

What Happens Downstream Stays Downstream, or Does It?

Potential Failure Modes from Spillway Exit Flows

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Abstract – In recent years, several serious incidents occurred at embankment dams which highlight the importance of evaluating and understanding spillway exit flow conditions at dams. In all cases, the peak spillway flows during these incidents were significantly less than the design flood flows; and although the spillways performed satisfactorily, the outflows from the spillways led to significant erosion and near breaching of the dam embankments or adverse impacts to the outlet works. In most cases, had the spillway design flows occurred, they would have likely resulted in complete breaching and catastrophic failure of the dams.

This paper presents the lessons learned from several case studies and discusses several failure mechanisms related to exit flows from spillways. Inspection techniques and modeling tools that are available to engineers to evaluate downstream spillway flow conditions and their potential to adversely impact embankment dams will also be discussed.

I. INTRODUCTION

In recent years, several serious incidents have occurred at embankment dams which highlight the importance of evaluating and understanding spillway exit flow conditions at dams. In all cases, the peak spillway flows during these incidents were significantly less than the design flood flows but still resulted in near breaching of the dam embankment, breaching of the spillway, or significant impairment of dam performance.

A potential failure mode is “a physically plausible process for dam failure resulting from an existing inadequacy or defect related to a natural foundation condition, the dam or appurtenant structures design, the construction, the materials incorporated, the operations and maintenance, or aging process, which can lead to an uncontrolled release of the reservoir.” (FEMA, 2003) Potential failure modes created or exacerbated by spillway exit flows can be categorized in one of the three following failure mechanisms:

1. Undermining or erosion of the spillway or exit channel
2. Erosion of the embankment
3. Impaired outlet works or spillway performance due to elevated tailwater conditions

An infinite number of potential failure modes could be identified for any one of these failure mechanisms for a given dam. The following sections provide a description of these three failure mechanisms as well as examples of how a potential failure might progress.

II. UNDERMINING OR EROSION OF THE SPILLWAY OR EXIT CHANNEL

Regardless of spillway type, outlets of spillways are subject to undermining and erosion if energy is not adequately dissipated. Failure of concrete or masonry lined channels, retaining walls, chutes, or stilling basins can subsequently lead to headcutting, erosion, or undermining of the spillway control section resulting in an uncontrolled release of reservoir storage. In some cases, such failures could also result in exposure of a dam embankment to spillway flows resulting in erosion of the embankment from the downstream side.

Earth or rock cut spillways are also susceptible to headcutting and erosion through the spillway, especially if discontinuities occur within the spillway exit channel or outlet. These discontinuities consist of roadways, drainage swales, fences, and ruts due to pedestrian or vehicular traffic among other things. These features can act as pre-existing headcuts at the spillway outlet and concentrate flow in a manner that accelerates erosion of the spillway. If spillway subsurface materials are erodible, this headcutting process can progress upstream through the spillway crest resulting in an uncontrolled release of reservoir storage. Headcutting of an earth cut spillway or exit channel can also undermine flow dikes or training walls, thereby endangering the embankment as flows escape the intended spillway channel and are directed towards the embankment.

A. Case Study: Ulley Dam, Yorkshire, England (2007)

Ulley Dam is a former water supply dam that is now used for recreation. In late June 2007, a flood with a roughly 200-year return period occurred at the dam. The spillway chute consisted of a series of cascades and plunge pools contained on each side by masonry training walls, and extended from the left abutment down the abutment contact to the natural stream channel. During the flood, velocities and turbulence in the spillway chute were so great that masonry blocks were plucked out of the wall, ultimately causing failure of the right training wall. Once the wall had failed, erosion of the adjacent embankment material ensued. Though flows subsided prior to complete failure of the dam embankment, officials did evacuate downstream areas as a precaution.

B. Case Study: Silver Lake Dam, Marquette County, Michigan (2003)

Silver Lake Dam was originally constructed in 1896. It is a 1,500-foot-long, 30-foot-high embankment dam used for water storage for downstream hydroelectric facilities. Upgrades were completed to the dam in 2002 in order to increase the spillway capacity to be able to pass the Probable Maximum Flood. These upgrades consisted of installing 5.5-foot-high fuse plugs in the emergency spillway and raising the dam embankment. On May 14, 2003, a 5- to 10-year recurrence interval flood occurred at the dam which activated the fuse plug emergency spillway. Rather than simply eroding the fuse plugs as intended, the channel downstream of the emergency spillway experienced significant erosion that progressed up through the spillway and into the reservoir. The final eroded spillway breach depth was 25 feet below the foundation of the fuse plugs. Outflows from the failed spillway caused evacuation of 1,700 people and more than \$100 million in damages. Because an Emergency Action Plan was in place and promptly executed, no fatalities occurred.



Figure 1. Channel cut through the Silver Lake Dam emergency spillway, looking upstream (Photo courtesy of FERC)

C. Case Study: Upper Sherando Dam, Augusta County, Virginia (2003)

Upper Sherando Dam was constructed by the Soil Conservation Service in 1958 for flood control purposes. In 1961, ownership of the dam was transferred to the U.S. Forest Service. On September 19, 2003, remnants of Hurricane Isabel caused significant flooding in the area of the dam. The auxiliary spillway, which had never previously been activated, experienced flow that was only a few inches deep. As a result of this flow through the spillway, the downstream exit channel which runs along the toe of the dam embankment experienced significant erosion with depths extending more than 20 feet in some places. Had flows continued or been greater in magnitude, significant erosion and failure of the embankment could have been possible.



Figure 2. Auxiliary spillway discharge channel before (TOP) and after (BOTTOM) initial activation of the spillway, looking upstream (Photos courtesy of Tom Roberts, VA DCR)

D. Case Study: Black Creek Site No. 53 Dam, Mississippi (1983)

Black Creek Dam is an NRCS flood control structure located in Holmes County, Mississippi. In May 1983, 14 inches of rain fell in the dam's watershed resulting in significant flows through the earth cut auxiliary spillway. At the time of the flood, the spillway was vegetated with grass that was in good condition, and no major discontinuities existed within the spillway. As-built profiles of the spillway indicate that a field road crossed the spillway exit channel perpendicular to the flow, forming two sharp drops (See Figure 3). These drops were determined to be the points of primary attack and initial headcut formation. The spillway, which was originally 5 feet deep and 100 feet wide, eroded to a depth of 40 feet and 160 feet wide. In all, about 4,500 acre-feet of water was released from the reservoir, and 187,000 cubic yards of material was eroded and deposited in the downstream river reach. Downstream roadways were severely damaged, but no loss of life occurred.

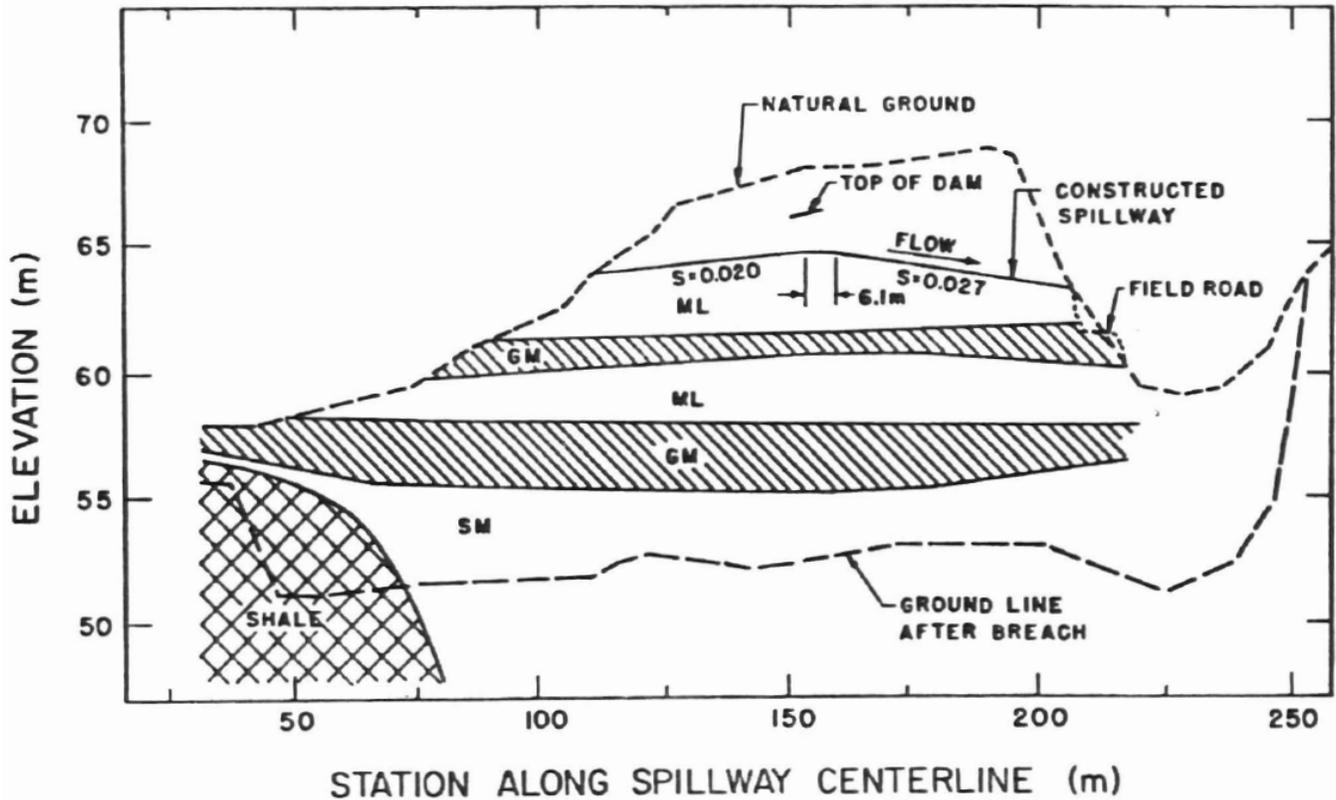


Figure 3. As-built profile of the auxiliary spillway at Black Creek No. 53 Dam. Note the “field road” excavated into the exit slope of the spillway (Figure courtesy of Darrell Temple).



Figure 4. Overview of the failed auxiliary spillway at Black Creek No. 53 Dam (Photo courtesy of Darrell Temple).

III. EROSION OF THE EMBANKMENT

When designing the downstream exit channel, it is important to consider possible unusual flow conditions that could cause the spillway flow to meander, change direction, and return to erode the dam embankment. This condition is not always evident as the subsurface geologic features that can cause this condition can be complex and not well defined. For many existing dams, the original spillway design was based upon simplified computational methods that neglected the complex, three-dimensional nature of spillway outflows. Because of this, a common oversight is the lack of consideration of flow conditions that may endanger the dam. If flows are redirected towards the dam and are significant in magnitude or duration, then erosion of the downstream slope of the dam embankment can occur. Unanticipated erosion or headcutting of the downstream spillway channel can also lead to redirection of flows towards the dam. Dam designers and inspectors need to be aware of this potential failure mode when assessing or designing dams.

A. Case Study: Sugar Creek Dam (L-44), Caddo County, Oklahoma (2007)

On the weekend of August 18-19, 2007, tropical depression Erin swept across Oklahoma. Rainfall amounts fell in parts of Caddo County that greatly exceeded that of a 100-year frequency storm. Preliminary measurements of the rainfall in the drainage area above Sugar Creek Dam L-44 indicate that over eight inches of rain fell in less than 12 hours and activated the auxiliary spillway. Flows from the auxiliary spillway were discharged beyond the toe of the earth embankment, but returned after encountering the Highway 81 road embankment to erode the downstream slope of the dam and nearly breach the dam. Backwater from debris plugging the culvert under Highway 81 may have contributed to the unusual flow conditions. Ultimately, the erosion advanced through more than half of the width of the dam embankment crest. Had spillway flows continued much longer, the dam would have failed due to erosion and instability of the remaining embankment material.



Figure 5. Photograph showing the erosion in the downstream slope of Sugar Creek Dam in Caddo County, Oklahoma (Photo courtesy of Danny McCook).



Figure 6. Photograph showing the flow path and erosion in the downstream slope of Sugar Creek Dam in Caddo County, Oklahoma (Photo courtesy of Danny McCook).

IV. IMPAIRED OUTLET WORKS OR SPILLWAY PERFORMANCE DUE TO ELEVATED TAILWATER CONDITIONS

Tailwater conditions downstream of a dam can negatively affect dam performance and potentially contribute to failure in many ways. For example, elevated tailwater levels can hinder operation or decrease the capacity of lake drain appurtenances and hydroelectric facilities. Localized increases in tailwater could also impact the functionality of certain types of spillways (e.g. fuse plugs, fuse gates, or flashboards) or could cause submergence of uncontrolled spillways resulting in decreased spillway capacity and increased risk of overtopping. On the other hand, lower than anticipated tailwater levels can reduce the effectiveness of stilling basins or other energy dissipaters, thereby increasing the risk of scour and erosion downstream of these facilities.

Furthermore, it is important to consider how tailwater conditions may change over time due to natural or man-made conditions downstream. For example, the construction of new road embankments or culvert replacements, the building of beaver dams and other natural obstructions, or the buildup of sediment in downstream channels due to erosion problems at the dam may result in significant and even sudden changes in tailwater conditions.

A. Case Study: Oroville Dam, Oroville, California (2017)

Oroville Dam is a hydroelectric dam constructed in the 1960's. At 770 feet tall, it is the tallest dam in the United States. The concrete main spillway chute at Oroville Dam experienced failure during a period of heavy rainfall and runoff in February 2017. Subsequent flows through the damaged main spillway and the activation of the emergency spillway resulted in significant erosion and deposition of more than 1.7 million cubic yards of material in the Thermalito Diversion Pool and the downstream reach of the Feather River. These deposits created a significant tailwater condition at the tailrace of the Hyatt Powerplant, Oroville Dam's hydroelectric generation facility, rendering the powerplant inoperable. Although the crisis was averted by diverting flows through the damaged main spillway, it is important to note that the three primary means of diverting flow through or around the dam were simultaneously damaged or rendered inoperable. When runoff subsided and the main spillway was able to be closed, crews worked around the clock to clear a path through the material obstructing the downstream channel. This was done in order to lower the tailwater at the Hyatt Powerplant rendering it usable once again.



Figure 7. Debris removal in the diversion pool below Oroville Dam with the damaged principal spillway in the background. (Photo courtesy of CA DWR).

V. SPILLWAY DESIGN AND ASSESSMENT TOOLS

Recent advances in hydraulic modeling and spillway integrity analysis software enable engineers to more effectively identify potential failure modes due to spillway outflows than was previously possible. For example, two- and three-dimensional hydraulic models allow engineers to analyze complex flow patterns for a wide range of flow conditions based on existing or proposed terrain. These analyses can be helpful in identifying areas of high velocity that may be more susceptible to erosion. They can also be used to ensure that outflows are directed away from the dam embankment and to estimate anticipated tailwater conditions at the dam. In addition to these hydraulic models, the NRCS has developed SITES and WinDAM software that include the ability to analyze the integrity of geologic profiles through both earth/rock cut spillways and embankments. These are powerful tools to estimate the magnitude of erosion that would occur during a flood and to identify spillways that may be susceptible to failure should the design flood occur.

Above all, it is important for engineers who design, assess, and inspect dams to be aware of these potential failure modes and consider their applicability to a specific dam site. The potential for complex flow conditions or significant erosion can often be identified as part of a site visit or a review of design drawings and documentation. Once the potential failure mode is identified, it can be investigated and validated through additional analysis.

VI. CONCLUSION

Spillway exit flow conditions at dams can cause damage to or even failure of embankment dams. There have been many cases where flows that were significantly less than the design flood resulted in near breaching of the dam embankment, breaching of the spillway and an uncontrolled release of reservoir storage, or significant impairment of dam performance. The potential conditions can often be identified during site visits or by reviewing design drawings and documentation. The application of recent advances in hydraulic modeling and spillway integrity analysis software can facilitate the identification of these potential failure modes.

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