reduces the potential energy stored in the system and therefore reduces the magnitude of damage downstream that could result from a dam breach, reducing the consequences. It also creates more retention volume in which flood water could be buffered if the outlet capacity is lower than the reservoir inflow. Imposing a restriction reduces the threat to the downstream public and allows for an engineered solution to be implemented.

Breach orders and zero storage restrictions may be warranted in some extreme cases because they minimize the risk to the downstream public. However, this level of restriction is not frequently warranted and may be overly punitive to the dam owner in many cases because it removes most, and sometimes all, of the beneficial uses of the reservoir.

Any amount of reservoir restriction can have undesirable impacts outside of dam safety. In addition to the primary purpose of the reservoir, secondary benefits are also impacted (e.g., recreation at a water storage reservoir) and reduces benefits of other stakeholders besides the owner such as customers, neighbors, and other project partners. The over-use of draconian measures may draw scrutiny from detractors, and reduce the overall credibility and effectiveness of the regulatory program. Restrictions must, therefore, be utilized judiciously and with adequate justification. The use of transparent methodologies supported by evidence and analysis consistent with industry standards allows regulators to maintain the trust of downstream populations, and also build trust with owners which will garner responsiveness to address dam safety issues in a timely and effective manner in the future.

The purpose of this paper is to describe a tiered approach that regulators can utilize to establish defensible reservoir restriction levels. The tiers include consequence reduction with simple, intermediate, and a more advanced, risk-based approach that regulators can use depending on the conditions observed at the structure and information available to evaluate its performance. Case studies[1] are presented that represent real-world scenarios where regulators utilized various tiers to justify restrictions. This paper also explores other considerations related to storage restrictions including enforceability, the life cycle of a reservoir restriction, and issuance of zero storage restrictions and breach orders.

II. CONSEQUENCE REDUCTION

When setting a storage restriction, the reduced impounded storage volume and hydraulic head decreases the pressure on the structure and potential energy stored by the system which will result in a smaller breach flood. This reduction in consequences may result in a reduced hazard posed downstream. If the stored energy can be reduced to the point that a breach flood no longer results in unacceptable consequences, then this may be an appropriate way to establish the reservoir restriction level.

Regulators must also abide by statutory limits to their authority. For example, Colorado statutes generally establish a limit on dam safety regulatory authority to apply primarily to dams exceeding 10 feet in height, or dams which impound a reservoir storage volume of 100 acre-feet or surface area of 20 acres. Setting the storage restriction to reduce the dam/reservoir to less than this size may be viewed as regulatory overreach unless the structure is still deemed to pose a significant or high hazard to the downstream public at the reduced size.

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[1] Case studies presented herein are based on real situations, but details and names may have been modified in an attempt to provide anonymity.

III. SIMPLE OBSERVATIONAL APPROACH

The simplest approach to establishing a reservoir restriction level relies solely on visual or instrumented observations of the behavior of the structure. When a dam exhibits an easily observable manifestation of distress, the reservoir level that initiates that behavior can be used for the reservoir restriction. Several examples include the following when observed to correspond to a specific reservoir level:

- Cloudy seepage.
- Increasing seepage over time.
- Phreatic surface changes observed in piezometers.
- Unfiltered seepage emanating on the downstream face.
- Spillway or other outlet structures deteriorated to the point that they are deemed unsafe to pass flow.

This approach relies on regular inspection and collection/analysis of monitoring data to identify the specific reservoir elevation below which physical manifestations of distress disappear. For example, if cloudy seepage is observed in drain flows when the reservoir pool exceeds a certain elevation, then this simple observational approach should be to lower the water elevation until seepage flow is sufficiently reduced or cloudiness abates. Documentation of these observations could serve as the sole basis for the restriction.

Since the simple approach may be based on limited data and employ simplifying assumptions, it should be conservative. At a minimum, the adequacy of the simple observational restriction should be determined. For example, if the pool level is lowered sufficiently to eliminate physical manifestations of distress (e.g., cloudy seepage), but a high-frequency rainfall event is sufficient to load the dam beyond acceptable limits, then the initial restriction may not be adequate. This would require stepping up to the intermediate tier to calculate the expected inflow volume of a frequent flood event that is necessary to store without triggering the undesirable response.

The U.K. Environment Agency 2017 Guide to drawdown capacity for reservoir safety and emergency planning [5] Table 2.3 identifies drawdown elevations required to avert failure for several failure mechanisms. The document gives the following overall guidance considered generally appropriate:

> *"The decision of how far to draw the reservoir down in an emergency should be based on advice by an inspecting engineer. The advice is likely to be to lower the water level until the symptoms of failure cease, and then lower it by a further amount to provide a margin of safety, for example to prevent flood inflows reinitiating the failure mode. In most cases, lowering a reservoir by one-third of its depth will significantly reduce the risk of failure progressing (this is equivalent to roughly halving the hydrostatic force)."*

This 'one-third depth' rule of thumb for establishing a restriction level is a good starting point when signs of distress are noted, but detailed observations of changing response with changing reservoir level are not available since it removes significant pressure from the system. It also removes a significant portion of reservoir storage since most reservoir storage exists in the upper third of the reservoir pool as illustrated in a typical stage-storage curve represented by the volume of an inverted cone as presented below. This curve shows that more than 60% of reservoir storage exists in the upper third of the reservoir pool.

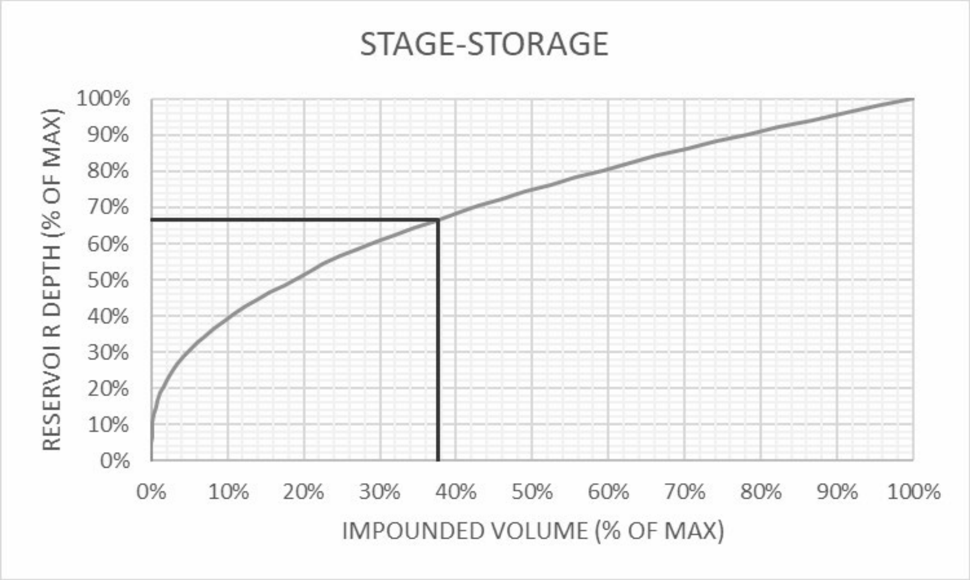


Figure 1: Typical reservoir stage-storage relationship (inverted cone)

Whatever type of simple analysis is used to justify the restriction, the regulator should clearly document and describe the observations that were utilized to set the restriction level in their communication to the dam owner. This will allow the dam owner to hire an engineer with adequate scope to evaluate the root cause of the restriction, investigate the site as needed, analyze the mechanisms that are believed to contribute, and design remedial measures accordingly.

A few case studies are described here to demonstrate this simple observational approach.

CASE STUDY

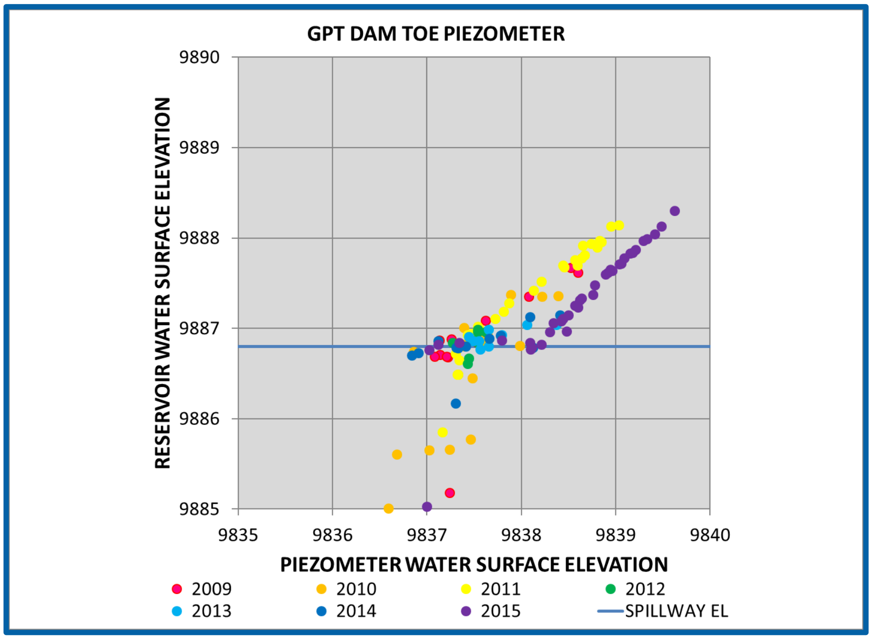
Duck Meadow Dam

Simple Observational Approach

Change in Character of Piezometer Response

Hazard: High
Dam Height: 60-ft
Impounded Volume: 800 ac-ft
Spillway Configuration: Reinforced Concrete Chute over Embankment

Duck Meadow Dam is an embankment dam in a narrow mountain valley. Although not ideal, the valley width and site constraints have resulted in both a service and emergency spillway being constructed on the embankment. The service spillway is a concrete-lined chute and the emergency spillway immediately adjacent is an RCC-lined chute. Over the course of several years of diligent monitoring performed by the owner, piezometers within the downstream shell located immediately adjacent to the service spillway which normally showed little to no influence from reservoir level began showing a significant response in pore water pressures when the reservoir water level exceeded the spillway entrance elevation. Plots of monitoring data from one of the piezometers is provided below which shows a clear change in behavior once the reservoir water surface exceeds the spillway elevation where the piezometer response transitions to a nearly a 1:1 response.



In addition to the change in behavior, the response was trending in an unfavorable direction year-over-year. The plot above shows several years of data collection and analysis indicated that the issue was getting worse which was particularly evident from 2011 to 2015. Further site investigation revealed that a seepage entry point had developed below the service spillway base slab which was transmitting seepage underneath the slab. A preferential flow path had developed under the slab which was conveying water to the piezometer.

The void acting as a seepage path indicated a loss of intimate contact of the spillway base slab with the underlying foundation. A storage restriction was issued to maintain the reservoir level 4-ft below the service spillway slab to allow for some flood routing capacity without re-initiating the seepage pathway.

Setting the restriction at 4-ft below the service spillway in this case was not based on any engineering calculations. It was established based on the lowest elevation achievable by lowering the adjacent RCC-lined emergency spillway. The emergency spillway modification was accomplished rapidly under an emergency contract to allow the owner time to hire an engineer to design a permanent solution. The owner’s responsiveness to monitoring and maintaining the reservoir below the service spillway and their readiness to deploy other emergency mitigation features also weighed into establishing the restriction level.

CASE STUDY

Muddy Waters Dam
Simple Observational Approach
Increasing Drain Flows

Dam Height: 80 ft
Impounded Volume: 1,500 Acre-ft
Hazard Class: High

This privately owned, high-hazard dam impounds a relatively small volume of water (less than 1,500 AF at full pool) but has such high seepage rates that it has filled only a handful of times since original construction in the 1950s. The downstream face is dry and free-draining; seepage exits primarily through glacial moraine material located along the right abutment contact. Several seepage entrance locations (sinkholes) have been observed within the reservoir pool, but none adjacent to the dam. A significant seepage upwelling located approximately 150 yards downstream of the toe requires careful monitoring. The dam is in a high-elevation basin that requires off-road vehicles for access and has no cell service. Failure would inundate much of a small town within 15 – 30 minutes with essentially no warning time. A second town would also be inundated with greater warning time.

A number of years after construction, the dam was likely damaged during a grouting project that used dynamite in the grout holes to attempt to increase uptake. It is also likely that the toe drain pipe was partially crushed shortly after construction and was built with bell-and-spigot style open joints.

For the first time in decades, the reservoir filled in back-to-back years in the 2010s – an event that was similar to a “first fill.” The next year, sediment was observed in the toe drain for the first time. Engineering inspection and documentation up to this point had historically been relatively good. However, the dam changed ownership and within a couple of years, documentation was poor and of limited value. After more careful monitoring was ultimately re-established, sediment was consistently observed in the toe drain in subsequent years. Available data also indicated that the toe drain flow rate was increasing at lower reservoir elevations, as compared to flow rates for the same reservoir elevation prior to back-to-back fills.

The spillway crest and maximum normal operating pool are at elevation 5118 ft. Engineering inspection reports prior to the back-to-back filling stated that the toe drain began to flow when the reservoir reached elevation 5095 feet, with an approximately 1-month lag time. Recent data indicate that the toe drain still flowed between 5 – 30 GPM at this elevation. Recent observations did not detect sediment in the toe drain if flow was reduced below approximately 20 GPM.

From a dam safety perspective, a drain flow of 20 GPM is still considerable for a dam of this size. Recent data indicate that at reservoir elevations of 5090 feet, corresponding toe drain flows are 10 GPM or less, with no sediment. Historical (pre-back-to-back filling) data indicate that drain flows were minimal or eliminated at or below this reservoir elevation.

In order to minimize drain flows and the potential for material transport, and to avoid hydraulically loading the dam above the elevation at which drain flows are known to occur, the regulatory agency implemented a reservoir level restriction of 5090 feet, representing a 28-foot and approximately 1,000-AF restriction. The actual impact is much less, since, even without the pool level restriction, the reservoir almost never fills completely. For example, in the 15 years preceding the restriction, the reservoir did not even reach the restricted pool elevation in one-quarter of the years.

No additional safety margin was applied to this restriction, as further decreases would make the reservoir non-viable for irrigation. However, the owners were required to install remote monitoring of the reservoir level given the difficult access. In addition, an analysis was made to understand the potential for a storm event to unexpectedly raise the reservoir.

CASE STUDY

Sadenbeck Dam
Simple Observational Approach
Staged Restriction based on Multiple Deficiencies

Dam Height: 30-ft
Impounded Volume: 851 Acre-ft
Hazard Class: High

This 30 foot high (crest to low-level outlet) earthen embankment dam has a reservoir volume of 851 AF at permitted pool level. The dam was built and permitted in 1988 for irrigation purposes. The 1,000 foot long dam is constructed as a zoned embankment dam with a sand shell and a 3 to 6 foot thick clay core layer as an impermeable barrier on the upstream face extending 30 feet from the upstream toe on the reservoir floor. The clay core layer is protected by a granular gravel filter and a rip rap cover. The dam has one low-level outlet which also includes a service spillway. Neither of the outlet gates were operable due to major damage and sediment buildup. The emergency spillway crest was partially overgrown and limited in capacity. The dam includes a toe drain constructed as a single PVC drainage pipeline (4”), wrapped in a geotextile filter with manholes every 200 feet. The estimated seepage gradient is 4.4H:1V from the permitted pool level at the service spillway crest elevation to the dam toe near the low-level outlet. The dam is considered a high-hazard dam based on reservoir volume and a potential loss of life due to the proximity to a major highway approximately 750 feet downstream. The highway grade is lower than the permitted water level and a potential breach flood would likey overtop the highway. The ownership remained unclear due to legal implications after two years of operation which left the dam abandoned for decades until finally the state gained ownership in 2017.

Reservoir restrictions were imposed in several steps by state officials. The first restriction limited the pool level by approximately 2-feet after wet spots were observed near the toe drain manholes during an inspection in 2005. The local watershed association, an organization for maintaining small privately owned water bodies, volunteered to execute the restriction and took responsibility to maintain the dam financed by the county. The wet spots disappeared after cleaning the clogged drainage pipe. This restriction also served to provide sufficient storage for the reservoir to impound a 1/100 annual exceedance probability flood event without the need to operate the non-functional outlet gates.

After the state obtained ownership of the abandoned dam in 2017, a full inspection was ordered including a sub-surface investigation, PMF evaluation, seepage monitoring, and review of stability calculations. The geotechnical investigation observed artesian groundwater near the low-level outlet during drilling. Calculations showed a very high likelihood of a toe failure (heave) which led to the second reservoir restriction and drawdown to gage height 16.4 feet, 6.5-ft from the already limited pool level in early 2019 as an emergency action response. The second restriction considered a PMF-event as hydraulic impact without causing overtopping and safe phreatic level near the toe in order to reduce pressure and seepage flow. Further, the reduced pool level is now below the highway grade which decreased the likelihood of overtopping the highway. The drawdown reduced the seepage gradient to 8H:1V. The reservoir volume decreased by nearly 50% (851 AF to roughly 405 AF). The flood retention volume doubled from 324 AF to 730 AF, and the modified Spillway capacity is able to handle a PMF event without overtopping.

The dam remains in a restricted state since the deficiencies (damage to outlet gates and sediment buildup) are not yet resolved. The owner has no interest in regaining the full capacity of the dam and ordered a feasibility study to repurpose the reservoir as flood control reservoir or recreational pond.

IV. INTERMEDIATE EVALUATION APPROACHES

Intermediate approaches utilize engineering analyses, calculations or modeling to establish a reservoir restriction. This may involve several disciplines including hydrologic, hydraulic, geotechnical, structural, mechanical or other types of calculations as described below.

A. Hydrologic

It may be that a spillway or outlet works is deemed unsafe to convey any flow. In this case, hydrologic calculations can be performed to determine how low the reservoir pool must be maintained in order to capture the flood of concern without activating the spillway and/or outlet. Hydrologic modeling can be used to estimate the volume of runoff anticipated for storms of varying frequencies. This information provides the regulator the ability to determine what probability of loading is acceptable.

When the tributary area is large, the dam/reservoir may not be able to fully retain an inflow design flood (IDF) established for the structure, particularly when the IDF is a very rare event (e.g., the Probable Maximum Flood), however, a significant level of protection and risk reduction may be gained simply by restricting the reservoir pool such that the dam can store the full volume of the 1/100 annual exceedance probability flood. This reduced probability of spillway flows for a relatively short time period may be acceptable. This provides the owner with some time to hire an engineer and contractor to design and construct a new spillway.

A common practice to inform decisions based on hydrologic loading is to develop a hydrologic loading curve to plot the peak reservoir level vs. annual exceedance probability of the flood event. This can be used to estimate probability of loading for risk-based analysis of hydrologically driven potential failure modes. Different curves can be developed based on different initial conditions in the reservoir to represent various restriction levels or operational scenarios as illustrated by the figure below..

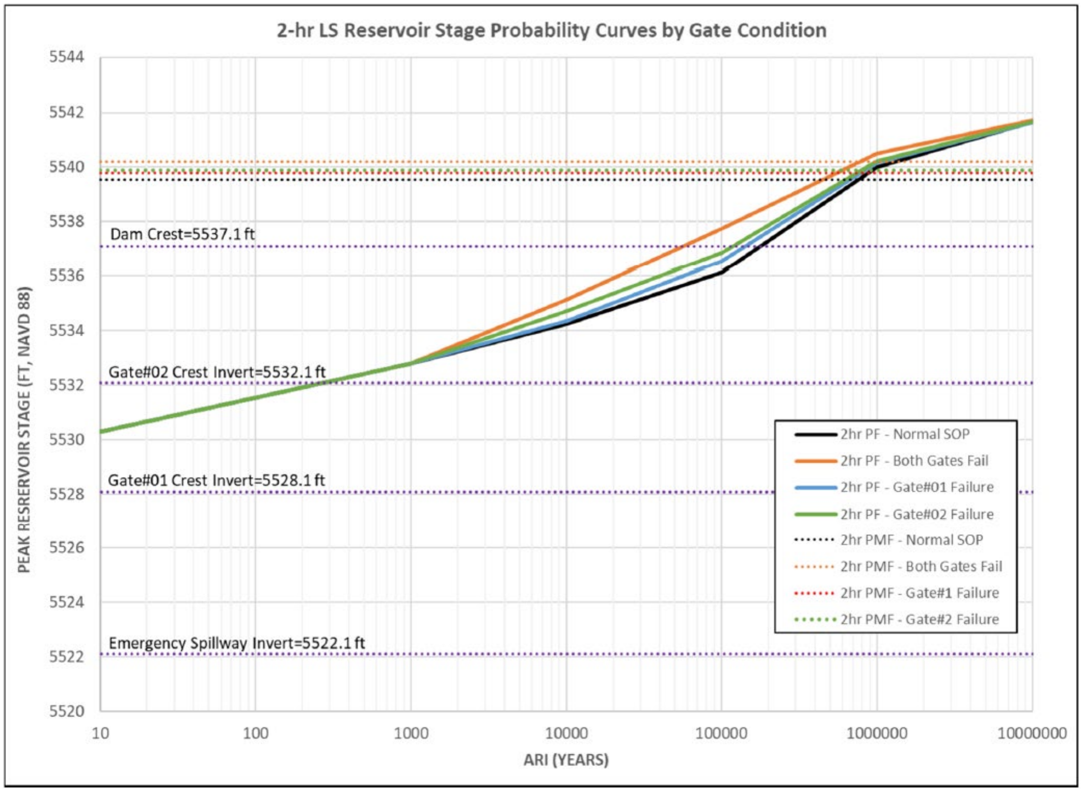


Figure 2: Example Hydrologic Loading Curve

In some cases, it may be acceptable to use a more frequent hydrologic event to establish a safety margin for loading the spillway. Some factors that could be used to justify this decision include: owner actively pursuing improvements so period of exposure will be limited, dam accessibility and ability to utilize low level outlet works to augment spillway capacity, owner's willingness and ability to rapidly deploy other means to lower reservoir including pumps/siphons, and reduced downstream consequences at the lower reservoir level, among others.

B. Hydraulic

Hydraulic modeling can be used to estimate flow velocity, depth, shear stress, cavitation potential and other hydraulic parameters which may indicate initiation of a failure mode. This could be used to determine what amount of flow, if any, can be allowed through a structure with a known defect. A combination of hydraulic and hydrologic modeling can be used to establish a reservoir level appropriate for outlet works restrictions such as limited spillway flows. Example calculations could include soil erosion and head-cutting for an un-lined spillway (shear force, stream power, etc.) or cavitation potential for high velocity, long duration flow events in a concrete-lined spillway chute.

The U.K. Environment Agency 2017 Guide to Drawdown Capacity for Reservoir Safety and Emergency Planning [5] provides comprehensive guidance for assessing and evaluating the outlet works capacity required to evacuate reservoir volume in an emergency. The outlet works must be designed to reliably perform under the maximum required discharge. USBR ACER TM-3 [8] provides similar guidance.

C. Geotechnical

Seepage modeling can be used to estimate phreatic level within the embankment, potential seepage exit points, and hydraulic gradients. Hydraulic gradients can be used to determine the likelihood of internal erosion or backward erosion piping of the embankment or foundation soils. The modeling can vary input reservoir level to determine the sensitivity of output to loading and identify what reservoir level reduces the gradient to the point that it is no longer a concern as estimated factor of safety agains particle detachment, or to the point that the seepage is no longer expected to reach an unfiltered exit.

There are several federal publications that establish standards for seepage and slope stability factors of safety. For example, the US Army Corps of Engineers Risk Management Center has established toolboxes for various geotechnical issues including internal erosion [6]. Internationally, the German Federal Institute for Hydraulic Engineering has established that a hydraulic gradient of 1V:10H is generally considered to be safe if certain geometrical conditions apply [1]. References like these can be utilized to establish safe conditions in combination with seepage modeling.

Slope stability modeling can also be utilized to determine the factor of safety against sliding of a particularly concerning failure surface. This modeling can utlilize monitoring data from piezometers for phreatic surface within the embankment or a seepage model as described above could be utilized to evaluate the range of phreatic level in the dam based on varying reservoir level input to see how it effects the calculated factor of safety for a failure envelope of concern.

D. Structural

Modeling of structural performance under various load combinations can be used to estimate the factor of safety against deflection or failure. Strength reduction factors can be used if the structural components are known to be compromised in any way, such as reduced section due to corrosion or general deterioration. Once factors of safety drop below acceptable levels for the category of load case (usual, unusual or extreme), a restriction may be warranted. This may involve reducing the reservoir level to reduce the load on the structure. It may also involve limiting other loads on the structure when possible (weight restricted bridges are an example). Structural calculations can also be used in combination with any of the other disciplines listed here to establish the load limit and justify a reservoir restriction.

E. Mechanical

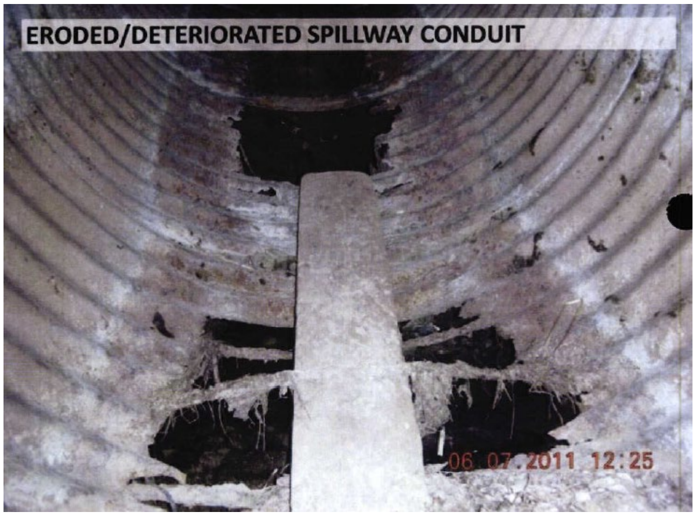
Mechanically operated features like gates and valves within a dam/reservoir system can also be evaluated for performance. Gates and valves should be designed to operate reliably under full reservoir head.

Standard operating procedures may also be warranted where mechanically induced loading can result in stressing the system. Closing gates or valves too rapidly may result in a water hammer where transient pressures spike within closed pipelines that must be accounted for in proper design. Any limitations in operation should be clearly incorporated into the standard operating procedure for the structure, even if they don't warrant a reservoir restriction.

CASE STUDY

Parshall Dam - Damaged Spillway
Intermediate Evaluation Approach
Hydrology Calculations Used to Establish Storage Restriction Level

Hazard: Significant
Dam Height: 20-ft
Impounded Volume: 300 ac-ft
Spillway Configuration: Corrugated Metal Pipe Culvert Through Embankment



Parshall Dam is a significant hazard dam with a corrugated metal pipe culvert spillway laid on a steep slope within the embankment. A routine inspection revealed that the pipe had deteriorated to the point that spillway flows were exposed to the surrounding soil and had eroded a scour hole within the embankment. In its damaged state, the spillway was deemed unsafe to pass any flow.

The prescriptive inflow design flood (IDF) for the significant hazard dam was the flood generated by the 50% Probable Maximum Precipitation (PMP) event. A hydrology study was performed by the regulator which estimated the runoff response and potential hydrologic loading of the reservoir to develop an hydrologic loading curve. The modeling was performed for various events from the 1/100 annual exceedance probability (AEP) event up to the 50% PMP event. The starting water surface in the reservoir was varied in the hydrology model for each event modeled to determine what level event would activate the spillway at various starting water levels. The reservoir did not have sufficient capacity to route the prescriptive IDF without activating the spillway, even with zero storage. However, it did have capacity to capture the 1/100 annual exceedance probability rainfall event if the reservoir was held to a maximum pool fo 3-ft below the spillway. A restriction was set at that level so the dam could retain the volume of the 1/100 flood without initiating flow in the spillway which was deemed adequate given the dam owner's due diligence to address the problem quickly.

Within 4 years, the dam owner was able to hire an engineer to design a replacement spillway, a new spillway was constructed, and the storage restriction was lifted. The CMP culvert spillway was completely removed from the embankment and replaced with an open channel spillway located on the abutment, a safe distance away from the dam, restoring the flood routing capacity of the dam and reservoir to route the prescriptive IDF and eliminating a potential failure mode of erosion of the embankment during spillway activation.

CASE STUDY

Stovepipe Dam

Intermediate Evaluation Approach

Maximum Depth of Flow Allowed in Spillway

Dam Height: 100 ft
Impounded Volume: 20,000 Acre-ft
Hazard Class: High

This large earthen dam impounds approximately 20,000 AF at normal full pool. This high-hazard dam is owned by a public agency with dedicated professional engineers on staff, but a water users association is responsible for day-to-day operations. Failure would inundate farms/ranches, roads/interstate, and small towns (populations of approximately 2,000 people), with the flood wave reaching the towns in 2 – 4 hours.

When originally constructed during the New Deal era, it was completed with an unlined spillway excavated into weathered gneiss in the left abutment. After being damaged upon activation, a concrete lining was installed in the mid-1940s; this same spillway is still in service and has reached or exceeded its design life.

The spillway has suffered from moderate concrete delamination and spalling, joint deterioration, and exposed water stops. Regular maintenance has included concrete repairs and joint sealing. For approximately 20 years, the owner has made an operational recommendation to minimize spillway flows to avoid further damage.

About five years ago, inspection by the owner's engineers and, subsequently, a specialty concrete firm revealed much more extensive deficiencies in the spillway – including joint faulting and extensive sub-slab voids – than was previously understood. The owner and regulatory agency immediately began working together, and the owner's engineers developed an operation plan to minimize depth of flow over the spillway.

The owner's engineer reviewed records of historical performance and concluded that minimal damage to the concrete would be expected at flows less than 100 CFS, corresponding to 0.5 ft of water depth over the ogee crest. Previous performance and engineering analyses indicate that the outlet works have a maximum operational discharge rate of 350 CFS that is sustainable on a continual basis. While the outlet's maximum capacity is approximately 700 CFS, cavitation damage is expected if flows exceed 350 CFS. The combined project capacity in this scenario is therefore 100 CFS over the spillway + 350 CFS through the outlet = 450 CFS combined.

The reservoir level restriction is based on passing the 1% annual exceedance chance (100-year) inflow hydrograph safely, without damage to the concrete spillway. In order to pass the 1% event under these criteria, the reservoir level was restricted to 4 ft below the spillway crest, equating to more than 3,000 AF of storage loss.

The owner and regulator agreed that more aggressive restrictions were not warranted because:

- The project has a relatively large outlet capacity (up to 700 CFS, though damage is expected above 350 CFS).
- The spillway is founded on Precambrian gneiss that is believed to be generally competent. Although further investigations would be needed, it is believed that, in the event the spillway fails, the rock foundation would be effective at delaying upstream erosion and preventing uncontrolled release of stored water.
- Planning efforts are underway to repair or replace the spillway, so the period of risk exposure is limited.

The pool level restriction may not affect water deliveries in most years. The usable capacity is reduced significantly, but it is still slightly more than the total volume of water marketed/delivered from the reservoir in a year. The restriction requires considerably more active management from the dam operator (to adjust releases and avoid entering the restricted pool) and may impact carryover storage from year to year. The modeling to support this restriction also assumed that the low level outlet gate is not operated to augment spillway flows during the event.

In this example, it is important to note that the dam owner, under the guidance of licensed engineers, proactively developed a reservoir level restriction and proposed it to the regulatory agency for review and approval.

CASE STUDY

Buck Brook Dam
Intermediate Evaluation Approach
Seepage, Hydraulic & Structural Evaluation

Dam Height: 55-ft
Reservoir Volume: 1,000 Acre-ft
Hazard Class: High Hazard

Buck Brook dam was constructed in the early 1960s in a narrow mountain valley consisting of glacial till deposits. In the early 1980s, a hydrology study indicated it’s spillway was inadequate to pass the prescriptive Inflow Design Flood (IDF). In order to pass the IDF, an overlay on the downstream face of the dam was proposed with roller compacted concrete (RCC). The RCC protection was installed butting up to the dam’s service spillway, constructed of conventionally cast in place reinforced concrete chute.

Inspections of the service spillway since its construction, showed a steady decline in its condition. Issues observed include ASR/AAR, general concrete deterioration, spalling and delamination, hollow areas observed when sounding with a rock hammer, wall deflections, offset construction joints, and seepage emanating from construction joints. In the mid-2000s, seepage through construction joints near the bottom of the spillway were to exhibiting artesian pressure. This pressure has appeared to increase in the past two decades.

In 2014, the owner performed a semi-quantitative risk assessment (SQRA) on their entire portfolio of high- and significant-hazard dams. At that time, failure of the spillway was deemed to pose a moderate risk. This evaluation was purely qualitative as they did not have the budget/scope to perform structural calculations to support their conclusions. The SQRA did identify that the low-level outlet works, consisting of gasketed reinforced concrete pipe, posed a high risk of failure due to potential for internal erosion to carry embankment material into the pipe. The low-level outlet works became the focus of improvements at the structure based on this conclusion.

Since the SQRA, regular inspections of the dam revealed continued deterioration of the service spillway chute. Given the ongoing concerns the regulator had about the spillway stability, particularly following the Oroville incident in 2017, an issue-specific potential failure modes analysis was performed by the regulator in 2020 to address the structural stability of the service spillway chute. Two failure modes were evaluated: floatation of the spillway base slab under no-flow condition, and slab-jacking of the spillway base slab during a flow event. To support the risk analysis, a seepage model was created and calibrated based on observed seepage conditions in the spillway. This allowed for structural flotation calculations to be performed which revealed a nominally acceptable factor of safety. For the slab jacking potential failure mode, hydraulic calculations were performed to estimate the stagnation pressure to estimate the likelihood of slab jacking initiation during a flow event. The likelihood of each failure mode was evaluated to be moderate, but only with medium confidence. The analysis made recommendations for decreasing likelihood, including a storage restriction, and also recommendations to increase confidence. Neither were implemented immediately due to the risk plotting in an acceptable range, and allowing the dam owner to develop a plan of action.

In 2021-22, based on the prioritization of the SQRA, an outlet works rehabilitation project was performed which installed a CIPP Liner, and a new intake structure/gate. This project required draining the reservoir to provide access for construction. Upon first filling in the spring of 2023, seepage emanating around outlet conduit penetration through RCC overtoppoing protection was observed. Seepage pressures under the spillway base slab also appeared to increase with the ‘fountains’ increasing several inches indicating additional pressure under the slab.

Based on the increase in pore pressure under service spillway slabs, and the analysis performed in the 2020 study, the factor of safety against flotation was deemed to be to reduced below tolerable limits and therefore increase the likelihood of the failure mode to ‘high’ requiring immediate action. Inspections were performed as the reservoir was drawn down to determine the reservoir level where pressure under the spillway was reduced. This elevation was utilized to institute a formal storage restriction.

CASE STUDY

Buck Brook Dam
Intermediate Evaluation Approach
Seepage, Hydraulic & Structural Evaluation

V. RISK-BASED APPROACH

Risk-based analysis can also be used as a basis for reservoir restriction. As a prerequisite for this approach, regulators must have a thorough understanding of risk and the agency policy makers must establish what level of risk is tolerable to the general public. The details of risk analysis are beyond the scope of this document. For more details, please refer to sources such as the 2019 U.S. Bureau of Reclamation (USBR) and U.S. Army Corps of Engineers (USACE) Best Practices in Dam and Levee Safety Risk Analysis [7], and the U.K. Environment Agency 2017 Guide to Drawdown Capacity for Reservoir Safety and Emergency Planning [5] Section 8.3.

In general, the risk-based approach involves identifying a potential failure mode (PFM) of concern, estimating the breach flood, and the likely consequences that would be realized. The risk-based approach requires describing the sequence of events that must occur leading to failure of the dam and the resulting consequences. This is commonly referred to as a PFM "Event Tree." A thorough understanding of each 'node' in the event tree and a comprehensive understanding of the site conditions is required in order to understand the range and likelihood of behavior that can be expected with any level of confidence.

At its most basic level, risk analysis involves estimating the likelihood of the failure mode resulting in the defined consequences. Estimating likelihood can be as simple as an overall estimation of the likelihood of the overall event (qualitative), or can be broken down into estimated individual nodal probabilities (semi-quantitative) and may even use variable site conditions and material properties to estimate nodal probabilities (fully quantitative). The more advanced levels of analysis of semi-quantitative and fully quantitative are generally more amenable to setting reservoir storage restrictions due to the ability to quantify/estimate the relative impact that each node has on the overall probability of the PFM leading to consequences in an objective manner.

Consequences could be relatively benign such as failure to perform as intended or could be as catastrophic as loss of life. From a regulatory perspective, the lower consequences of failure to perform as intended is not likely to result in a reservoir storage restriction since the consequences are only realized by the dam owner. However, this may lead a dam owner to self-impose a restriction on their facility as it would prevent them from fulfilling their core mission (water delivery in the case of a water utility, recreation in the case of park owners, etc.). Regulatory restrictions of reservoirs typically are limited to failure modes that would result in consequences to the general public which result from an uncontrolled release of impounded water. Note that this includes events that may not lead to loss of life.

In the risk-based approach, a reservoir restriction is warranted if the calculated risk posed by the reservoir at full pool elevation exceeds the established tolerable limit for the regulatory agency or dam owner. Risk analysis can be used to evaluate several approaches to reduce that risk including reduced loading by a reservoir restriction, increasing the likelihood of detection or intervention by requiring more frequent monitoring, and reduced consequences through a reduced breach flood (due to reservoir storage restriction) or early warning system program which can lead to more advance warning to evacuate the population at risk.

The benefit of using semi-quantitative risk analysis is that individual nodal probabilities can be adjusted to reflect the increasing or decreasing likelihood due to the proposed intervention until the overall risk is reduced to a tolerable level. That can include the reduced probability of occurrence of any nodes in the event tree, reduced consequences, or most likely a combination of both. To establish a reservoir restriction, interventions or mitigations are added until the overall risk is reduced to a tolerable level.

Without a thorough understanding of the site, structure, and downstream conditions, the risk-based approach generally requires conservative assumptions of nodal probability estimates. These assumptions should be documented and incorporated into a confidence statement about the overall likelihood estimate. If the risk posed by the PFM exceeds tolerable limits and the confidence is high, then intervention and/or reservoir restriction is warranted. For similar instances where confidence is low, intervention and/or reservoir restriction may still be warranted, but other investigations and/or analyses can be initiated concurrently to increase understanding of the site or loading conditions which will improve confidence in the risk assessment. This additional analysis and/or data acquisition should be incorporated into a re-evaluation of the likelihood of the potential failure mode and can result in refinement or elimination of the intervention and/or reservoir restriction. Data collection and analysis can be incorporated into a compliance plan providing the owner with a clear path forward to address the concern as they work toward reduction of the risk and removal of the reservoir restriction.

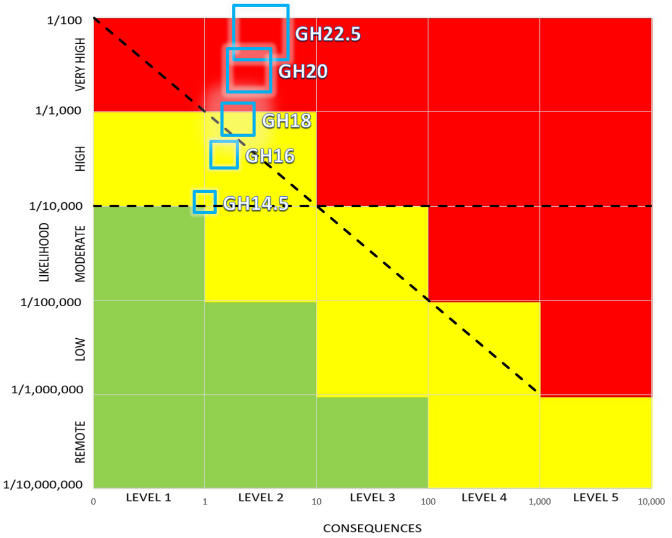
CASE STUDY

Lion Pool Dam - Seepage Incident
Risk-Based Approach
Seepage Gradient, Flow Velocity and Consequence Reduction to Establish Storage Restriction

Dam Height: 25-ft
Reservoir Volume: 2,400-AF
Hazard Class: High
Dam Type: Homogeneous Rolled Earth
Foundation:Soil

A recent inspection of this dam revealed a seepage entry pont on the upstream slope of the dam at approximately mid-height (GH 14.5). Following the inspection, an issue-specific PFMA was performed to evaluate the likelihood and consequences of failure. The PFMA was informed by evaluation of loading probability, likelihood of contact erosion by comparing seepage gradients and velocities to embankment/foundation soil information, and estimated life loss for various levels of storage allowed. The PFMA was performed with the dam owner present to inform them of the factors being weighed into the likelihood and consequences. Through evaluation of various reduced reservoir levels, the hydraulic load was reduced, decreasing the seepage gradient successively until velocities were reduced below the threshold where erosion would continue. The reduced storage volume also reduced the severity of a hypothetical breach flood, thereby reducing consequences as well. The result was that a tolerable level of risk was calculated for an 8-ft storage restriction.

A plot of the f-n chart for this PFM is presented below showing reduced risk and consequences as the reservoir pool is lowered. The box size also represents some level of uncertainty that exists at higher pool levels compared to reduced (restricted) pools.



VI. OTHER CONSIDERATIONS

Utilizing engineering calculations or observations to establish a safe storage level is sometimes the easiest part of managing reservoir storage restrictions. Other non-physical factors often play into the decision as well, including public communication, organizational and human factors.

Dams with higher risk/consequences always demand more rigorous analysis and documentation to support the restricted level. The higher the level of scrutiny that the restriction will receive, the stronger the case should be made. Many times, decisions must be made despite a dearth of information. In these cases, reasonable, yet conservative assumptions should be made and documented. Detailing the basis for the assumptions used in the analysis supporting the restriction level provides the opportunity for additional data to be collected to increase confidence in the decision. This may result in a basis for reducing or increasing the restriction. If the dam owner collects new information, that data and analysis should be provided to the regulator who can review it when considering whether it warrants a revision to the storage restriction. In these cases, the regulator is justified in making conservative assumptions in the interest of public safety. The burden of proof to provide additional data or analysis should fall on the dam owner. The same level of rigor should apply to high-profile dams/reservoirs, particularly if they provide great value to the community in the form of water supply or economic benefit.

In some high-profile cases, a public information campaign may be warranted. This could be as simple as setting up a briefing with community leaders to communicate the dam safety concerns and describe the measures being taken to address those concerns. It could also be very complex and include setting up informational websites where the concerned public can go for information. These cases should necessarily include informing dam safety organizational leadership and potentially the agency public information officer so they can provide accurate information in response to inquiries from the press and general public.

For contentious restriction orders, it may be beneficial for the regulator to hire a third-party engineer to perform an independent review of the supporting analysis used to justify the restriction. An independent review could lend credibility to the restriction by providing an objective opinion on the justification of the assumptions, validity of the analysis/results, and reasonableness of the conclusions of the regulator.

In addition to loading conditions and consequences commonly identified in dam safety regulation, site accessibility during extreme loading events should be considered when analyzing the overall risk and establishing a storage restriction. During extreme flood events, dams must operate near the limits of their design. The level of event that the dam is designed for often exceed thresholds of other adjacent infrastructure including roads and bridges used to access the structure. When this is the case, the dam should be designed to function assuming that operating staff and equipment cannot mobilize to the site to operate gates or otherwise intervene. Critical passages include bridges, roads along rivers or through canyons, unpaved or unimproved roads, roads below steep slopes prone to mudslides or rockfall, and roads in forested areas should all be considered. Dams with single access roads are more vulnerable than dams with multiple access roads on safer ground. These access issues should be considered for dams that are not staffed continuously for monitoring or operations as they may greatly reduce the probability of incident detection or intervention during an emergency. All modes of access including helicopter may be required during an emergency. A frank assessment of that possibility should be evaluated when considering a restriction.

Mobility around the dam site should also be considered. Extreme rainfall may make maintenance access roads impassable due to mud. All-weather access is needed at or near critical areas of the dam including the: crest, toe, low spots along the reservoir perimeter, outlets, drains, spillway, and powerhouse. A dam should always be accessible with heavy equipment at any time, especially under extreme weather conditions. If a dam is regularly inaccessible during a certain season (closed mountain roads in winter) the reservoir operation should be adjusted accordingly.

In higher elevations, snowpack may influence reservoir accessibility. If reservoir storage during spring runoff is a loading condition that poses an unacceptable risk, dam owners should work with land managers and road maintenance crews to ensure access roads are cleared of snow sufficiently as early in the spring as needed. Alternately, tracked vehicles such as snowcats or snowmobiles should be available to provide access to monitor and operate the structure. Heavy equipment and material stockpiles may need to be stored on-site for use during an emergency.

CASE STUDY

Spoon Dam
Other Considerations
Zero Storage → Breach Order

Dam Height: 135-ft
Impounded Volume: 35,000 Acre-ft
Hazard Class: High
Tributary Area: 650 sq-mi
Dam Tyhpe: Concrete Faced Rockfill

Spoon dam was a concrete-faced rockfill dam constructed in the early 1900s on the main stem of the Spoon River. Unfortunately, this intermittent stream never produced runoff regularly enough to serve as reliable irrigation water for the farmland below. The structure fell into disrepair due to lack of beneficial use and lack of productivity of the farmland it was intended to serve. Occasionally, the dam would capture runoff from large storms, but those storms also produced a significant sediment load which began to reduce the active storage the reservoir could impound, further diminishing its value.

The dam had settlement issues due to poor foundation preparation/shaping of the steep canyon walls and poor compaction of the rockfill which resulted in cracking of the upstream facing, the dam’s impermeable barrier. The dam nearly failed in the late 1980s when a large flood filled the reservoir inducing seepage through the cracked upstream face. Total seepage was estimated to be on the order of 100 cfs, and it nearly failed the embankment due to internal erosion. Complete dam failure was averted by the quick lowering of the spillway channel which allowed rapid reduction in the reservoir level. A storage restriction was issued shortly thereafter limiting the reservoir to gage height 100-ft citing an inadequate spillway, deteriorated upstream concrete facing and poor condition of the outlet works.

No further action was taken until 2012, when the spillway was lowered significantly, but other issues remained including the deteriorated upstream facing and poor condition of the outlet works. Due to lack of action on these issues, the storage restriction was revised to a zero storage restriction in 2014. As part of the zero storage restriction, a compliance plan was implemented between the regulator and dam owner requiring remedial actions on a schedule toward addressing the safety issues. Despite the spillway lowering, given the large tributary basin and significant sedimentation in the reservoir pool, the dam still had insufficient capacity to safely route the Inflow Design Flood (IDF).

Given the difficulties surrounding the structure, particularly the flashy and sporadic nature of the tributary basin and its unreliable production of water for irrigation, and the expensive repairs required to remove the storage restriction and regain full storage, the structure ownership changed. The new owner did not meet the requirements of the compliance plan which led to the regulator issuing a breach order requiring removal of the dam.

In 2018, a wildfire burned approximately 12-percent of the tributary basin. The potential for more runoff from a partially burned basin pushed the risk posed by the structure to intolerable levels, and emergency action was deemed necessary. State statutes allowed the regulator to take control of a dam and reservoir under emergency conditions and that authority was exercised in this case. The regulator designed an engineered breach and emergency funds were utilized to execute a contract with a local contractor to breach the dam.

The ability to rapidly reduce the storage in the reservoir is another consideration when establishing a storage restriction. The “Guide to Drawdown Capacity for Reservoir Safety and Emergency Planning [5] describes this requirement in detail. The outlet works must be robust enough and maintained well enough to ensure that this drawdown capacity is available under the most extreme loading conditions. Otherwise, failure of the outlet works during emergency drawdown should be evaluated as a potential failure mode. Reclamation document ACER TM-3 [8] also provides recommendations for reservoir evacuation capability.

Predictability of the critical loading that initiates a failure mode of concern should also be taken into consideration. For the cases of seismic loading, there is little to no chance of advance warning of the loading. Hydrologic loading may not provide much warning either if the basin is small and the critical loading event is a small convective thunderstorm. Dams with larger basins fed by snowmelt may have significantly more warning as the snowpack in the basin can be monitored and runoff is more predictable.

The loss of utilities could lead to severe problems during an emergency. Power outages are common during flood events through inundated power stations or damaged overhead lines. With a loss of power the electric-driven gates, valves, and computer-controlled equipment may not be operable. These critical functions should include redundant emergency backup power and/or manual override options.

Dam owner disposition should also be considered when establishing a storage restriction. Most dam owners are conscientious and recognize their responsibility for the safety of the downstream public. But, unfortunately, there are some that take less care and view regulators as bureaucrats standing in the way of their business. In the case of the latter, extra care is warranted in educating the owner and their staff about the reason behind the restriction and their liability should something happen. In extreme cases, where the owner is not expected to be responsive, a more punitive restriction may be necessary until they demonstrate that the dam safety deficiencies are being taken seriously and they have implemented a plan to address them.

Zero storage restrictions should be issued when the dam is deemed unsafe for any storage. A zero storage restriction typically requires the owner to maintain the low level outlet gate open. But zero storage does not mean zero risk. There is always the possibility that a hydrologic even could be captured by the reservoir which would load the structure. This possibility should be considered when considering a zero storage restriction and whether a breach order is warranted.

Breach orders are a last resort. They are generally reserved for projects that are no longer viable for the owner financially. Unfortunately, breaching a structure is a complicated process and not without cost. If the owner does not have the financial resources to design and construct a breach, or the will to expend those resources on a project that will have no financial return, other means of compelling compliance with the breach order may be necessary. In some cases, court orders and financial penalties may be needed. State statutes that govern these processes vary dramatically from state to state. Regulators should work closely with the Attorney General of their state to determine what possible courses of action is available to them. These actions should be supported with the types of engineering analysis described herein.

VII. RESTRICTION REVISION/REMOVAL

When a regulatory authority or dam owner imposes a reservoir restriction to address unsafe conditions, it is a best practice to clearly identify what conditions must be met to lift or revise the restriction. It is generally appropriate to lift or revise a reservoir restriction after sufficient physical or operational interventions take place, or as new data is collected or analysis is performed to demonstrate that the dam will perform safely under the expected loading conditions. This can allow the reservoir restrictions to be reconsidered. If unsafe conditions no longer exist and the project meets current design and safety standards, the reservoir restriction is no longer warranted. If unsafe conditions are partially addressed through the implementation of mitigation or re-analysis with better data or more sophisticated techniques, the reservoir restriction may be reassessed under the new conditions using the methods discussed herein.

Physical interventions such as repairs or modifications to a dam may warrant reconsideration or removal of a reservoir restriction. For example, the reservoir at the FERC-regulated Swinging Bridge Dam in New York was drawn down in 2005 following the discovery of a sinkhole. After investigating the cause of the sinkhole, physical interventions included addressing the sinkhole-initiating water leakage at the penstock through the dam by filing the penstock with concrete and repairing the sinkhole and the damaged embankment. Following this repair, the reservoir restriction was lifted in July 2007.

Operational interventions are generally measures that reduce the time to detect potentially hazardous conditions paired with a plan for preventative or mitigating actions. Operational intervention is often less expensive than physical intervention. However, it is not always possible for operational interventions alone to address the unsafe conditions triggering a reservoir restriction. Appropriate intervention measures should be selected based on the project, the identified unsafe conditions, the consequences of failure, and engineering judgment.

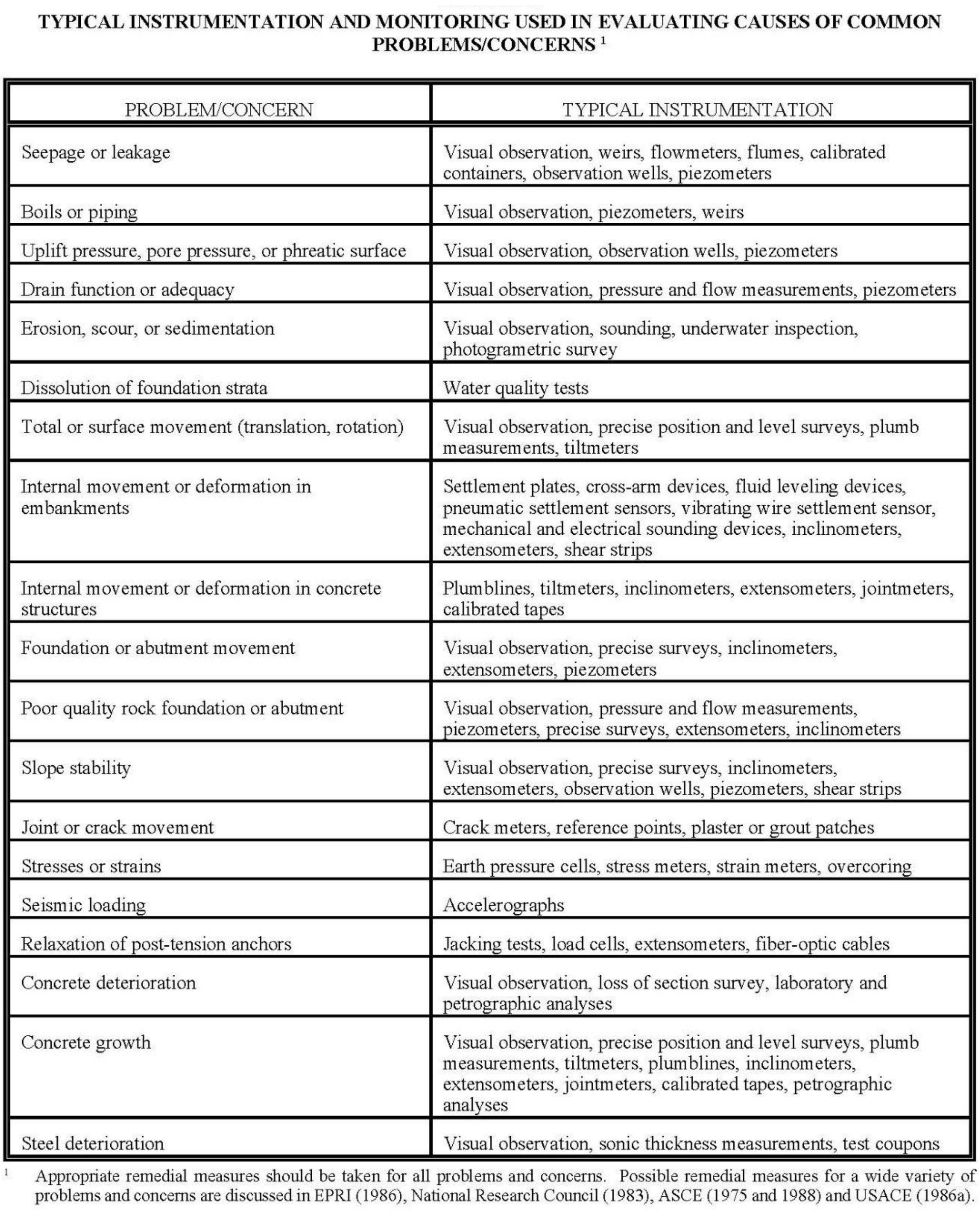
Detection time may be decreased by additional instrumentation and monitoring designed to provide early warning. Such additions may include more frequent visual inspections, added instrumentation such as those indicated in the FERC Engineering Guidelines Chapter 9 [4], provided in the table below, and regular review of available forecasting and flow monitoring resources. Any additional instrumentation should be selected to provide information useful and relevant to detection of potential hazards at a project.

Operational intervention may be directed in a standard operating plan (SOP) for reservoir drawdown or other remediation measures following “triggering” observations related to potential unsafe conditions. Following detection of an unsafe condition, emergency intervention techniques and appropriate emergency response can stop or minimize the consequences of a dam failure [3].

Along with reservoir restriction, common emergency interventions may include temporary measures to increase freeboard, mitigate active seepage, prevent or redirect erosion, and increase outflow capacity [2]. Operational intervention to address a reservoir restriction may include advanced preparation and planning for these emergency measures such as improving downstream notification and stockpiling tools and materials such as sand or gravel in an accessible location.

Outside of emergency response, most issues that warrant a reservoir restriction are slowly developing. This may warrant developing a path toward compliance with deadlines and consequences. This ‘compliance plan’ approach can be utilized to provide the dam owner with clear objectives, milestones and time to hire an engineer, collect additional information, perform analysis, design mitigation, and construct improvements.

Refilling a reservoir after an extended restriction should be performed in a cautious and measured manner. In some cases, refiling will load new or modified features for the first time. Prolonged operation at less than full level may also result in changes to the system which must be evaluated for proper performance once re-loaded. A first filling and monitoring plan should be developed by an engineer to identify the frequency of monitoring and visual inspection, and possibly hold points to evaluate performance when a reservoir restriction is lifted.



TYPICAL INSTRUMENTATION AND MONITORING USED IN EVALUATING CAUSES OF COMMON PROBLEMS/CONCERNS [1]

PROBLEM/CONCERN	TYPICAL INSTRUMENTATION
Seepage or leakage	Visual observation, weirs, flowmeters, flumes, calibrated containers, observation wells, piezometers
Boils or piping	Visual observation, piezometers, weirs
Uplift pressure, pore pressure, or phreatic surface	Visual observation, observation wells, piezometers
Drain function or adequacy	Visual observation, pressure and flow measurements, piezometers
Erosion, scour, or sedimentation	Visual observation, sounding, underwater inspection, photogrametric survey
Dissolution of foundation strata	Water quality tests
Total or surface movement (translation, rotation)	Visual observation, precise position and level surveys, plumb measurements, tiltmeters
Internal movement or deformation in embankments	Settlement plates, cross-arm devices, fluid leveling devices, pneumatic settlement sensors, vibrating wire settlement sensor, mechanical and electrical sounding devices, inclinometers, extensometers, shear strips
Internal movement or deformation in concrete structures	Plumblines, tiltmeters, inclinometers, extensometers, jointmeters, calibrated tapes
Foundation or abutment movement	Visual observation, precise surveys, inclinometers, extensometers, piezometers
Poor quality rock foundation or abutment	Visual observation, pressure and flow measurements, piezometers, precise surveys, extensometers, inclinometers
Slope stability	Visual observation, precise surveys, inclinometers, extensometers, observation wells, piezometers, shear strips
Joint or crack movement	Crack meters, reference points, plaster or grout patches
Stresses or strains	Earth pressure cells, stress meters, strain meters, overcoring
Seismic loading	Accelerographs
Relaxation of post-tension anchors	Jacking tests, load cells, extensometers, fiber-optic cables
Concrete deterioration	Visual observation, loss of section survey, laboratory and petrographic analyses
Concrete growth	Visual observation, precise position and level surveys, plumb measurements, tiltmeters, plumblines, inclinometers, extensometers, jointmeters, calibrated tapes, petrographic analyses
Steel deterioration	Visual observation, sonic thickness measurements, test coupons

[1] Appropriate remedial measures should be taken for all problems and concerns. Possible remedial measures for a wide variety of problems and concerns are discussed in EPRI (1986), National Research Council (1983), ASCE (1975 and 1988) and USACE (1986a).

Table 1: FERC Recommended Instrumentation & Monitoring for Evaluating Dam Problems/Concerns

CASE
STUDY

Plains Dam
Restriction Revision & Removal
Refill Monitoring Plan

Dam Height: 35-ft
Impounded Volume: 24,000 Acre-ft
Hazard Class: High

Plains Dam and Reservoir is a large irrigation reservoir serving a significant amount of farmland. The geology in the area consists of deep deposits of Eolian sands with relatively low fines content. The dam was constructed with these sandy soils and included a reinforced concrete facing system which served as the dam's impermeable barrier.

The reservoir has had multiple issues over the past half-century including seepage, a spillway that was too small to pass the prescriptive inflow design flood (IDF), and erosion of the dam crest and downstream slope due to wave action exacerbated by the smooth upstream dam facing. Acknowledging these problems, the dam owner has operated the structure under a self-imposed storage restriction since the mid-1960s. A formal storage restriction was issued by the regulator in 1990.

Over the past 15 years, the owner has been progressively addressing the issues identified in the storage restriction. In 2007, a new spillway was completed to pass the prescriptive IDF. And in 2022, both a wave breaker system was installed on the upstream concrete face and a filtered toe drain was installed at the location of the most troublesome seepage.

Acceptance of the 2022 construction and removal of the storage restriction was issued in early 2023 under the condition that reservoir filling be closely monitored to assess the performance of the structure under the increased hydraulic load which the dam has not experienced in nearly 60 years. The owner’s engineer prepared the fill and monitoring plan which was reviewed and approved by the regulator. The fill plan requires fill rates to be controlled and reservoir level hold points where dam performance can be evaluated. It also delineates frequent visual observations and monitoring of instrumentation along with observing the performance of the wave break system after wind events. Monitoring data is collected by the owner, evaluated by their engineer, and transmitted to the regulator for review.

VIII. CONCLUSION

The authority to impose reservoir restrictions is a powerful tool in the regulatory toolbox to maintain the safety of the public. While regulators can and should consider the loss of resources that the dam owner will realize due to a storage restriction, they must hold public safety paramount. Utilizing well-documented analysis, appropriate data, industry-standard practices, and engineering judgment in exercising this authority is required to maintain the trust that has been placed in regulators by both the general public and dam owners.

The various tiers of analysis described herein should provide regulators with several defensible approaches to establish the safe storage level based on the conditions present at a dam. That data and analysis can be provided to dam owners, the public, or policy makers to explain why the storage restriction is warranted in a transparent manner. It can also establish the basis for a path toward lifting the restriction that the dam owner can follow to mitigate the safety concerns and re-establish their ability to use the reservoir to its full potential, once all safety issues have been addressed.

Reservoir storage is clearly required and beneficial for a properly functioning society. The proper implementation of reservoir restrictions and the subsequent improvements to remove those restrictions can help us work toward a future where all dams are safe.

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