# ADDRESSING OPERATIONAL RISKS AND UNCERTAINTIES FOR GATED SPILLWAYS

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## ABSTRACT

Gated spillways are commonly incorporated into dam design to provide flexibility with regard to reservoir operations and/or to pass large floods. Spillway gates present operation and maintenance challenges to dam owners. Gate operations during floods can require on-site personnel to react quickly, often during storms when flooding can limit access to the site or gates and compromise the availability of power. Additionally, the operation of gates requires decision making related to releasing large flows that could cause downstream damage. Interpretation of flooding potential has to be considered in the decision making process, since a delayed reaction could result in a dam safety emergency. Even when post-incident assessments validate that gate operations did not increase flooding, downstream landowners are often quick to condemn the dam owner for mis-operation of gates. In addition to operational challenges, dam owners are faced with costly ongoing maintenance to ensure that gates will function as designed when the need arises. This includes maintenance of structural and mechanical components (including hydraulics, electrical systems, and power feeds), training of operators, regular testing of the gate systems, and debris removal.

This paper discusses common structural, mechanical, electrical, instrumentation, and operational issues along with recommendations for regular maintenance of spillway gates. Hydraulically-efficient fixed crest labyrinth and piano key weirs are discussed as an option to reduce reliance on spillway gates during floods. Case histories include projects where gated spillways presented challenges to the dam owner and were partially or completely replaced with passive, fixed crest spillways or automated gates. Finally, a hypothetical example is presented to illustrate changes in risks through replacement of a gated spillway with a fixed crest labyrinth weir.

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## INTRODUCTION

Gated spillways are commonly incorporated into dams and are generally more typical for structures where:

- frequent regulation of the reservoir level is required
- outflows need to be controlled for different flood events (e.g. flood control dams)
- significant discharge capacity is required to pass the design flood (e.g. dams on large watersheds), sometimes making a fixed crest spillway impractical

Spillway gates can be categorized as "underflow" gates, or "overflow" gates. Underflow gates are raised and flow is pressurized unless the gate is lifted to above the upstream water level, allowing free discharge over the fixed spillway crest. Overflow gates are lowered and flow passes over the gate until it is completely lowered to the fixed crest elevation. Common underflow gates include radial (or Tainter) gates and lift gates. Overflow or crest gates can be hinged at the fixed crest and hydraulically or pneumatically actuated. Other types of overflow gates include inflatable bladders (rubber dams) and Hydroplus Fusegates, a proprietary system designed such that the gate(s) tip during an extreme flood. Typically, radial gates are not designed for overflow; however, gates can be specially fabricated to facilitate overflow (e.g. Fontana Dam, NC – Photo 1).

Photo 1. Radial Gate designed to accommodate overflow, Fontana Dam, NC.

Gated spillways can provide significantly more discharge capacity in a given spillway footprint than conventional fixed crest weirs by effectively increasing the head over the fixed crest as the gates are operated. Additionally, gates can accommodate significant flood storage with little or no outflow until the gates are operated, making gated spillways very effective for flood risk reduction projects. However, spillway gates present operation and maintenance challenges to dam owners.

## GATED SPILLWAY ISSUES AND RISKS

Spillway gates generally require more operation and maintenance than fixed crest spillways. The following is an excerpt from the US Army Corps of Engineers' *Hydraulic Design of Spillways* (USACE, 1990):

> *"The value of an uncontrolled fixed crest spillway in providing an extremely reliable operation and a very low cost maintenance facility is undeniable. [Various] considerations at many damsites may restrict the use of an uncontrolled fixed crest spillway."*

USACE (1990) recommends that where possible, fixed crest spillways should be incorporated into designs, particularly when the watershed response time is short. In addition, USACE (1990) recommends installation of two or more gates to "satisfy safety concerns"; presumably to provide redundancy in case a spillway gate cannot be operated.

Common issues with gated systems are associated with their relatively complex mechanical systems (when compared to passive systems) and the user supplied input required to operate them.

Risks related to spillway gates can result from:

Un-intended and uncontrolled releases from:

- accidental gate operation through failure of automation equipment or some other unexpected occurrence;
- structural failure of the gate from damaged components or from unexpected loadings (hydraulic, seismic, debris loads, vibration, etc.); and,
- inability to close gates due to damage, binding or debris obstruction.

Reduction in spillway capacity and increased potential for overtopping and failure of the dam from:

- inability to operate the gates during large floods; and,
- blockage of spillway gate openings from debris.

Flooding impacts can often result from the operational issues listed above and include:

- downstream flooding from un-intended and uncontrolled releases;
- upstream flooding from reduced spillway capacity due to inability to operate gates or blockage of the spillway gate openings; and,
- downstream flooding from failure of the dam due to reduced spillway capacity.

In addition to these issues with the gates and appurtenant works, effective operation of spillway gates commonly requires actions by the dam owner/operator, which introduces risks and uncertainties related to the human element. On-site personnel have to react quickly, often during storms when flooding can limit access to the site or gates and compromise the availability of power. Additionally, the operation of gates requires decision making related to releasing large flows that could cause downstream damage.

Interpretation of flooding potential has to be considered in the decision making process, since a delayed reaction could result in a dam safety emergency.

Resources. There have been several publications summarizing historic gate failures and lessons learned (including Graham and Hilldale, 2001 and ASDSO/EPRI, 2000). Additionally, several publications provide best practices for gate operations and maintenance (including ASCE, 2012 and USSD, 2002) By following current best practices in gate operation, maintenance and training, risks related to gated spillways can be dramatically reduced, but not eliminated.

## Dam or Gate Failure Examples

Poor maintenance, infrequent inspections, and operational issues can all lead to failure of either the gate or, in cases where gates cannot be effectively operated during extreme floods, overtopping and failure of the dam.

Using the National Performance of Dams Program (NPDP) Dam Incident Query tool (NPDP, 2014), eighteen "Gate Structural Failure" incidents are identified. Six of these incidents were related to failure of lifting systems, including hoisting mechanisms (1) and lifting chains or wire ropes (5). Three events were reportedly a result of concrete failure at piers that support gates. Only two events were reported as a gate failure, resulting in an uncontrolled release.

One of the more notable gate failures was at Folsom Dam in 1995 (Photo 2), where a Tainter gate failed during opening, reportedly as the result of trunnion pin friction. This failure generated significant interest in evaluating gated spillway systems by numerous agencies (ASDSO/EPRI, 2000).

Photo 2. Gate failure at Folsom Dam, 1995
(courtesy of Bureau of Reclamation)

The 2010 failure of Delhi Dam (Photo 3) has been partially attributed to inability to operate one of the spillway gates during an extreme flood event. Fiedler et al (2011) concluded that the failure was the result of internal erosion combined with overtopping of the embankment due to inadequate spillway capacity. The inability to operate one of the gates likely contributed to both failure modes as the internal erosion failure mode was believed to be initiated due to high reservoir levels.

Photo 3. Delhi Dam failure
(courtesy of Iowa Wing Civil Air Patrol)

**Examples of Flooding Impacts Resulting from Gate Operations**

In addition to the potentially catastrophic consequences related to failure of the dam or spillway gate(s), dam owners are faced with the challenge of operating the gate systems to consider potential upstream and downstream flooding impacts. These impacts may be real or merely public perception.

The 2014 operation of floodgates at two dams in India are notable recent examples of significant downstream impacts. On June 8, water was released from the Larij Hydropower Project and 24 students and a tour guide were carried away in the floodwaters; the bodies of 12 students have been recovered and the remaining 13 people are feared dead (NDTV, 2014). Less than two weeks later, ten boys were stranded in floodwaters reportedly caused by operation of gates at the Tenughat Dam (The Telegraph, 2014). The boys were rescued by divers following the closing of the gates. Both of these incidents have triggered inquiries with regard to the operations at the dams. The Larij inquiry report noted an increase in discharge from about 700 cfs to nearly 16,000 cfs over one hour and criticized the dam operators (NDTV, 2014):

> *"There are not standard operating procedures with the release of water…[Those] involved in powerhouse operation and those handling [dam] operations are not working in tandem…"*
>
> *"The warning system is also inadequate. All this constitutes a systemic failure…"*

A search for papers and articles related to the impacts of gate operations at dams results in numerous interesting and controversial case histories.  As recent as July 2014, the US Army Corps of Engineers had to defend itself against criticisms related to releases at Coralville Reservoir in Iowa, which included charges from residents of both not releasing enough water prior to the flood and releasing too much water during the flood (O'Leary, 2014).

The Washington Suburban Sanitary Commission (WSSC) was criticized for causing flooding in downtown Laurel, Maryland by operations at Duckett Dam during a storm in April 2014, with claims from residents and politicians including:

> *"I don't have a problem with natural flooding that may take place.  I have a problem with manufacturing a flood, and that's exactly what WSSC did"* (quote obtained from Shaver, 2014)
>
> *"I wonder about WSSC's mitigation plans.  Can we release that water sooner?  With all that technology at their disposal, you'd think they could avoid this."* (quote obtained from Pichaske, 2014)

The WSSC (Johnson, 2014) and many residents defended the operations, noting that the gate operations were necessitated due to a concern with the safety of the dam.

A major difference between these examples is that Coralville Dam is operated as a flood control structure while Duckett Dam impounds a water supply reservoir and was not intended to reduce downstream flooding during storms.

The Pompton Lakes Dam Floodgate Facility was developed to provide flood reduction benefits to upstream properties; however, there have been claims that operations at the dam have contributed to downstream flooding (Augenstein, 2012).  An extensive study was performed to evaluate the impacts of gate operations on downstream flooding, with the finding that "the gates function as intended with no significant downstream impacts" (Miller et al, 2013).

There are also cases where dam operators are blamed for creating upstream flooding as the result of gate mis-operation.  Lack of maintenance and the resulting inability to operate gates was alleged to cause flooding around Lady Bird Lake in Austin, Texas (Buchele, 2013).

Graham and Hilldale (2001) summarized several other notable incidents resulting from spillway gates opened intentionally during floods, including:

- Dominican Republic, 1998, Sabaneta Dam: During Hurricane George spillway gates were operated without notification of downstream residences. Flooding from the gate operation contributed to numerous deaths in the village downstream of the dam.

- Nigeria, 1999, Jebba and Shiriro Dams: Gates were operated during heavy seasonal rains, the gates were operated to prevent overtopping of the dams. The resultant flooding submerged 400 villages, killing hundreds and leaving 300,000 homeless.

- Mexico,1999, Penitas Dam: Spillway gates were operated to prevent overtopping of the dam resulting in heavy damage downstream of the dam. More than 400 deaths were blamed on the flood.

It is clear that whether or not the operation of gates during a flood contributes to downstream flooding, it is likely that the owner of the facility will be criticized for mis-operation of the structure.

Gate Operation Plans. Most projects with spillway gates have some form of operations plan to define the opening of gates during floods. These plans can range from "if the lake is rising, keep opening the gates" to complex plans that require monitoring of precipitation (forecasted and actual), lake levels, and upstream and downstream stream gage data.

While flood operations plans are prudent, the execution of these plans can be unrealistic or impracticable especially if the plan requires early operation of gates to increase flood storage prior to the actual rainfall event. For example, the authors have encountered one plan that required full opening of all spillway gates prior to the start of the storm event in order to lower the pool sufficiently to create additional flood storage to pass the design flood. Considering that opening of a single gate by only five percent causes downstream flooding of residences, it is unlikely that operators will follow the plan, since this would cause downstream flooding before the rain even starts. However, delaying these actions could put the dam at risk.

## ADDRESSING RISKS RELATED TO SPILLWAY GATES

As presented in the examples herein, risks related to spillway gates can result from:

- inability to operate the gates during large floods, reducing spillway capacity and increasing the potential for overtopping and failure of the dam
- improper gate operations which cause downstream or upstream flooding (and create the potential for liability related to this flooding)
- spillway gates are opened accidentally through failure of automation equipment or some other unexpected occurrence
- spillway gates are opened intentionally during a major flood in accordance with a flood operating plan resulting in major downstream flooding
- spillway gates fail structurally
- debris blockage of spillway gate openings impedes flow, possibly leading to damage to the gates and/or potential overtopping and failure of the dam

To reduce these risks, actions can range from improved operation and maintenance and training, replacement of manual operations with systems that are programed for automated response in addition to manual and remote operation, to replacement of some or all of the gates with a more reliable passive, fixed crest spillway.

## Maintenance and Modifications

Proper maintenance is critical to preventing failure of the gates and improving reliability of operations. This includes:

- periodic visual and hands-on structural inspection of the gate components;
- periodic gate performance testing;
- development of a maintenance manual and implementation of a preventive maintenance plan; and,
- providing a reliable power back-up system and maintaining this system.

Development of a written record of the gate design, components, modifications, inspections, operations, and maintenance is an important part of the gate life cycle and aids in the transition of key personnel responsible for gate operation and maintenance.

Gate rehabilitation could include structural modifications or reinforcement, replacement of lifting mechanisms, and automation of operations.

## Effective Gate Operation Plans

An effective and well thought out gate operation plan can significantly reduce risk related to improper gate operations. The plan should include:

- gate operation procedures for normal and flood/emergency operations;
- identification of primary gate operations personnel and secondary responders for emergency gate operations;
- training on gate operations procedures for the primary and secondary responders

As with any critical plan, table top and full scale exercises should be conducted on a regular basis and include training for primary and secondary personnel. The effect of failure of different components of the operations plan should be analyzed, including loss of communications, road closures, un-availability of key personnel, power failure, etc. After exercises are conducted an appropriate amount of time should be allocated to conduct an after action review of the exercise to talk through failures and lessons learned, develop solutions, and incorporate the solutions into the plan and the next training cycle.

Dam owners need to balance downstream flooding impacts with gate operation for the safety of the project. Many older dams, designed and built when there was limited downstream development, could now impact downstream landowners with routine gate operations. As part of their gate operations plan, owners should evaluate the practicality of their plans in respect to upstream and downstream flooding impacts as well as dam safety. Every dam that includes gates for spillway capacity should have a well thought out operations plan. In developing the plan, an incremental damage assessment should be performed for various gate operation scenarios to reduce flooding impacts. For example, opening the gates “in advance of the storm” to preserve flood storage and increase spillway capacity for the peak of the event could present a higher risk to downstream residents than opening the gate after natural flooding begins to occur downstream. This is particularly true if the dam owner does not provide adequate warning with regard to gate operations.

**Replacement**

For projects where mechanical gates are significantly deteriorated, structurally or operationally deficient, or operations are difficult or present significant potential risks, replacement of some or all of the spillway gates may be justified. Options for replacement could include:

- Hydraulic or pneumatic controlled gates which utilize automated operations
- Fusegates, which do not rely on manual or automated systems for operation
- Fixed crest spillways which require little maintenance and no operation - Labyrinth and piano key weirs are hydraulically efficient solutions

The next section discusses specific examples related to alternatives to gated spillways, including case histories where traditional gated spillways were replaced.

## ALTERNATIVES FOR GATED SPILLWAYS: EXAMPLES AND CASE HISTORIES

Numerous projects have included replacement of either deteriorated or antiquated gate systems.

Pneumatically actuated steel crest gates have been used to replace mechanically operated radial, flap, and slide gates for many projects (such as the patented bottom hinged spillway gates by Obermeyer Hydro, Inc.), which include automated operation to reduce the risk and uncertainty related to human error in manual operations. Similarly, rubber bladders have replaced mechanical systems.

Tipping Fusegates were selected in lieu of more traditional Tainter gates at Canton Lake Dam in Oklahoma (Hydroplus, 2014a) and Jindabyne Dam in Australia (Hydroplus, 2014b). This was reportedly based on initial and long term (maintenance) costs.

For several projects where gate operations presented challenges to the dam owner, fixed crest labyrinth and piano key weirs have been used to reduce routine maintenance and prevent operational issues.

The original design for Ute Dam in New Mexico included 27-ft high gates which were not installed as part of the 1962 construction. In the early 1980s, the US Bureau of Reclamation (Reclamation) evaluated options to increase reservoir storage by installing gates or identifying a more economical solution, which resulted in selection of a labyrinth spillway (Houston, 1982). In addition to being more cost effective to construct, this structure was presumably more reliable and considerably reduced operation and maintenance costs.

Examples of labyrinth spillways being used to replace gated structures include the Brazos Dam in Texas and the New London Dam in Minnesota. At Brazos Dam, the original drum gates did not maintain a reliable water level and were replaced in 1985 with hydraulically actuated leaf gates, which also had operational problems. In 2007, construction of a new labyrinth spillway was completed to replace the gated spillway (Vasquez et al, 2009). New London Dam also experienced problems with the original gate system and was replaced with a labyrinth spillway in 2010 (Minnesota DNR, 2014).

Piano key weirs are similar to labyrinth spillways, with a smaller foundation footprint that allows construction of the weir on gravity dams. At Malarce Dam in France (Photo 4), a piano key weir was installed to supplement the capacity of the existing gated spillway and increased total discharge capacity from about 140,000 to more than 160,000 cfs. In addition, the piano key weir was designed to discharge flood flows prior to needing to operate the gates. This provided twice as much time for the dam operator to get to the dam to open gates, which was very important given the rapid watershed response time (Laugier et al, 2014).

Photo 4. Piano key weir at Malarce Dam

Additional detailed project case histories follow.

**Sugar Hollow Dam**

Sugar Hollow Dam is a concrete gravity dam with a maximum height of about 80 feet, owned and operated by the Rivanna Water and Sewer Authority. The dam was constructed in 1947 to provide water supply for the City of Charlottesville, Virginia and surrounding communities. The 225-foot long ogee spillway was originally equipped with a system of eight, 25-foot wide by 5-foot high vertical lift gates. The gates were operated manually during floods using a hoisting system mounted to a rail that traversed a bridge over the spillway (Photo 5). This system was difficult to operate during floods and the bridge and other superstructure reduced hydraulic capacity. In addition, the configuration of the gates and superstructure made the spillway prone to clogging from logs and debris, further reducing capacity. Finally, the crest of the non-overflow sections of the dam was only five feet higher than the top of gates. Given the very steeply sloping watershed, the dam operator had to respond quickly during floods to operate the gates to prevent overtopping of the dam.

Photo 5. Sugar Hollow Dam: original gated spillway and hoisting system

The dam was found to have inadequate spillway capacity to pass the design flood without overtopping the non-overflow sections of the dam. Furthermore, stability analyses indicated the structure did not meet criteria for flood loading conditions. Rehabilitation of the dam was completed in 2000 and included installation of post tensioned rock anchors for stability, raising portions of the non-overflow sections to contain extreme flows to the central part of the dam, and replacement of the gate system with a five foot high inflatable bladder crest gate (Photo 6). The upgrading of the dam and design of the crest gate system is documented in (Campbell et al, 2000) and (Paxson et al, 1999).

Photo 6. Sugar Hollow Dam: inflatable bladder crest gate

With the removal of the piers and superstructure, the inflatable bladder crest gate provided better hydraulic performance and passage of debris than the original system. In addition, the bladder system was equipped with a computer system to automate operations, based on the reservoir level. Given the rapid hydrologic response of the watershed and the presence of several homes within the downstream floodplain, the designers were concerned with the potential for a sudden release from the gate system during operations. Therefore, various operating scenarios were evaluated under hypothetical flooding conditions to reduce the potential for surges in outflows. A spreadsheet program was developed to characterize outflow conditions for a wide range of operating conditions using a small computational time step.

The inflatable bladder system operates on water level control: the system attempts to maintain a specified constant water surface elevation throughout deflation. For this project, the target water surface elevation corresponded to one foot of flow over the inflated bladder (e.g. operations initiated with the reservoir at one foot above normal pool). Two methods of control ("fine" and "coarse") are commonly incorporated into the operating system. Each of these control modes samples water surface elevation at a discrete time interval (say every five minutes) and deflates the bladder incrementally in response to a water level above the target elevation. The target elevation for coarse control is higher than for fine control, and the deflation increment is typically larger for coarse control. The typical operating scenario used by the manufacturer was evaluated and found to result in surges in the flow from bladder deflation, as shown in Figure 1 (Paxson et al, 1999).

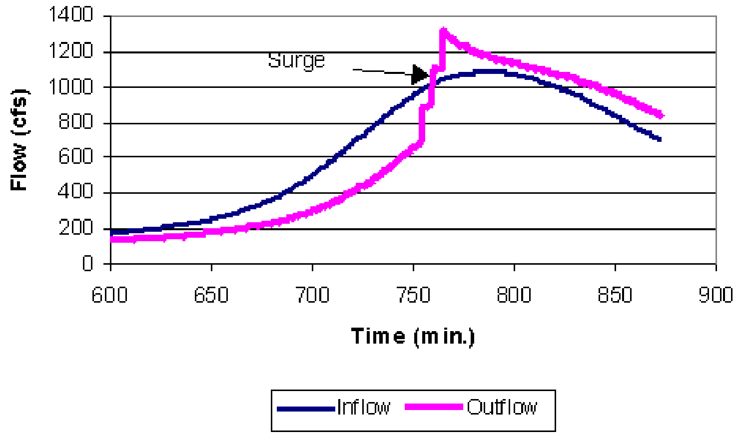


Figure 1. "Typical" gate operation model results – 2 year flood

Using the spreadsheet tool, an operating scheme was developed that would provide adequate hydraulic capacity while reducing the impacts of gate operations on downstream properties. As designed, operation (deflation) of the bladder will initiate for a storm between the 1- and 2-year events and would be fully deflated for a storm corresponding to roughly the estimated 100-year flood.

The replacement of the antiquated steel lift gates, piers, and superstructure with an inflatable bladder crest gate with an automated operating system successfully reduced risks related to inability to operate the gates during floods. The original gates required regular maintenance to ensure operability and manual operation was difficult during large floods. In addition, the replacement system is more suitable for passing debris, further reducing hydrologic risks. The automated gate operating system was programmed to consider site specific hydrologic and hydraulic conditions, to reduce the potential for sudden releases from the dam. The new gate system has performed without notable issues for nearly fifteen years.

**<u>Lake Townsend Dam</u>**

Lake Townsend provides the primary water supply for the City of Greensboro, North Carolina. The dam was constructed in 1967 and consisted of a 25-ft high concrete spillway flanked by earth embankments. The spillway was an ogee-shaped weir divided into nine, 25-ft wide bays and one 15-ft wide bay, with a total spillway width of 276-ft. Ten foot high steel vertical roller gates were located in each of bays and floods were passed by operating the gates as needed to maintain the reservoir level near the normal pool (top of gates).

By the late 1970s, cracking of the concrete spillway was observed and was eventually revealed to be the result of alkali-silica reactivity (ASR). Not only was the ASR a concern with regard to the integrity of the concrete structure, it presented potential issues related to gate operations, due to expansion and deterioration of the piers on which the gates were mounted. The staff at the dam reported vibration of the gates when they are overtopped by more than a few inches but also had concerns with vibration when the gates were operated and potential damage to the deteriorated piers. Based on these concerns, operations staff installed stops on the gates to prevent opening of the gates more than two feet.

In addition to the ASR concerns, the spillway had inadequate capacity to pass the design flood required by North Carolina dam safety regulations, even if the gates could be fully opened to allow unobstructed weir flow over the ogee.

Based on the structural and hydraulic concerns, the concrete gated spillway was replaced with a 7-cycle labyrinth spillway; two 20-ft high cycles were set with the crest at normal pool and the remaining five cycles are 21-ft high, with crest one foot above normal pool. The spillway has a total width of 307-ft, which includes a single bay with a low level and skimmer gate. The labyrinth spillway has capacity to pass about 80,000 cfs with the reservoir at top of dam, which is similar to the capacity of the original gated spillway, assuming full gate operation. Weir submergence from tailwater made it impractical to design the spillway to pass the design flood. Therefore, the embankments were armored to allow overtopping for extreme floods (Paxson et al, 2008).

A comparison of the discharge rating curves for the original gated spillway and the labyrinth weir is presented in Figure 2. The rating curve for the gated spillway assumed that the gates can be fully opened and that gates are operated as needed to maintain the reservoir within about three inches of the normal pool. As previously noted, the gated and labyrinth spillways have similar hypothetical discharge capacity with the pool at top of dam (EL 725.5); however, if operated as shown, outflows for a given storm event would be higher for the gated spillway. For the fixed crest labyrinth spillway, the pool levels would be higher for a given inflow, resulting in more flood attenuation. Although the dam was not designed to provide flood protection, this is considered an ancillary benefit of the new labyrinth spillway. It should be noted that there are no structures around Lake Townsend with elevations below the top of dam.

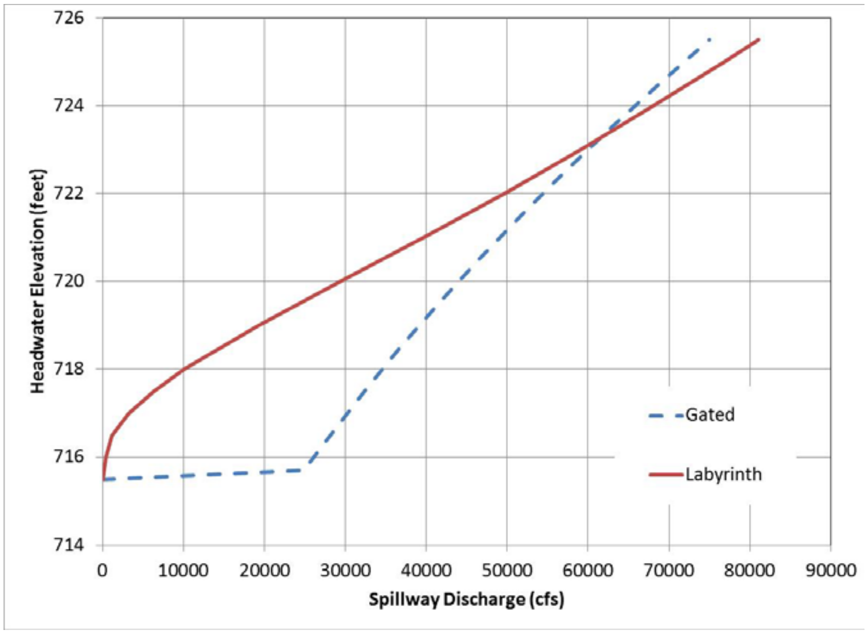


Figure 2. Lake Townsend discharge rating curves

For the Lake Townsend project, complete replacement of the gated spillway with a fixed crest labyrinth (Photo 7) reduced operational and hydrologic risks of the project. The need for complete replacement due to structural deterioration and concerns also made this a cost effective approach.

Photo 7. Lake Townsend Dam: Labyrinth spillway constructed downstream of original gated spillway

**Linville Land Harbor Dam**

Linville Land Harbor Dam, located in western North Carolina, is a high hazard dam owned and operated by the Linville Land Harbor Property Owners Association (POA). The dam was originally constructed in 1927, destroyed by floods in 1940, and was rebuilt in 1971. The concrete primary spillway, located at the left abutment, included five

Tainter gates and a 10-ft long fixed crest weir (Photo 8). Two gates were 16-ft wide and 12.1-ft high and three gates were 25-ft wide and 16.5-ft high. A concrete auxiliary spillway was located at the right abutment, with the crest set just above the normal pool.


Photo 8. Linville Land Harbor Dam: original spillways

Based on dam safety concerns related to significant deterioration of the spillway concrete (ASR) and gates, the State of North Carolina ordered the POA to lower the lake by about one foot until the structure was replaced or repaired. In addition, rigorous notification protocols were implemented so maintenance personnel could raise the gates in advance of floods to reduce stresses on the structure and provide hydraulic capacity.

Based on the significant deterioration of the structures, a complete replacement of the spillways was the preferred alternative. A fixed crest labyrinth spillway was found to be a cost effective replacement, eliminating the operation and maintenance issues related to the gates. A four cycle labyrinth weir (Photo 9) with a total width of 125-ft (included a single bay for low flow releases and drawdown) was found to have adequate discharge capacity to pass the design flood (about 25,000 cfs) without overtopping the embankment. If the original gated spillway could be operated such that all gates could be fully opened, the discharge capacity with the reservoir at top of dam would have been about 47,000 cfs, which is more than the required spillway design flood. However, based on past experience, it is unlikely that all of the gates could have been fully opened. The original auxiliary spillway had an estimated maximum capacity of about 8,000 cfs and if the gates could not be operated at all, the total capacity (flow overtopping gates plus auxiliary spillway) would have been about 16,500 cfs. However, there is a high probability that the gates would fail structurally under the high loads resulting from overtopping flow.


Photo 9. Linville Land Harbor Dam: labyrinth replacement spillway

Similar to the Lake Townsend project, the complete replacement of the gated spillway with a fixed crest labyrinth weir met regulatory criteria, reduced hydrologic and operational risks, and eliminated operation and maintenance costs related to the gates.

## HYPOTHETICAL REPLACEMENT EXAMPLE

To illustrate potential reduction in risks through replacement of a gated spillway with a fixed crest spillway, a hypothetical example was developed. The hypothetical dam is a flood control structure located on a 250 square mile watershed. The dam includes an outlet works structure for smaller releases and a gated overflow spillway. Properties of the dam are presented in Table 1.

Table 1. Hypothetical dam - properties

| | |
|---|---|
| Normal pool elevation | 1000 ft |
| Gated spillway fixed crest elevation | 1020 ft |
| Top of gates elevation | 1060 ft |
| Top of dam elevation | 1063 ft |
| Normal pool storage | 44,000 acre-ft |
| Top of dam storage | 137,400 acre-ft |
| Spillway gate width | 40 ft |
| Number of gates | 5 |
| Total effective spillway width | 200 ft |

A hypothetical gate operations plan was developed and used to develop a discharge rating curve. The operations plan was designed to reduce outflows for more “frequent” storms but still allow passage of the PMF with three feet of freeboard (i.e. PMF peak stage EL 1060). HEC-HMS was used to perform rainfall and runoff calculations and route flows through the reservoir and dam. This is considered a simplified model since dynamic gate operations were not included in the model. Results of the analysis for several storm events are presented in Table 2.

Table 2. Hypothetical results – gates operated per design

| Storm | Inflow (cfs) | Outflow (cfs) | Peak Stage (EL, ft) |
|---|---|---|---|
| 10-year | 14,660 | 624 | 1026.0 |
| 50-year | 24,870 | 4,947 | 1032.2 |
| 100-year | 30,030 | 7,306 | 1035.0 |
| 500-year | 44,610 | 22,110 | 1037.5 |
| 1000-year | 52,260 | 29,960 | 1038.8 |
| PMF | 174,200 | 153,300 | 1060.0 |

To evaluate potential risks resulting from mis-operation of the gates or possible inability to operate gate(s), two additional operational plans were considered and discharge rating curves developed. The first considered gate operations sooner than recommended (i.e. gates were opened when the reservoir reached a lower elevation). The results of this model are presented in Table 3.

Table 3. Hypothetical results – gates operated too early in storm*

| Storm | Outflow (cfs) | Peak Stage (EL, ft) |
|---|---|---|
| 10-year | 2,432 | 1022.1 |
| 50-year | 8,185 | 1026.8 |
| 100-year | 11,450 | 1028.9 |
| 500-year | 22,450 | 1033.7 |
| 1000-year | 28,540 | 1036.2 |
| PMF | 152,600 | 1059.9 |

* Inflow same as Table 2

As expected, the outflows for the smaller storms are higher than if the gates are operated as designed (Table 4). Outflow for the 100-year flood is 57 percent higher than for the "as designed" case.

For the second case, the rating curve was developed to simulate one inoperable gate and opening of the other gates as needed to pass the flows. As anticipated, for this example the gated spillway had inadequate capacity to pass the PMF, resulting in about one foot of overtopping of the dam.

To address the potential risks related to gate operations, a labyrinth spillway was sized to replace the gates and provide similar flood attenuation, but still have capacity to pass the PMF with three feet of freeboard. To meet these requirements, a rating curve was developed for a three cycle labyrinth with a weir height of 30 feet, crest EL 1040, and a total spillway width of 216 feet. This spillway was modeled within HEC-HMS; results for the various storms are presented in Table 4.

Table 4. Hypothetical results – labyrinth spillway

| Storm | Outflow (cfs) | Peak Stage (EL, ft) |
|---|---|---|
| 10-year | 50 | 1027.3 |
| 50-year | 1,888 | 1040.2 |
| 100-year | 6,549 | 1040.8 |
| 500-year | 19,780 | 1042.5 |
| 1000-year | 26,970 | 1043.5 |
| PMF | 161,200 | 1059.3 |

* Inflow same as Table 2

As shown, the labyrinth spillway results in similar or lower outflows for the return period storms but has adequate capacity to pass the PMF with the required freeboard. This would appear to be a reliable method for replacing the gated spillway.

The results for each of the scenarios are compared in Figures 3 and 4.

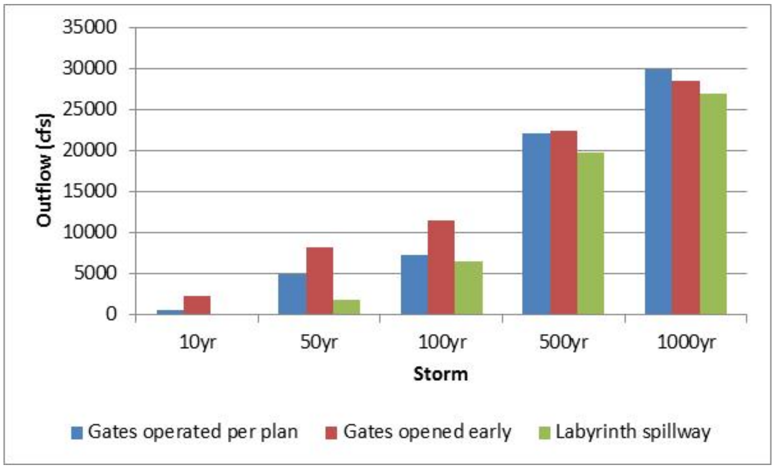


Figure 3. Hypothetical results – peak outflow

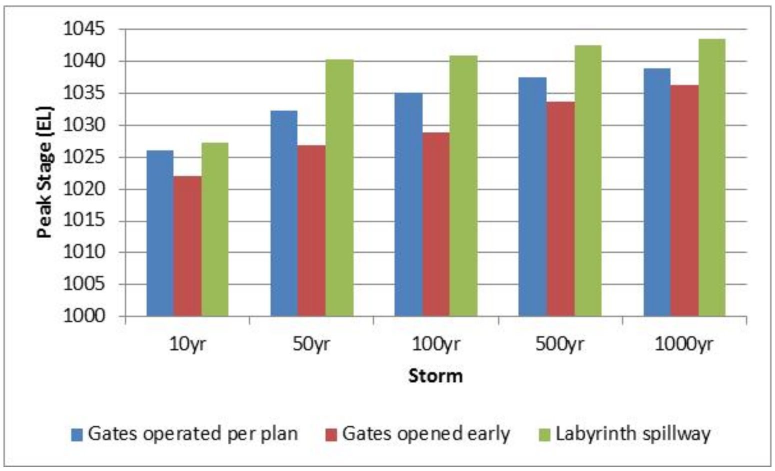


Figure 4. Hypothetical results – peak stage

Considering gate operations is considered critical to risk analysis. Figure 3 shows that operating the gates earlier than described in the plan would result in potential increased damages and loss of life for the smaller (higher probability) storm events (e.g. outflow for the 10- and 100-year events are 275 and 57 percent higher, respectively, than if the gates are operated per plan). The use of a fixed crest spillway to replace the gated structure would essentially eliminate the risks related to improper operation. However, for an embankment dam, it is possible that the labyrinth spillway could actually increase risks for geotechnical failure modes (e.g. internal erosion), since the higher peak stage would result in higher loadings for the more frequent (probable) events.

To be able to adequately consider risks, the probability of gate misoperation would need to be included in the event tree. Estimating the probability and type of misoperation presents a challenge in the risk analysis. Some insight with regard to this challenge could be gleaned through real-time emergency response testing with operations personnel.

It is important to note that this example is for a flood control dam, where even the misoperation of gates does not increase downstream consequences compared to the conditions before the dam was constructed. Another example could be evaluated for a gated spillway at a dam where flood control is not considered. For many of these structures, the gates are operated to maintain a given reservoir level through the storm (e.g. outflow = inflow). In this example, a misoperation of the gates could result in a significant increase in downstream damage over what would have occurred prior to the construction and operation of the dam.

## CONCLUSIONS

Gated spillway systems present challenges to dam owners and if improperly maintained, can contribute to a dam incident or failure. In addition, the operation of gates needs to balance considerations related to downstream flooding resulting from operations and the potential for reduced spillway capacity if gates are not operated, which could lead to a dam failure.

Regular maintenance, vigilant inspections and testing of operations, and training of staff will significantly reduce the risks related to spillway gates presented herein. Development of a realistic and easy to follow flood operations plan is also critical.

Control systems also present operational risks. While manual control at the site is the most common means for operation, it also presents the highest risks (USSD, 2002). Automating the controls will reduce these risks; however, the owner needs to consider the potential for issues related to automated controls where the owner is not on site to observe operations. Remote automated controls should be combined with alarms that notify the owner of operations.

In cases where significant dam upgrades are required to address spillway structural, hydraulic, or other deficiencies, it may be possible to replace the gated spillway with a fixed crest weir without significantly increase project cost. Labyrinth and piano key weirs provide a potential solution to achieve desired hydraulic performance. This solution has been used successfully for several projects. While complete replacement of the gated spillway would eliminate the risks related to gate operations, it may not be practical for all projects, particularly where gates are essential to the project purpose (e.g. hydropower or flood control) or the required spillway capacity is so large that fixed crest spillway cannot meet the requirements. In these cases, one solution is to supplement or replace a portion of the gated spillway with a labyrinth or piano key weir. To reduce reliance on gate operation for more frequent floods, the fixed crest weir crest could be set such that this passive spillway flows before gate operations are needed. This reduces the risk related to increased downstream flooding (even if only perceived) from misoperation and also would provide more time for the dam owner to reach the site to operate gates during larger storms. It also provides more time for decision making during a flood event.

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